WHITE PAPER SERIES

Paper 1

Are Cannabis-Derived Terpenes Actually Different from Botanical Terpenes?

Isomerism and Stereochemistry in Cannabis Essential Oil

Nexus Agriscience

2026

I. Executive Summary

The term "isomer" is seldom heard in cannabis-product marketing. What you do hear are claims that botanically derived terpenes — limonene from oranges, linalool from lavender, β-pinene from turpentine — are chemically identical to the terpenes cannabis produces, and therefore interchangeable with them. On the surface, these claims have merit: the chemical compound called limonene does exist in both oranges and cannabis. Look closer, through the lens of stereochemistry, and the picture changes.

This paper presents chiral gas-chromatography data from three Nexus Agriscience hemp cultivars, two leading commercial "cannabis terpene" mimic products, and several authentic botanical essential oils. Across the most important chiral monoterpenes — limonene, linalool, and β-pinene — the cannabis samples cluster together at one stereochemical signature, and the commercial mimic products cluster with the commodity botanical sources at the opposite signature.

Cannabis produces approximately 95–96% S-(l)-limonene; the mimic products contain 97–99% R-(d)-limonene, the form found in citrus peel oil. Cannabis produces 96–98% S-(+)-linalool; the mimics contain 90–97% R-(−)-linalool, the form found in lavender. Cannabis β-pinene contains 15–28% of the (+)-enantiomer; the mimics contain only 3–4%, matching pine-derived turpentine. Principal Component Analysis of the full 11-compound stereochemical dataset shows the cannabis samples occupying a region of chemical space all their own.

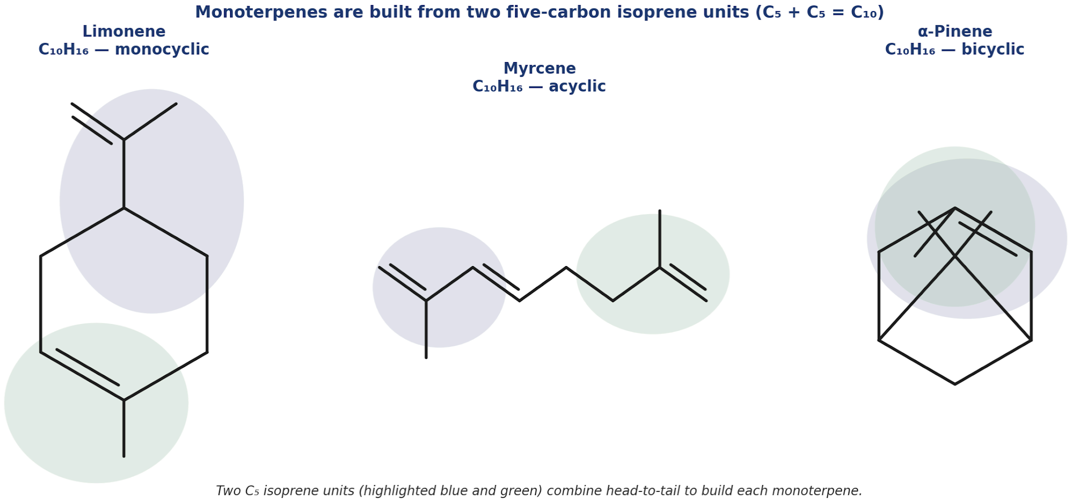
These differences matter because stereoisomers — molecules with the same atoms and the same connectivity but different three-dimensional arrangements — interact with biological receptors and olfactory pathways differently. The chiral signature of cannabis terpenes is not an arbitrary detail. It is the chemical record of the enzymes that built them.

II. Introduction

Cannabis essential oil is a chemical mosaic. The fragrance, flavor, and pharmacology that the cannabis plant produces emerge from dozens of terpenes and terpenoids combining at concentrations that span four orders of magnitude — from the major monoterpenes (limonene, myrcene, β-pinene) present at percent-level abundance, down through the sesquiterpenes (β-caryophyllene, humulene, bisabolol), the oxygenated terpenoids (linalool oxides, terpinen-4-ol, α-terpineol), and finally the volatile thiols and esters that contribute disproportionately to cultivar identity at parts-per-million.

All of these compounds are built from a common five-carbon building block called the isoprene unit. Two isoprene units (5 + 5 = 10 carbons) combine head-to-tail to make a monoterpene;

three units (15 carbons) build a sesquiterpene; and so on. The atoms are the same in every case — only the way they are arranged differs.


Monoterpenes are built from two five-carbon isoprene units ($C_5 + C_5 = C_{10}$)

Two C_5 isoprene units (highlighted blue and green) combine head-to-tail to build each monoterpene.

Figure 1. Three common monoterpenes (limonene, myrcene, α-pinene) all share the molecular formula $C_{10}H_{16}$, built from two C_5 isoprene units (highlighted blue and green). They differ in how those building blocks are connected.

Botanical flavoring companies have built their businesses on recreating the major-compound profiles of popular cannabis cultivars using terpenes sourced from non-cannabis feedstocks: limonene from citrus peel, linalool from lavender, β-pinene from pine turpentine. The marketing claim that supports this industry is that any given molecule called "limonene" is the same molecule regardless of where it comes from.

That claim is partially correct. The molecular formula $C_{10}H_{16}$ that we call limonene is indeed the same in both sources. But this paper documents a finding that becomes obvious under chiral analysis: the specific three-dimensional form of limonene in cannabis is not the same as the form in oranges. The two are mirror images of each other — distinct molecules with distinct biological behavior.

To explain what this means and why it matters, the first half of this paper sets up the chemistry: what isomerism is, what kinds of isomers exist, how stereochemistry is named and measured. The second half presents Nexus Agriscience's chiral gas-chromatography data, compares it to commercial mimic products and to natural botanical sources, and explains why the differences arise.

III. What Is Isomerism?

When you see designations like d/l, +/−, R/S, cis/trans, or α/β on a terpene analysis report, those letters are not random. They are precise notations identifying which isomer of a compound is present. To understand what they mean, we need to start with the chemistry of bonds.

A. Carbon, bonds, and how molecules are drawn

Carbon is the backbone of all organic molecules — including every terpene in cannabis. A carbon atom has four valence electrons, meaning it can form four bonds to other atoms by sharing electron pairs. A single bond is a single shared pair of electrons. A double bond is two shared pairs. A triple bond is three. The geometry around a carbon depends on what types of bonds it has: single bonds allow free rotation around themselves, double and triple bonds are rigid.

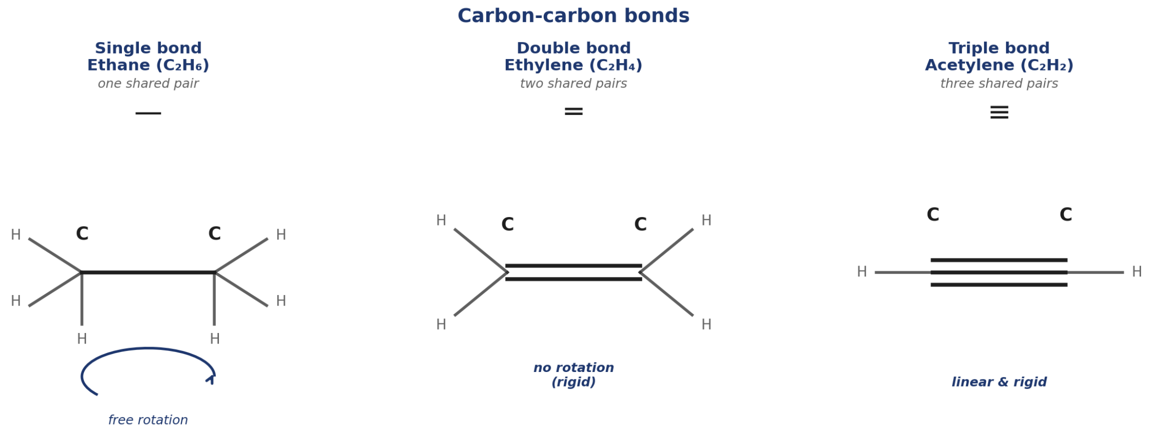
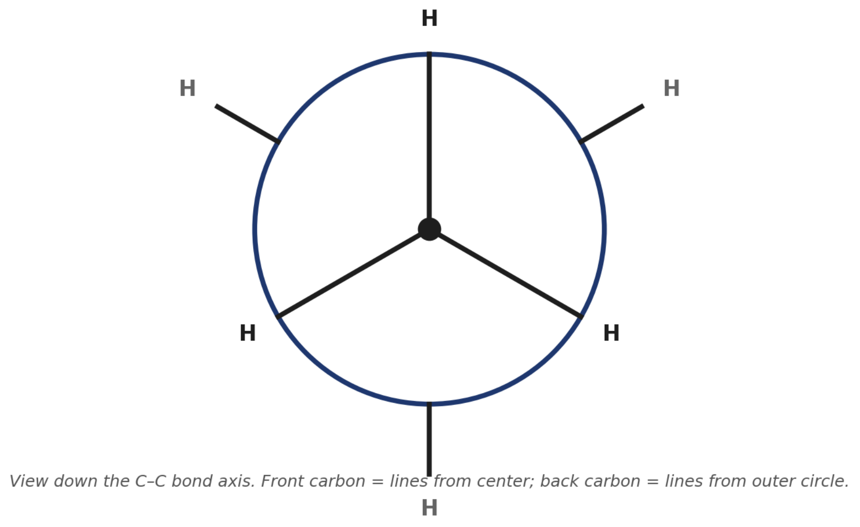


Figure 2. Single, double, and triple carbon-carbon bonds illustrated with ethane (C_2H_6), ethylene (C_2H_4), and acetylene (C_2H_2). Single bonds permit free rotation; double and triple bonds are rigid.

