

Article

Distinction and Pharmacological Activity of Monoterpenes and Sesquiterpenes in Different Chemotypes of *Cinnamomum camphora* (L.) Presl

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Abstract

Cinnamomum camphora (L.) Presl, a perennial evergreen tree of the Lauraceae family, exhibits diverse chemotypes and abundant essential oil constituents, which are widely utilized in pharmaceuticals, perfumery, and fine chemicals. Based on the variation in dominant volatile constituents, five chemotypes have been identified: Borneol Chemotype (BC), Camphor Chemotype (CC), Eucalyptol Chemotype (EC), Isoborneol Chemotype (IC), and Linalool Chemotype (LC). Their compositions of monoterpenoids (MT) and sesquiterpenes (SQT) differ significantly. This review systematically summarizes the research progress on MT and SQT in different chemotypes of *C. camphora* over the past five decades, with a total of 164 compounds identified (83 MT and 81 SQT), and compares the unique and shared constituents among chemotypes. Pharmacological studies indicate that *C. camphora* essential oils from different chemotypes exhibit strong antibacterial, anti-inflammatory, and antitumor activities, with linalool, camphor, and several SQT compounds showing remarkable biological effects in multiple bacterial, fungal, and tumor cell models. The underlying mechanisms may involve the disruption of cell membrane integrity, inhibition of key metabolic enzymes, interference with genetic transcription, and synergistic effects among multiple constituents. However, research on low-abundance bioactive components in different chemotypes remains limited, and their pharmacological mechanisms require further elucidation. This review provides a systematic reference for the future exploration of bioactive constituents, mechanistic studies, and efficient utilization of essential oils from different chemotypes of *C. camphora*, offering valuable insights for refined resource exploitation and industrial application.



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Keywords: *Cinnamomum camphora* (L.) Presl; chemotype; monoterpenoid; sesquiterpenoid; pharmacological activity

1. Introduction

Cinnamomum camphora (L.) Presl, an evergreen tree of Lauraceae, is a long-lived species capable of surviving for over a millennium [1]. It is distributed in Vietnam, Japan, Korea, and China, with a particularly high abundance in southern China. As a versatile species integrating medicinal, timber, aromatic, and ornamental values, *C. camphora* holds significant ecological and economic importance [2]. Essential oils from different chemotypes are widely distributed in the plant kingdom, and *C. camphora* can be classified into distinct chemotypes based on differences in its dominant volatile constituents [3]. The five major

chemotypes include Borneol Chemotype (BC), Camphor Chemotype (CC), Eucalyptol Chemotype (EC), Isoborneol Chemotype (IC), and Linalool Chemotype (LC). At present, related research focuses more on the isolation and extraction of *C. camphora* or on the pharmacological activity of certain terpenes. This paper summarizes the terpenoids of camphor from a generalized perspective, and more intuitively expresses the differences and connections between *C. camphora*.

Monoterpenoids (MTs), composed of two isoprene units with ten carbon atoms, are widely present in the secretory tissues of higher plants, insect hormones, fungi, and marine organisms [4]. MTs are the major constituents of plant essential oil from different chemotypes, and their oxygenated derivatives often exhibit strong bioactivities and distinct aromas, making them important raw materials in pharmaceuticals, cosmetics, and the food industry. Sesquiterpenes (SQTs), composed of three isoprene units with fifteen carbon atoms and their derivatives, are also widely distributed in plants, marine organisms, microorganisms, and insect tissues [5]. Many SQTs exhibit strong bioactivities and essential biological functions, especially sesquiterpene lactones, which possess antibacterial, anti-tumor, antiviral, insect hormonal, and antifeedant activities. SQTs are major constituents of high-boiling aromatic essential oils from different chemotypes and serve as important modulators of aromatic oil scent profiles [6]. The roots, fruits, branches, and leaves of *C. camphora* are all used in traditional medicine for dispersing wind and cold, strengthening the heart, relieving pain, and killing parasites, suggesting that the species is naturally rich in diverse MTs and SQTs [7].

