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Review

A Review on Composition and Bioactivities of Essential Oils from Prominent *Piper* Species

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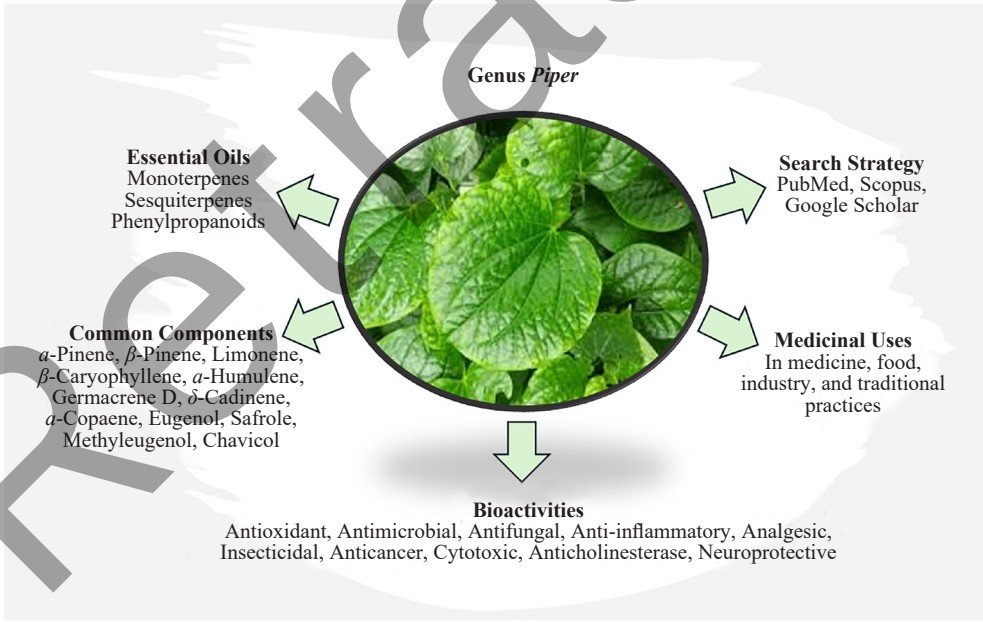
Graphical Abstract:



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Abstract: The genus *Piper*, a prominent member of the Piperaceae family, comprises over 2,000 species and is widely distributed, especially in Southeast Asia. It is well-known for several species of medicinal and economic importance, which have been utilized in their native regions for various purposes. *Piper* species show remarkable diversity in tropical areas worldwide, predominantly as aromatic shrubs and trees that produce substantial amounts of essential oils. These oils are highly valued for their therapeutic properties and have been used for centuries in food, pharmaceuticals, and cosmetics. Recent studies on the essential oils of Malaysian *Piper* species have unveiled remarkable pharmacological properties. This review seeks to comprehensively explore the medicinal applications, chemical profiles, and bioactivities of essential oils derived from prominent *Piper* species. The information presented was gathered through extensive searches of electronic databases, including PubMed, Scopus, and Google Scholar, as well as through library-based investigations of peer-reviewed journal articles. The focus is on the chemical components of *Piper* species, particularly their essential oils, offering insights into selecting species with optimal chemical profiles for various applications.

***Keywords*:** Piperaceae, *Piper*, essential oil, composition, bioactivity

1. Introduction

The Piperaceae family comprises approximately 2,000 species across four primary genera: *Piper*, *Peperomia*, *Sarchorhachis*, and *Ottonia*. Some studies recognize up to 13 genera, reflecting ongoing taxonomic revisions and differing classification criteria. Members of this family are predominantly found in tropical regions, particularly in Latin America and Malaysia, inhabiting diverse environments such as moist forests, secondary vegetation, and dry highlands.[1] The Piperaceae family exhibits significant morphological and anatomical diversity. The Piperaceae family holds significant ethnobotanical value, particularly in the genera *Piper* and *Peperomia*.[1-3]

The genus *Piper* (Figure 1), a vital component of the Piperaceae family, encompasses over 1,000 species that are broadly distributed across tropical and subtropical regions worldwide. The name *Piper* originates from the Sanskrit word “pippali”, which referred to long pepper (*Piper longum*), a spice of historical importance in ancient trade networks.[4-5] Over time, species within the genus have become integral to traditional medicine, culinary practices, and cultural customs. The *Piper* genus is geographically widespread, with an estimated 2,000 species distributed across Asia, Africa, and the Americas.[6] Significant concentrations are notably found in Southeast Asia, particularly in Malaysia and Indonesia as well as in Latin America, underscoring their adaptability to diverse tropical ecosystems.[7] Among the numerous species, *Piper betle*, *Piper nigrum*, and *Piper longum* are particularly notable for their traditional applications. *Piper betle*, commonly referred to as betel leaf, is culturally significant in South and Southeast Asia, where it is chewed with areca nut and slaked lime as part of various rituals. Additionally, it is prized for its antimicrobial and stimulant properties.[8] *Piper nigrum*, commonly known as black pepper and celebrated as the “King of Spices”, is highly valued for its dried fruit, which is extensively utilized in culinary applications and traditional medicine. It is particularly effective in addressing colds and digestive disorders.[9] Similarly, *Piper longum* (long pepper) holds a prominent place in Ayurvedic and traditional Chinese medicine, renowned for its anti-inflammatory and analgesic properties, especially in the treatment of respiratory ailments.[10]

Recently, there has been a growing interest in essential oils and other aromatic compounds derived from plants and used in alternative medicine. Therefore, a review on *Piper* essential oils is necessary to consolidate and simplify the available information. Data for this review was gathered through electronic searches in databases including PubMed, Scopus, and Google Scholar. The purpose of this review is to provide a comprehensive summary of all published studies on the chemical composition, biological activities, and medicinal applications of *Piper* essential oils.

