



Hemp (*Cannabis sativa* L.) essential oils and terpene-rich fractions for industrial applications

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ABSTRACT

Industrial hemp (*Cannabis sativa* L.) essential oils (EO) and terpene-rich fractions are emerging as renewable inputs for antimicrobial, biopesticide, and bio-based materials. Unlike the EO of the long established medicinal and aromatic crops, hemp EO remains poorly standardized, and reported performance is strongly influenced by chemotype, harvest stage, postharvest handling, and extraction design. This review synthesizes recent advances linking composition to industrial functionality across the value chain. Multi-cultivar studies demonstrate 10–20-fold variation in EO yield and pronounced shifts among α -pinene, β -myrcene, limonene, and β -caryophyllene, with antimicrobial activity correlating more closely to terpene class ratios than to total EO content. Drying, curing, and storage are major determinants of terpene integrity, often equaling genetic effects, yet are rarely reported in efficacy studies. Time-resolved distillation enables fraction-by-purpose strategies: early monoterpene-rich cuts provide rapid antimicrobial and repellent action, whereas later sesquiterpene-enriched fractions and hydrolates offer complementary, longer-acting profiles. Evidence for applications includes inhibition of Gram-positive bacteria, activity against fleas, ticks, agricultural pests and mosquitoes, and incorporation into active packaging and coatings. Translation to real systems depends on formulation platforms, particularly nanoemulsions, protein-based encapsulation, and electrospun matrices, that stabilize volatiles and control their release. Key barriers include inconsistent metadata, limited field validation, and risk of cannabinoid carryover in late fractions. We propose a minimum reporting standard and a research agenda integrating postharvest science, analytical harmonization, and comparative evaluation of EO, hydrolate, and extracts. With coordinated development, hemp EO can progress from promising laboratory material to reliable components of next-generation antimicrobial agents, biopesticides, and sustainable packaging.

1. Introduction

Industrial hemp (*Cannabis sativa* L.) has re-emerged as a multipurpose crop supplying fiber, grain, cannabinoids, and a rapidly expanding portfolio of biobased products (Górski et al., 2025). While most research and commercial attention have focused on cannabidiol (CBD) and food ingredients, hemp inflorescences are also a rich source of essential oil (EO) and terpene-rich fractions with potential applications in antimicrobial systems, biopesticides, and functional materials (Mazzara et al., 2023; Šovljanski et al., 2024; Pieracci et al., 2021). The global shift toward sustainable and residue-reduced agricultural inputs has renewed interest in plant volatiles as alternatives to synthetic preservatives and pesticides (Kumar et al., 2025; Ona et al., 2022). However, hemp EO remains far less standardized than EOs derived from peppermint, spearmint, lavender, rosemary, clove, and many other aromatic plants.

Hemp differs from traditional aromatic crops in several fundamental aspects. First, it is cultivated primarily for non-volatile products (e.g., cannabinoids, fixed oil, etc.), and the EO represents a secondary, often

opportunistic stream (Spinozzi et al., 2025). Second, industrial hemp is regulated under ultra-low Δ^9 -tetrahydrocannabinol (THC) thresholds, introducing compliance constraints rarely encountered in other plant EO sectors (Haczkiwicz et al., 2025). Third, hemp exhibits exceptional chemotypic diversity. In Europe, more than 50 approved industrial hemp cultivars are registered with THC concentrations below 0.2%, encompassing a wide range of intermediate chemotypes (Borrito Fernandez et al., 2020). Moreover, EO composition is strongly influenced by genetic background, breeding history, developmental stage, environmental conditions, and the specific plant organ analyzed (Borrito Fernandez et al., 2020; Zheljaskov et al., 2020). Collectively, these factors underpin the substantial phytochemical variability observed in hemp and distinguish it from more chemically stable aromatic crops.

Most studies consistently report up to a 10–20-fold variation in EO yield, while the relative abundance of major terpenes (e.g., α -pinene, β -myrcene, limonene, and β -caryophyllene) varies substantially in response to genotype and developmental stage (Mazzara et al., 2023;

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Pieracci et al., 2021; Zheljzkov et al., 2022)(Mazzara et al., 2022; Zheljzkov et al., 2022). Moreover, wild or feral populations of *C. sativa* represent an important reservoir of genetic diversity and adaptive traits that may have been diminished in modern cultivated varieties (Cahoon and Zhang, 2022)(Woods et al., 2022). Genomic analyses indicate that these populations retain significant genetic variation, including loci associated with stress response and disease resistance, reflecting adaptation to natural environments (Woods et al., 2022). In addition, studies of feral germplasm have revealed substantial variation in cannabinoid composition and population genetic structure, supporting breeding programs and the development of new industrial hemp cultivars adapted to diverse regions (Aina et al., 2025). Similarly, chemical and genetic variation across environmental conditions shows that wild populations exhibit multiple chemotypes and diverse phytochemical profiles, underscoring their importance for both ecological research and crop improvement (Busta et al., 2022). Collectively, these findings demonstrate that wild-growing hemp populations are valuable resources for plant breeding, conservation, and for advancing our understanding of the domestication and evolution of *C. sativa* (Clarke and Merlin, 2016). At the same time, the extensive genetic, chemical, and phenotypic diversity of these populations presents both opportunities for novel research and challenges for the standardization and industrial utilization of hemp-derived products.

Recent studies have generated a growing body of evidence demonstrating that hemp EO possesses significant biological activity. Antimicrobial studies demonstrated reproducible inhibition of Gram-positive bacteria, with efficacy strongly influenced by terpene class ratios rather than total EO content (Pieracci et al., 2024; Zheljzkov et al., 2025a). Hemp EO has demonstrated toxicity and repellency against fleas, ticks, agricultural pests, and mosquito vectors (Dadé et al., 2025; Eschwech et al., 2023; Soares et al., 2023). In parallel, its volatile constituents are being incorporated into nanoemulsions, biopolymer films, and electrospun fibers for emerging materials applications (Aguzzi et al., 2023; Mazzara et al., 2023; Yang et al., 2025). Recent reviews also point to the growing exploitation of hemp phytochemicals in agrochemical, cosmetic, and food industries, reflecting increasing recognition of hemp EO and terpene-rich fractions as multifunctional, value-added ingredients (Trono, 2026). Moreover, recent phytochemical studies demonstrate that hemp leaves, traditionally considered an agricultural by-product, contain diverse terpenes and other bioactive metabolites, including cannabinoids, cannflavins, policosanols, and squalene, supporting their valorization as additional sources of high-value compounds (Marani et al., 2026). Hydrolates and spent biomass from distillation are also emerging as valuable co-products, highlighting the need to view hemp EO within a broader biorefinery framework.

Despite these advances, literature remains fragmented. Many chemical surveys lack functional endpoints, whereas bioactivity papers often omit essential metadata on cultivar identity, postharvest history, or distillation design (Baek et al., 2025; Chen et al., 2021). Postharvest handling-drying, curing, storage, and distillation technique has been shown to modify terpene profiles as much as genetic factors (Clarke and Merlin, 2016) Das et al., 2025; Spadafora et al., 2024; Spinozzi et al., 2025) yet it is rarely reported in efficacy trials. Furthermore, few studies distinguish among EO fractions, hydrolates, and extracts, even though these matrices differ markedly in composition, safety, and regulatory status (Sut et al., 2024). Without harmonized analytical and reporting frameworks, translation from laboratory findings to industrial products is slow (Chaiwangrach et al., 2025; Joy et al., 2025a).

Formulation science is emerging as the critical bridge. Nanoemulsions, protein-based encapsulation, and electrospun matrices can stabilize volatile terpenes and control their release, enabling realistic deployment in crop protection or active packaging (Aguzzi et al., 2023; Mazzara et al., 2023; Yang et al., 2025; Zhang et al., 2025). However, optimal pairing of chemotype, fraction, and formulation remains largely unexplored. Equally important is the management of THC carryover, particularly in late hydrodistillation fractions (Zheljzkov et al., 2020;

2025b), which may challenge regulatory acceptance if not monitored with validated methods (Joy et al., 2025a).

The objective of this review is to synthesize current knowledge on hemp EOs and terpene-rich fractions from an industrial perspective. We integrate evidence across the value chain - from terpene biology and postharvest determinants to extraction design, analytics, formulation, and application performance. Particular emphasis is placed on (i) how genotype, harvest, and processing shape functional chemistry; (ii) comparative potential of EO, hydrolates, and extracts; (iii) formulation platforms enabling real-world efficacy; and (iv) standardization needs to ensure reproducibility and compliance. By framing hemp EO within product-development logic rather than solely as a phytochemical curiosity, we aim to identify actionable pathways for commercialization in antimicrobial systems, biopesticides, and sustainable materials.

2. Bibliographic database search

Publication records related to EOs of *C. sativa* for industrial applications were retrieved from the Web of Science, Scopus, CABI Digital Library, and Google Scholar databases. Furthermore, relevant studies published in peer-reviewed journals between 2010 and 2025, and aligned with the objectives of this review, were selected and analyzed.

3. Biology of Terpene Production in Hemp

This section examines the biological basis of terpene production and chemotypic diversity in industrial hemp and its comparison with feral (spontaneous/wild) hemp (Aina et al., 2025; Pieracci et al., 2021; Zheljzkov et al., 2022).

3.1. Glandular trichomes and biochemical framework. Influence of genotype $\times$ environment drivers (light, temperature, water, nutrition, density)

The glandular trichomes of *C. sativa* are classified into three types: bulbous, capitate-sessile, and capitate-stalked trichomes (Dayanandan and Kaufman, 1976). The capitate-sessile trichomes often are larger glands than other two types, but most abundant types are capitate-stalked trichomes (Hancock et al., 2024). In *C. sativa*, terpene biosynthesis occurs predominantly in capitate-stalked and capitate-sessile glandular trichomes (Punja et al., 2023). Among these, capitate-stalked trichomes are especially concentrated on the bracts of female flowers compared with other plant organs (Hancock et al., 2024). Structurally, they comprise a single basal cell, a multicellular stalk, and a secretory head enclosed by a large subcuticular storage cavity (Rodziewicz et al., 2019).

Capitate-sessile trichomes and capitate-stalked trichomes are located on inflorescences and subtending leaves, whereas bulbous trichomes give a significantly minor contribution. The number and types of hemp trichomes depend on cultivar, stalk length during flower development, a shift from sessile to stalked forms as flowering progresses (Punja et al., 2023; Sutton et al., 2023). They synthesize and accumulate resins and other phytochemicals within an extracellular storage cavity formed between the cuticle layer and the secretory cells (Hancock et al., 2024). These structures represent highly specialized metabolic factories in which the methylerythritol phosphate (MEP) and mevalonate (MVA) pathways generate monoterpenes and sesquiterpenes, respectively (Andre et al., 2016; Pancaldi et al., 2025; Pieracci et al., 2021).

Furthermore, cannabinoids accumulate within the subcuticular storage cavity of glandular trichomes, while cannabinoid synthases and associated enzymes in the secretory cells convert cannabigerolic acid (CBGA) into the major cannabinoids Δ^9 -*trans*-tetrahydrocannabinolic acid (THCA), cannabidiolic acid (CBDA), and cannabichromenic acid (CBCA) (Rodziewicz et al., 2019). The biosynthesis of these cannabinoids depends on two key precursors: olivetolic acid (OA), derived from the polyketide pathway, and geranyl diphosphate (GPP), generated via

the methylerythritol phosphate (MEP) pathway (Fellermeier and Zenk, 1998).

Although terpene and cannabinoid biosynthetic pathways share common precursors, they are regulated at least partially independently, which helps explain why industrial hemp cultivars with similar CBD concentrations can exhibit markedly different volatile profiles (Palmieri et al., 2021). Comparative studies of industrial hemp genotypes indicate that terpene accumulation is influenced not only by genetic background but also by developmental stage, canopy microclimate, and postharvest handling, rendering hemp EO a highly dynamic yet tunable natural product (Baek et al., 2025; Zheljaskov et al., 2022). Multi-year studies further demonstrate that the accumulation of terpenes and other phytochemicals in hemp inflorescences is significantly affected by genotype, growing season, and genotype $\times$ environment interactions, with environmental conditions often accounting for the largest proportion of variation (Beleggia et al., 2023). Moreover, individual cultivars differ markedly in the stability and abundance of specific metabolites, including α -humulene, β -caryophyllene, CBD, and CBG, underscoring the importance of cultivar selection and environmental characterization for achieving reproducible EO composition and bioactivity.

3.2. Chemotypes and compositional diversity in industrial *C. sativa*

The chemotaxonomic classification of *C. sativa* is a new approach to systematizing and understanding the diversity of forms within the species. Generally, more than 545 chemical compounds by different biogenic classes were found in *C. sativa* (Lowe et al., 2021). Industrial hemp contains a complex phytochemical profile, in terms of secondary metabolites, composed mainly of cannabinoids, terpenes, and phenolic compounds. Some published data on phytochemical composition of industrial *C. sativa* are presented in Table 1. The reviewed studies (2010–2025) show that CBD is the predominant cannabinoid in industrial hemp (Table 1), with a lower number of strains containing cannabigerol (CBG) as the main compound (Gargiulo et al., 2024). Overall, 104 phytocannabinoids were initially identified (ElSohly, Gul, 2014), with more recent estimates indicating approximately 120 or more compounds (Gülck and Möller, 2020; Jurga et al., 2024). Minor cannabinoids such as cannabichromene (CBC) are generally present in lower concentrations.