When carbons are connected by single bonds, the molecule can flex and rotate freely around each bond. A useful way to visualize this rotation is the Newman projection, which looks straight down the axis of a single bond:


Newman projection — Ethane (staggered)

View down the C–C bond axis. Front carbon = lines from center; back carbon = lines from outer circle.

Figure 3. Newman projection of ethane (C_2H_6) in the staggered conformation. The lines from the center represent bonds on the front carbon; the lines from the outer circle represent bonds on the back carbon. The bond between them can rotate freely.

Carbons can also form rings. Cyclohexane (C_6H_{12}) is six carbons in a ring, all connected by single bonds. The ring as a whole is rigid even though each bond can flex.

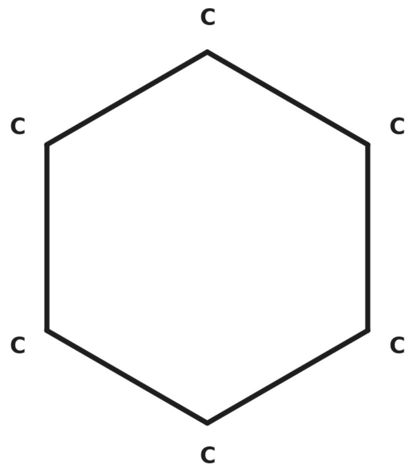

Cyclohexane (C_6H_{12})
Six carbons in a ring — rigid, no rotation around the ring

Figure 4. Cyclohexane. Six carbons connected in a ring — each ring carbon is fixed in place because it is bonded to two other ring carbons.

B. Structural (constitutional) isomers

Structural isomers are molecules that share the same molecular formula but differ in the connectivity of their atoms — that is, which atom is bonded to which. Most cannabis monoterpenes share the molecular formula $C_{10}H_{16}$, but they are structural isomers of one another. Limonene has a six-carbon ring with a methyl substituent and an isopropenyl group. Myrcene is acyclic — no ring at all, just a chain. α- and β-pinene are bicyclic, with two fused rings (see Figure 1 above for the structures).

C. Geometric isomers (cis/trans)

Geometric isomers — also called cis/trans isomers, or sometimes E/Z under the more modern nomenclature — arise around rigid structures like double bonds or rings. Because a double bond cannot rotate, the substituents on either side of it are locked into either the same side (cis, Latin for "on the same side of") or opposite sides (trans, Latin for "across"). The smallest molecule that illustrates this is 2-butene:

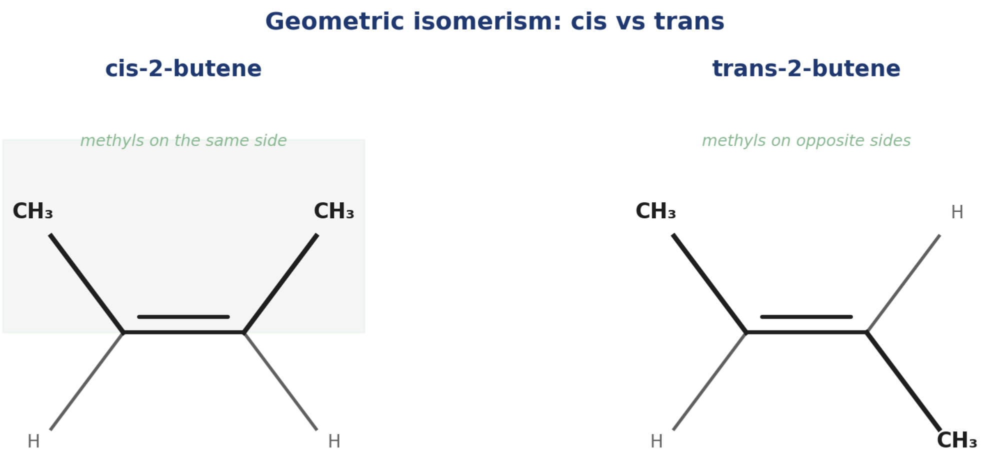


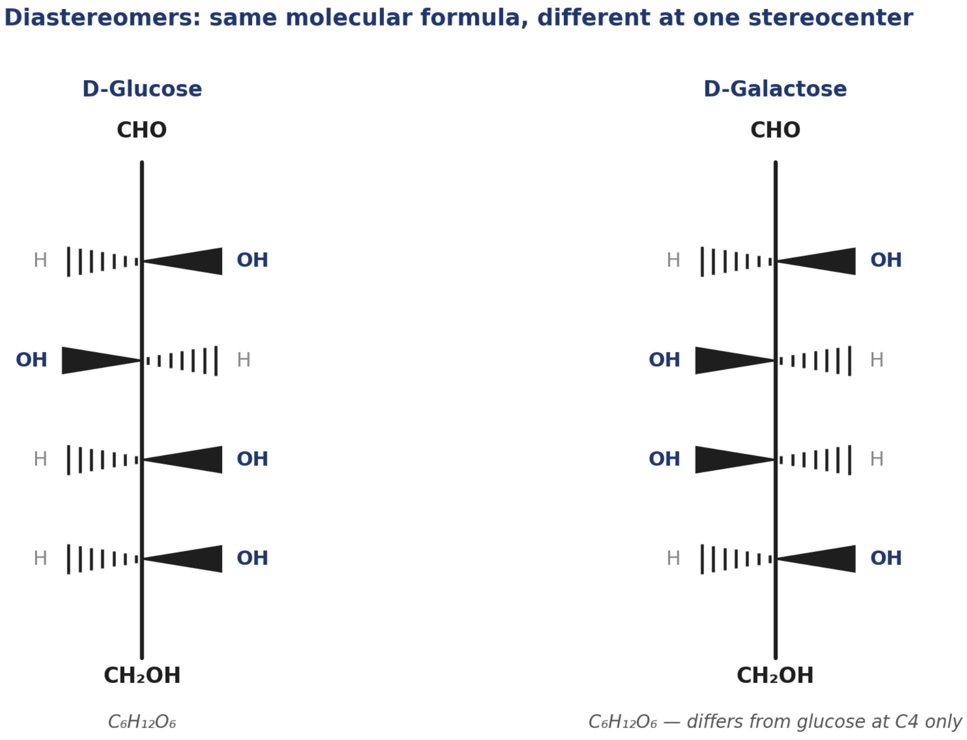
Figure 5. Cis- and trans-2-butene. The two methyl groups are forced onto the same side or opposite sides of the central double bond because the C=C cannot rotate. Same atoms, same connectivity, but two distinct compounds.

A note on nomenclature that the cannabis literature sometimes gets wrong: the prefixes α (alpha) and β (beta) refer to structural isomers in terpene chemistry, not geometric isomers. α-Pinene and β-pinene are structural isomers — the double bond is in a different position in the ring system. Cis- and trans-β-ocimene are geometric isomers of the same structural isomer (β-ocimene). These are distinct concepts and should not be conflated.

D. Stereoisomers, diastereomers, and enantiomers

Stereoisomers share both molecular formula and atom-to-atom connectivity, but differ in three-dimensional arrangement. Geometric isomers are one subtype. The other two main subtypes are diastereomers and enantiomers.

Diastereomers are stereoisomers that are not mirror images of each other and that have different physical properties (different boiling points, different solubilities, different chromatographic behavior). They are uncommon among the major cannabis monoterpenes, but they exist among more complex terpenes — β-caryophyllene has multiple stereocenters and its various diastereomers differ in biological activity. In organic chemistry, diastereomers are commonly illustrated with simple sugars:


Diastereomers: same molecular formula, different at one stereocenter

D-Glucose

$C_6H_{12}O_6$

D-Galactose

$C_6H_{12}O_6$ — differs from glucose at C4 only

Figure 6. D-Glucose and D-galactose are diastereomers. They share the molecular formula $C_6H_{12}O_6$ and differ only in the orientation of the hydroxyl group at one carbon (C4), but the two sugars taste different and are metabolized differently.

E. Enantiomers and chirality

Enantiomers are stereoisomers that are non-superimposable mirror images of each other. They share nearly all physical properties — same boiling point, same density, identical NMR spectra in achiral solvents — except for two: they rotate plane-polarized light in opposite directions, and they interact differently with other chiral molecules (which means, in biological terms, that they bind differently to receptors and enzymes).