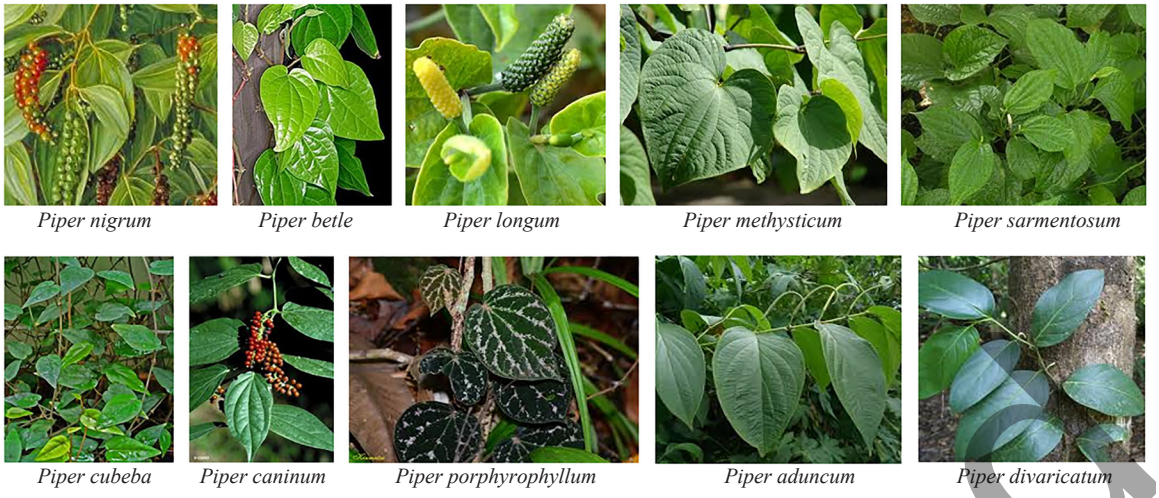

Figure 1. Common *Piper* species

2. Search strategy

The protocol for performing this study was developed following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses statement (PRISMA): (a) the first step was to exclude duplicate articles, (b) titles and abstracts were then read and the inclusion and exclusion criteria were applied and (c) all articles resulting from this stage were read in full, and the inclusion and exclusion criteria were applied again. Following this step, we reached the articles chosen for this study. This systematic review was conducted through searches using PubMed, Scopus, and Google Scholar. The keywords used were '*Piper*', 'essential oil', and 'biological activity' for articles over the period from the beginning of the database until January 2025. The inclusion of articles considered the following criteria: (1) type of publication-original research articles, (2) only articles in English, (3) articles must present the chemical composition of *Piper* essential oils, (4) articles must discuss the bioactivity of the essential oils. As the exclusion criteria, the following were used: (1) articles that did not present the search terms in the title and abstract; (2) review articles, (3) full-text articles not found, (4) articles without one of the keywords and (5) articles that did not present the composition of the essential oils.

3. Medicinal uses

For centuries, *Piper* species have been celebrated for their diverse medicinal properties. Various plant parts, including fruits, roots, leaves, and bark, serve as sources for essential oils with a wide range of therapeutic applications. These components are used in many forms, such as pharmaceutical preparations administered individually or combined with traditional Chinese medicines, brewed as tea, or consumed directly. Traditionally, essential oils have been employed as daily remedies to alleviate discomfort and enhance both physical and mental well-being. The genus *Piper* embodies a fascinating blend of cultural heritage and modern commercial significance. Iconic species such as *P. betle*, *P. nigrum*, and *P. longum* continue to play pivotal roles in cultural practices, culinary traditions, and medicinal uses. Table 1 provides a summary of the medicinal applications of various *Piper* species.[11-72]

The commercial value of *P. betle* is evident in the production of betel leaf essential oils and extracts, which are marketed for their antiseptic and medicinal benefits. In India, the betel leaf industry significantly contributes to the economy, with products exported globally for use in oral care and medicinal applications. Similarly, *P. nigrum* has a robust global market, with black and white pepper being major exports from Vietnam, India, and Brazil, which dominate global production. Black pepper extracts, particularly piperine, are utilized in nutraceuticals and pharmaceuticals to enhance the bioavailability of drugs and supplements.[73] Products derived from *P. longum* have gained recognition for their therapeutic applications. Long pepper extracts are commonly used in herbal supplements and traditional medicine

formulations, especially in India and China, to treat respiratory and gastrointestinal disorders. Additionally, *P. longum* has gained popularity in modern wellness products, such as herbal teas, capsules, and powders, marketed for their health benefits.[74] The increasing demand for natural and plant-based remedies has driven the commercialization of *P. longum*-based products in international markets, including Europe and North America.