Terpenes represent another important group of bioactive compounds contributing to the plant's aroma and biological activity. The most frequently reported terpenes include α -pinene, myrcene, limonene, terpinolene, β -caryophyllene, and α -humulene, and with reported ranges varying considerably depending on cultivar, environmental conditions, extraction method, and storage length. In several studies, β -caryophyllene was identified as the dominant terpene, with concentrations reaching up to 40% of the total terpene fraction (Table 1). Studies by Barčauskaitė et al. (2022), Mazzara et al. (2022), and Pieracci et al. (2021) demonstrate that multi-genotype evaluations in temperate production systems consistently reveal significant chemotypic heterogeneity among certified industrial hemp cultivars. Analyses of more than ten genotypes grown under identical agronomic conditions showed significant differences in total EO yield and pronounced variation in the content of dominant constituents such as α -pinene, myrcene, terpinolene, limonene, β -caryophyllene, and caryophyllene oxide (Barčauskaitė et al., 2022; Mazzara et al., 2022; Pieracci et al., 2021). These studies highlight that 'industrial hemp EO' cannot be treated as a single commodity; rather, it represents a spectrum of compositional types with distinct functional potential.

Work from our group comparing a number of hemp selections demonstrated that antimicrobial efficacy tracked more closely with terpene class ratios than with total EO yield alone (Zheljaskov et al., 2025a). Cultivars enriched in monoterpene hydrocarbons exhibited different activity spectra than those dominated by oxygenated sesquiterpenes, underscoring the need for chemotype-specific product development (Šovljanski et al., 2024). Importantly, even within a single

Table 1

Reported phytochemical composition (ranges) of industrial hemp for the period 2010–2025 year.

Author (Year)	Terpenes and Cannabinoids in %	Extraction / Analysis	Country
Andre et al. (2016)	β -caryophyllene (12–20); myrcene (7–14); limonene (3–7); CBD (1–4); CBG (0.1–0.5); THC (<0.2)	Supercritical CO ₂ + GC-MS / HPLC	Belgium
Ascrizzi et al. (2024)	β -caryophyllene (19.1–27.1); α -humulene (7.8–11.3); CBD (1–3)	GC-MS	Italy
(Bakali et al., 2022)	β -caryophyllene (13.39–25.32); myrcene (10.03–20.09); α -humulene (4.88–8.73); caryophyllene oxide (1.46–6.07); decane (1.41–4.46); α -pinene (1.91–3.66)	Hydrodistillation + GC-MS	Morocco
Benelli et al. (2018a)	β -caryophyllene (23.8); α -pinene (16.4); myrcene (14.2); α -humulene (8.3); β -pinene (5.2); (<i>E</i>)- β -ocimene (5.1); CBD (1–3)	Steamdistillation + GC-MS	Italy
Benelli et al. (2018b)	β -caryophyllene (21.4); myrcene (11.3); α -pinene (7.8); terpinolene (7.6); α -humulene (7.1); CBD, (11.1)	Hydrodistillation + GC-MS	Italy
De Vita et al. (2022)	β -caryophyllene (13.82); α -humulene (5.33); caryophyllene oxide (5.7); α -bisabolol oxide B (5.12); CBD (28.48)	GC-MS	Italy
Eržen et al. (2021)	α -pinene (2.5–11.6); β -pinene (2.1–7.0); myrcene (10.5–29.9); terpinolene (2.7–16); β -caryophyllene (10.5–21.3); CBD (0.05–0.78); CBD A (1.7–6.59); CBG A (0.16–1.62); Δ^9 -THC (0.01–0.11)	Hydrodistillation; GC-FID;	11 different phenotypes; 3 var. Slovenia
Fischedick et al. (2010)	myrcene (0.8–19); α -pinene (0.0–6.7); terpinolene (0–11.3); CBD (0.0–79.8)	GC-MS / HPLC	Netherlands 11var.
Haczkiwicz et al. (2025)	β -caryophyllene (18.37–30.07); α -trans-bergamotene	Solvent extraction (methanol, ethanol, acetone, isopropanol, hexane, and mixtures of	Poland

(continued on next page)

Table 1 (continued)

Author (Year)	Terpenes and Cannabinoids in %	Extraction / Analysis	Country
	(3.52–7.30); α -humulene (28.54–31.27); caryophyllene oxide (2.41–6.39); Δ^9 -THC (1.64–2.06); CBD (44.53–57.74); CBG (1.74–2.22); CBC (1.94–2.42); CBN (1.22–1.39)	hexane/ethanol and hexane/isopropanol in a 7:3 v/v ratio) + GC-MS	
Ingallina et al., (2020)	β -caryophyllene (6.3–28.0); α -humulene (1.3–16.7); caryophyllene oxide (10.09–72.2); humulene epoxide (0–14.0); phytol (0–20.2); CBDV; CBG; CBN, THC; CBC	GC/MS, UHPLC, HPLC-PDA/FD; spectrophotometry	Italy, different harvesting period.
Iseppi et al. (2019)	α -pinene (4.8–20.4); β -pinene (2.1–8.2), myrcene (4.5–34.4); β -caryophyllene (8.5–29.8); CBD (1–2.5)	Steam distillation; GC-MS and GC-FID;	Samples from France and Italy
Mazzara et al. (2022)	α -pinene (0.74–21.19); myrcene (7.16–29.23); limonene (2.20–9.17); terpinolene (0.18–30.47); β -caryophyllene (10.40–19.70); α -humulene (2.96–8.57); CBD (2.30–5.25); THC (0.09–0.20)	Hydrodistillation + HPLC-DAD-MSn Analysis of LE, DM and UM	Italy – 9 cultiv.
Pavlovic et al. (2019)	β -caryophyllene (11–50); α -humulene (5.3–15); CBDA (2.3–2.7); CBGA; CBD (0.056–0.27)	HPLC-high-resolution mass spectrometry, SDS-PAGE LC-MS/MS, HS-SPME GC-MS, and GC-FID	Italy
Judžentienė et al. (2023)	β -caryophyllene (≤ 46.64); ($\leq 14.53\%$), α -pinene (≤ 20.25); α -humulene (≤ 11.48); CBD (≤ 64.56)	HPLC/DAD/TOF and GC/MS techniques.	Lithuania
Zengin et al. (2018)	myrcene (15.55–33.45); α -pinene 5.13–12.88; CBD (0.8–2.1)	Supercritical CO ₂ + GC-MS	Italy
Zheljaskov et al., (2025a)	α -pinene (1.72–11.07); β -pinene (0.66–6.21); myrcene (7.40–27.28); limonene (0.90–8.32);	Hydrodistillation GC-MS	Serbia

Table 1 (continued)

Author (Year)	Terpenes and Cannabinoids in %	Extraction / Analysis	Country
	β -(E)-ocimene (1.41–7.56); α -terpineol (1.47–3.85)		

cultivar, year-to-year variability was substantial, indicating a strong genotype $\times$ environment interaction that must be accounted for in any industrial standard (Barčauskaitė et al., 2022).

Phenolic compounds and flavonoids, including cannflavin A and cannflavin B, are also consistently detected, although typically in lower concentrations compared with cannabinoids and terpenes. These compounds are reported either as total phenolic content (approximately 2–10 mg/g) or as specific flavonoids present in trace amounts (Table 1).

3.3. Industrial vs drug-type or cannabinoid-type hemp comparisons, and wild (feral, spontaneous) (with emphasis on industrial hemp cultivars)

As widely recognized, the taxonomy of *C. sativa* is highly controversial (Koren et al., 2020). Likewise, no unified or universally accepted classification exists for wild or feral hemp. According to Koren et al. (2020), the interbreeding of wild *Cannabis* populations contributes to taxonomic uncertainty by maintaining continuous variation in quantitative traits. Overall, contemporary wild (feral, spontaneous) *Cannabis* populations are largely composed of escaped and naturalized cultivated plants (Aina et al., 2025; Koren et al., 2020). Furthermore, these populations are regionally adapted and represent a potential source of untapped genetic and phytochemical diversity (Aina et al., 2025). There is not much research on the phytochemical composition of wild hemp. The analyzed literature for the period 2010–2025 of phytochemical composition of wild hemp is shown in Table 2. The phytochemical composition of cultivated and wild populations of *C. sativa* varies markedly as a result of domestication, selective breeding, and environmental adaptation (Tables 1 and 2). Modern cultivated types have been developed for distinct end uses, including industrial applications (fiber-type, seed/oilseed-type, and dual-purpose), medicinal uses (medical marijuana), and cannabinoid production (cannabinoid-type hemp, often referred to in industry as “floral hemp”). These targeted breeding efforts have resulted in comparatively stable and predictable profiles of cannabinoids, terpenes, and phenolic compounds within each type.

In particular, industrial hemp cultivars are characterized by low THC concentrations and relatively high CBD levels, consistent with breeding programs designed to meet regulatory THC limits and support agronomic performance (Small, 2015; Ren et al., 2021). In contrast, cannabinoid-type hemp is bred to maximize floral biomass and cannabinoid yield, whereas fiber- and seed-type cultivars are selected primarily for stem biomass and grain production, respectively, and

Table 2

Reported phytochemical composition (ranges) of wild (feral, spontaneous) *Cannabis sativa* for the period 2010–2025 year.

References	Phytochemical Composition in %	Country
Zheljaskov et al. (2020)	β -caryophyllene (15.4–29.6); α -humulene (5.3–11.9); caryophyllene oxide (0.2–31.2); humulene epoxide II (1.2–9.5); CBD: EO (6.9–52.4); δ^9 -THC ($\sim 2.4\%$, 0–3.4);	Serbia
Nagy et al. (2019)	β -caryophyllene (24.9–28.3); CBD (7.4–24.9); α -humulene (8.9–9.3); β -selinene (4.3–7.3);	Hungary
Busta et al. (2022)	CBD; CBDA; CBG; CBN; THC; THCA	USA
Aina et al. (2025)	THC (0.04–1.16); CBD (0.02–2.18); Total Cannabinoid content (0.51–3.19);	USA

consequently exhibit distinct phytochemical profiles associated with these end uses.

In contrast, wild and feral *Cannabis* populations exhibit substantially greater phytochemical diversity than cultivated types. Feral *Cannabis* populations display diverse cannabinoid profiles, including variable ratios of THC, CBD, and minor cannabinoids, reflecting the absence of controlled breeding and the influence of natural selection (Busta et al., 2022; Aina et al., 2025). These populations may also harbor a broader diversity of terpenoids and other secondary metabolites associated with environmental stress responses, herbivore defense, and adaptation to local ecological conditions (Andre et al., 2016).

Anthropogenic pressures may further contribute to phytochemical diversity in feral populations. For example, plants growing in or near agricultural systems may experience selection pressures from repeated herbicide applications (e.g., glyphosate in Roundup®-based systems), potentially influencing metabolic pathways linked to stress tolerance and chemical defense. Although this area remains underexplored, such pressures may contribute to the observed variability in secondary metabolite composition among feral *Cannabis* populations.

Furthermore, the chemical diversity observed in wild (feral) hemp populations may include ancestral or intermediate chemotypes that were partially lost during domestication and modern breeding programs. Because of this broader phytochemical variability, feral *C. sativa* populations are considered valuable genetic resources for identifying novel cannabinoids, terpene combinations, and stress-related metabolites that could be useful for crop improvement and pharmaceutical research (Woods et al., 2022; Ren et al., 2021). Overall, while cultivated hemp generally exhibits more uniform and targeted phytochemical profiles, wild populations tend to retain greater chemical diversity and ecological adaptation.

4. Agronomy for terpene/EO yield and consistency

Section 4 examines how agronomic practices influence terpene and EO production, composition, and consistency in *C. sativa* (Palmieri et al., 2021; Zheljaskov et al., 2025b). Cultivar selection is one of the most important factors, as different genetic backgrounds exhibit significant variation in terpene profiles and EO productivity. Harvest timing also strongly influences terpene concentration, with maximum accumulation typically occurring at specific stages of floral development. Cultivation systems can further influence yield and chemical stability; although open-field production predominates in industrial hemp, protected environments such as greenhouses may provide greater environmental control and compositional consistency for high-value cultivars when supported by economic and agronomic considerations. However, agronomic strategies aimed at maximizing terpene or EO production may involve trade-offs with other production goals, including fiber yield, grain production, or cannabinoid content, requiring growers to balance cultivation objectives depending on the intended end use of the crop.

4.1. Influence of harvest stage and agronomic practices of terpenes profiles

Harvest timing is among the most powerful levers for manipulating hemp EO composition. In controlled field experiments, inflorescences collected at early flowering contained EOs richer in monoterpenes, whereas later harvests showed progressive increases in sesquiterpenes and trace cannabinoids (Abdollahi et al., 2020; Palmieri et al., 2021; Zheljaskov et al., 2022). Our longitudinal sampling across three developmental stages revealed that the relative abundance of myrcene and limonene could decline by more than 40% from early to late bloom, while β -caryophyllene and α -humulene increased concurrently (Zheljaskov et al., 2022). These compositional shifts were accompanied by changes in antimicrobial activity, indicating that harvest timing should be optimized according to the intended end use of the EO rather than biomass yield alone (Pieracci et al., 2024).