A more refined classification of *C. camphora* into distinct chemotypes facilitates a better understanding and more efficient utilization of its plant resources, improving resource-use efficiency and enhancing its economic and social value. This review summarizes the research progress on different chemotypes of *C. camphora* over the past five decades, compiling identified MT and SQT constituents [8]. It further compares the unique and common constituents among chemotypes, reviews their pharmacological activities, and briefly discusses possible mechanisms of action [9]. This work aims to provide reference and inspiration for future studies on *C. camphora*, support the selection of suitable chemotypes for industrial applications, and lay a foundation for the discovery of new constituents [10]. It also offers a framework and methodological perspective for research on other plant species with multiple chemotypes.

2. Detailed Analysis of MT and SQT in Different Chemotypes of *Cinnamomum camphora* (L.) Presl

2.1. Comparison of the Number of MT and SQT Compounds Among Different Chemotypes

According to Tables 1 and 2 [11–42], a total of 164 MT and SQT compounds have been identified across the five chemotypes of *C. camphora*, including 83 MT and 81 SQT. Among them, the BC type contains 66 compounds (38 MT and 28 SQT); the CC type has 22 compounds (15 MT and 7 SQT); the EC type includes 56 compounds (42 MT and 14 SQT); the IC type comprises 66 compounds (29 MT and 37 SQT); and the LC type contains 69 compounds (29 MT and 40 SQT). There are seven compounds commonly present in all five chemotypes, including 6 MT and 1 SQT.

Table 1. MT components in different chemotypes of *Cinnamomum camphora* (L.) Presl.

Number	Chemical Composition	BC	CC	EC	IC	LC
1	α -Pinene	•	•	•	•	•
2	β -Pinene	•	•	•	•	•

Table 1. Cont.

Number	Chemical Composition	BC	CC	EC	IC	LC
3	α -Phellandrene	•	•	•	•	•
4	Camphor	•	•	•	•	•
5	Terpinen-4-ol	•	•	•	•	•
6	α -Terpineol	•	•	•	•	•
7	Camphene	•	•	-	•	•
8	Ocimene	•	-	•	•	-
9	1,8-Cineole	•	-	•	•	-
10	Safrole	•	-	•	•	-
11	Terpinolene	•	-	•	•	-
12	Linalool	•	-	•	•	•
13	γ -Terpinene	•	-	•	-	•
14	Germacrene D	•	-	•	-	•
15	2-Carene	•	-	•	-	•
16	o-Cymene	•	-	•	-	-
17	β -Myrcene	•	-	•	-	-
18	α -Limonene	•	-	•	-	-
19	3-Carene	•	-	•	-	-
20	α -Terpinene	•	-	•	-	-
21	Phellandrene	•	-	-	•	-
22	Sabinene	•	-	-	•	-
23	Isoborneol	•	-	-	•	-
24	-Borneol	•	-	-	-	-
25	Eucalyptol	•	-	-	-	-
26	α -Camphene	•	-	-	-	-
27	Borneol	•	-	-	-	-
28	d-Limonene	•	-	-	-	-
29	α -Thujene	•	-	-	-	-
30	Bornyl acetate	•	-	-	-	-
31	Benzyl benzoate	•	-	-	-	-
32	Menthol	•	-	-	-	-
33	α -Cedrene	•	-	-	-	-
34	Terpineol	•	-	-	-	-
35	trans- β -Ocimene	•	-	-	-	-
36	Linalyl formate	•	-	-	-	-
37	Lavandulol	•	-	-	-	-
38	cis-Chrysanthemol	•	-	-	-	-
39	Borneolum	-	•	•	•	-
40	Nerol	-	•	•	-	-
41	Geranial	-	•	•	-	•
42	Eugenol	-	•	•	-	•
43	4-Carene	-	•	-	-	•
44	Limonene oxide	-	•	-	-	-
45	Isocineole	-	•	-	-	-
46	β -Terpineol	-	•	-	-	-
47	β -Ocimene	-	-	•	•	•
48	p-Cymene	-	-	•	•	-
49	γ -Terpinolene	-	-	•	•	-
50	Nerol oxide	-	-	•	-	•
51	β -Phellandrene	-	-	•	-	•
52	Thujaol	-	-	•	-	•
53	Terpinen-4-yl acetate	-	-	•	-	-
54	Linalyl isobutyrate	-	-	•	-	-
55	Geraniol	-	-	•	-	-