From the findings, it can be concluded that the genus *Piper* is widely recognized for its diverse medicinal applications. Various *Piper* species demonstrate therapeutic properties, including antimicrobial, anti-inflammatory, and antioxidant activities. They are commonly utilized in traditional medicine to treat ailments such as respiratory problems, digestive disorders, and infections. The evidence highlights the significant role of *Piper* species in ethnomedicine and their potential as valuable sources of bioactive compounds for modern drug development.

Table 1. Medicinal uses of several *Piper* species

Species	Part	Medicinal uses
P. longum	Fruit	It is used as a liver tonic, abortifacient, and for treating insomnia, jaundice, and snakebites. [11]
	Root	It is used for managing heart diseases.[11]
P. aduncum	Leaf	It is used for the treatment of wounds, diarrhea, and infections.[12]
	Root	It is used for the treatment of stomach and respiratory ailments, as well as skin wounds and dysentery.[13]
P. aborescens	Leaf	It is used for rheumatism and antiplatelet aggregation.[14]
P. abbreviatum	Leaf	It is used to treat splenomegaly.[15]
	Fruit	It is used to treat coughs and colds and to relieve flatulence.[16]
P. hispidum	Leaf	It is used as a poultice for healing wounds and for treating symptoms of cutaneous leishmaniasis.[17]
P. caninum	Leaf	It is used for treating hoarseness and as an antiseptic for throat aches.[18]
P. ribesioides	Leaf	It is used for treating asthma, diarrhea, abdominal pain, and for relieving chest congestion.[19]
P. capense	Fruit	It is used for treating diarrhea and cough.[20]
P. sarmentosum	Leaf	It is used to treat skin diseases, rheumatism, headaches, and diarrhea.[21]
	Root	It is used to treat toothache, foot dermatitis, cough, and asthma.[22]
P. betle	Leaf	It is used for treating wounds, burns, impetigo, furunculosis, and lymphangitis.[23]
	Root	It provides relief from allergic symptoms.[24]
P. methysticum	Fruit	It is used to treat asthma, bronchitis, and fever effectively.[25]
	Leaf	It is used for treating gonorrhea, tuberculosis, menstrual pain, and chronic pain related to arthritis.[21]
P. cubeba	Leaf	It is used to treat renal disorders, gonorrhea, syphilis, abdominal pain, enteritis, and asthma.[26]
	Fruit	It is used to manage coughs, bronchitis, sinusitis, throat and genito-urinary infections, poor digestion, and amebic dysentery.[26]
P. acutifolium	Leaf	It is used for antiseptic purposes and to treat wound healing, vaginal infections, gastritis, skin ulcerations, and other conditions.[27]
P. auritum	Leaf	It is used to treat chronic laryngitis, asthma, and serves as a diaphoretic, diuretic, and stimulant. It is also utilized for tonsillitis, erysipelas, fevers, gout, antiblenorrhagic therapy, rheumatism, and sores.[28]
P. umbellatum	Leaf	It is used for treating wounds, reducing swelling, and alleviating skin irritations.[29]
	Fruit	It is used for the treatment of poisoning, pitting edema, fetal malpresentation, filariasis, rheumatism, hemorrhoids, and dysmenorrhea.[30]
	Root	It is used for digestive issues, including dyspepsia, constipation, and dysentery.[31]

Table 1. (cont.)

Species	Part	Medicinal uses
P. porphyrophyllum	Leaf	It is used for the treatment of leprosy, abdominal discomfort, skin disorders, postpartum complications, and bone pain.[32]
P. nigrum	Leaf	It is used to relieve pain, treat atrophic arthritis, influenza, fever, act as a stimulant, and provide digestive support.[33]
	Fruit	It is used for asthma, colon toxins, obesity, chronic indigestion, sinus congestion, cholera, colic pain, diarrhea, gastric issues, worms, and hemorrhoids.[34]
P. carpunya	Leaf	It is used for skin irritations.[24]
P. officinarum	Fruit	It is used as a digestive aid and carminative in asthma and for gastrointestinal ulcers.[35]
P. guineense	Root	It is used for aphrodisiac purposes, as well as to treat colds, respiratory diseases, and dental caries.[36]
	Seed	It is used to treat bronchitis, gastrointestinal disorders, venereal diseases, and rheumatism.[37]
P. ovatum	Leaf	It is used for inflammation and as an analgesic.[38]
P. truncatum	Leaf	It is used in the treatment of hypertension.[39]
P. regnellii	Leaf	It is used to heal wounds, alleviate swelling, and soothe skin irritation.[38]
P. obliquum	Leaf	It is used to relieve pain, ease muscular aches, and manage arthritis.[40]
	Root	It is used to address diarrhea, dysentery, nausea, ulcers, and genitourinary infections.[24]
P. marginatum	Leaf	It is used to treat inflammation, snake bites, and disorders of the liver and bile duct.[24]
P. sylvaticum	Root	It is used as a remedy for snake venom poisoning.[24]
P. angustifolium	Leaf	It is used for disinfection wounds and sores.[41]
P. alatabaccum	Leaf	It is used to relieve stomach aches and treat diarrhea.[42]
P. cumanense	Leaf	It is used to combat malaria and reduce fever.[43]
P. barbatum	Leaf	It is used for treating headaches, stomach pain, dermatitis, as a disinfectant, and for wound healing.[44]
P. boehmeriifolium	Root	It is used as a laxative, anthelmintic, and carminative agent.[45]
	Leaf	It is used in antiplatelet therapies and to treat thrombotic diseases.[46]
P. chaba	Root	It is used for asthma, bronchitis, fever, abdominal pain, as a stimulant, and in the treatment of hemorrhoidal conditions.[47]
P. claussenianum	Leaf	It is used to treat yeast infections and vaginal disorders.[48]
P. dennisii	Leaf	It is used to alleviate rheumatic pain and arthritis.[49]
P. glabratum	Leaf	It is used to treat skin conditions, skin ulcerations, wounds, and functions as an antiseptic.[50]
P. grande	Leaf	It is used for treating leishmaniasis-associated lesions.[51]
P. lanceaefolium	Leaf	It is used to treat skin infection.[52]
P. hayneanum	Leaf	It is used to treat wounds and skin disorders.[53]
P. holtanii	Leaf	It is used to treat leishmaniasis symptoms.[51]
P. jacquemontianum	Leaf	It is used to treat skin conditions, infections, anemia, and body aches.[54]
P. multiplinervium	Leaf	It is used to treat gastrointestinal issues, snakebites, body aches, menorrhagia, promote wound healing, act as a hemostatic, and for teeth whitening.[55]
P. pulchrum	Leaf	It is used as antidote for snakebite.[56]