Beyond genetics and phenology, crop management practices exert measurable effects on secondary metabolism. Fertilization regimes, particularly nitrogen and sulfur availability, have been shown to modify both EO yield and composition (Barčauskaitė et al., 2022). Trials evaluating organic and mineral nutrient sources reported alterations in the ratio of monoterpenes to sesquiterpenes, likely mediated through C-N balance and trichome density (Pancaldi et al., 2025). Although irrigation and plant density have received less attention, preliminary observations suggest that canopy humidity and light interception influence volatile retention and should be integrated into future experimental designs (Chen et al., 2021).

Recent field studies further demonstrate that cultivar selection, row spacing, and growth stage interactively influence EO yield, terpene composition, and fiber characteristics in dual-purpose hemp systems. For example, cultivar-dependent differences in EO productivity and dominant sesquiterpenes have been reported, alongside spacing-induced changes in fiber cell wall composition and lignin content (Viskovic et al., 2026). Notably, correlations between specific terpenes (e.g., β -caryophyllene, α -humulene) and lignin were observed at early developmental stages but diminished later, indicating temporal shifts in the relationship between secondary metabolism and structural components (Viskovic et al., 2026). These findings highlight the importance of integrating agronomic practices across production goals, particularly when optimizing both EO and fiber outputs within dual-purpose systems.

4.2. Cannabinoids in Hemp Essential Oils and Regulatory Considerations

Because terpene-rich fractions are generally collected early in the distillation process, whereas trace cannabinoids become more concentrated in later fractions, distillation time can influence both aroma composition and regulatory compliance of hemp EO products. Although industrial hemp is bred for low THC, trace cannabinoids are frequently detected in late distillation fractions (Spinozzi et al., 2025; Sut et al., 2024; Zheljaskov et al., 2025b). Our analyses demonstrated that cannabinoid carryover is negligible in early monoterpene-rich fractions but increase as distillation progresses, particularly when biomass is finely ground (Fiorini et al., 2019, 2020; Spinozzi et al., 2025; Zheljaskov et al., 2020). Consequently, optimization of distillation conditions is essential to achieve desired aroma profiles while maintaining compliance with stringent THC regulations (Haczkiwicz et al., 2025).

In the United States, the regulatory landscape has evolved significantly since the 2018 Farm Bill, which defined hemp as *C. sativa* containing $\leq 0.3\%$ Δ^9 -THC on a dry weight basis. However, regulatory attention has increasingly extended beyond field-level compliance to downstream ingredients and finished products, where even trace amounts of THC can raise legal and safety concerns, particularly in food and beverage applications. This issue has gained importance with the rapid expansion of hemp-derived ingredients in consumer products, including functional beverages, flavoring systems, and botanical infusions, for which product consistency, safety, and regulatory compliance are essential (Sant'Ana et al., 2026).

The growing interest in hemp-derived ingredients for foods and beverages (Sant'Ana et al., 2026) underscores the need to produce terpene-rich hemp EOs that are free of detectable THC. Early distillation fractions are particularly promising because they are enriched in volatile terpenes while containing negligible cannabinoid carryover, making them attractive as natural flavoring agents and functional ingredients. However, the co-extraction or carryover of cannabinoids in later fractions presents a challenge for their direct use in regulated consumable products. Consequently, regulatory uncertainty and the risk of THC contamination remain significant obstacles to the broader commercialization of hemp-derived ingredients.

The partial independence of terpene and cannabinoid biosynthesis suggests opportunities to develop cultivars and processing strategies that maximize terpene yield and minimize cannabinoid accumulation,

thereby reducing the risk of THC carryover (Baek and Vergara, 2025). Advances in fractionation technologies, selective breeding, and post-distillation purification could further enable the production of compliant, terpene-rich hemp ingredients tailored for the food and beverage industry. Overall, aligning agronomic practices, processing methods and regulatory requirements will be essential for unlocking the full potential of hemp EOs as safe, consistent, and commercially viable ingredients in consumer products.

5. Postharvest: drying, curing, storage, and volatile retention

This section examines the effects of postharvest practices on terpene retention, chemical composition, and EO quality in *C. sativa* (Baek et al., 2025; Chen et al., 2021). Postharvest processing, particularly drying, curing, and storage, is critical for preserving the aromatic and functional properties of hemp products and has received increasing attention in recent reviews (Addo et al., 2021; Al Ubeed et al., 2022; Das et al., 2022). The main postharvest factors affecting terpene integrity and functionality are shown in Table 3. As the *Cannabis* industry continues to grow, optimizing postharvest processes to maximize terpene retention and ensure consistent product quality has become a major priority.

5.1. Drying as the primary bottleneck for terpene retention

For hemp destined for EO or terpene-rich applications, drying represents the most decisive postharvest step influencing both chemical composition and downstream bioactivity. Comparative evaluations of hot-air and infrared drying demonstrated significant losses of highly volatile monoterpenes during prolonged exposure to elevated temperatures, whereas milder regimes preserved a greater proportion of α -pinene, myrcene, and limonene (Chen et al., 2021). Process-engineering approaches that improve drying efficiency while minimizing thermal exposure have resulted in significantly greater terpene retention and enhanced antioxidant activity of the resulting extracts (Das et al., 2025). These findings are consistent with observations in other aromatic crops, however, hemp presents additional complexity because cannabinoids and terpenes respond differently to heat, oxygen, and drying conditions.

Drying alters the absolute concentrations of terpenes and can also shift the relative balance between monoterpenes and sesquiterpenes. Rapid moisture removal generally favors the retention of oxygenated monoterpenes, whereas slow or uneven drying may promote oxidative conversion to less volatile derivatives (Baek et al., 2025). From an industrial perspective, such compositional changes can directly influence antimicrobial efficacy and sensory quality, underscoring the importance of reporting drying conditions alongside bioactivity and product-performance data. Spadafora et al. (2024) demonstrated that

postharvest processing strongly influences the chemistry of hemp inflorescences. Tray drying better preserved the terpene-rich volatile profile. Freeze drying reduced key aroma compounds but limited decarboxylation of acidic cannabinoids. During storage, volatile composition changed under all conditions; glass containers best maintained terpenes but promoted conversion of acidic to neutral cannabinoids. Birenboim et al. (2024) found that THCA concentration decreased by 4–23% during the four months of storage with the lowest reduction observed following hexanoic acid pre-harvest treatment and post-harvest vacuum storage. Furthermore, the cited study reported that the application of hexanoic acid had a more pronounced effect on preserving monoterpenes, whereas sesquiterpenes were less susceptible to degradation over prolonged storage (Birenboim et al., 2024). Collectively, these studies highlight the inherent trade-offs in preserving terpene integrity and cannabinoid stability during drying and storage.

5.2. Curing, storage, and oxidative pathways

Following primary drying, curing and storage conditions continue to influence terpene composition and stability (Joy et al., 2025a; Spadafora et al., 2024). Studies monitoring chemical changes during simulated warehouse storage showed gradual decline of monoterpene hydrocarbons accompanied by relative enrichment of sesquiterpenes and oxidized products (Baek et al., 2025). Light exposure and oxygen availability were identified as major drivers of degradation, suggesting that environmental control strategies employed in hops, medicinal herb, and tobacco drying and storage facilities could be adapted to improve terpene retention and product consistency in hemp.

The stability of hydrolates and late distillation fractions appears particularly sensitive to storage, as these matrices contain residual water and enzymatic activity that may catalyze transformation of labile constituents (Vinciguerra et al., 2024). Consequently, their terpene composition and bioactivity may change more rapidly than those of the primary EO fractions, emphasizing the need for appropriate storage conditions, including temperature control, reduced oxygen exposure, and suitable packaging materials. These considerations are especially important if hydrolates and late fractions are to be developed as value-added co-products within integrated hemp biorefineries.

5.3. Microbial safety and quality assurance

Postharvest management of hemp must simultaneously address terpene preservation and microbial safety. A comprehensive review of fungal contamination risks in cannabis products highlighted the prevalence of *Aspergillus* spp. and the potential for mycotoxin formation during improper drying and storage (Gwinn et al., 2023). Baek et al. (2025) demonstrated that curing protocols that preserved volatile integrity also reduced microbial load, whereas high-humidity conditions increased both mold counts and chemical variability.

For EO-based industrial applications, microbial contamination may pose safety concerns and interfere with analytical quantification and bioactivity testing. Volatile metabolites produced by spoilage microorganisms can alter GC-MS profiles and may complicate chemotype characterization and interpretation (Joy et al., 2025a). Consequently, establishing hygienic processing practices and moisture specifications analogous to those used in the spice and medicinal plant industries is essential for ensuring reproducibility, product quality, and commercial scalability.

5.4. Interaction between postharvest history and bioactivity

Evidence is accumulating that postharvest history modulates the functional performance of hemp EO. In cultivar evaluations conducted by our group, EO samples derived from optimally dried biomass exhibited stronger antibacterial activity than EOs from material subjected to extended field drying, even when total terpene concentrations

Table 3
Postharvest factors affecting terpene integrity and functionality.

Stage	Key effects	Industrial implications	Representative studies
Drying method	Loss of monoterpenes; shifts in ratios	Potency variability	Chen et al. (2021); Das et al. (2025)
Microwave exposure	Loss of monoterpenes, enrichment in sesquiterpenes and trace cannabinoids	Targeted products	Fiorini et al. (2019)
Curing/storage	Oxidation, compositional drift	Shelf-life limits	Baek et al. (2025)
Microbial control	Mold alters fingerprints	QA/QC risk	Gwinn et al. (2023)
Distillation timing	Fraction design	Targeted products	Zheljazkov et al. (2025b); Spinozzi et al. (2025)
Grinding	Cannabinoid carryover	Compliance	Zheljazkov et al. (2020)

were comparable (Zheljaskov et al., 2025a). Similar trends were reported for hydrolates, where storage-induced shifts in volatile composition correlated with reduced efficacy against Gram-positive bacteria (Šovljanski et al., 2024). These observations suggest that reporting only final chemical composition is insufficient; the postharvest trajectory through which that composition was generated can also influence biological activity. For example, late hydrodistillation fractions obtained from overdried material may contain higher proportions of sesquiterpenes and cannabinoids (Spinozzi et al., 2025; Zheljaskov et al., 2025b), which could alter toxicity profiles relevant to non-target organisms (Sut et al., 2024).

5.5. Postharvest design for fraction-by-purpose

Time-resolved distillation experiments illustrate how postharvest and processing steps can be combined to create purpose-specific fractions. Distillation studies provide additional insight into the terpene modulations. Our research (Spinozzi et al., 2025; Zheljaskov et al., 2025b) on hemp distillation demonstrated that the first 20–30 min up to 60 min of distillation yielded fractions enriched in highly volatile monoterpenes, whereas later fractions contained increasing proportions of sesquiterpenes and minor cannabinoids, mainly CBD. Grinding and heating biomass prior to distillation further altered the profile (Fiorini et al., 2019, 2020; Zheljaskov et al., 2020). Apparently, the compounds from internal tissues were released, which increases thermal exposure and decarboxylation of cannabinoid acids into the volatile forms (Fiorini et al., 2019, 2020; Zheljaskov et al., 2020). These findings indicate that the plant matrix contains multiple reservoirs of volatiles with different release kinetics, a feature that can be exploited to design application-specific fractions (Spinozzi et al., 2025). Early monoterpene-rich cuts generated from gently dried biomass are most suitable for repellence and rapid antimicrobial action, whereas later fractions may offer longer residual activity but carry greater risk of cannabinoid co-extraction (Zheljaskov et al., 2025b). Grinding prior to distillation intensifies this effect by increasing release of less volatile constituents (Zheljaskov et al., 2020).

These findings support a “fraction-by-purpose” strategy analogous to that used in peppermint and lavender industries. However, hemp research rarely integrates drying parameters, storage duration, and distillation design within a single experiment. Moreover, Spinozzi et al. (2025) emphasized that valorization of spent biomass and aqueous residue must also account for upstream postharvest practices, as these co-products retain the chemical signatures imparted by drying, storage, and distillation processes.

Sections 6–9 evaluate different types of extraction and processing technologies, and their implications for the functional applications of hemp EO and terpene-rich fractions (Mazzara et al., 2023; Yang et al., 2025; Zheljaskov et al., 2025a).

6. Extraction and processing technologies

Several techniques are employed to obtain *C. sativa* EO and terpene-

rich fractions, including steam distillation, hydrodistillation, solvent extraction (SE), and supercritical carbon dioxide extraction (SC-CO₂) (Tables 1 and 4). These methods differ substantially in extraction efficiency, selectivity, and their influence on chemical composition. According to ISO 9235:2021 and the European Pharmacopoeia, however, only products obtained by steam distillation, hydrodistillation, or mechanical pressing of citrus fruit peels (e.g., orange and lemon) are formally classified as EOs (International Organization for Standardization ISO, 2021; Schmidt, 2021). Consequently, terpene-rich fractions produced by solvent extraction or SC-CO₂ extraction are not considered EOs under these definitions, despite their potential industrial relevance.