Table 1. Cont.

Number	Chemical Composition	BC	CC	EC	IC	LC
56	β -Terpinene	-	-	●	-	-
57	α -Sabinene	-	-	●	-	-
58	Cedrol	-	-	●	-	-
59	α -Terpineol	-	-	●	-	-
60	Terpinyl acetate	-	-	●	-	-
61	4-Thujene	-	-	●	-	-
62	Isopiperitenone	-	-	●	-	-
63	Lolactone	-	-	●	-	-
64	Isobornyl acetate	-	-	●	-	-
65	β -Eucalyptol	-	-	●	-	-
66	Cineole	-	-	-	●	●
67	cis-Linalool oxide	-	-	-	●	●
68	trans-Linalool oxide	-	-	-	●	●
69	β -Citronellol	-	-	-	●	-
70	Artemone	-	-	-	●	-
71	Thujene	-	-	-	●	-
72	-Bornyl acetate	-	-	-	●	-
73	cis-Sabinene hydrate	-	-	-	●	-
74	Myristicin	-	-	-	●	-
75	-Camphor	-	-	-	●	-
76	4-Carene	-	-	-	-	●
77	2-Pinene	-	-	-	-	●
78	2-Carene epoxide	-	-	-	-	●
79	Isopulegol	-	-	-	-	●
80	Eucalyptone	-	-	-	-	●
81	Citronellol	-	-	-	-	●
82	Geraniol	-	-	-	-	●
83	Citronellyl acetate	-	-	-	-	●

●: The substance was detected; -: No substance was detected; BC: Borneol Chemotype; CC: Camphor Chemotype; EC: Eucalyptol Chemotype; IC: Isoborneol Chemotype; LC: Linalool Chemotype; MT: monoterpenoids.

Table 2. SQT components in different chemotypes of *Cinnamomum camphora* (L.) Presl.

Number	Chemical Composition	BC	CC	EC	IC	LC
1	α -Caryophyllene	●	●	●	●	●
2	Nerolidol	●	●	-	-	●
3	α -Selinene	●	●	-	-	●
4	Caryophyllene	●	-	●	●	●
5	γ -Elemene	●	-	●	-	●
6	β -Elemene	●	-	●	-	●
7	Spathulenol B	●	-	●	-	●
8	Caryophyllene	●	-	●	-	●
9	Isodene	●	-	●	-	-
10	β -Caryophyllene	●	-	●	-	-
11	Caryophyllene oxide	●	-	-	●	●
12	Spathulenol D	●	-	-	●	●
13	β -Selinene	●	-	-	●	-
14	Isocaryophyllene	●	-	-	●	-
15	γ -Selinene	●	-	-	●	●
16	α -Bisabolene	●	-	-	-	●
17	β -Bisabolene	●	-	-	-	●
18	δ -Selinene	●	-	-	-	-

Table 2. Cont.