Table 1. (cont.)

Species	Part	Medicinal uses
P. pyrifolium	Leaf	It is used to treat diarrhea and as a diuretic.[57]
	Root	It is used to treat blennorrhagia.[57]
	Stem	It is used to treat asthma and neuralgia.[57]
P. retrofractum	Root	It is used for relieving colic, dyspepsia, and stomach pain.[58]
	Fruit	It is used as an antidiarrheal, aromatic, carminative, oxytocic, stimulant, and stomachic, and is commonly applied in the treatment of coughs, colds, and hemorrhoids.[58]
P. sintenense	Leaf	It is used as a sedative and a remedy for snake bites.[59]
P. strigosum	Leaf	It is used to treat symptoms related to parasitic infections, leishmaniasis, and wounds.[60]
P. stylosum	Leaf	It is used to treat fever and relieve pain.[19]
	Root	It is used as a poultice or drink after childbirth.[19]
P. tuberculatum	Leaf	It is used as a calming agent and to treat snake bites.[61]
P. xanthostachyum	Leaf	It is used to treat symptoms of leishmaniasis.[51]
P. alyreanum	Leaf	It is used to boost the immune system, relieve pain, and treat depression in traditional medicine.[62]
	Fruit	It is used to reduce chest pain and swelling.[63]
P. amalago	Leaf	It is used to ease stomach cramps, stomachaches, and muscle pain.[64]
	Root	It is used to promote urination and treat kidney stone.[65]
P. anduncum	Leaf	It is used for venereal diseases and urinary tract infections.[66]
P. dilatatum	Leaf	It is used to relieve headaches, muscle pain, and abdominal discomfort.[66]
P. elongatum	Leaf	It is used as a treatment for gonorrhea, constipation, and wounds.[67]
P. jaborandi	Leaf	It is used as a local anaesthetic.[68]
P. kadsura	Leaf	It is used to treat asthma and arthritis.[46]
P. lanceaefolim	Fruit	It is used for treating skin infections.[69]
P. piscatorum	Root	It is used as s a fish poison and toothache remedy.[70]
P. taiwanense	Leaf	It is used to treat respiratory ailments such as coughs, colds, and bronchitis.[71]
P. tricuspe	Fruit	It is used for antimalarial and snake bites.[72]

4. Chemical composition of essential oils

In recent years, essential oils derived from the *Piper* genus have garnered substantial scientific interest due to their complex chemical compositions and wide-ranging potential applications. This increased attention is evident in the growing number of studies indexed in reputable databases like Scopus, many of which originate from countries rich in *Piper* biodiversity, such as Brazil, India, and Ecuador. These regions offer favorable climates and unique ecological conditions that significantly influence the yield and composition of essential oils, resulting in diverse chemical profiles across species.

A review of essential oils from 86 *Piper* species (as shown in Table 2)[75-131] highlights this chemical diversity, with Brazil contributing the majority of the studies. This trend underscores the Amazon region's role as a biodiversity hotspot and its potential as a valuable reservoir for natural product discovery. The essential oils are primarily extracted

from different parts of the plants, including leaves, stems, and fruits, which further contributes to their varied chemical compositions. Notably, *Piper pedicellatum* stands out for having the highest number of identified constituents (84), while species such as *P. caldense* and *P. klotzschianum* display remarkable oil yields of 14.7% and 13.0%, respectively.

The chemical profile of *Piper* essential oils is predominantly characterized by sesquiterpene hydrocarbons, monoterpene hydrocarbons, oxygenated monoterpenes, and phenylpropanoids. For instance, *P. arboreum* is notable for its high caryophyllene oxide content (30.5%),[107] highlighting the prominence of sesquiterpenes in the genus. Monoterpenes such as *α*-pinene and *β*-pinene are also well represented, particularly in *P. hispidum*[77] and *P. tuberculatum*,[96] where they contribute significantly to the aromatic and therapeutic qualities of the oils. These compounds play important roles in the biological activity of the oils, including antimicrobial and anti-inflammatory effects.