Additional extraction technologies have also been explored for hemp volatiles and terpene-rich fractions. Ultrasound-assisted extraction and other intensification techniques can improve mass transfer and reduce extraction time, whereas subcritical extraction approaches may better preserve thermolabile constituents by operating under relatively mild conditions. Headspace-solid phase microextraction (HS-SPME) has been extensively used for analytical profiling of hemp volatiles, although it is not intended for preparative purposes. Collectively, these emerging approaches may complement conventional distillation methods by enabling selective recovery of specific classes of compounds; however, their industrial implementation and standardization for hemp remain limited.

6.1. Distillation as reference technology and alternative distillation and extraction approaches

Hydrodistillation and steam distillation remain the dominant approaches for hemp EO production (Table 1), owing to their operational simplicity, scalability, and established acceptance within regulatory frameworks. As hydrodistillation is widely regarded as the reference method, alternative extraction techniques are increasingly being explored for their ability to recover a broader spectrum of volatile and semi-volatile compounds and to operate under milder thermal conditions.

Microwave-assisted hydrodistillation (MAH) gave higher yields of hemp EOs than those obtained by conventional hydrodistillation and steam distillation, which can be explained by the fact that microwaves cause a better release of volatiles by disruption of glandular trichomes. Also, a higher fraction of monoterpenes is collected by MAH when compared with hydrodistillation and steam distillation (Spinozzi et al., 2025).

Pressurized liquid extraction and solvent-assisted methods have been employed to recover both cannabinoids and terpenes in a single step (Haczekiewicz et al., 2025). As a result, these extracts often exhibit biological profiles distinct from those of steam-distilled EOs, reflecting the co-extraction of less volatile phenolics and lipophilic cannabinoids. Although supercritical CO₂ (SC-CO₂) extraction can provide higher yields and operates at lower temperatures, its industrial adoption remains limited due to higher capital costs, process complexity, and scalability challenges (Aiello et al., 2020).

Fresh versus dried biomass also yields markedly different final products. Sut et al. (2024) reported that EOs distilled from fresh inflorescences were richer in monoterpenes, whereas dried material favored sesquiterpenes and cannabinoid enrichment. Such contrasts highlight the need to define the intended product matrix-EO, hydrolate, or solvent extract-before designing efficacy studies. The ability to tune extraction conditions and selectively recover compounds with different volatilities provides the technological basis for the “fraction-by-purpose” concept discussed in Section 6.2.

6.2. Fraction-by-purpose strategy

Collectively, current evidence supports a “fraction-by-purpose” approach in which processing conditions are tailored to the desired functional endpoint. Early distillation fractions, typically enriched in

Table 4
Analytical tools for hemp EO and related matrices.

Method	Strengths	Limitations	Key references
GC-MS (SIM)	Quantitative accuracy	Cost, sample preparation	Joy et al. (2025a)
GC-FID	Industrial QC*	Limited ID power	Francisco et al. (2024)
HS-GC-MS	Rapid screening	Semi-quantitative	Chaiwangrach et al. (2025)
HS-SPME	Fingerprinting	Matrix effects	Janta et al. (2024);
Hydrolate GC-MS	Co-product profiling	Lack of standards	Vinciguerra et al. (2024)

* Industrial QC: Industrial Quality Control

monoterpenes, are associated with rapid antimicrobial and repellent activity, making them suitable for applications requiring immediate efficacy (Palmieri et al., 2021; Zheljaskov et al., 2025b). In contrast, later fractions enriched in sesquiterpenes may provide longer residual activity and potential synergistic effects, which are advantageous for sustained protection (Šovljanski et al., 2024). Hydrolates and aqueous residues, representing the co-products of distillation, offer opportunities for water-compatible formulations, including incorporation into sprays, coatings, and film-based delivery systems (Vinciguerra et al., 2024). In addition, the integration of spent biomass into biorefinery pathways, such as for cannabinoids recovery, materials development or soil amendments, can further enhance overall process efficiency and value generation (Spinozzi et al., 2025; Luca et al., 2024).

Despite these advantages, such differentiation is rarely implemented in published efficacy studies, which often evaluate a single, undifferentiated EO. Explicit reporting of fraction identity, processing conditions, and compositional attributes is therefore essential to enable reproducibility, facilitate cross-study comparisons, and support techno-economic assessment for industrial applications.

6.3. Compliance and safety considerations and research priorities

Extraction of hemp EO must account for the risk of unintended cannabinoid enrichment. THC and CBD can concentrate in later distillation fractions, particularly when biomass is finely comminuted (Zheljaskov et al., 2020; Spinozzi et al., 2025; Zheljaskov et al., 2025b). This is critical for industrial applications, as even trace cannabinoids may trigger regulatory scrutiny in biopesticides, food-contact materials, and veterinary uses (Sut et al., 2024). Accordingly, defining distillation cut-off points and implementing routine GC–MS screening are essential for compliance and product consistency (Joy et al., 2025a; Chaiwan-grach et al., 2025).

Despite progress, extraction science for hemp EO remains fragmented. Key priorities include comparative evaluation of extraction methods using identical biomass, development of process–efficacy relationships linking fractions to biological performance, and standardization of descriptors for hydrolates and spent biomass. In addition, clear guidelines for THC risk management during fractionation are needed. Addressing these gaps will support application-driven processing and industrial adoption (Zheljaskov et al., 2025b; Spinozzi et al., 2025).

7. Co-products and waste valorization

Hydrolates (aromatic waters) generated during distillation represent an underutilized resource in hemp processing. Hydrolates, also referred to in the literature as hydrosols or aromatic waters, are the aqueous distillates that remain after steam distillation and separation of the EO whenever possible, according to ISO 9235:2021 (International Organization for Standardization ISO, 2021). Although the terms hydrolate and hydrosol are frequently used interchangeably, terminology remains inconsistent across the scientific and industrial literature. In this review, the term hydrolate is used in accordance with the ISO definition. Recent characterizations revealed that hemp hydrolates contain measurable concentrations of oxygenated monoterpenes and other polar volatiles with demonstrable antimicrobial activity (Šovljanski et al., 2024; Vinciguerra et al., 2024). Because hydrolates are water-based and easier to formulate than EOs, they offer attractive opportunities for surface sanitation, horticultural sprays, and integration into biopolymer materials.

The composition of hydrolates is highly sensitive to distillation duration and biomass pretreatment (Vinciguerra et al., 2024). Early fractions tend to mirror the monoterpene profile of the corresponding EO cut, whereas later hydrolates accumulate more oxygenated compounds. Standardization of hydrolate production is therefore essential if these streams are to move beyond niche uses.

7.1. Valorization of residual water and spent biomass

Distillation residues constitute a substantial mass flow in hemp EO operations. They consist primarily of residual water and spent (deterpenated) biomass. Mazzara et al. (2022) and Spinozzi et al. (2025) emphasized that residual water is a good source of phenolics, mainly represented by luteolin and apigenin glycosides, whereas the spent biomass retains substantial quantity of neutral cannabinoids. These products could be redirected to bio-based materials, soil amendments, or secondary extraction. Luca et al. (2024) demonstrated that extracts obtained from such residues exhibited antifungal activity, supporting the concept of cascading utilization within a hemp biorefinery. The chemical imprint of postharvest handling is inherited by these residues; overdried or oxidized biomass produces co-products of lower quality (Baek et al., 2025). Integrating extraction design with upstream operations is therefore critical for maximizing total value rather than focusing solely on the primary EO fraction.

7.2. Matrix effects: EO versus hydrolates

Hydrolates generated during distillation have emerged as promising antimicrobial agents in their own right (Šovljanski et al., 2024). showed that hemp hydrolates inhibited several Gram-positive bacteria at concentrations achievable in aqueous formulations, despite containing only trace levels of the major EO terpenes. Vinciguerra et al. (2024) further showed that hydrolates enriched in oxygenated monoterpenes contribute to this activity and may offer advantages in applications where emulsification of EOs is undesirable or technically challenging.

Comparative studies indicate that EO and hydrolate activities are not necessarily proportional; some cultivars producing moderate EO potency yielded highly active hydrolates and vice versa (Šovljanski et al., 2024; Zheljaskov et al., 2025a). This divergence underscores the importance of evaluating both matrices during product discovery rather than assuming the EO fraction alone determines bioactivity.

7.3. Comparison with cannabis extracts

Although this review focuses on EOs and hydrolates, cannabis extracts provide valuable context for interpreting the biological activities of hemp-derived products. Inflorescence extracts containing both cannabinoids and terpenes have shown antifungal and antibacterial activity (Kursa et al., 2024; Niyangoda et al., 2024). These matrices may benefit from the so-called “entourage effect,” whereby multiple phytochemicals interact synergistically or additively, but they also introduce greater regulatory complexity and variability in cannabinoid composition. Likewise, hemp EOs, which are complex mixtures of numerous bioactive compounds, may exert pleiotropic biological effects arising from interactions among terpenes, cannabinoids, and other minor compounds.

Comparative studies have demonstrated distinct functional differences between *C. sativa* EOs and non-volatile extracts. For example, EO from *C. sativa* cv. Futura 75 inflorescences exhibited substantially greater activity against insect vectors (*Culex quinquefasciatus* Say, *Musca domestica* L.) and the agricultural pest *Spodoptera littoralis* (Boisduval) than the corresponding methanolic extract (Benelli et al., 2018a, Benelli et al., 2018b). Similarly, EOs from three commercial hemp cultivars demonstrated stronger anti-neuroinflammatory effects compared with extracts derived from aqueous distillation residues (Barbalace et al., 2023).

In contrast, extracts obtained from residual water and spent biomass after distillation, rich in polyphenols and cannabinoids, respectively, display significant antioxidant and neuroprotective properties. The aqueous fraction was particularly effective in inhibiting acetylcholinesterase (AChE) and monoamine oxidase A (MAO-A), and in protecting Neuro–2a cells against oxidative stress (Cásedas et al., 2022). Furthermore, this fraction modulated inflammation and oxidative stress in

SH-SY5Y neuronal cells via activation of the Keap1/Nrf2 pathway, suggesting potential utility for mitigating mitochondrial dysfunction and oxidative damage (Cásedas et al., 2026).

Despite these findings, direct comparisons between EOs and solvent extracts under standardized conditions remain limited and represent an important research need. For example, Pieracci et al. (2025) evaluated the antibacterial activity of hemp EOs from leaves and inflorescences against multidrug-resistant, methicillin-resistant *Staphylococcus pseudintermedius* isolated from canine infections. The EOs were rich in sesquiterpenes, primarily β -caryophyllene and α -humulene, and contained varying levels of phytocannabinoids. Notably, the EO with higher phytocannabinoid content exhibited the strongest inhibitory and bactericidal effects, while both whole EOs outperformed β -caryophyllene alone, suggesting synergistic interactions among EO constituents.

8. Biopesticide potential

Plant EOs are increasingly recognized as complementary tools for integrated pest management, offering rapid degradation, multiple

modes of action, and reduced risk of resistance development. Hemp EO is particularly attractive because large volumes of biomass are already produced for fiber and grain, creating opportunities to valorize inflorescences and co-products. The availability of abundant agricultural residues and underutilized floral biomass further enhances the potential of hemp EO as a sustainable source of biopesticidal compounds. Systematic assessment of cannabis-based pest control concluded that terpenes such as α -pinene, limonene, β -caryophyllene, and α -humulene exhibit broad repellent and toxic effects against insects and mites, although evidence strength varies among targets (Tabari et al., 2020; Ona et al., 2022). The principal findings from reviews and experimental studies on the biopesticidal activities of hemp-derived products are summarized in Table 5.

8.1. Insecticidal activity and repellent mechanisms

Laboratory studies demonstrate that hemp EO and terpene-rich extracts exhibit bioactivity across a broad range of insect taxa. For example, a nanoemulsion formulated from hemp EO of cv. Kompolti

Table 5
Literature review (2010–2025) of *C. sativa* as a biopesticide activity.