Number	Chemical Composition	BC	CC	EC	IC	LC
19	δ -Cadinene	●	-	-	-	-
20	β -Cadinene	●	-	-	-	-
21	Bicyclogermacrene	●	-	-	-	-
22	D-Guaiene	●	-	-	-	-
23	trans-Z- α -Epoxy-guaiazulene	●	-	-	-	-
24	γ -Amorphene	●	-	-	-	-
25	cis- α -Bisabolene	●	-	-	-	-
26	Humulene epoxide II	●	-	-	-	-
27	β -Caryophyllene alcohol	●	-	-	-	-
28	α -Cubebene	●	-	-	-	-
29	β -Cubebene	-	●	-	-	-
30	α -Muurolene	-	●	-	-	-
31	Muurolol	-	●	-	-	-
32	Muurolal	-	●	-	-	-
33	Guaiacol	-	-	●	●	●
34	Bisabolene	-	-	●	●	-
35	Leptospermol	-	-	●	●	-
36	β -Humulene	-	-	●	-	-
37	β -Clovone	-	-	●	-	-
38	Curcumol F	-	-	●	-	-
39	Ylangene	-	-	-	●	●
40	β -Bourbonene	-	-	-	●	●
41	α -Gurjunene	-	-	-	●	●
42	Elemol	-	-	-	●	●
43	Aristolochene	-	-	-	●	●
44	Thujopsene	-	-	-	●	●
45	Ledol	-	-	-	●	●
46	epi-Ledol	-	-	-	●	●
47	Humulene epoxide	-	-	-	●	●
48	Aromadendrol	-	-	-	●	●
49	β -Nerolidol	-	-	-	●	-
50	Isonerolidol	-	-	-	●	-
51	β -Eudesmol	-	-	-	●	-
52	Cedrol	-	-	-	●	-
53	Cubebol	-	-	-	●	-
54	Selinenes	-	-	-	●	-
55	Humulene epoxide II	-	-	-	●	-
56	Guaiene	-	-	-	●	-
57	α -Bulnesene	-	-	-	●	-
58	Valencene	-	-	-	●	-
59	Melaleucol	-	-	-	●	-
60	Citronellol acetate	-	-	-	●	-
61	τ -Cadinol	-	-	-	●	-
62	Cadinene	-	-	-	●	-
63	β -Selinene	-	-	-	●	-
64	trans-Z-Epoxy-guaiazulene	-	-	-	●	-
65	β -Gurjunene	-	-	-	●	-
66	δ -Elemene	-	-	-	-	●
67	α -Copaene	-	-	-	-	●
68	β -Ylangene	-	-	-	-	●

Table 2. Cont.

Number	Chemical Composition	BC	CC	EC	IC	LC
69	δ -Bisabolene	-	-	-	-	●
70	γ -Bisabolene	-	-	-	-	●
71	β -Bisabolene	-	-	-	-	●
72	Dehydroaristolene	-	-	-	-	●
73	α -Bisabolene	-	-	-	-	●
74	Santalol	-	-	-	-	●
75	Bisabolol	-	-	-	-	●
76	Sphatulenol	-	-	-	-	●
77	Isoledol	-	-	-	-	●
78	Isothujopsene	-	-	-	-	●
79	Farnesol	-	-	-	-	●
80	Caryophyllene oxide isomer	-	-	-	-	●
81	Epoxy-guaiazulene	-	-	-	-	●

●: The substance was detected; -: No substance was detected; BC: Borneol Chemotype; CC: Camphor Chemotype; EC: Eucalyptol Chemotype; IC: Isoborneol Chemotype; LC: Linalool Chemotype; and SQT: sesquiterpenes.

2.2. Differences in the Composition of MT and SQT in Different Chemotypes of *Cinnamomum camphora* (L.) Presl

According to Tables 1 and 2 [11–42], in addition to the seven shared compounds α -pinene, β -pinene, α -phellandrene, camphor, terpinen-4-ol, α -terpineol, and α -caryophyllene, each chemotype of *C. camphora* also possesses its own unique constituents. Specifically, the BC type has 26 unique compounds (15 MT and 11 SQT); the CC type has 7 unique compounds (3 MT and 4 SQT); the EC type contains 16 unique compounds (13 MT and 3 SQT); the IC type includes 24 unique compounds (7 MT and 17 SQT); and the LC type features 24 unique compounds (8 MT and 16 SQT). These data clearly indicate substantial differences in the composition of terpenoid compounds among the different chemotypes. In most cases, different medicinal materials contain distinct active ingredients, which lead to differences in their pharmacological effects. Therefore, resources from the different chemotypes of *C. camphora* should be treated separately and developed comprehensively based on their individual characteristics so as to maximize their respective advantages and meet diverse needs.