Oxygenated monoterpenes further contribute to the complexity and bioactivity of *Piper* essential oils. Compounds like camphor and linalool are present in high concentrations in species such as *P. malacophyllum*, *P. variabile*, *P. jacquemontianum*, and *P. claussenianum*, adding to their potential value in pharmaceutical and cosmetic applications.[54,86,102,120] Additionally, phenylpropanoids such as myristicin, safrole, and apiole are dominant in species like *P. sarmentosum*, *P. betle*, and *P. sanctifelicis*, respectively.[81,95,127] These constituents contribute to the distinctive biological properties of the oils, including antifungal, sedative, and insecticidal activities.

Despite the growing body of literature on *Piper* essential oils, further investigation is needed to understand the broader implications of their chemical diversity. Environmental factors such as temperature, altitude, soil pH, and humidity are known to influence essential oil composition, yet their specific effects on *Piper* species remain insufficiently explored. Likewise, genetic variation between species plays a critical role in determining both yield and chemical profile. The notable differences in oil yield between *P. caldense* and *P. klotzschianum*, for example, likely reflect underlying genetic factors. However, cultivation practices, plant maturity, and seasonal changes may also contribute to these variations.[83]

Moreover, the consistency of essential oil composition under varying environmental and cultivation conditions is an area that warrants deeper study. Such information is crucial, particularly when evaluating the bioactivity of these oils for pharmaceutical or industrial use, as even minor shifts in chemical makeup can influence efficacy. Standardizing extraction methods and integrating chemometric and genetic analyses can offer more precise insights into the relationships between species, their environments, and the essential oils they produce.

Table 2. Major components identified from the essential oils of several *Piper* species

Species	Locality (Parts)	Total (No. %)	Yield (%)	Major components
P. aduncum	Brazil (Inflorescence)	52 (99.4)	0.4	Piperitone (23.4%), terpinen-4-ol (12.3%), *β*-caryophyllene (7.2%), *α*-humulene (6.9%), myristicin (6.5%)[75]
	Brazil (Leaf)	52 (99.1)	0.3	Myristicin (12.4%), piperitone (11.8%), germacrene D (6.9%), terpinen-4-ol (6.3%), dillapiole (6.3%)[75]
	Cuba (Leaf)	92 (97.4)	NM	Piperitone (23.7%), camphor (17.1%), viridiflorol (14.5%)[76]
P. cubeba	India (Fruit)	37 (96.5)	NM	*β*-Cubebene (18.9%), cubebol (13.3%), sabinene (9.6%), *α*-copaene (7.4%), *β*-caryophyllene (5.3%)[21]
	Brazil (Fruit)	13 (83.7)	NM	Sabinene (20.0%), 1,8-cineole (11.9%), terpinen-4-ol (6.4%), *β*-pinene (5.8%), camphor (5.6%)[21]
P. hispidum	Venezuela (Leaf)	34 (95.2)	0.2	*α*-Pinene (15.3%), *β*-pinene (14.8%), *β*-elemene (8.1%), caryophyllene oxide (7.8%), *δ*-3-carene (6.9%)[77]
P. lenticellosum	Ecuador (Leaf)	28 (98.8)	2.0	Piperitone (33.9%), 1,8-cineole (11.9%), limonene (11.0%), safrole (8.1%), *α*-pinene (4.4%)[78]

Table 2. (cont.)