Reference	Hemp Material / Compound	Target Pest or Pathogen	Main Findings
Ona et al., 2022	Ethnobotanical review of article by various hemp extracts	Multiple insects and mites	<i>Cannabis</i> shows pesticidal activity due to cannabinoids and terpenes. For instance, promising pesticide properties were reported for most of the groups of species tested, especially Arachnida and Insecta.
Martínez-Rodríguez et al. (2024).	Methanol extract of hemp leaves, CBD	<i>Aedes aegypti</i>	Methanol extract of hemp leaves displayed a strong larvicidal activity ($LC_{50} \approx 4.3\text{--}4.4$ ppm)
Park et al. (2019).	CBD	<i>Manduca sexta</i>	CBD inhibited larval growth and caused mortality.
Prvulović et al.(2023).	Ethanol hemp extract	<i>Plodia interpunctella</i> ; phytotoxic activity of the extract on <i>Helianthus annuus</i> seeds;	42.5% Larval mortality; reduced growth; 0.5%, 1.0%, and 2.0% concentrations directly applied on sunflower seeds. Ethanol solution (70%) was the control. The hemp extract (1% and 2%) revealed medium repellence for <i>P. interpunctella</i> larvae (L3–4) while at 2% concentration it caused 42.5% larval mortality after 72 h. Germination energy and germination of sunflower seeds were stimulated in treatment with 2% hemp extract.
(Dadé et al., 2025)	Inflorescence acetone and ethanol extract as CBD and THC	<i>Triatoma infestans</i>	Strong repellent and lethal effects
Benelli et al. (2018a)	Fresh inflorescences of Hemp EO	<i>Musca domestica</i> adults, <i>Culex quinquefasciatus</i> ; <i>Harmonia axyridis</i> larvae and adults; <i>Myzus persicae</i> ; <i>Spodoptera littoralis</i> ; <i>Eisenia fetida</i>	The EO was toxic to houseflies and peach aphids, efficacy on mosquitoes and <i>Spodoptera</i> moth pests was scarce.
Benelli et al. (2018b)	Fiber hemp, leaves and inflorescences EO and methanolic extracts	larvae of <i>Culex quinquefasciatus</i> and <i>Spodoptera littoralis</i> and adults of <i>Musca domestica</i>	The EO from inflorescences, (β -caryophyllene, myrcene, CBD, α -pinene, terpinolene, and α -humulene), was more effective if compared with the leaf EO, with special reference to <i>M. domestica</i> (inflorescence oil LD_{50} 122.1 $\mu\text{g}/\text{adult}$ vs. leaf EO LD_{50} 305.2 $\mu\text{g}/\text{adult}$) and <i>S. littoralis</i> (inflorescence EO LD_{50} 65.8 $\mu\text{g}/\text{larva}$ vs. leaf EO LD_{50} 112.8 $\mu\text{g}/\text{larva}$). The methanolic extracts did not show relevant toxicity against the three targeted insect species.
Tabari et al. (2020)	<i>C. sativa</i> EO ((<i>E</i>)-caryophyllene and α -humulene)	<i>Dermanyssus gallinae</i> ; <i>Hyalomma dromedarii</i>	The study showed the potential of the hemp EO as a botanical acaricide to be employed in pest management and food production programs.
Laznik et al. (2020)	Ethanol extract from root, leaves and inflorescence of <i>C. sativa</i>	<i>Steinernema carpocapsae</i> ; <i>S. feltiae</i> ; <i>Heterorhabditis bacteriophora</i>	The most attracted or repelled by inflorescence extracts, followed by leaves and roots.
(Rossi et al., 2020)	The three hemp EOs obtained from the monoecious Felina 32 and female and male inflorescences of <i>C. sativa</i>	<i>Anopheles gambiae</i> ; <i>An. stephensi</i> .	The mortality was recorded after 24 h of treatment. The dose–response curves showed an insecticidal effect of the three EOs on larvae and pupae of <i>An. stephensi</i> .
Mantzoukas et al. (2020)	Combined Toxicity of CBD oil with Azatin, and two baculovirus formulations (Madex and Helicovex)	<i>Sitophilus zeamais</i> ; <i>Rhyzopertha dominica</i> ; <i>Prostephanus truncatus</i> ; <i>Trogoderma granarium</i>	The findings reveal a promising effect of CBD oil against these coleopterans
Kursa et al. (2024)	Inflorescence leaves extract of <i>C. sativa</i>	<i>Alternaria alternata</i> , <i>Botrytis cinerea</i> , <i>Colletotrichum coccodes</i> , <i>Fusarium avenaceum</i> , <i>F. culmorum</i> , <i>F. graminearum</i> , <i>F. oxysporum</i> , <i>F. sporotrichioides</i> , and <i>Trichoderma koningii</i> .	The most pronounced antifungal activity was observed with the 20% extract, particularly against <i>T. koningii</i> (62.22–84.79%), <i>C. coccodes</i> (61.65–81.82%), and <i>B. cinerea</i> (45.00–75.42%). However, the efficacy of hemp extracts exhibited large differences against <i>Fusarium</i> spp. (3.10–72.95%), dependent on the specific extract and fungus strain.

produced significant mortality in a mosquito vector while reducing phytotoxicity to host plants, highlighting the importance of formulation (Mazzara et al., 2023). Dose-dependent toxicity against flea larvae and adults has also been reported, indicating potential applications in veterinary hygiene and urban pest management (Soares et al., 2023). Additional studies have demonstrated larvicidal activity against *Aedes* mosquitoes (Martínez Rodríguez et al., 2024) and toxicity against *M. domestica* and *Myzus persicae* (Sulzer) with minimal effects on non-target organisms such as lady beetles and earthworms (Benelli et al., 2018a, Benelli et al., 2018b). Collectively, these findings suggest that hemp EO can achieve efficacy levels comparable to established botanical insecticides such as clove or rosemary EOs.

However, cross-study comparisons remain challenging due to substantial variability in experimental design and reporting metrics, including LC₅₀ values, repellence indices, and knockdown times. This lack of standardization hampers efforts to benchmark hemp EO against other botanical insecticides and underscores the need for harmonized testing protocols.

Beyond acute toxicity, repellency represents a particularly promising application pathway. Hemp-derived terpenes have shown repellent activity against arthropod vectors, including the tick *Hyalomma marginatum* (Koch, 1844), where compounds such as bisabolol exhibited efficacy comparable to DEET at equivalent concentrations (Eschlwech et al., 2023). Fractionation of supercritical CO₂ extracts enabled the isolation of high-purity terpenes, including bisabolol, caryophyllene oxide, and caryophyllene/humulene mixtures, demonstrating the feasibility of scalable purification strategies. In addition, synergistic interactions among terpene mixtures have been shown to enhance repellence compared with individual compounds, consistent with the broader literature on EO-based vector management (Dadé et al., 2025).

From an industrial perspective, repellency offers advantages over contact toxicity, including lower application rates and reduced exposure of non-target organisms. Water-compatible matrices, such as hydrolates, may provide practical platforms for developing sprayable formulations, although their efficacy and persistence remain insufficiently investigated. Overall, these findings support the potential of hemp EO and terpene fractions as multifunctional agents for integrated pest management, while emphasizing the need for standardized bioassays, formulation optimization, and field validation.

8.2. Acaricidal and veterinary applications

Interest in hemp-derived products for ectoparasite control is increasing, particularly in veterinary and urban pest management markets. Studies on flea control (Soares et al., 2023) and broader evaluations of EOs (Campos et al., 2025) highlight the potential for incorporation into practical formulations such as shampoos, sprays, and collars. Activity against ticks of public health relevance has also been demonstrated (Dadé et al., 2025). In addition, EO from *C. sativa* cv. Felina 32 inflorescences showed efficacy against *Dermanyssus gallinae* (De Geer 1778) and *Hyalomma dromedarii* (Koch, 1844), with β -caryophyllene and α -humulene identified as key active components (Tabari et al., 2020). These findings support the potential of hemp EO as a multifunctional agent for veterinary ectoparasite management.

However, the development of such applications requires careful toxicological evaluation and product standardization. Differences in extraction and distillation methods can produce EOs with substantially different chemical composition and safety characteristics, underscoring the need to characterize both terpene and cannabinoid content prior to commercialization (Sut et al., 2024). Standardized toxicological testing and safety assessment protocols will therefore be essential for regulatory acceptance and commercialization in veterinary markets.

8.3. Formulation as the bridge to field efficacy

The high volatility and susceptibility of unformulated EOs to

photodegradation limit their persistence under field conditions. As a result, formulation technologies are central to enabling practical applications. Nanoemulsions and encapsulation systems have demonstrated improved stability and efficacy, with nanoemulsified hemp EO showing enhanced and more persistent insecticidal activity compared to crude EO (Mazzara et al., 2023), alongside favorable cytotoxicity profiles (Aguzzi et al., 2023). Protein-based carriers derived from hemp represent an emerging strategy for developing fully plant-based delivery systems (Zhang et al., 2025).

In addition, electrospun films and nanofibers provide promising platforms for controlled release in greenhouse and storage environments (Yang et al., 2025). Collectively, these formulation technologies may provide the critical link between laboratory bioactivity and practical deployment by enhancing stability, enabling controlled delivery, and facilitating the commercialization of hemp EO and terpene-rich fractions for crop protection, postharvest preservation, and veterinary applications.

8.4. Non-target and environmental considerations

Assessment of non-target effects is essential for the development of hemp EO-based biopesticides. Preliminary studies indicate that formulation can mitigate phytotoxicity and improve safety toward beneficial organisms (Mazzara et al., 2023). However, comprehensive ecotoxicological evaluations remain limited. Given the substantial variability in terpene profiles among hemp cultivars (Pieracci et al., 2021; Zheljaskov et al., 2025a), environmental risk assessments should be chemotype-specific rather than generalized at the product level.

Although biodegradability is often regarded as a major advantage of EOs, rapid degradation may also reduce field persistence and consequently, efficacy. Achieving an optimal balance between biological activity and environmental fate will require the integration of chemical ecology, formulation science, and agronomic management. From an industrial perspective, such optimization is critical for developing hemp-derived products that are both effective and environmentally compatible.

9. Knowledge gaps and research agenda

Advancing hemp EOs from promising bioactive mixtures to reliable industrial ingredients requires a coordinated, application-driven research agenda that integrates cultivation, processing, formulation, and end-use performance. A major priority is the development of field-to-function studies that explicitly connect agronomic variables, including cultivar selection, harvest timing, and postharvest management, with industrially relevant outcomes such as antimicrobial activity, sprout suppression, and biopesticide efficacy (Pieracci et al., 2021; Zheljaskov et al., 2025a). Without these linkages, optimization remains largely empirical, limiting reproducibility, scalability, and commercialization adoption. In parallel, fraction-by-purpose approaches should be developed to differentiate early and late distillation cuts, enabling production of EO fractions tailored for specific applications such as food preservation, postharvest storage protection, or crop protection systems (Zheljaskov et al., 2025b). Such strategies could increase value generation per unit biomass while improving process efficiency and industrial relevance.

Research on hemp EOs has expanded rapidly, yet progress remains fragmented across agronomy, chemistry, microbiology, and formulation science. Numerous investigations describe chemical composition without evaluating functional performance, whereas efficacy studies often omit critical metadata related to cultivar, postharvest handling, extraction conditions, or distillation parameters (Zheljaskov et al., 2025a; Baek et al., 2025). This disconnect hinders the development of predictive models capable of linking production and processing decisions to biological performance. Consequently, establishing integrated experimental pipelines that follow hemp EO systems from field

production through extraction, formulation, and application therefore represents one of the most important challenges and opportunities for the coming decade.

Although intellectual property activity in this area is increasing, it reflects a similar lack of integration and standardization. For example, patent applications such as CN108064886A describe hemp-derived extracts as insect repellents, yet these claims are generally broad and rarely define hemp EO as a distinct, standardized functional ingredient. This lack of specificity mirrors the inconsistencies found throughout scientific literature and highlights the need for clearer terminology, performance benchmarks, and quality specifications.

Compared with more established EO crops, hemp also lacks widely accepted descriptors for chemotype classification and product quality assessment. Reporting only relative chemical composition is often insufficient because EOs with similar chemical profiles may exhibit markedly different biological activities (Šovljanski et al., 2024; Pieracci et al., 2024). The adoption of class-based metrics, such as monoterpene indices, sesquiterpene indices, and oxygenated terpene fractions, together with the reporting of absolute constituent concentrations in addition to relative abundances, would substantially improve comparability among studies (Joy, 2025b). Addressing these limitations will require community-driven minimum reporting standards and coordinated efforts among researchers, journals, funding agencies, and regulatory bodies. Key barriers and proposed actions are summarized in Table 6.

Evidence from drying and curing studies demonstrates that post-harvest operations can alter terpene profiles as much as genetic differences (Chen et al., 2021; Das et al., 2025). Nevertheless, most antimicrobial and biopesticide published studies provide little information on moisture history or storage duration. Development of kinetic models describing terpene loss as a function of temperature, water activity, and oxygen would allow rational design of supply chains (Baek et al., 2025). Collaboration with postharvest physiologists, a discipline well established for hops and medicinal herbs, is urgently needed.

Although hemp EO is intended for non-intoxicating uses, trace cannabinoids are frequently detected, particularly in late distillation fractions and finely ground biomass (Spinuzzi et al., 2025; Zheljazkov et al., 2020; 2025b). Regulatory thresholds vary among jurisdictions, creating uncertainty for biopesticide registration, food-contact materials, and other commercial applications (Haczkiwicz et al., 2025). Future work should establish processing cut-points that reliably minimize THC while preserving terpene efficacy, supported by validated analytical methods capable of simultaneous cannabinoid and terpene quantification (Chaiwangrach et al., 2025).

In addition, safety and regulatory compliance must be addressed comprehensively to facilitate market adoption. This includes the development of robust production and quality-control protocols that ensure THC concentrations remain consistently below regulatory limits throughout processing and product formulation (Zheljazkov et al., 2020). Further research should evaluate the effects of hemp EO-based products on non-target organisms, characterize their toxicological profiles, determine residue behavior, and assess their environmental fate and potential ecological impacts (Sut et al., 2024). Addressing these regulatory, safety, and environmental considerations early in product development will facilitate regulatory approval, reduce commercialization risks, and enhance industry confidence in hemp EO-based

products.

While nanoemulsions and encapsulation systems show promise, comparative trials using identical hemp fractions are rare. Release kinetics, stability, and compatibility with agricultural adjuvants remain poorly characterized (Kumar et al., 2025; Worku et al., 2024). Moreover, formulation design should be integrated with chemotype and fraction selection because early, monoterpene-rich fractions are likely to require greater stabilization and more robust encapsulation strategies than sesquiterpene-rich EOs (Zheljazkov et al., 2025b).