A molecule is chiral when it has at least one carbon atom bonded to four different substituents. That carbon is called a stereocenter or a chiral center. The smallest possible chiral molecule is one carbon bonded to four different atoms — for example, bromochlorofluoroiodomethane (CHFClBrI). There are exactly two non-superimposable mirror-image arrangements of those four atoms around the central carbon, and they are different molecules:

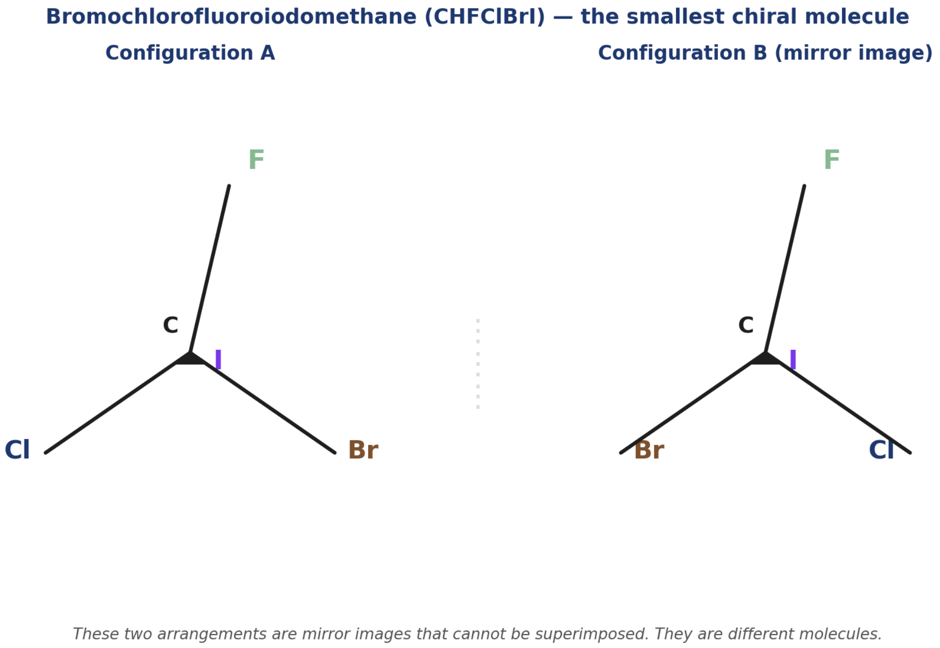
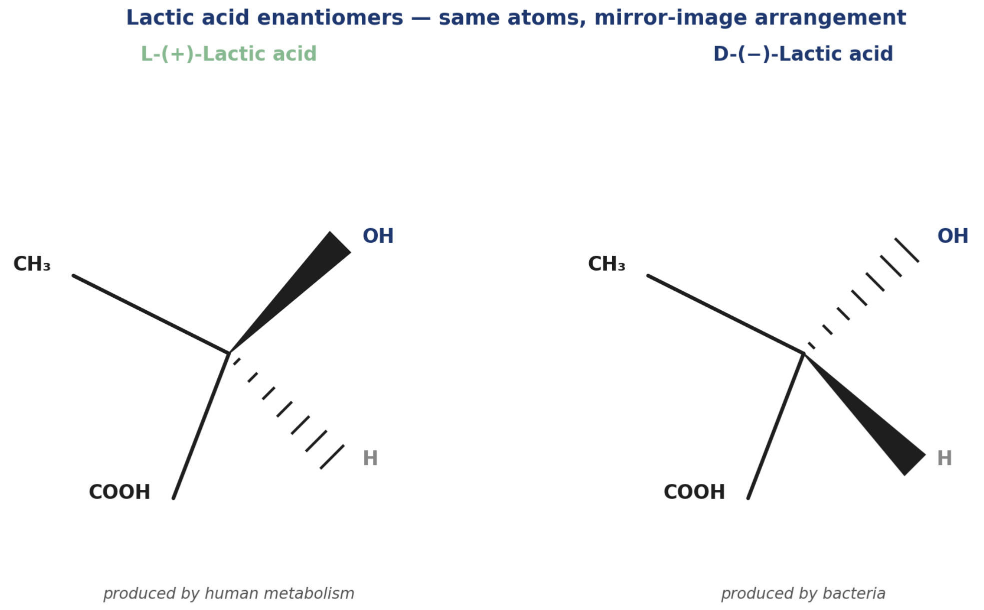


Figure 7. The smallest chiral molecule: one carbon bonded to four different atoms (F, Cl, Br, I). The two arrangements are mirror images that cannot be superimposed.

A familiar everyday analogy: a person's right and left hands are mirror images of each other but cannot be superimposed. This is why chirality is often called "handedness."

Chirality is everywhere in living systems. Lactic acid exists as two enantiomers: L-lactic acid is produced by human metabolism, while D-lactic acid is produced primarily by bacteria. Amino acids are predominantly the L-form in proteins; D-amino acids are biologically rare. Sugars come predominantly in one chirality. And, critically for this paper: many terpenes are chiral, and the enantiomer that cannabis produces is often not the enantiomer that the global commodity supply chain delivers.



Lactic acid enantiomers — same atoms, mirror-image arrangement

L-(+)-Lactic acid

D-(−)-Lactic acid

produced by human metabolism

produced by bacteria

Figure 8. L- and D-lactic acid — chemically identical except for the spatial arrangement around the central chiral carbon. L-lactic acid is the form found in human metabolism; D-lactic acid is produced by bacteria.

IV. Naming Conventions in Stereochemistry

Three naming systems are commonly used for chiral molecules in essential-oil chemistry. They describe the same underlying property — handedness — but use different conventions, and they don't always line up the way one might expect.

The d/l system

The d (dexter, Latin for "right") and l (laevus, Latin for "left") designators come from a 19th-century convention that compares a chiral compound's spatial arrangement to the reference molecule glyceraldehyde. The dextrorotatory form of glyceraldehyde was assigned the "d" label; the levorotatory form was "l." For a given compound like limonene, the d- or l- prefix indicates which configuration matches the d- or l- form of glyceraldehyde at the analogous chiral center.

The (+)/(−) system

The plus and minus designators come from experimental optical rotation: a (+) compound rotates the plane of polarized light clockwise as seen by an observer looking back at the source; a (−) compound rotates it counter-clockwise. This is the only one of the three systems that uses an experimental measurement rather than a structural rule, and it is the convention most widely used in the flavor and fragrance industry.

The R/S system

The R (rectus, Latin for "right") and S (sinister, Latin for "left") designators come from a formal rule (the Cahn–Ingold–Prelog priority rules) applied to each chiral center. Each substituent around the chiral carbon is ranked by atomic priority, and the configuration is named R or S based on whether those priorities trace a clockwise or counter-clockwise path. This is the modern systematic convention and the one published organic-chemistry literature uses.

A subtlety worth noting: the three systems don't always agree on the sign. For example, (−)-linalool is the R-enantiomer, but (−)-β-pinene is the S-enantiomer. The mapping between (+)/(−) and R/S depends on the substituent priorities at the chiral center, which differ from compound to compound.

V. Chirality and Biology

Chirality matters in living systems because nearly all biological receptors, enzymes, and signaling molecules are themselves chiral. They are built from L-amino acids that fold into chiral three-dimensional shapes, and like a hand fitting a glove, they interact selectively with the matching enantiomer of a small-molecule ligand.

The standard analogy for this is the lock and key. A right-handed key opens a right-handed lock; the mirror-image key, even though it is otherwise identical, does not fit. In the same way, a (+)-enantiomer of a small molecule may bind one receptor strongly, while its (−)-counterpart may bind the same receptor weakly, not at all, or to a different receptor entirely.

Real-world examples are well documented in pharmaceutical chemistry. Thalidomide's (R)-enantiomer was a safe sedative, while its (S)-enantiomer caused birth defects. (R)-(−)-Albuterol is the active bronchodilator in inhalers; its (S)-(+)-enantiomer is inactive. (S)-(+)-Ketamine is a more potent anesthetic than its (R)-(−)-counterpart and the two have different psychoactive profiles. Drug development now routinely tracks and separates enantiomers because the two forms can behave like entirely different molecules.

The same principle applies to terpenes. Three specific cases are well-documented:

Limonene enantiomers

Sun (2007) reviewed the bioactivity of d-limonene (the (R)-(+)-enantiomer, found in citrus), noting its chemopreventive and anticancer properties in rodent models. The mirror-image l-limonene ((S)-(−)-form, the form dominant in cannabis) has received far less research attention, and there is no published evidence that it produces equivalent biological outcomes.

Linalool enantiomers

Höferl, Krist, & Buchbauer (2006) measured the effects of (+)- and (−)-linalool inhalation on physiological stress markers in human subjects. Both enantiomers reduced cortisol levels, but the cardiovascular effects diverged: (+)-linalool tended to activate heart rate and blood pressure, while (−)-linalool tended to reduce heart rate. Aprotosoaie and colleagues (2014), in a comprehensive review of linalool pharmacology, reported that (−)-linalool exhibits stronger sedative, stress-relieving, anticonvulsant, and anti-inflammatory effects than (+)-linalool, while (+)-linalool is generally less potent and can even produce mild activating cardiovascular effects.