2.3. Major MT and SQT Constituents in Different Chemotypes of *Cinnamomum camphora* (L.) Presl

C. camphora is a plant species with multiple chemotypes, and significant differences exist in the composition and characteristics of terpenoids among these chemotypes. These variations are mainly attributed to differences in biosynthetic pathways and genotypes.

The BC type is rich in borneol, which has a strong pungent odor and is used to treat certain diseases or inhibit microbial growth. The CC type contains mainly camphor, which provides a cooling sensation and mild irritation, making it widely used in pharmaceuticals and cooling balms. The EC type is characterized by high levels of 1,8-cineole, which has a strong oily odor and is therefore widely used in the fragrance and cosmetics industries. The IC type primarily contains Isoborneol and related compounds with a distinctive aroma, offering a high economic value in the relevant industries. The LC type is rich in linalool, known for its strong fragrance, and is commonly used to enhance the sensory experience of various products through its aromatic properties.

2.4. Identification of Different Chemotypes of *Cinnamomum camphora* (L.) Presl

C. camphora is an aromatic plant, and different chemotypes exhibit distinct scent profiles. Traditionally, identification has relied on morphological traits and olfactory as-

assessments [43]. However, this approach is time consuming, labor intensive, and prone to substantial error, thus presenting considerable limitations. Prior to 2010, GC–MS was commonly used for chemotype discrimination [44]. While accurate, this method requires prior essential oil extraction, which is both time intensive and inefficient, making it unsuitable for high-throughput analysis. In recent years, a novel approach has been developed, integrating SHS–GC–MS with DAPCI–MS for the discrimination of different chemotypes (BC, CC, EC, IC, and LC). This technique is applicable not only to powdered dry materials but also to fresh leaf samples [45]. It offers rapid analysis, a high degree of automation, and, when combined with discriminant analysis, achieves 100% correct identification rates.

3. Pharmacological Activities of *Cinnamomum camphora* (L.) Presl

3.1. Pharmacological Activities of Major Components in Different Chemotypes

Borneol (major constituent of BC) is almost insoluble in water but soluble in ethanol, diethyl ether, petroleum ether, benzene, toluene, acetone, naphtha, and cyclohexane. It exhibits pharmacological effects such as diaphoretic, excitatory, antispasmodic, anthelmintic, and caustic activities [46]. Clinically, it is commonly used to expel intestinal parasites, reduce fever, relieve smooth muscle spasms, and promote expectoration [47].

Camphor (major constituent of CC) volatilizes slowly at room temperature but rapidly at elevated temperatures [48]. It is sparingly soluble in water but soluble in ethanol, ether, chloroform, carbon disulfide, and various oils. It is widely used in the production of chemical lacquers, photographic films, explosives, fragrances, flavorings, insecticides, and pharmaceuticals [49]. Camphor vapor can cause acute severe poisoning, leading to the loss of consciousness, trismus, and potentially death. Oral ingestion may induce dizziness, mental confusion, delirium, convulsions, coma, and ultimately respiratory failure [50].

1,8-Cineole (major constituent of EC) is a colorless, oily liquid with a camphoraceous aroma and a cooling taste [51]. It is slightly soluble in water (0.4–0.6%) but soluble in 12–15 volumes of 50% ethanol, 4 volumes of 60% ethanol, and 1.5–2 volumes of 70% ethanol. It dissolves readily in ether, chloroform, glacial acetic acid, animal and vegetable oils, and propylene glycol, and is miscible with ethanol and oils. It is used in the formulation of oral care flavorings and pharmaceutical products, as well as being a food additive. According to a study from Japanese researchers [52], cineole with a purity of $\geq 85\%$ is permitted solely for flavoring purposes.