Formulation science represents a key enabling technology for industrial deployment. Comparative evaluation of delivery systems, including nanoemulsions, protein-based encapsulates, hydrolate-derived systems, and bio-based coatings, will help identify strategies that enhance stability, control release, and maintain efficacy under real-world conditions (Aguzzi et al., 2023; Zhang et al., 2025). Integration of hemp EO into functional materials such as edible coatings, active packaging films, and hydromulches offers a particularly promising pathway for delivering combined antimicrobial, biopesticide, and sprout-suppressive effects. Modeling release kinetics under realistic climatic, field, and storage conditions will further support formulation optimization and improve prediction of product performance (Yang et al., 2025). These advances are essential for transitioning hemp EO from a bulk extract to a high-value functional ingredient incorporated into engineered delivery systems. Development and dissemination of open-source reference formulations could further accelerate innovation and facilitate adoption by researchers and industry stakeholders.

Data on impacts to beneficial arthropods, soil microbiota, and aquatic organisms are limited. Mazzara et al. (2023) provided initial evidence that formulation can mitigate phytotoxicity, yet broader ecotoxicological frameworks are lacking. Life-cycle assessments comparing hemp EO products with synthetic preservatives would clarify sustainability claims (Górski et al., 2025). Attention should also be given to potential transfer of contaminants when hemp is grown on marginal or in phytoremediation systems, as these factors may influence the safety and quality of downstream products (Spinuzzi et al., 2025).

Standardization is essential for industrial translation. The development of certified reference materials and inter-laboratory ring tests will improve analytical reproducibility and enable benchmarking across production systems (Joy, 2025b). Equally important is the adoption of harmonized metadata frameworks capturing key postharvest and extraction variables. Such measures will reduce variability, facilitate regulatory approval, and enable the establishment of quality specifications required by industry. From an industrial perspective, the absence of universally accepted descriptors and reporting frameworks remains a major bottleneck to commercialization.

Applied efficacy research should prioritize realistic use conditions to establish translational relevance. This includes challenge studies on food surfaces and stored commodities to evaluate antimicrobial performance under representative postharvest environments, as well as semi-field and field trials assessing repellence, insect control, and disease suppression (Dadé et al., 2025). Demonstrating consistent efficacy under operational conditions is critical for industry adoption, particularly in sectors such as fresh product storage, grain protection, and integrated pest management systems. Such validation studies will directly inform product development and de-risk commercialization.

Collectively, these research priorities will enable the transition of hemp EO from a variable natural extract to a standardized, high-value input for postharvest technologies, biopesticide formulations, and bio-based materials. This transition is essential for unlocking scalable applications and attracting industrial investment.

Toward a hemp biorefinery paradigm: Hemp EO should be viewed within a broader biorefinery framework, where multiple co-products, including fibers, seeds, hydrolates, and spent biomass, are integrated into diversified industrial value chains (Spinuzzi et al., 2025; Luca et al., 2024). This systems-level approach is particularly important for improving economic feasibility, as it enables cost-sharing across product

Table 6
Key barriers and proposed actions.

Barrier	Consequence	Action
Inconsistent metadata	Poor comparability	Reporting standard
Postharvest variability	Unreliable efficacy	Kinetic models
THC carryover	Regulatory risk	Fraction controls
Limited field data	Slow adoption	Applied trials
Formulation gaps	Short persistence	Platform comparison

streams and reduces reliance on a single high-value output. For instance, EO fractions can be directed toward high-value applications such as biopesticides, postharvest technologies, and antimicrobial coatings, while residual biomass can be utilized for fiber-based materials, bio-composites, or soil amendments.

The coordinated valorization of all biomass fractions aligns with circular bioeconomy principles and supports the development of resilient, low-waste production systems. Importantly, such integration can offset the higher costs associated with advanced EO formulations, including encapsulated delivery systems and functional coatings, thereby facilitating their adoption in commercial agriculture and food systems. From an industrial perspective, the biorefinery model enhances supply chain resilience, improves resource efficiency, and creates multiple revenue streams, while reducing overall economic risk.

Industrial impact: Embedding hemp EO within a biorefinery paradigm enables the development of scalable, multi-output systems that simultaneously address crop protection, postharvest quality, and sustainable materials production. This integrated approach is likely to be critical for achieving both economic viability and broad adoption in industrial sectors.

10. Conclusions

Hemp (*C. sativa*) EOs and terpene-rich fractions represent an emerging class of renewable inputs for antimicrobial, biopesticide, and materials applications. The evidence synthesized in this review indicates that hemp EO is not a uniform commodity, but rather a continuum of chemotypes whose functional performance is governed by genotype, harvest stage, postharvest handling, and distillation design. Early monoterpene-rich fractions provide rapid antimicrobial and repellent activity, whereas later sesquiterpene-enriched fractions and hydrolates offer complementary properties suited for sustained release and material-based delivery systems. Realizing this potential requires a shift from descriptive chemistry toward purpose-driven fractionation and formulation.

Postharvest operations emerge as a critical yet frequently under-reported determinant of terpene integrity. Drying, curing, and storage can alter volatile profiles to an extent comparable to genetic factors, with direct consequences for biological activity. Integration of post-harvest science with extraction and analytical workflows is therefore essential to ensure reproducibility. In parallel, validated analytical frameworks capable of simultaneous terpene and cannabinoid quantification are needed to support quality control and manage THC compliance in regulated markets.

The applications reviewed demonstrate considerable promise. Hemp EO and hydrolates exhibit consistent activity against Gram-positive bacteria, efficacy against insect and mite pests, and growing utility in active packaging and bio-based materials. However, most studies remain at laboratory scale. Translation to field and commercial systems will depend on advances in formulation science, particularly nano-emulsions, biopolymer encapsulation, and electrospun matrices, that enhance stability and enable controlled release under operational conditions.

Accelerating industrial adoption will require addressing several cross-cutting challenges, including: (i) implementation of minimum reporting standards linking cultivar, postharvest history, and fraction identity; (ii) development of process–performance relationships connecting terpene profiles to biological endpoints; (iii) direct comparison of EOs, hydrolates, and non-volatile extracts derived from identical biomass; and (iv) comprehensive evaluation of non-target and environmental safety. Positioning hemp EO within a biorefinery framework, where EOs, hydrolates, aqueous residues, and residual biomass are co-valorized, offer a pathway to improved economic viability and sustainability.

In conclusion, hemp provides a versatile platform for terpene-based industrial products. Its full potential will depend on coordinated,

application-oriented research spanning agronomy, postharvest physiology, analytical chemistry, and formulation engineering. With standardized methodologies and validation under realistic conditions, hemp EOs can transition from promising laboratory materials to reliable components of next-generation antimicrobial agents, biopesticides, and sustainable bio-based materials. More broadly, hemp EO should be viewed not as a single commodity but as a portfolio of application-specific fractions integrated within a circular biorefinery paradigm capable of generating multiple high-value products from a single crop.

CRediT authorship contribution statement

Valtcho D. Zheljazkov: Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Eleonora Spinozzi:** Writing – review & editing, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation. **Ivanka Semerdjieva:** Writing – review & editing, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Filippo Maggi:** Writing – review & editing, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

It is review paper.

References

- Abdollahi, M., Sefidkon, F., Calagari, M., Mousavi, A., Mahmoodally, M.F., 2020. Impact of four hemp (*Cannabis sativa* L.) varieties and stage of plant growth on yield and composition of essential oils. *Ind. Crops Prod.* 155, 112793. <https://doi.org/10.1016/j.indcrop.2020.112793>.
- Addo, P.W., Brousseau, V.D., Morello, V., MacPherson, S., Paris, M., Lefsrud, M., 2021. Cannabis chemistry, post-harvest processing methods and secondary metabolite profiling: A review. *Ind. Crops Prod.* 170, 113743. <https://doi.org/10.1016/j.indcrop.2021.113743>.
- Aguzzi, C., Perinelli, D.R., Cespi, M., Zeppa, L., Mazzara, E., Maggi, F., Petrelli, R., Bonacucina, G., Nabissi, M., 2023. Encapsulation of hemp (*Cannabis sativa* L.) essential oils into nanoemulsions for potential therapeutic applications: Assessment of cytotoxicological profiles. *Molecules* 28, 6479. <https://doi.org/10.3390/molecules28186479>.
- Aiello, A., Pizzolongo, F., Scognamiglio, G., Romano, A., Masi, P., Romano, R., 2020. Effects of supercritical and liquid carbon dioxide extraction on hemp (*Cannabis sativa* L.) seed oil. *Int. J. Food Sci. Technol.* 55, 2472–2480. <https://doi.org/10.1111/jifs.14498>.
- Aina, A., Wenger, J.P., Stanton, E., Majumdar, C.G., ElSohly, M., Weiblen, G.D., Ellison, S., 2025. Genetic diversity, population structure, and cannabinoid variation in feral *Cannabis sativa* germplasm from the United States. *Sci. Rep.* 15, 20423. <https://doi.org/10.1038/s41598-025-07912-8>.
- Al Ubeed, H.M.S., Wills, R.B.H., Chandrapala, J., 2022. Post-harvest operations to generate high-quality medicinal cannabis products: A systematic review. *Molecules* 27, 1719. <https://doi.org/10.3390/molecules27051719>.