Pinene enantiomers

Rivas da Silva and colleagues (2012) evaluated the biological activities of the (+)- and (−)-enantiomers of both α- and β-pinene. The (+)-enantiomers demonstrated potent antimicrobial activity against pathogenic fungi (Candida albicans, Cryptococcus neoformans) and against methicillin-resistant Staphylococcus aureus. The (−)-enantiomers, even at substantially higher concentrations, showed no comparable activity. This is a categorical functional difference — the same molecule with the same molecular formula, but only one mirror image is biologically active in this assay.

Stereochemistry, in other words, is not a curiosity. It is the difference between a compound that does something biologically and a compound that does not.

VI. The Major Chiral Terpenes of Cannabis

Three monoterpenes — limonene, linalool, and β-pinene — are the most consequential chiral compounds in cannabis essential oil.

A. Limonene

Limonene is the chiral monoterpene most familiar to consumers, because the d-form gives orange peel its characteristic aroma. It exists as two enantiomers: d-limonene (R-(+)-limonene) with a sweet, citrus character, and l-limonene (S-(−)-limonene) with a sharper, piny, turpentine-like character.

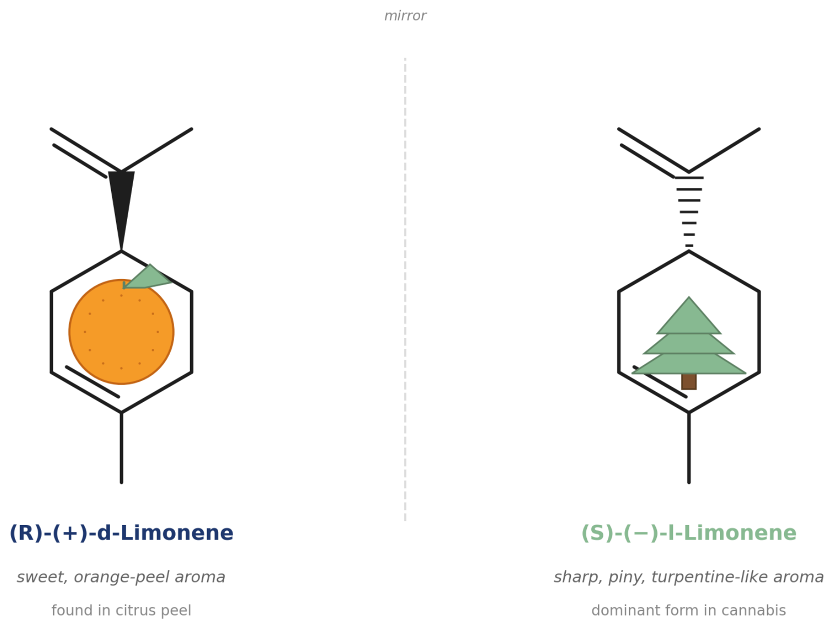


Figure 9. The two enantiomers of limonene. (R)-(+)-d-limonene (left) is the form found in citrus peel. (S)-(−)-l-limonene (right) is the dominant form in cannabis. The structures differ only in the orientation of the isopropenyl group at the chiral center.

Cannabis predominantly produces l-limonene. Citrus predominantly produces d-limonene. This single fact, more than any other, is what chiral analysis of cannabis-mimic products reveals.

B. Linalool

Linalool is the chiral monoterpene most associated with floral and lavender notes. It exists as two enantiomers: (−)-linalool (R-(−)-licareol), the form abundant in lavender oil; and (+)-linalool (S-(+)-coriandrol), found principally in coriander seed oil.

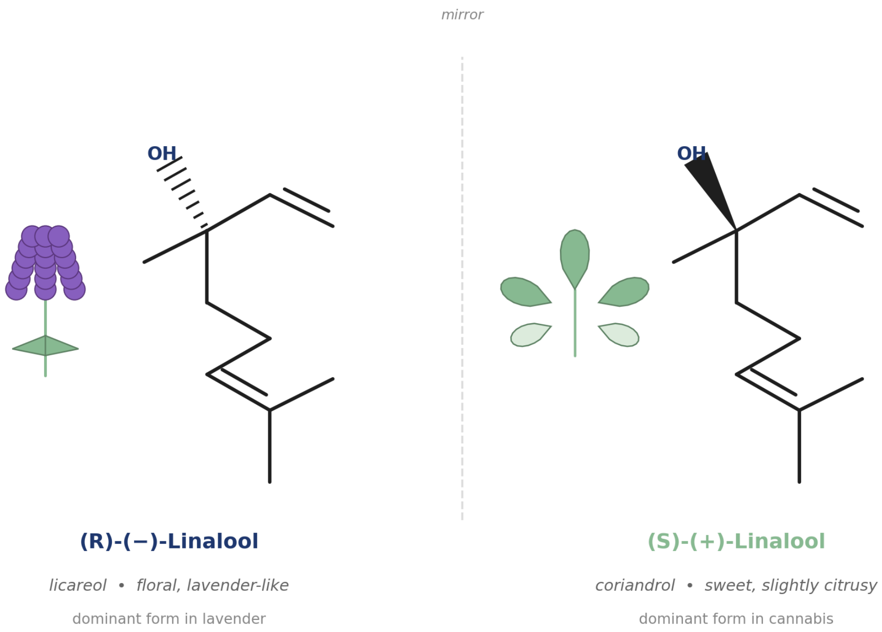


Figure 10. The two enantiomers of linalool. (R)-(−)-linalool (left) is dominant in lavender oil. (S)-(+)-linalool (right) is the dominant form in cannabis.

Cannabis predominantly produces (+)-linalool. Lavender produces predominantly (−)-linalool. Synthetic linalool, manufactured by chemical hydration of myrcene, is racemic (50/50). None of these three commodity sources delivers cannabis-matching material.

C. Pinene (α and β; β-pinene enantiomers)

Pinene exists in two structural forms — α-pinene and β-pinene — that differ only in the position of the double bond in the bicyclic ring system.

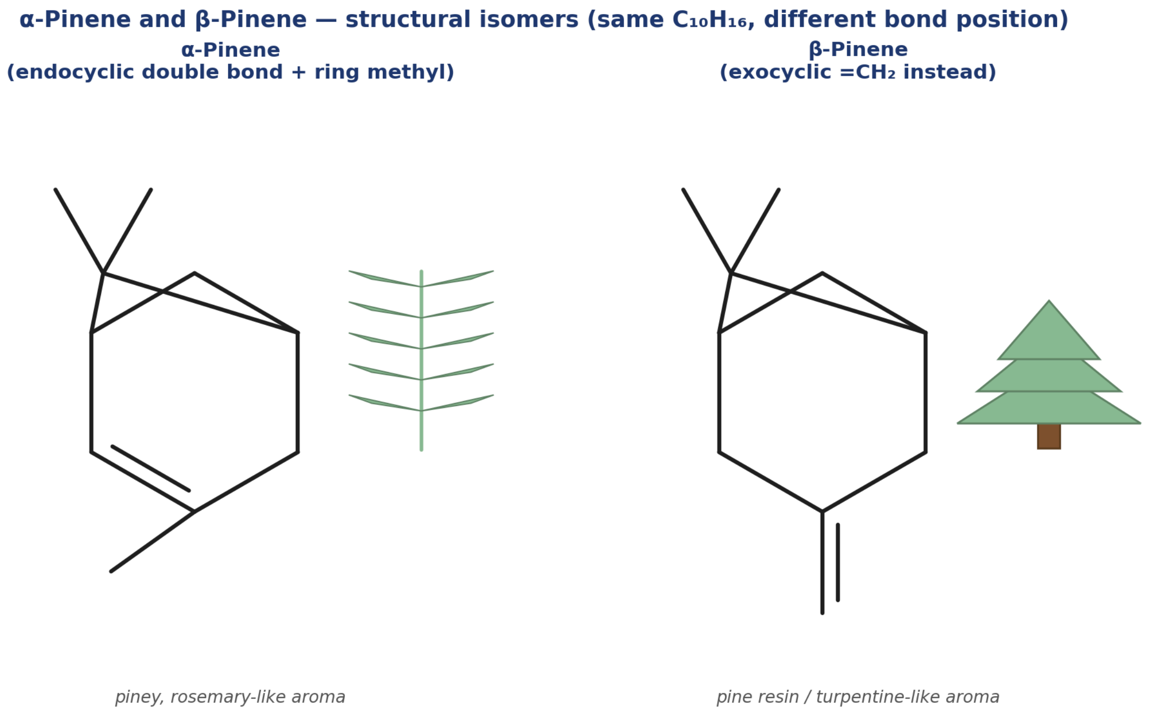
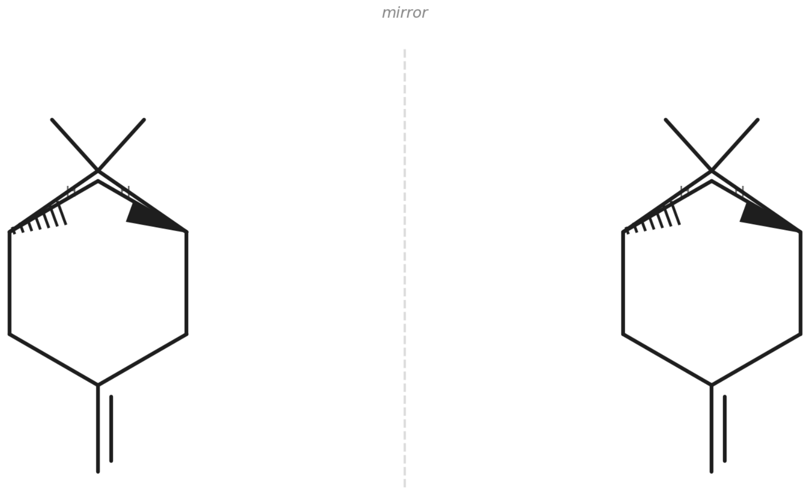


Figure 11. α-Pinene and β-pinene are structural isomers (same molecular formula $C_{10}H_{16}$, different bond position).