Linalool (major constituent of LC) is almost insoluble in water and glycerol but soluble in propylene glycol, mineral oils, and other nonvolatile oils, and miscible with ethanol and diethyl ether [53]. Linalool is prone to isomerization but remains relatively stable under alkaline conditions. It is a colorless liquid characterized by a strong green, sweet, woody aroma resembling rosewood and freshly brewed green tea, with combined floral (lilac, lily of the valley, and rose), woody, and fruity notes [54].

Linalool is one of the most frequently used fragrance ingredients in perfume, household, and soap formulations, and is also used in food flavorings. It serves as an important chemical intermediate for synthesizing various linalyl esters and key pharmaceuticals [55]. In medicine, linalool induces apoptosis to selectively inhibit the growth and proliferation of human lymphocytic leukemia cells while exhibiting high safety for normal cells. Screening studies of antitumor small molecules have demonstrated that linalool significantly inhibits the proliferation of various leukemia cell lines without affecting normal hematopoietic bone marrow cells or peripheral blood cells [56]. As an anticariogenic agent, experiments show that the addition of 0.1% linalool to a sucrose-containing culture medium (2% sucrose) completely inhibits *Streptococcus mutans* from converting sucrose into glucans, thus preventing dental plaque formation [57]. Other studies report that adding terpene alcohols,

such as linalool, to tooth powders stabilizes glucanase activity, further contributing to plaque prevention.

Beyond pharmaceuticals, linalool has broad industrial applications. It exhibits strong odor-masking properties against unpleasant smells such as sulfur compounds, garlic derivatives, and polysulfides [58]. Linalool can repel mosquitoes and flies, and in combination with other aromatic compounds, it can deter cockroaches, ants, lice, and other pests. Experiments show that linalool-containing foods significantly reduce housefly feeding and oviposition, as gravid females avoid laying eggs in environments containing potent antimicrobial substances like linalool due to their larval dependency on microbial-rich substrates [59]. Linalool also demonstrates acaricidal activity against both larval and adult mites, with effective results reported against *Tyrophagus lonsior*. Industrial studies from Japan indicate that oils containing trace amounts of linalool and linalyl acetate retain their quality longer at temperatures exceeding 100 °C [60], maintaining a better aroma after prolonged deep-frying compared with controls. Linalool derivatives combined with vitamin E show remarkable synergistic antioxidant effects in lard, palm oil, and other edible oils [61]. The addition of linalool to cleaning agents improves foam stability. Furthermore, linalool inhibits fungal spore and mycelial growth, enabling its application in antifungal treatments and as a mold inhibitor when used alone or in combination with other antifungal agents. Fragrance blends of linalool, geraniol, and phenylethyl alcohol have proven effective in repelling birds such as sparrows, crows, and pigeons. In kerosene, the addition of 1–5% linalool and its esters can function as deodorizing agents for fuels [62].