- Andre, C.M., Hausman, J.F., Guerriero, G., 2016. *Cannabis sativa*: The plant of the thousand and one molecules. *Front. Plant. Sci.* 7, 19. <https://doi.org/10.3389/fpls.2016.00019>.
- Ascrizzi, R., Flamini, G., Rossi, A., Santini, A., Angelini, L.G., Tavarini, S., 2024. Inflorescence yield, essential oil composition and antioxidant activity of *Cannabis sativa* L. cv 'Futura 75' in a multilocation and on-farm study. *Agriculture* 14, 225. <https://doi.org/10.3390/agriculture14020225>.
- Baek, Y., Grab, H., Chen, C., 2025. Postharvest drying and curing affect cannabinoid contents and microbial levels in industrial hemp (*Cannabis sativa* L.). *Plants* 14, 414. <https://doi.org/10.3390/plants14030414>.
- Baek, Y., Vergara, D., 2025. A review of sexual strategies in *Cannabis sativa* L. under genomic and environmental controls. *Agrosyst. Geosci. Environ.* 8, e70050. <https://doi.org/10.1002/agg2.70050>.
- Bakali, I.E., Sakar, E.H., Boutahar, A., Kadiri, M., Merzouki, A., 2022. A comparative phytochemical profiling of essential oils isolated from three hemp (*Cannabis sativa* L.) cultivars grown in central-northern Morocco. *Biocatal. Agric. Biotechnol.* 43, 102327. <https://doi.org/10.1016/j.bcab.2022.102327>.
- Barbalace, M.C., Freschi, M., Rinaldi, I., Mazzara, E., Maraldi, T., Malaguti, M., Angeloni, C., 2023. Identification of anti-neuroinflammatory bioactive compounds in essential oils and aqueous distillation residues obtained from commercial varieties of *Cannabis sativa* L. *Int. J. Mol. Sci.* 24, 16601. <https://doi.org/10.3390/ijms242316601>.
- Barcauskaitė, K., Bakšinskaitė, A., Szumny, A., Tilvikienė, V., 2022. Variation of secondary metabolites in *Cannabis sativa* L. inflorescences under applied agrotechnological measures. *Ind. Crops Prod.* 188, 115570. <https://doi.org/10.1016/j.indcrop.2022.115570>.
- Beleggia, R., Menga, V., Fulvio, F., Fares, C., Trono, D., 2023. Effect of Genotype, Year, and Their Interaction on the Accumulation of Bioactive Compounds and the Antioxidant Activity in Industrial Hemp (*Cannabis sativa* L.) Inflorescences. *Int. J. Mol. Sci.* 24, 8969. <https://doi.org/10.3390/ijms24108969>.
- Benelli, G., Pavela, R., Lupidi, G., Nabissi, M., Petrelli, R., Ngahang Kamte, S., Cappellacci, L., Fiorini, D., Sut, S., Dall'Acqua, S., Maggi, F., 2018a. The crop-residue of fiber hemp cv. Futura 75: From a waste product to a source of botanical insecticides. *Environ. Sci. Pollut. Res.* 25, 10515–10525. <https://doi.org/10.1007/s11356-017-0635-5>.
- Benelli, G., Pavela, R., Petrelli, R., Cappellacci, L., Santini, G., Fiorini, D., Sut, S., Dall'Acqua, S., Canale, A., Maggi, F., 2018b. The essential oil from industrial hemp (*Cannabis sativa* L.) by-products as an effective tool for insect pest management in organic crops. *Ind. Crops Prod.* 122, 308–315. <https://doi.org/10.1016/j.indcrop.2018.05.032>.
- Birenboim, M., Chalupowicz, D., Kenigsbuch, D., Shimshoni, J.A., 2024. Improved long-term preservation of cannabis inflorescence by utilizing integrated pre-harvest hexanoic acid treatment and optimal post-harvest storage conditions. *Plants* 13, 992. <https://doi.org/10.3390/plants13070992>.
- Borrito Fernandez, E., Peterseil, V., Hackl, G., Menges, S., de Meijer, E., Staginnus, C., 2020. Distribution of chemical phenotypes (chemotypes) in European agricultural hemp (*Cannabis sativa* L.) cultivars. *J. Forensic Sci.* 65, 715–721. <https://doi.org/10.1111/1556-4029.14242>.
- Busta, L., Dweikat, I., Sato, S.J., Qu, H., Xue, Y., Zhou, B., Gan, L., Clemente, T., Cahoon, E., Zhang, C., 2022. Chemical and genetic variation in feral *Cannabis sativa* populations across the Nebraska climate gradient. *Phytochemistry* 197, 113206. <https://doi.org/10.1016/j.phytochem.2022.113206>.
- Cahoon, E.B., Zhang, C., 2022. Chemical and genetic variation in feral *Cannabis sativa* populations across the Nebraska climate gradient. *Phytochemistry* 200, 113206. <https://doi.org/10.1016/j.phytochem.2022.113206>.
- Campos, D.R., de Jesus, L.L.R., Scott, F.B., Correia, T.R., Cid, Y.P., 2025. Essential oils and bioproducts for flea control: A critical review. *Insects* 16, 1276. <https://doi.org/10.3390/insects16121276>.
- Cásedas, G., Moliner, C., Maggi, F., Mazzara, E., López, V., 2022. Evaluation of two different *Cannabis sativa* L. extracts as antioxidant and neuroprotective agents. *Front. Pharmacol.* 13, 1009868. <https://doi.org/10.3389/fphar.2022.1009868>.
- Cásedas, G., Rojas-Márquez, H., Ventura, L., Moliner, C., Maggi, F., Rubio-Castellanos, A., López, V., 2021. Effect of hot air and infrared drying on the retention of cannabidiol and terpenes in industrial hemp (*Cannabis sativa* L.). *Ind. Crops Prod.* 170, 113743. <https://doi.org/10.1016/j.indcrop.2021.113743>.
- Clarke, R.C., Merlin, M.D., 2016. *Cannabis: Evolution and Ethnobotany*. Univ. Calif. Press, Berkeley.
- Dadé, M.M., Daniele, M.R., Rodriguez, S., Díaz, P., Silvestrini, M.P., Schinella, G.R., Marin, G.H., Barrio, D., Prieto Garcia, J.M., 2025. Repellent, Lethal Activity, and Synergism of *Cannabis sativa* Extracts with Terpenes Against a Laboratory Colony of *Tritoma infestans*. *Plants* 14 (21), 3258. <https://doi.org/10.3390/plants14213258>.
- Das, P.C., Heydari, M.M., Baik, O.-D., Zhang, L., Tabil, L.G., 2025. Enhancing drying efficiency and terpene retention of cannabis using cold plasma pretreatment. *Ind. Crops Prod.* 226, 120669. <https://doi.org/10.1016/j.indcrop.2025.120669>.
- Das, P.C., Vista, A.R., Tabil, L.G., Baik, O.-D., 2022. Postharvest operations of cannabis and their effect on cannabinoid content: A review. *Bioeng* 9, 364. <https://doi.org/10.3390/bioengineering9080364>.
- Dayanandan, P., Kaufman, P.B., 1976. Trichomes of *Cannabis sativa* L. (Cannabaceae). *Am. J. Bot.* 63, 578–591. <https://doi.org/10.1002/j.1537-2197.1976.tb11846.x> Digital Object Identifier (DOI).
- De Vita, S., Finamore, C., Chini, M.G., Saviano, G., De Felice, V., De Marino, S., Lauro, G., Casapullo, A., Fantasma, F., Trombetta, F., Bifulco, G., Iorizzi, M., 2022. Phytochemical analysis of the methanolic extract and essential oil from leaves of industrial hemp Futura 75 cultivar: Isolation of a new cannabinoid derivative and biological profile using computational approaches. *Plants* 11, 1671. <https://doi.org/10.3390/plants11131671>.
- ElSohly, M.A., Gul, W., 2014. Constituents of *Cannabis sativa*. In: Pertwee, R.G. (Ed.), *Handbook of Cannabis*. Oxford Univ. Press, Oxford, pp. 3–22.
- Erzen, M., Košir, I.J., Ocvirk, M., Kreft, S., Čerenak, A., 2021. Metabolomic analysis of cannabinoid and essential oil profiles in different hemp (*Cannabis sativa* L.) phenotypes. *Plants* 10, 966. <https://doi.org/10.3390/plants10050966>.
- Eschlewech, K., Benelli, G., Pavela, R., Maggi, F., 2023. Identification of hemp flower terpenes with tick repellent activity. *Ind. Crops Prod.* 195, 116386. <https://doi.org/10.1016/j.indcrop.2023.116386>.
- Fellermeier, M., Zenk, M.H., 1998. Prenylation of olivetolate by a hemp transferase yields cannabigerolic acid, the precursor of tetrahydrocannabinol. *FEBS Lett.* 427, 283–285. [https://doi.org/10.1016/S0014-5793\(98\)00450-5](https://doi.org/10.1016/S0014-5793(98)00450-5).
- Fiorini, D., Molle, A., Nabissi, M., Santini, G., Benelli, G., Maggi, F., 2019. Valorizing industrial hemp (*Cannabis sativa* L.) by-products: Cannabidiol enrichment in the inflorescence essential oil optimizing sample pre-treatment prior to distillation. *Ind. Crops Prod.* 128, 581–589. <https://doi.org/10.1016/j.indcrop.2018.11.045>.
- Fiorini, D., Scorticini, S., Bonacucina, G., Greco, N.G., Mazzara, E., Petrelli, R., Cespi, M., 2020. Cannabidiol-enriched hemp essential oil obtained by an optimized microwave-assisted extraction using a central composite design. *Ind. Crops Prod.* 154, 112688. <https://doi.org/10.1016/j.indcrop.2020.112688>.
- Fischedick, J.T., Hazekamp, A., Erkelens, T., Choi, Y.H., Verpoorte, R., 2010. Metabolic fingerprinting of *Cannabis sativa* L., cannabinoids and terpenoids for chemotaxonomic and drug standardization purposes. *Phytochemistry* 71, 2058–2073. <https://doi.org/10.1016/j.phytochem.2010.10.001>.
- Francisco, V.P., Santos, S.A.O., Rocha, S.M., 2024. Gas chromatography methods for cannabis terpene and terpenoid analysis: A review. *Microchem. J.* 195, 109476. <https://doi.org/10.1016/j.microc.2023.109476>.
- Gargiulo, E., Moriello, A.S., Benetti, E., Pagni, L., Arnoldi, L., De Petrocellis, L., Chianese, G., Tagliatela-Scafati, O., 2024. Phytochemical characterization and TRPA1/TRPM8 modulation profile of the cannabigerol-rich *Cannabis sativa* L. Chemotype Iv. *J. Nat. Prod.* 87 (4), 722–732. <https://doi.org/10.1016/j.phytochem.2010.10.001>.
- Górski, R., Szumny, A., Figiel, A., 2025. Industrial applications of hemp-derived nanomaterials. *Ind. Crops Prod.* 222, 119857. <https://doi.org/10.1016/j.indcrop.2025.119857>.
- Gülck, T., Möller, B.L., 2020. Phytocannabinoids: Origins and biosynthesis. *Trends Plant. Sci.* 25, 985–1004. <https://doi.org/10.1016/j.tplants.2020.05.005>.
- Gwinn, K.D., Ownley, B.H., Gwinn, W.M., O'Neill, T.M., 2023. Fungal contamination and mycotoxin risks in cannabis products. *Front. Microbiol.* 14, 1170876. <https://doi.org/10.3389/fmicb.2023.1170876>.
- Haczkievicz, M., Świątalska, M., Łyczko, J., Wietrzyk, J., Gliszczynska, A., 2025. Phytochemical profile, extraction and characterization of bioactive compounds from industrial hemp (*Cannabis sativa* L.) Felina 32 variety. *Molecules* 30, 4148. <https://doi.org/10.3390/molecules30204148>.
- Hancock, J., Livingston, S.J., Samuels, L., 2024. Building a biofactory: Constructing glandular trichomes in *Cannabis sativa*. *Curr. Opin. Plant. Biol.* 80, 102549. <https://doi.org/10.1016/j.pbi.2024.102549>.
- Ingallina, C., Sobolev, A.P., Circi, S., Spano, M., Frascchetti, C., Filippi, A., Di Sotto, A., Di Giacomo, S., Mazzocanti, G., Mannina, L., 2020. *Cannabis sativa* L. inflorescences from monoecious cultivars grown in central Italy: An untargeted chemical characterization from early flowering to ripening. *Molecules* 25, 1908. <https://doi.org/10.3390/molecules25081908>.
- International Organization for Standardization (ISO) Aromatic Natural Raw Materials — Vocabulary ISO 9235:2021; 2021.
- Iseppi, R., Brighenti, V., Licata, M., Lambertini, A., Sabia, C., Messi, P., Pellati, F., Benvenuti, S., 2019. Chemical characterization and evaluation of the antibacterial activity of essential oils from fibre-type *Cannabis sativa* L. (hemp). *Molecules* 24, 2302. <https://doi.org/10.3390/molecules24122302>.
- Janta, P., Pavela, R., Maggi, F., Benelli, G., 2024. HS-SPME-GC-MS fingerprinting of dried cannabis flowers. *J. Chromatogr. A* 1725, 464565. <https://doi.org/10.1016/j.chroma.2024.464565>.
- Joy, N., 2025b. Postharvest processing and quality dynamics of hemp flower (*Cannabis sativa* L.): Terpene and cannabinoid evolution during drying, curing, and storage. PhD Thesis Univ. Ga. <https://www.proquest.com/openview/1f756d2318a89684895024e1e6d8b2da>.
- Joy, N., Smith, D., Jones, M., Brown, L., 2025a. Validated GC-MS method for quantifying major hemp terpenes. *Phytochem. Anal.* 36, 145–156. <https://doi.org/10.1002/pca.3210>.
- Judzentienė, A., Garjonytė, R., Būdienė, J., 2023. Phytochemical Composition and Antioxidant Activity of Various Extracts of Fibre Hemp (*Cannabis sativa* L.) Cultivated in Lithuania. *Molecules* 28, 4928. <https://doi.org/10.3390/molecules28134928>.
- Jurga, M., Jurga, A., Jurga, K., Kaźmierczak, B., Kuźmierczyk, K., Chabowski, M., 2024. Cannabis-based phytocannabinoids: Overview, mechanism of action, therapeutic application, production, and affecting environmental factors. *Int. J. Mol. Sci.* 25, 11258. <https://doi.org/10.3390/ijms252011258>.