β-Pinene itself is chiral and exists as two enantiomers: (−)-β-pinene (the (1S,5S)-form), the dominant form in pine turpentine; and (+)-β-pinene (the (1R,5R)-form), much less abundant in natural sources.



(1S,5S)-(−)-β-Pinene

natural form • pine resin / turpentine

dominant in pine, abundant in cannabis

(1R,5R)-(+)-β-Pinene

rare in nature • herbal, lemony notes

antimicrobially active (Rivas da Silva 2012)

Figure 12. The two enantiomers of β-pinene. (1S,5S)-(−)-β-pinene (left) is the natural form. (1R,5R)-(+)-β-pinene (right) is rare in nature but antimicrobially active per Rivas da Silva (2012).

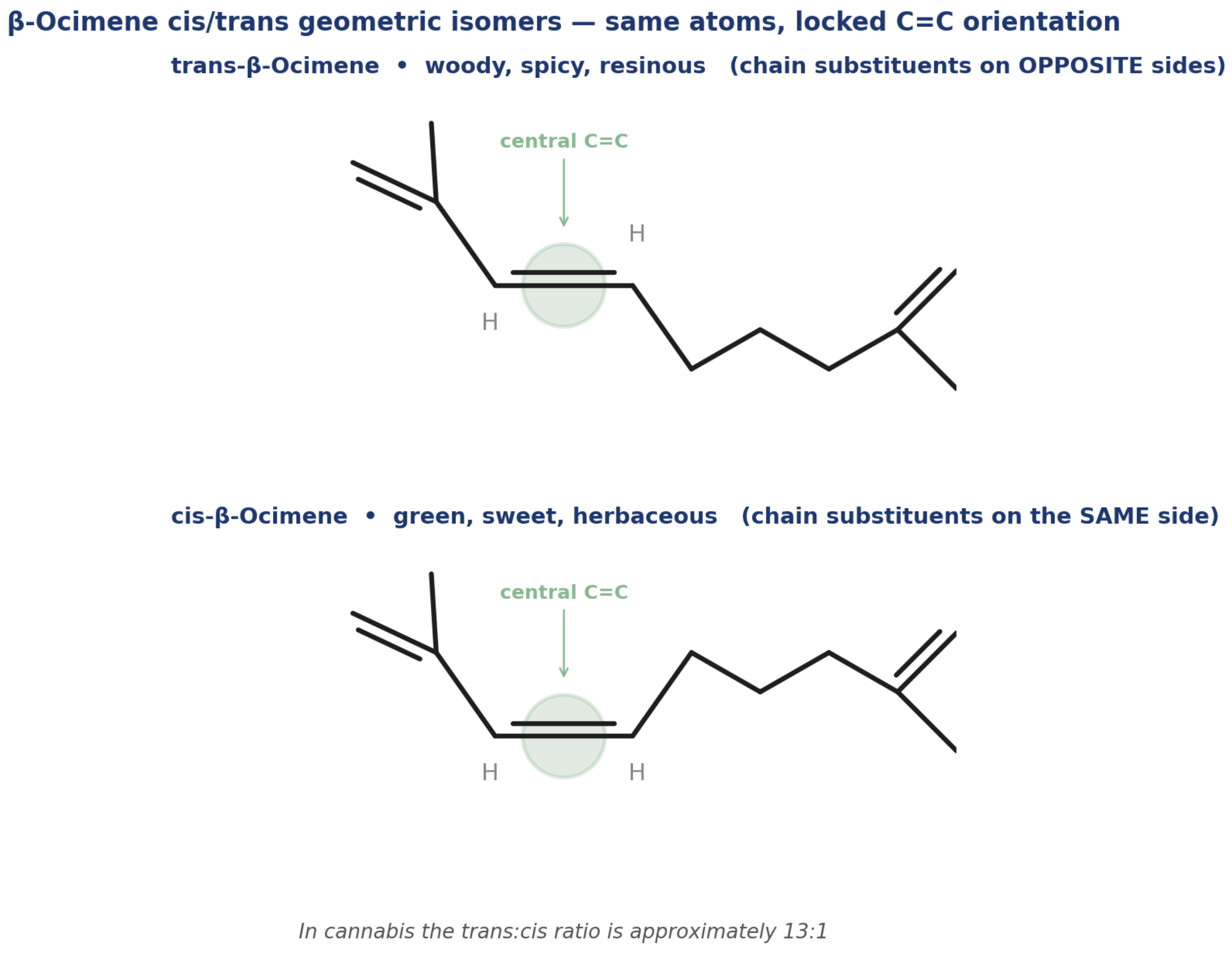
Cannabis β-pinene is more complicated than limonene or linalool. Both cannabis and pine produce (−)-β-pinene as the major enantiomer, but the enantiomeric ratios differ substantially. Pine turpentine produces β-pinene at roughly 96–98% (−), with only 2–4% (+). Cannabis produces it at 71–84% (−), with 15–28% (+).

VII. Other Isomeric Terpenes in Cannabis

Beyond the three primary chiral monoterpenes, cannabis essential oil contains other terpenes whose isomerism — either geometric or structural — distinguishes the cannabis profile from botanical alternatives.

A. Ocimene (cis/trans-β-ocimene)

Ocimene exists in two main structural forms (α-ocimene and β-ocimene), and β-ocimene further exists as cis- and trans-geometric isomers around its central double bond.



β-Ocimene cis/trans geometric isomers — same atoms, locked C=C orientation

trans-β-Ocimene • woody, spicy, resinous (chain substituents on OPPOSITE sides)

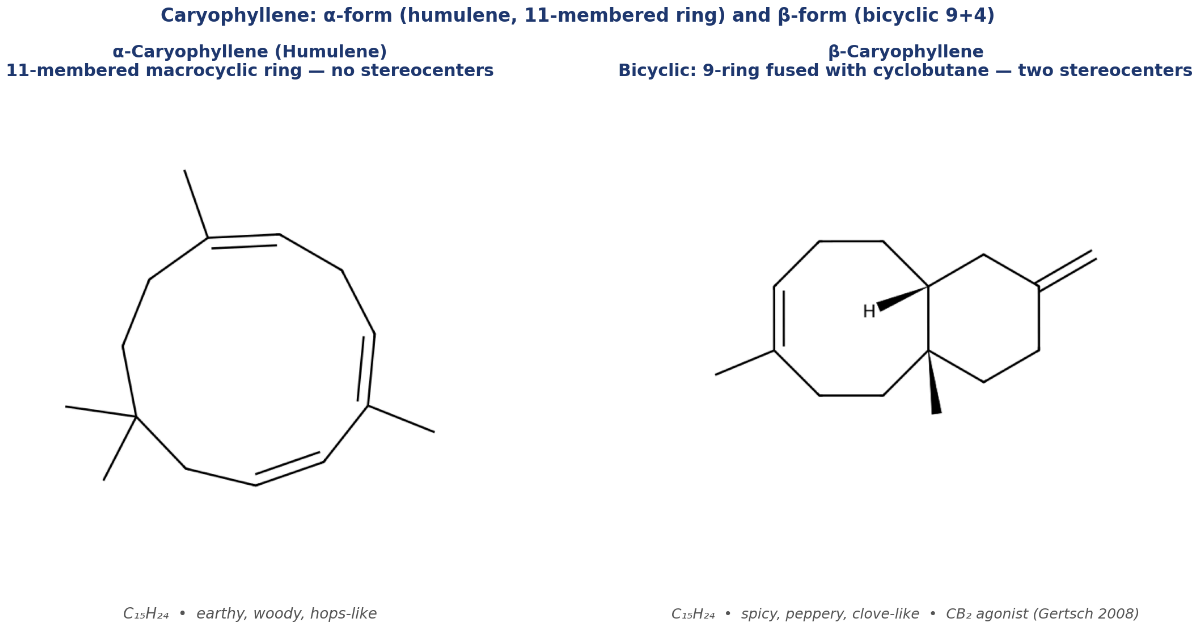
cis-β-Ocimene • green, sweet, herbaceous (chain substituents on the SAME side)

In cannabis the trans:cis ratio is approximately 13:1

Figure 13. Cis- and trans-β-ocimene differ in the orientation of substituents around the central double bond (highlighted green). In cannabis, the trans:cis ratio is approximately 13:1.

B. Caryophyllene (α and β)

Caryophyllene is the most abundant sesquiterpene in cannabis. It exists in two structural forms: α-caryophyllene (humulene), an 11-membered ring with no stereocenters; and β-caryophyllene, a bicyclic structure with two stereocenters.