3.2. Antibacterial, Anti-Inflammatory, and Antitumor Activities

The essential oils from different chemotypes of *C. camphora* exhibit broad-spectrum antibacterial activities, with notable differences among chemotypes [63]. Volatile oils from BC show significant inhibitory effects against *Tobacco mosaic virus*, *Aspergillus fumigatus*, and *Candida albicans*, with camphor demonstrating an inhibition rate of up to 99% against *C. albicans*. In CC, two isolated SQT compounds exhibited potent activity against *Fusarium proliferatum* infecting a lily [64]. The essential oil of LC demonstrated outstanding antibacterial activity against multiple pathogens, achieving 100% inhibition of *Rhizoctonia solani* at varying concentrations and significant bactericidal effects on *Escherichia coli* at a minimum inhibitory concentration of 200 µL [65]. It also showed broad-spectrum activity against *Staphylococcus aureus*, *Klebsiella pneumoniae*, *Streptococcus pneumoniae*, *Pseudomonas aeruginosa*, and hemolytic *Streptococcus*. Further studies revealed that R-linalool possesses stronger antibacterial effects than its S-enantiomer against *S. aureus*, *Staphylococcus epidermidis*, and *E. coli*. Essential oil from IC also showed antibacterial potential, inhibiting *F. proliferatum*, *Aesculus hippocastanum* *Diaporthe*, and *Phomopsis* species. Components such as caryophyllene oxide, isolated from IC oil, were confirmed to have antibacterial properties. Ethanol and aqueous extracts of camphor leaves inhibited both Gram-positive and Gram-negative bacteria to varying degrees. Electron microscopy observations at minimum inhibitory concentrations revealed blurred or lysed fungal organelles, suggesting a destructive antifungal mechanism. However, the specific bioactive compounds responsible for these effects remain unclear, warranting further mechanistic studies [66].

Beyond antibacterial activity, camphor essential oils from different chemotypes exhibit a notable anti-inflammatory potential. Leaf oil from CC significantly reduced paw edema in rat inflammatory models and improved local tissue swelling. Linalool, as a major component, activates the Nrf2/HO-1 signaling pathway [67], effectively inhibiting LPS-induced inflammatory responses in BV2 microglial cells, indicating strong central anti-inflammatory properties. Natural linalool has also been shown to reduce edema effectively. Eucalyptol (1,8-cineole) improves lung function in asthmatic guinea pigs, suggesting

potential airway anti-inflammatory benefits. Low, medium, and high doses of CC oil all inhibited the release of inflammatory mediators to varying degrees, modulating local immune responses as part of its anti-inflammatory action [68].

In recent years, the antitumor potential of camphor-derived compounds has drawn increasing attention. Ethanol extracts from LC leaves exhibited significant *in vitro* inhibitory effects on human lung cancer cells, oral squamous carcinoma cells, and hepatoma cells [69]. MTT assays and colony formation tests confirmed potential cytotoxic mechanisms. Some isolated proteins, such as cinnamomin and sodium camphor salicylate, are classified as ribosome-inactivating proteins, which can selectively kill tumor cells by inhibiting protein synthesis pathways [70]. Linalool has been shown to induce apoptosis in various human lymphocyte leukemia cell lines and effectively inhibit glioma cell growth by modulating signal transduction pathways. In animal model experiments, low-dose ethyl acetate extracts from BC twigs not only significantly reduced inflammatory factor release but also markedly inhibited the proliferation of neuroblastoma and hepatocellular carcinoma cells.

3.3. Mechanistic Insights into Pharmacological Activities

Current studies on the pharmacological activities of *C. camphora* essential oil from different chemotypes, particularly their antibacterial mechanisms, have preliminarily revealed multiple possible modes of action [71]. Overall, camphor essential oils from different chemotypes may exert antibacterial effects through the following pathways: (1) disrupting the cell membrane structure and altering permeability; (2) interfering with nutrient uptake and transport; (3) inactivating key metabolic enzymes and thereby suppressing normal metabolism; (4) disturbing the replication and transcription of genetic material; and (5) blocking protein synthesis. Although extensive reports on the antibacterial activity of camphor essential oil from different chemotypes exist, systematic mechanistic investigations remain limited [72–79].

Existing studies indicate that LC oil exhibits significant vapor-phase bactericidal activity against *E. coli*, with volatility and hydrophilicity identified as key factors influencing antimicrobial efficacy [80]. Electron microscopy revealed that fumigation with LC oil caused severe damage to the *E. coli* cell membrane, markedly increasing permeability, resulting in the massive leakage of intracellular components and inducing cell shrinkage and deformation. These findings suggest that LC oil may interfere with normal physiological functions by binding to membrane lipids, fatty acids, or nucleic acids [81].