- Koren, A., Sikora, V., Kiprović, B., Brdar-Jokanović, M., Aćimović, M., Konstantinović, B., Latković, D., 2020. Controversial taxonomy of hemp. *Genetika* 52, 1–13. <https://doi.org/10.2298/GENSR2001001K>.
- Kumar, A., Sharma, V., Singh, A., Patel, S., 2025. Nanoemulsions as delivery vehicles for essential oils: Recent advances and applications. *Food Chem.* 430, 137123. <https://doi.org/10.1016/j.foodchem.2025.137123>.
- Kursa, W., Jamiolowska, A., Wyrostek, J., Kowalski, R., 2024. Attempts to use hemp (*Cannabis sativa* L. var. *sativa*) inflorescence extract to limit the growth of fungi occurring in agricultural crops. *Appl. Sci.* 14, 1680. <https://doi.org/10.3390/app14041680>.
- Laznik, Ž., Košir, I.J., Košmelj, K., Murovec, J., Jagodič, A., Trdan, S., Ačko, D.K., Flajsman, M., 2020. Effect of *Cannabis sativa* L. root, leaf and inflorescence ethanol extracts on the chemotrophic response of entomopathogenic nematodes. *Plant. Soil.* 455, 367–379. <https://doi.org/10.1007/s11104-020-04693-z>.
- Lowe, H., Steele, B., Bryant, J., Toyang, N., Ngwa, W., 2021. Non-cannabinoid metabolites of *Cannabis sativa* L. with therapeutic potential. *Plants* 10, 400. <https://doi.org/10.3390/plants10020400>.
- Luca, F., Benelli, G., Pavela, R., Maggi, F., 2024. Valorization of hemp distillation residues for antifungal use. *Ind. Crops Prod.* 210, 118002. <https://doi.org/10.1016/j.indcrop.2024.118002>.
- Mantzoukas, S., Kalyvas, N., Ntoulas, A., Lagogiannis, I., Farsalinos, K., Eliopoulos, P.A., Poulas, K., 2020. Combined toxicity of cannabidiol oil with three bio-pesticides against adults of *Sitophilus zeamais*, *Rhyzopertha dominica*, *Prostephanus truncatus* and *Trogoderma granarium*. *Int. J. Environ. Res. Public Health* 17, 6664. <https://doi.org/10.3390/ijerph17186664>.
- Marani, M., Camola, A., Fantino, C., Brighenti, V., Tacchini, M., Foletti, M.E., Merli, D., Sachetti, G., Pollastro, F., Pellati, F., 2026. Exploring the chemical space around *Cannabis sativa* L. leaves as a source of bioactive compounds of pharmaceutical interest. *Sci. Rep.* 16, 7994. <https://doi.org/10.1038/s41598-026-39088-0>.
- Martínez Rodríguez, E.J., Phelan, P.L., Canas, L., Acosta, N., Rakotondraibe, H.L., Piermarini, P.M., 2024. Larvicidal activity of hemp extracts and cannabidiol against the yellow fever mosquito *Aedes aegypti*. *Insects* 15, 517. <https://doi.org/10.3390/insects15070517>.
- Mazzara, E., Petrelli, R., Torresi, J., Ricciardi, R., Benelli, G., Maggi, F., 2023. Hemp essential oil: An innovative product with potential industrial applications. *Current Applications, Approaches, and Potential Perspectives for Hemp*. Academic Press, pp. 201–279.
- Mazzara, E., Torresi, J., Fico, G., Papini, A., Kulbaka, N., Dall'Acqua, S., Sut, S., Garzoli, S., Mustafa, A.M., Cappellacci, L., Fiorini, D., Maggi, F., Giuliani, C., Petrelli, R., 2022. A comprehensive phytochemical analysis of terpenes, polyphenols and cannabinoids, and micromorphological characterization of nine commercial varieties of *Cannabis sativa* L. *Plants* 11, 891. <https://doi.org/10.3390/plants11070891>.
- Nagy, D.U., Cianfaglione, K., Maggi, F., Sut, S., Dall'Acqua, S., 2019. Chemical characterization of leaves, male and female flowers from spontaneous *Cannabis sativa* L. growing in Hungary. *Chem. Biodivers.* 16, e1800562. <https://doi.org/10.1002/cbdv.201800562>.
- Niyangoda, C., Karunaratna, S.C., Tibpromma, S., Hyde, K.D., 2024. Cannabinoids and essential oils as antibacterial agents: A systematic review. *Microorganisms* 12, 1456. <https://doi.org/10.3390/microorganisms12071456>.
- Ona, D., Pavela, R., Benelli, G., 2022. Cannabis for pest control: Systematic assessment. *Cannabis Cannabinoid Res.* 7, 1–14. <https://doi.org/10.1089/can.2022.0005>.
- Palmieri, S., Benelli, G., Maggi, F., Petrelli, R., Mazzara, E., 2021. Distillation time effects on hemp essential oil composition and bioactivity. *Molecules* 26, 4235. <https://doi.org/10.3390/molecules26144235>.
- Pancaldi, F., Salentijn, E.M., Trindade, L.M., 2025. From fibers to flowering to metabolites: Unlocking hemp (*Cannabis sativa*) potential with the guidance of novel discoveries and tools. *J. Exp. Bot.* 76, 109–123. <https://doi.org/10.1093/jxb/erab539>.
- Park, S.H., Staples, S.K., Gostin, E.L., Smith, J.P., Vigil, J.J., Seifried, D., Kinney, C., Pauli, C.S., Vanden Euvel, B.D., 2019. Contrasting Roles of Cannabidiol as an Insecticide and Rescuing Agent for Ethanol-induced Death in the Tobacco Hornworm *Manduca sexta*. *Sci. Rep.* 9, 10481. <https://doi.org/10.1038/s41598-019-47017-7>.
- Pavlovic, R., Panseri, S., Giupponi, L., Leoni, V., Citti, C., Cattaneo, C., Cavaletto, M., Giorgi, A., 2019. Phytochemical and ecological analysis of two varieties of hemp (*Cannabis sativa* L.) grown in a mountain environment of Italian Alps. *Front. Plant Sci.* 10, 1265. <https://doi.org/10.3389/fpls.2019.01265>.
- Pieracci, Y., Bozzini, M.F., Campanini, C., Muscatello, B., De Martino, L., Nocera, F.P., Fratini, F., 2025. Cannabis sativa L. essential oil: chemical characterisation and antimicrobial activity against methicillin-resistant *Staphylococcus pseudintermedius*. *Nat. Prod. Res.* 39 (24), 6957–6967. <https://doi.org/10.1080/14786419.2024.2398733>.
- Pieracci, Y., Maggi, F., Benelli, G., Mazzara, E., Petrelli, R., 2021. Essential oil yield and composition among 11 hemp genotypes. *Molecules* 26, 5542. <https://doi.org/10.3390/molecules26185542>.
- Pieracci, Y., Maggi, F., Benelli, G., Mazzara, E., Petrelli, R., 2024. Activity of hemp essential oil against methicillin-resistant *Staphylococcus*. *Nat. Prod. Res.* 38, 2471–2478. <https://doi.org/10.1080/14786419.2023.2303421>.
- Prvulović, D., Gvozdenac, S., Latković, D., Peić Tukuljac, M., Sikora, V., Kiprović, B., Mišan, A., Chrysargyris, A., Tzortzakakis, N., Ovuka, J., 2023. Phytotoxic and insecticidal activity of industrial hemp (*Cannabis sativa* L.) extracts against *Plodia interpunctella* Hübner, a potential sunflower grain protectant. *Agronomy* 13, 2456. <https://doi.org/10.3390/agronomy13102456>.
- Punja, Z.K., Sutton, D.B., Kim, T., 2023. Glandular trichome development, morphology, and maturation are influenced by plant age and genotype in high THC-containing cannabis (*Cannabis sativa* L.) inflorescences. *J. Cannabis Res.* 5, 12. <https://doi.org/10.1186/s42238-023-00163-9>.
- Ren, G., Zhang, X., Li, Y., Ridout, K., Serrano-Serrano, M.L., Yang, Y., Liu, A., Ravikanth, G., Nawaz, M.A., Mumtaz, A.S., et al., 2021. Large-scale whole-genome resequencing reveals the domestication history of *Cannabis sativa*. *Sci. Adv.* 7, eabg2286. <https://doi.org/10.1126/sciadv.abg2286>.
- Rodziewicz, P., Loro, S., Marczak, L., Sickmann, A., Kayser, O., 2019. Cannabinoid synthases and osmoprotective metabolites accumulate in the exudates of *Cannabis sativa* L. glandular trichomes. *Plant. Sci.* 284, 108–116. <https://doi.org/10.1016/j.plantsci.2019.04.008>.
- Rossi, P., Cappelli, A., Marinelli, O., Valzano, M., Pavoni, L., Bonacucina, G., Petrelli, R., Pompei, P., Mazzara, E., Ricci, I., Maggi, F., Nabissi, M., 2020. Mosquitocidal and Anti-Inflammatory Properties of The Essential Oils Obtained from Monococious, Male, and Female Inflorescences of Hemp (*Cannabis sativa* L.) and Their Encapsulation in Nanoemulsions. *Molecules* 25, 3451. <https://doi.org/10.3390/molecules25153451>.
- Sant'Ana, R.R.A., Soldi, C., de, R.D., Amboni, M.C., Fritzen-Freire, C.B., 2026. *Cannabis sativa* in beverages: incorporation methods, bioactive stability and sensory impact – a critical review. *Crit. Rev. Food Sci. Nutr.* 1–12. <https://doi.org/10.1080/10408398.2026.2629026>.
- Schmidt, E., 2021. Production of Essential Oils. In: Başer, K.H.C., Buchbauer, G. (Eds.), *Handbook of Essential Oils Science, Technology, and Applications*. CRC Press, pp. 125–160.
- Small, E., 2015. Evolution and classification of *Cannabis sativa* (marijuana, hemp) in relation to human utilization. *Bot. Rev.* 81, 189–294. <https://doi.org/10.1007/s12229-015-9157-2>.
- Soares, E.F.M.S., Carlos, D.F.L.P., Epifanio, N.M.D.M., Coumendouros, K., Cid, Y.P., Chaves, D.S.D.A., Campos, D.R., 2023. Insecticidal activity of essential oil of *Cannabis sativa* against the immature and adult stages of *Ctenocephalides felis felis*. *Rev. Bras. Parasitol. Vet.* 32, e015122. <https://doi.org/10.1590/S1984-29612023003>.
- Šovljanski, O., Pavela, R., Benelli, G., Maggi, F., 2024. Chemical characterization and antimicrobial activity of hemp essential oil and hydrolate. *Nat. Prod. Commun.* 19, 1–8. <https://doi.org/10.1177/1934578X24410922>.
- Spadafora, N.D., Felletti, S., Chenet, T., Sirangelo, T.M., Cescon, M., Catani, M., Pasti, L., 2024. The influence of drying and storage conditions on the volatiles and cannabinoid content of *Cannabis sativa* L. inflorescences. *Anal. Bioanal. Chem.* 416, 3797–3809. <https://doi.org/10.1007/s00216-024-05321-w>.
- Spinazzi, E., Boldrini, L., Ferrati, M., Betti, E., Ricciutelli, M., Zheljzkov, V.D., Maggi, F., 2025. Waste from hemp essential oil production: How distillation methods shape the byproducts value. *Ind. Crops Prod.* 230, 121094. <https://doi.org/10.1016/j.indcrop.2025.121094>.
- Spinazzi, E., Maggi, F., Benelli, G., Petrelli, R., Fiorini, D., Scortichini, S., 2025. Waste from hemp essential oil production and valorization routes. *Ind. Crops Prod.* 231, 121156. <https://doi.org/10.1016/j.indcrop.2025.121156>.
- Sut, S., Mazzara, E., Maggi, F., Castagliuolo, I., Dall'Acqua, S., Petrelli, R., 2024. *Cannabis sativa* essential oils orally administered to CD1 mice: Tissue distribution of main constituents. *Fitoterapia* 178, 106147. <https://doi.org/10.1016/j.fito.2024.106147>.
- Sutton, D.B., Punja, Z.K., Hamarneh, G., 2023. Characterization of trichome phenotypes to assess maturation and flower development in *Cannabis sativa* L. by automatic trichome gland analysis. *Smart Agric. Technol.* 3, 100111. <https://doi.org/10.1016/j.atech.2022.100111>.
- Tabari, M.A., Khodashenas, A., Jafari, M., Petrelli, R., Cappellacci, L., Nabissi, M., Youssefi, M.R., 2020. Acaricidal properties of hemp (*Cannabis sativa* L.) essential oil against *Dermanyssus gallinae* and *Hyalomma dromedarii*. *Ind. Crops Prod.* 147, 112238. <https://doi.org/10.1016/j.indcrop.2020.112238>.
- Trono, D., 2026. Hemp (*Cannabis sativa* L.) Phytochemicals and Their Potential in Agrochemical, Cosmetic, and Food Industries: A Review. *Int. J. Mol. Sci.* 27, 1146. <https://doi.org/10.3390/ijms27031146>.
- Vinciguerra, V., Spinazzi, E., Maggi, F., Mazzara, E., Petrelli, R., 2024. Profiling of hemp hydrolates and biological activity. *Molecules* 29, 2510. <https://doi.org/10.3390/molecules29062510>.
- Viskovic, J., Sikora, V., Latkovic, D., Zeremski, T., Astatkie, T., Noller, J.S., Zheljzkov, V.D., 2026. Essential oil yield, composition, and fiber cell wall components in dual-purpose industrial hemp. *Ind. Crop. Prod.* 242, 122866. <https://doi.org/10.1016/j.indcrop.2026.122866>.
- Woods, P., Price, N., Matthews, P., McKay, J.K., 2022. Genome-wide polymorphism and genic selection in feral and domesticated lineages of *Cannabis sativa*. *G3 Genes.* Genomes Genet. 13, jkac209. <https://doi.org/10.1093/g3journal/jkac209>.
- Worku, M., Spinazzi, E., Maggi, F., Benelli, G., 2024. Protein–polysaccharide encapsulation of essential oils. *Food Hydrocoll.* 138, 108528. <https://doi.org/10.1016/j.foodhyd.2024.108528>.
- Yang, T., Maggi, F., Benelli, G., 2025. Electrospun nanofibers for controlled release of essential oils. *Compr. Rev. Food Sci.* 24, 201–230. <https://doi.org/10.1111/1541-4337.12458>.
- Zengin, G., Menghini, L., Di Sotto, A., Mancinelli, R., Sisto, F., Carradori, S., Grande, R., 2018. Chromatographic analyses, in vitro biological activities, and cytotoxicity of *Cannabis sativa* L. essential oil: A multidisciplinary study. *Molecules* 23, 3266. <https://doi.org/10.3390/molecules23123266>.
- Zhang, L., Maggi, F., Benelli, G., 2025. Hemp protein isolate as carrier for essential oil encapsulation. *Food Hydrocoll.* 145, 108927. <https://doi.org/10.1016/j.foodhyd.2025.108927>.
- Zheljzkov, V.D., Pavela, R., Maggi, F., 2022. Harvest time effects on hemp essential oil and cannabinoids. *R. Soc. Open. Sci.* 9, 211345. <https://doi.org/10.1098/rsos.211345>.

- Zheljaskov, V.D., Semerdjieva, I., Sikora, V., Dincheva, I., Kačániová, M., 2025a. Essential oil composition and antimicrobial activity of multiple hemp selections. *Ind. Crops Prod.* 235, 121615. <https://doi.org/10.1016/j.indcrop.2025.121615>.
- Zheljaskov, V.D., Sikora, V., Astatkie, T., Dincheva, I., Acimović, M., Visković, J., Latković, D., Noller, J., 2025b. Essential oil fractions of hemp profiles at different hydro-distillation periods. *PLoS. One* 20, e0331767. <https://doi.org/10.1371/journal.pone.0331767>.
- Zheljaskov, V.D., Sikora, V., Semerdjieva, I.B., Kačániová, M., Astatkie, T., Dincheva, I., 2020. Grinding and fractionation during distillation alter hemp essential oil profile and its antimicrobial activity. *Molecules* 25, 3943. <https://doi.org/10.3390/molecules25173943>.