Caryophyllene: α-form (humulene, 11-membered ring) and β-form (bicyclic 9+4)

α-Caryophyllene (Humulene)
11-membered macrocyclic ring — no stereocenters

β-Caryophyllene
Bicyclic: 9-ring fused with cyclobutane — two stereocenters

$C_{15}H_{24}$ • earthy, woody, hops-like

$C_{15}H_{24}$ • spicy, peppery, clove-like • CB_2 agonist (Gertsch 2008)

Figure 14. α-Caryophyllene (humulene, left) has no stereocenters. β-Caryophyllene (right) is bicyclic with two stereocenters. Natural (−)-trans-β-caryophyllene was identified by Gertsch et al. (2008) as a CB_2 receptor agonist.

VIII. How We Measured It

A. Chiral gas chromatography

Enantiomers are notoriously difficult to distinguish using standard analytical chemistry. They have identical mass, identical NMR spectra in achiral solvents, identical infrared spectra, and (most relevantly for the flavor industry) they elute at exactly the same retention time on a standard gas chromatography column.

To resolve enantiomers chromatographically, a specialized chiral-stationary-phase column is required. These columns are coated with chiral selectors that interact differentially with each enantiomer:

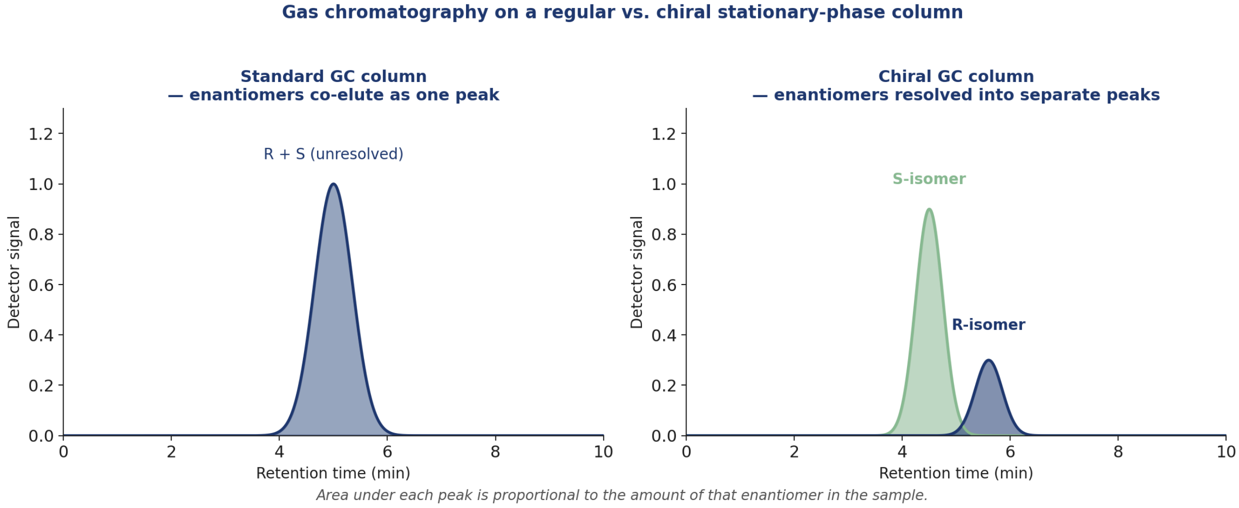


Figure 15. On a standard GC column, the two enantiomers of a chiral compound co-elute as a single peak (left). On a chiral column, they are resolved into separate peaks (right).

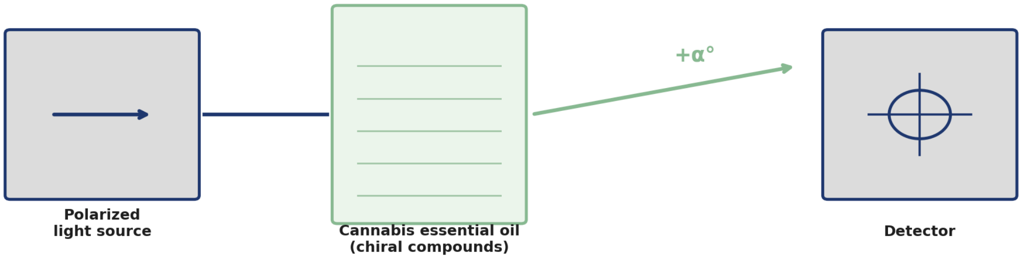
B. Enantiomeric excess and enantiomeric ratio

Enantiomeric excess (ee) is the absolute difference between the percentages of the two enantiomers. A racemic mixture (50/50) has ee = 0%. A pure enantiomer has ee = 100%. A mixture that is 96% S and 4% R has ee = 92% S. Throughout this paper, ee is the headline number used to summarize each sample.

Enantiomeric ratio (er) is the ratio of major to minor enantiomer. A racemic mixture has er = 1:1. A sample that is 96% S and 4% R has er = 24:1.

C. Optical rotation (polarimetry)

Although enantiomers cannot be distinguished by ordinary spectroscopy, they can be distinguished by their interaction with polarized light. A pure (+)-enantiomer rotates the plane of polarized light clockwise; a pure (−)-enantiomer rotates it counter-clockwise; a racemic mixture produces zero net rotation.



Optical rotation (polarimetry) — measuring chirality with light

A solution of chiral molecules rotates plane-polarized light. The rotation angle and direction (clockwise = +, counter-clockwise = −) fingerprints the enantiomeric composition.

Figure 16. Polarimetry — a 19th-century technique still in routine commercial use. A solution of chiral molecules rotates plane-polarized light by an angle characteristic of its enantiomeric composition.

Polarimetry is one of the oldest analytical techniques in chemistry — used by Louis Pasteur in 1848 to first discover molecular chirality — and it remains in routine commercial use in the flavor and fragrance industry as an adulteration test.

IX. The Data: Cannabis vs. Botanicals vs. Mimics

We performed chiral GC analysis on three Nexus Agriscience hemp cultivars (2024 Fruit 135, 2024 Purple 103, 2024 Dessert 45), two leading commercial cannabis-mimic terpene products (Cannabis Mimic 1 and Cannabis Mimic 2), and authentic natural essential oils from orange, thyme, lavender, and pine. Eleven compounds were resolved across the panel.

The three most consequential results — for the three primary chiral monoterpenes — are shown below. Each chart shows the percentage of R-isomer (Sci Blue) and S-isomer (Ag Green) for each sample, with the enantiomeric excess (ee) reported above each bar.

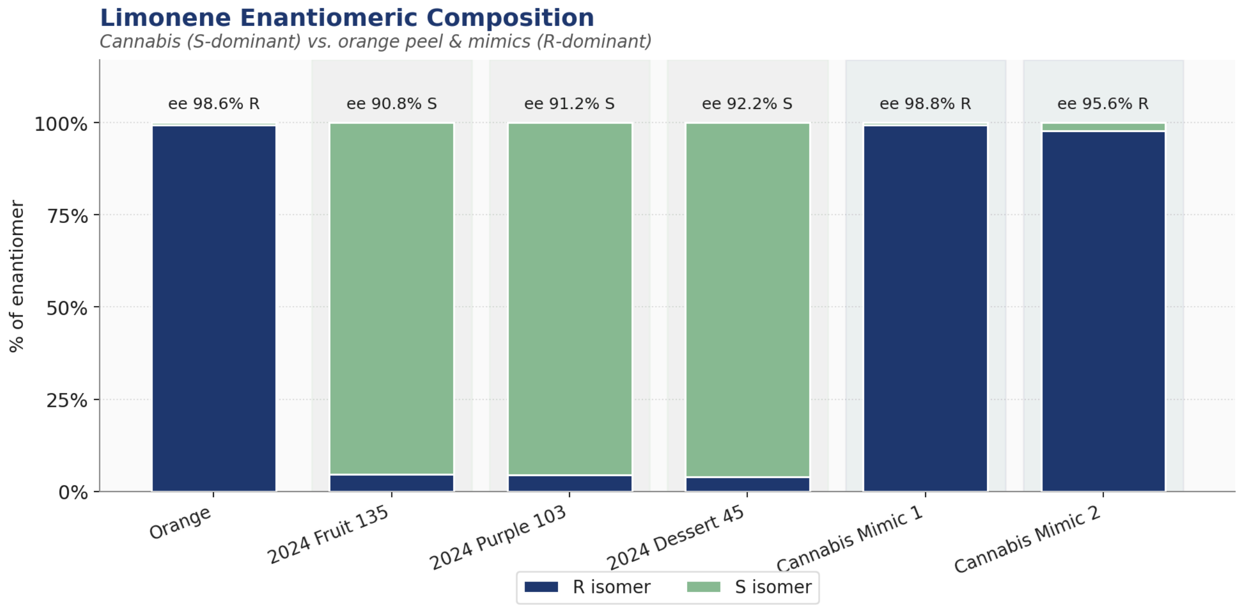


Figure 17. Enantiomeric composition of limonene. Orange essential oil is ~99% R (d-limonene). Cannabis is ~96% S (l-limonene). Both cannabis mimics test as nearly pure R — matching the citrus source, not cannabis.