Species	Locality (Parts)	Total (No. %)	Yield (%)	Major components
P. amalago	Ecuador (Leaf)	38 (90.2)	0.2	*β*-Phellandrene (20.4%), spathulenol (10.3%), bicyclogermacrene (8.5%), *α*-pinene (7.2%)[79]
	Brazil (Flower)	28 (95.5)	0.5	Germacrene D (18.5%), silphiperfol-6-ene (13.5%), limonene (10.5%), *p*-cymene (9.3%)[80]
P. amalago	Brazil (Leaf)	52 (96.5)	0.7	*α*-Amorphene (25.7%), *p*-cymene (9.4%), (*E*)-methyl geranate (7.8%), cubenol (6.17%)[80]
	Brazil (Root)	48 (99.0)	0.02	*α*-Amorphene (14.4%), *α*-muurolol (6.3%), *α*-gurjunene (4.4%)[80]
	Brazil (Stem)	51 (94.1)	0.05	*α*-Amorphene (23.3%), *α*-muurolol (9.3%), longifolene (6.6%)[80]
P. betle	India (Leaf)	65 (100)	0.3	Safrole (25.6%), eugenol (18.2%), eugenol acetate (8.0%)[81]
P. glabratum	Brazil (Leaf)	46 (100)	0.3	*β*-Pinene (13.0%), longiborneol (12.0%), *α*-pinene (9.7%), *β*-caryophyllene (8.0%), viridiflorene (7.4%), *β*-copaene (6.6%), *β*-damascone (5.9%)[82]
P. cernuum	Brazil (Leaf)	27 (98.4)	2.0	*trans*-Dihydroagarofuran (36.7%), *γ*-eudesmol (13.3%), 4-*epi*-*cis*-dihydroagaro-furan (11.4%)[83]
P. corcovadensis	Brazil (Leaf)	31 (96.6)	0.2	1-Butyl-3, 4-methylenedioxy-benzene (30.7%), *α*-terpinolene (17.5%), *β*-caryophyllene (6.3%), *α*-pinene (6.0%)[84]
P. longum	India (Stem)	36 (97.2)	0.03	*β*-Pinene (34.8%), *α*-pinene (14.0%), limonene (10.3%), *β*-caryophyllene (9.3%), camphene (6.6%)[85]
	India (Root)	38 (96.9)	0.05	*β*-Pinene (26.4%), camphene (13.9%), *α*-pinene (11.8%), bornyl acetate (10.0%), limonene (6.3%)[85]
P. longum	India (Fruit)	29 (97.1)	0.01	*β*-Pinene (43.1%), *α*-pinene (15.3%), limonene (9.6%), (*E*)-nerolidol (8.8%), *β*-caryophyllene (5.7%)[85]
	India (Leaf)	37 (76.7)	0.08	(*E*)-Nerolidol (22.5%), *β*-caryophyllene (16.8%), *α*-humulene (5.8%)[85]
P. capitarianum	Brazil (Leaf)	48 (96.3)	1.2	*β*-Caryophyllene (20.0%), *α*-caryophyllene (10.2%), myrcene (10.5%)[86]
	Brazil (Stem)	48 (94.7)	0.9	*β*-Caryophyllene (19.7%), *α*-caryophyllene (9.1%), *α*-selinene (7.0%)[86]
	Brazil (Inflorescence)	48 (94.1)	0.6	*β*-Caryophyllene (15.3%), *α*-caryophyllene (12.7%)[86]
P. majusculum	Indonesia (Leaf/bark)	12 (93.8)	0.02	*β*-Caryophyllene (17.3%), caryophyllene oxide (14.3%), *α*-selinene (14.3%), spathulenol (8.8%)[87]
P. umbellatum	Ivory Coast (Leaf)	40 (97.7)	0.02	Linalool (25.5%), limonene (16.2%), *β*-caryophyllene (15.4%), *β*-pinene (7.3%), *α*-pinene (6.8%)[88]
P. guineense	Ivory Coast (Aerial)	45 (96.8)	0.09	*α*-Phellandrene (18.9%), linalool (12.8%), (2*E*,6*E*)-farnesol (10.7%), (*Z*)-*β*-ocimene (6.4%)[88]
P. regnellii	Brazil (Leaf)	61 (97.9)	0.3	Myrcene (22.0%), (*E*)-anethole (16.0%), dillapiole (14.5%), bicyclogermacrene (9.5%), junicedranol (9.0%)[89]

Table 2. (cont.)

Species	Locality (Parts)	Total (No. %)	Yield (%)	Major components
P. regnellii	Brazil (Flower)	61 (99.2)	0.4	(*E*)-Anethole (28.3%), myrcene (23.1%), bicyclogermacrene (9.6%), *γ*-muurolene (7.3%)[89]
	Brazil (Stem)	64 (100)	0.2	Dillapiole (30.2%), (*E*)-anethole (13.5%), myrcene (15.0%), junicedranol (7.9%)[89]
P. lolot	Vietnam (Leaf)	47 (93.9)	0.06	*β*-Caryophyllene (20.6%), *β*-bisabolene (11.6%), *β*-selinene (8.4%), *β*-elemene (7.7%), *trans*-muurola-4(14),5-diene (7.4%)[90]
P. capense	Ethiopia (Fruit)	42 (82.0)	0.3	*cis*-Muurola-3,5-diene (15.6%), dihydroxy-isocalamendiol (11.6%), germacrene D (9.3%), *γ*-muurolene (7.2%)[91]
	Africa (Seed)	31 (95.6)	3.0	Bicyclogermacrene (14.0%), *α*-phellandrene (12.9%), *δ*-2-carene (11.2%), *p*-cymene (11.1%)[92]
P. gaudi-chaudianum	Brazil (Leaf)	47 (92.3)	0.5	(*E*)-Nerolidol (22.4%), *α*-caryophyllene (16.5%), *β*-caryophyllene (8.9%), bicyclogermacrene (7.4%)[93]
P. demeraranum	Brazil (Aerial)	74 (87.3)	0.6	Limonene (20.2%), sabinene (12.9%), *β*-pinene (7.7%), *α*-pinene (7.3%)[94]
P. multipli-nervium	Panama (Leaf)	43 (90.0)	0.2	*β*-Selinene (19.0%), *β*-elemene (16.1%), *α*-selinene (15.5%)[55]
P. coruscans	Ecuador (Aerial)	26 (90.2)	0.4	*β*-Bisabolene (33.4%), (*E*)-nerolidol (10.2%), *β*-caryophyllene (8.0%)[95]
P. tuberculatum	Ecuador (Aerial)	16 (89.3)	0.8	*β*-Bisabolene (40.2%), *δ*-cadinene (9.8%), *β*-caryophyllene (9.7%), *β*-caryophyllene (9.7%)[95]
P. tuberculatum	Brazil (Fruit)	21 (99.6)	NM	*β*-Pinene (31.6%), *α*-pinene (28.4%), (*Z*)-*β*-ocimene (20.3%), *β*-terpinyl acetate (6.52%)[96]
	Brazil (Fruit)	NM (98.9)	0.3	*β*-Pinene (27.8%), *α*-pinene (26.6%), *β*-caryophyllene (14.4%)[97]
P. obliquum	Ecuador (Aerial)	31 (88.2)	0.1	Bicyclogermacrene (7.9%), *β*-caryophyllene (6.3%) *α*-pinene (6.0%)[95]
*P. heterophyllu*m	Italy (Aerial)	21 (93.9)	0.9	1,8-Cineole (39.0%), *α*-pinene (9.3%), asaricin (8.8%), (*E*)-*β*-ocimene (6.5%), *β*-pinene (6.2%)[98]
P. lhotzkyanum	Brazil (Inflorescence)	39 (93.9)	2.4	*α*-Phellandrene (56.4%), *β*-phellandrene (14.5%), *β*-pinene (6.9%), *α*-pinene (6.8%)[99]
P. divaricatum	Brazil (Fruit)	16 (94.6)	0.1	*β*-Pinene (12.0%), 1,8-cineole (12.0%), *α*-phellandrene (10%), *β*-caryophyllene (9.0%)[100]
P. divaricatum	Brazil (Leaf/stem)	16 (98.5)	3.0	Methyl eugenol (77.1%), eugenol (7.9%)[101]
P. malacophyllum	Brazil (Leaf)	28 (96.0)	0.4	Camphor (32.8%), camphene (17.8%), (*E*)-nerolidol (9.1%), *α*-pinene (5.0%)[102]
P. chaba	Bangladesh (Leaf)	53 (95.1)	0.3	*α*-Caryophyllene (16.4%), caryophyllene oxide (12.2%), viridiflorol (8.1%), globulol (7.4%), *β*-selinene (7.1%)[103]