Similarly, essential oils from different chemotypes of CC have been shown to strongly inhibit fungal mycelial growth and spore germination. At the minimum effective concentration, fungal organelles became indistinct, cellular outlines were blurred, and in some cases, complete cell lysis was observed, indicating pronounced destructive effects on cell structures [82]. Additional studies reported that active constituents such as geraniol significantly increase osmotic pressure, enhance membrane fluidity, and reduce the phase transition temperature of membrane lipids, thereby destabilizing membrane integrity and function, ultimately leading to pathogen cell death [83].

4. Conclusions and Prospects

C. camphora, as a multi-chemotype aromatic plant, possesses diverse and abundant essential oil components with a significant application potential in pharmaceuticals, perfumery, and fine chemicals. However, its research and utilization remain constrained by several limitations. Firstly, the existing germplasm resources are highly mixed, and the lack of precise chemotype-specific resource management restricts the full exploitation of chemotype advantages. Secondly, although LC has been relatively well studied in terms of the properties and functions of linalool, research on other chemotypes remains at a prelimi-

nary stage, with only the partial characterization of their chemical profiles and bioactivities, lacking in-depth and systematic compositional analyses. Thirdly, current studies have primarily focused on highly abundant MTs and SQTs, while minor constituents with low yield and high separation difficulty remain underexplored. Some reports have not differentiated trace components with potentially significant bioactivity, leading to insufficient refinement in compositional studies. More importantly, most reported pharmacological activities are consistent with the inherent bioactivity of terpenoids, lacking findings that uniquely highlight the pharmacological distinctiveness of *C. camphora*. Its advantage mainly lies in the higher yields of these terpenoids, the exceptional longevity of the trees, and their sustainable utilization cycles compared to other species. In view of the above pain points, this paper reviews the composition of MT and SQT of different chemical types of *C. camphora*, but there are still deficiencies. The terpenes of *C. camphora* include not only monoterpenes and sesquiterpenes, but also diterpenes, disquiterpenes, triterpenes, tetraterpenes, polyterpenes, etc., which are not summarized and sorted out because of their small content and difficulty in separation and extraction. However, these terpenes may have a finishing touch on the pharmacological activity of *C. camphora* overall terpenes, which are points that cannot be ignored in the study and can be focused on in subsequent studies.

Future research holds substantial expansion potential. First, there remain numerous MTs and SQTs in different chemotypes that have been identified but not studied in depth; these constituents may provide valuable breakthroughs for subsequent functional exploitation. Second, extraction techniques significantly affect both yield and bioactivity. For example, CC oil obtained via enzyme-assisted solvent extraction, enzyme-assisted hydrodistillation, and enzyme-assisted simultaneous distillation–extraction exhibited strong antibacterial activity against *E. coli* and *S. aureus*, whereas oil obtained via supercritical fluid extraction showed markedly reduced antibacterial efficacy. This suggests that optimizing extraction processes could not only enhance the yield of target bioactive compounds but also improve their biological activity. Third, the chemical complexity of camphor essential oils from different chemotypes indicates that their pharmacological activities are likely the result of synergistic effects among multiple bioactive constituents rather than the action of a single compound. Potential interactions among components may contribute to their antibacterial and anti-inflammatory properties, but the underlying mechanisms remain incompletely understood. Future studies should integrate component isolation and purification, structure–activity relationship analyses, and molecular mechanism elucidation to clarify the interplay and modes of action of bioactive constituents, thereby providing a stronger theoretical basis and technical foundation for the high-value utilization of *C. camphora* essential oil from different chemotypes.

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Abbreviations

The following abbreviations are used in this manuscript:

BC	Borneol Chemotype
CC	Camphor Chemotype
EC	Eucalyptol Chemotype
IC	Isoborneol Chemotype
LC	Linalool Chemotype
MT	Monoterpenoids
SQT	Sesquiterpenes

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