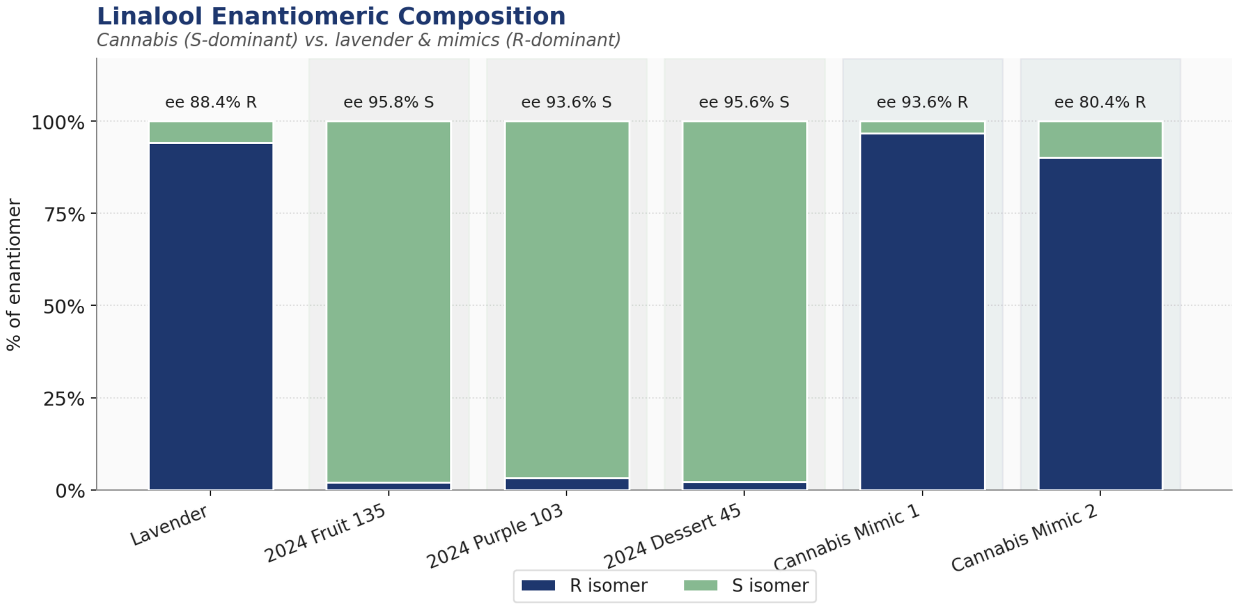


Figure 18. Enantiomeric composition of linalool. Lavender oil is ~94% R ((−)-linalool). Cannabis is 96–98% S ((+)-linalool). Cannabis mimics test at 90–97% R — matching lavender, not cannabis.

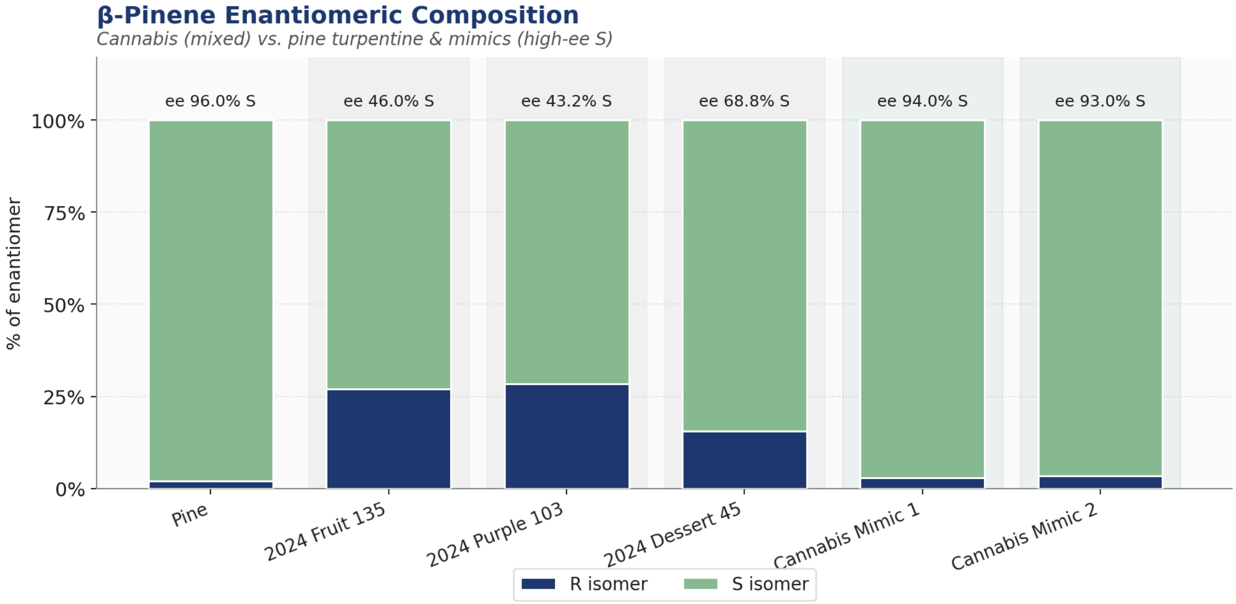


Figure 19. Enantiomeric composition of β-pinene. Pine-derived β-pinene is ~96% S. Cannabis β-pinene contains 15–28% R — substantially more than turpentine. Cannabis mimics match the turpentine profile (~93–94% S), not the cannabis profile.

A pattern is visible: in each compound, the two cannabis-mimic products cluster with the dominant commodity botanical source, not with the cannabis samples. Limonene mimics match orange. Linalool mimics match lavender. β-Pinene mimics match pine.

Principal Component Analysis: cannabis stands alone

A single-compound view tells one story; the multi-compound view tells a stronger one. Principal Component Analysis (PCA) projects the high-dimensional stereochemical data into a two-dimensional plot, in such a way that samples with similar overall profiles are placed close together.

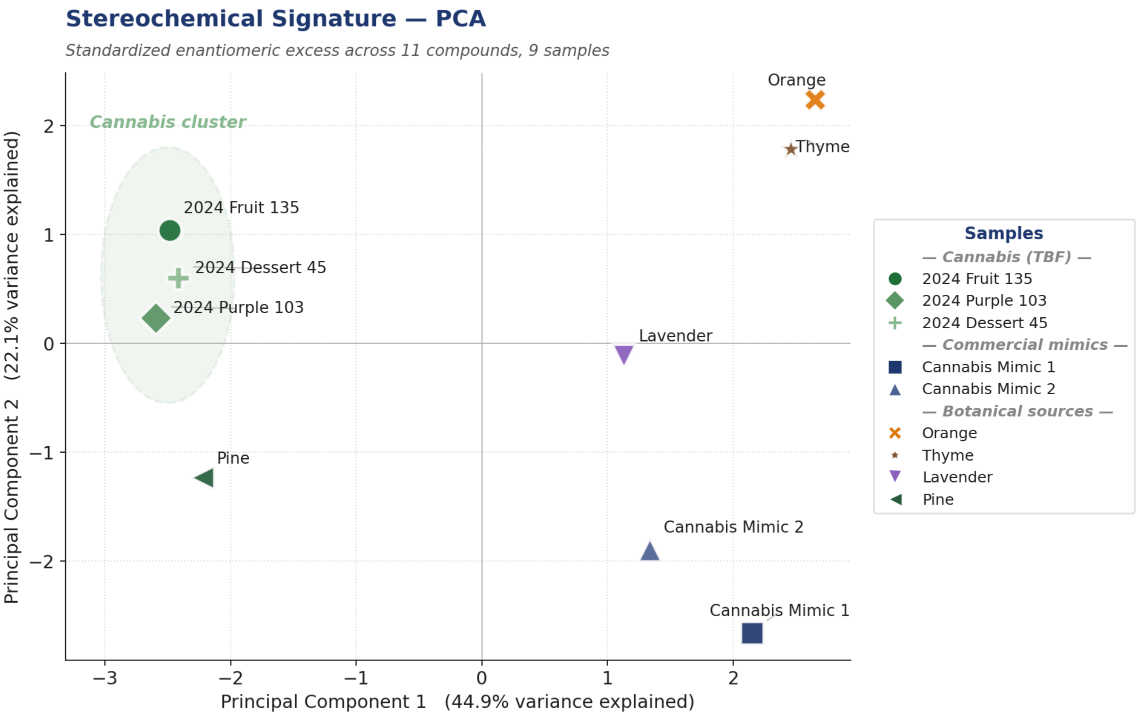


Figure 20. PCA of standardized enantiomeric excess values across 11 compounds. The three cannabis samples cluster tightly in their own region. Both cannabis mimics scatter to a different region of stereochemical space. Cannabis stands alone.

This is the headline finding. Cannabis essential oil — sampled across three independent cultivars in our 2024 harvest — produces a stereochemical signature that does not match any commercial botanical source we tested, and does not match either of the two leading commercial cannabis-mimic products.