Table 2. (cont.)

Species	Locality (Parts)	Total (No. %)	Yield (%)	Major components
P. diospyrifolium	Brazil (Leaf)	21 (100)	0.1	(*E*)-Eudesma-6,11-diene (21.2%), *β*-caryophyllene (16.8%), *γ*-muurolene (10.6%), limonene (8.5%)[104]
P. artanthe	Colombia (Aerial)	41 (87.0)	0.8	Apiole (14.6%), *δ*-elemene (11.7%), *β*-caryophyllene (10.3%), *epi*-cubebol (8.9%), myristicin (6.4%), cubebol (6.3%)[105]
P. truncatum	Brazil (Leaf)	10 (94.3)	NM	(*Z*)-3-Hexenol (35.3%), *β*-caryophyllene (24.2%), germacrene D (11.1%), (*E*)-nerolidol (10.5%)[106]
	Brazil (Stem)	16 (74.9)	NM	N-Isobutyl-(6*Z*, 8*E*)-decadien-amide (16.2%), *α*-cadinol (9.0%), 1,10-Di-epcubenol (7.3%), *β*-springene (6.5%)[106]
P. truncatum	Brazil (Root)	5 (89.6)	NM	*N*-Isobutyl-(6*Z*, 8*E*)-decadien-amide (67.6%), *epi*-longipinanol (7.6%), (*E*)-nerolidol (6.3%)[106]
	Brazil (Inflorescence)	13 (99.2)	NM	Germacrene D (56.0%), (*E, Z*)-*α*-farnesene (10.4%), camphene (10.3%)[106]
P. dumosum	Ecuador (Aerial)	29 (88.6)	0.1	Bicyclogermacrene (16.5%), germacrene D, (10.4%), apiole (8.9%), *β*-caryophyllene (9.7%)[95]
P. anonifolium	Ecuador (Aerial)	22 (80.0)	0.1	*β*-Caryophyllene (11.3%), germacrene D (9.6%), *α*-humulene (6.6%)[95]
P. reticulatum	Ecuador (Aerial)	24 (80.0)	0.07	Apiole (15.0%), germacrene D (12.6%), bicyclogermacrene (8.1%), *δ*-cadinene (6.0%)[95]
P. soledadense	Ecuador (Aerial)	18 (75.5)	1.2	Limonene (38.5%), caryophyllene oxide (8.4%), *β*-copaene (5.8%), eudesma-3,7-(11)-diene (5.8%)[95]
P. sancti-felicis	Ecuador (Aerial)	14 (82.0)	0.5	Apiole (76.1%), *β*-caryophyllene (4.1%)[95]
P. mituense	Ecuador (Aerial)	23 (78.8)	0.1	Apiole (51.6%), bicyclogermacrene (9.0%), germacrene D (6.7%)[95]
P. arboreum	Brazil (Leaf)	20 (67.5)	NM	Caryophyllene oxide (30.5%), myristicin (7.0%), spathulenol (6.2%), humulene epoxide II (5.0%)[107]
P. consan-guineum	Brazil (Leaf)	40 (96.1)	0.3	*γ*-Eudesmol (18.6%), *γ*-cadinene (11.3%), (*E*)-nerolidol (6.2%), *α*-muurolol (5.0%)[108]
P. acutilimbum	Brazil (Leaf)	47 (98.0)	0.1	*γ*-Eudesmol (7.5%), germacrene B (6.9%), *α*-muurolol (6.4%), *β*-longipinene (6.2%), epi-cubenol (5.6%)[108]
P. durilignum	Brazil (Leaf)	38 (95.5)	0.1	Germacrene D (11.1%), limonene (10.7%), *β*-caryophyllene (9.1%)[108]
P. bellidifolium	Brazil (Leaf)	41 (96.3)	0.01	(*E*)-Nerolidol (20.3%), aromadendrene (13.3%), *α*-copaene (10.9%)[108]
P. nigrum	Cuba (Fruit)	21 (67.8)	NM	Caryophyllene oxide (29.3%), *α*-terpinene (7.3%), *β*-caryophyllene (6.9%)[109]
P. ovatum	Brazil (Aerial)	44 (97.6)	2.3	*δ*-Amorphene (16.5%), *cis*-muurola-4(14),5-diene (14.2%), *γ*-muurolene (13.2%)[38]

Table 2. (cont.)