X. Where the Differences Come From

Why does cannabis produce one enantiomer of limonene while orange produces the other? Why do cannabis cultivars share a β-pinene signature that is distinctly different from pine? The answer is enzymology. Cannabis terpenes are not assembled by random chemistry; they are assembled by enzymes called terpene synthases, and those enzymes are stereoselective by design.

A. Synthesis vs. enzymatic biosynthesis

When terpenes are synthesized in a chemical reactor — by chemical hydration of myrcene, by isomerization of an existing terpene, or by total synthesis from smaller precursors — the reactions involved are generally not stereoselective. They produce racemic mixtures.

When nature synthesizes terpenes inside a plant cell, the situation is very different. The reactions are catalyzed by chiral enzymes — folded proteins with active sites that can only accommodate the substrate in one orientation, and which therefore produce one enantiomer of product preferentially over the other.

B. Terpene synthases

A terpene synthase is a tiny biological machine. It takes a simple substrate — geranyl pyrophosphate (GPP) for monoterpenes — and rearranges its carbon skeleton through a series of conformational changes that fold the chain, cyclize it into a ring (or not), and place new bonds in specific stereochemical orientations.

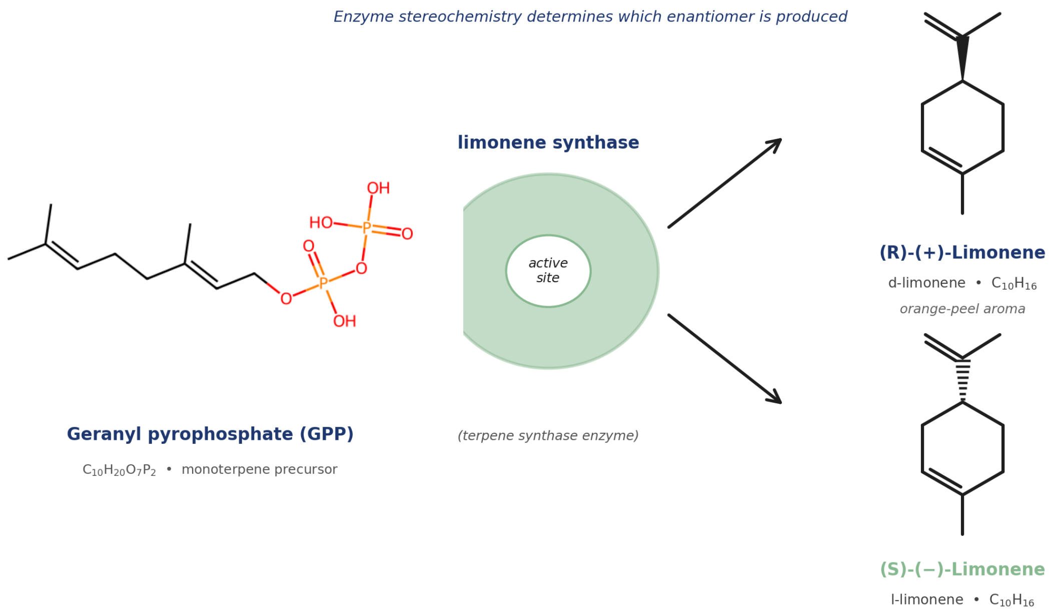
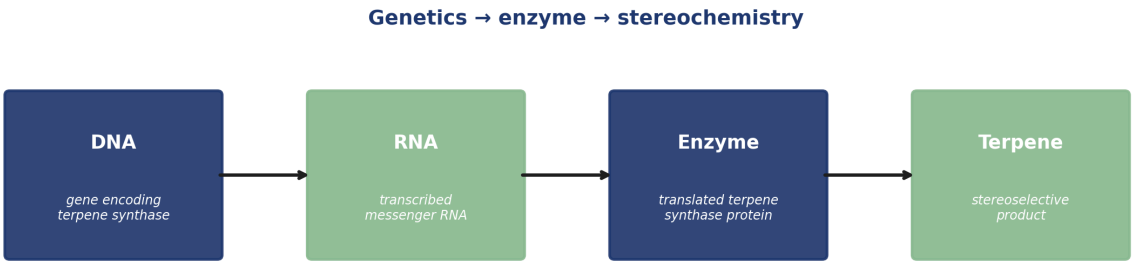


Figure 21. Limonene synthase converts geranyl pyrophosphate (GPP) into limonene. Depending on the orientation of the substrate in the active site, the enzyme produces either (R)-(+)-limonene (the d-form, found in citrus) or (S)-(−)-limonene (the l-form, the dominant form in cannabis).

A useful (if imperfect) analogy: imagine you are an enzyme assembling a molecule from a kit. If you hold the kit in your left hand, you might attach a particular component on the right side. If you hold it in your right hand, you might attach it on the left side. Either way, you end up with a recognizable molecule — but the two products are mirror images of each other.

C. Genetics drives chemistry

A plant's genome encodes the terpene synthase enzymes it expresses. A cell's DNA is transcribed into RNA, which is translated into proteins — including the terpene synthases that build the terpene profile in the trichomes of cannabis flowers.



The cannabis genome encodes terpene synthase enzymes; those enzymes determine which enantiomer is produced.

Figure 22. From genome to product: DNA encodes the terpene synthase gene, which is transcribed into RNA, then translated into the enzyme, which produces a stereoselective terpene.

Among cannabis cultivars, terpene synthase gene families have been characterized that produce specific enantiomeric profiles. The cannabis stereochemical signature is the chemical fingerprint of the specific enzymes that the cannabis plant expresses — enzymes that are, in some cases, unique to the cannabis genome and absent from the citrus, lavender, and pine genomes that supply the commodity terpene market.

XI. Conclusion

Years of large-scale cultivation and essential-oil extraction have revealed a largely unexplored and undervalued world of isomerism and stereochemistry in cannabis. The data presented in this paper makes the case at three levels.

At the single-compound level: limonene, linalool, and β-pinene in cannabis are stereochemically different from the same compounds as supplied by the commodity botanical market. The mimic products tested match the commodity sources, not cannabis.

At the multi-compound level: PCA across 11 chiral compounds shows that cannabis occupies its own region of stereochemical space — distinct from any botanical source tested, and distinct from both commercial cannabis-mimic products.

At the mechanistic level: these differences are the chemical fingerprint of the terpene synthase enzymes that cannabis cells express. They are not accidental, not subjective, and not interchangeable with the enzymatic outputs of citrus, lavender, or pine.

Botanical mimics used in cannabis-adjacent consumer products do not have the same chemical signature as cannabis-derived material. They do not taste the same, they do not smell the same, and where biological activity is enantiomer-specific (as it is for limonene, linalool, and β-pinene), they do not behave the same.

Paper 2 of this series turns from the laboratory to the marketplace and explains why this mismatch is structurally inevitable: the global terpene supply chain produces the wrong enantiomer of each of these compounds, and the price of correcting the stereochemistry exceeds what botanical-blending business models can absorb.

XII. Citations

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Appendix: Full 11-Compound Stereochemical Dataset

The table below presents the enantiomeric ratios (R% / S%) for the 11 compounds analyzed across all samples. Blank cells indicate the compound was not detected in that sample.

Compound	Orange R%	Orange S%	Thyme R%	Thyme S%	Lavender R%	Lavender S%	Pine R%	Pine S%	2024 Fruit 135 R%	2024 Fruit 135 S%	2024 Purple 103 R%	2024 Purple 103 S%	2024 Dessert 45 R%	2024 Dessert 45 S%	Cannabis Mimic 1 R%	Cannabis Mimic 1 S%	Cannabis Mimic 2 R%	Cannabis Mimic 2 S%
Limonene	99.3	0.7	62.7	37.3	31.1	68.9	4.5	95.5	4.6	95.4	4.4	95.6	3.9	96.1	99.4	0.6	97.8	2.2
Linalool	8.6	91.4	95.2	4.8	94.2	5.8	37	63	2.1	97.9	3.2	96.8	2.2	97.8	96.8	3.2	90.2	9.8
β-Pinene	66.8	33.2	99.3	0.7	45	55	2	98	27	73	28.4	71.6	15.6	84.4	3	97	3.5	96.5
α-Terpineol	98.7	1.3	98.7	1.3	56.9	43.1	9.7	90.4	6.2	93.8	4.8	95.2	5.5	94.5	27.3	72.7	22.3	77.7
Camphene	73	27			11.3	88.7	9.9	90.1	12.8	87.2	11	89	8.1	91.9	38.9	61.2	29.2	70.8
Borneol					49.5	50.5	7.9	92.1	3.1	96.9	4.2	95.8	1.7	98.3	99.9	0.1	62.7	37.3
Terpinen-4-ol			39.7	60.3	3.3	96.7	71.9	28.1	75	25	76.9	23.1	74	26			59.3	40.7
α-Thujene	60.7	39.3	50.9	49.1			25.2	74.8	21	79	1	99	28	72				
Δ3-Carene	99	1	99	1			0.1	99.9	99	1			90	10			90	10
Caryophyllene Oxide									94.6	5.4	92.2	7.8	91.5	8.5	77.4	22.6	80.5	19.5
α-Phellandrene			52	48					28	72	63	37	22.4	77.6			43.1	56.9

Source data: Nexus Agriscience internal chiral GC analysis, 2024 harvest cohort.