Species	Locality (Parts)	Total (No. %)	Yield (%)	Major components
P. japurense	Brazil (Leaf)	45 (95.1)	0.05	α-Eudesmol (22.0%), 10-epi-γ-eudesmol (6.0%) γ-cadinene (5.8%)[110]
P. coariense	Brazil (Leaf)	35 (95.5)	0.1	α-Eudesmol (27.3%), β-dihydro-agarofuran (15.3%) γ-cadinene (5.8%), 10-epi-γ-eudesmol (13.3%)[110]
P. cachimboense	Brazil (Leaf)	49 (82.5)	1.0	δ-Cadinene (9.2%), β-caryophyllene (7.5%), γ-amorphene (6.9%), germacrene D (6.4%)[111]
P. auriculifolium	Brazil (Leaf)	40 (95.5)	0.2	Premnaspirodien (32.2%), α-bulnesene (10.0%)[110]
P. curtistilum	Brazil (Leaf)	33 (92.0)	0.03	Caryophyllene oxide (28.6%), γ-muurolene (6.3%)[110]
P. alatipetiolatum	Brazil (Leaf)	18 (96.2)	0.1	Germacrene D (5.7%), viridiflorene (3.4%)[110]
P. brevesanum	Brazil (Leaf)	27 (91.3)	0.05	Bicyclogermacrene (11.6%), γ-cadinene (8.2%), germacrene D (7.0%), valencene (6.2%)[110]
P. septup-linervium	Colombia (Aerial)	63 (91.8)	NM	α-Pinene (21.0%), β-pinene (13.8%), citronellal (10.3%), α-himachalene (7.3%)[112]
P. subtomentosum	Colombia (Leaf)	63 (92.0)	NM	δ-Cadinene (45.2%), β-caryophyllene (14.6%), β-cadinene (6.5%), (*E, Z*)-α-farnesene (7.5%)[112]
	Colombia (Inflorescence)	63 (86.9)	NM	α-Pinene (27.3%), β-pinene (15.0%), caryophyllene oxide (12.5%), β-caryophyllene (7.4%), 10-*epi*-italacene (5.3%)[112]
P. borbonense	Africa (Leaf)	39 (99.2)	3.3	Spathulenol (27.3%), bicyclogermacrene (16.3%), α-phellandrene (8.3%), *p*-cymene (6.8%), δ-2-carene (6.6%)[92]
	Africa (Branch)	18 (100)	0.6	α-Bisabolol (32.4%), (*E, E*)-α-farnesene (24.7%), α-caryophyllene (9.3%), α-selinene (8.7%)[92]
P. klotzs-chianum	Brazil (stem)	16 (99.8)	0.1	1-Butyl-3,4-methylenedioxybenzene (84.8%)[113]
P. marginatum	Brazil (Leaf)	29 (99.6)	0.4	(*Z*)-Asarone (30.4%), patchouli alcohol (16.0%), elemol (9.7%)[114]
	Brazil (Stem)	16 (99.7)	0.03	(*E*)-Asarone (32.6%), patchouli alcohol (25.7%), (*Z*)-asarone (8.5%), elemicin (6.9%), β-caryophyllene (6.8%), seychellene (5.8%)[114]
	Brazil (Inflorescence)	18 (99.1)	0.02	Patchouli alcohol (23.4%), (*E*)-asarone (22.1%), β-caryophyllene (13.1%), α-acoradiene (9.7%)[114]
P. flaviflorum	China (Leaf)	30 (95.3)	0.3	(*E*)-Nerolidol (40.5%), β-caryophyllene (14.6%), elixene (12.3%)[115]
P. flaviflorum	China (Stem)	42 (90.1)	0.1	β-Caryophyllene (26.6%), (*E*)-nerolidol (16.7%), α-copaene (7.5%), elixene (5.3%)[115]
P. aleyreanum	Brazil (Leaf)	15 (93.8)	0.9	β-Caryophyllene (18.6%), isocaryophyllene (17.5%), β-pinene (14.4%)[116]
	Brazil (Aerial)	35 (81.7)	1.0	Caryophyllene oxide (11.5%), β-pinene (9.0%), spathulenol (6.7%)[62]

Table 2. (cont.)

Species	Locality (Parts)	Total (No. %)	Yield (%)	Major components
P. renitens	Brazil (Stem)	16 (99.8)	NM	Guaiol (13.9%), germacrene D (13.8%), *α*-pinene (12.5%), *β*-pinene (12.4%)[117]
P. bavinum	Vietnam (Leaf/ flower)	50 (85.0)	0.2	Bicyclogermacrene (10.6%), globulol (5.7%), viridiflorene (5.1%)[118]
P. claussenianum	Brazil (Leaf)	16 (92.4)	1.0	(*E*)-Nerolidol (81.5%), linalool (5.2%)[119]
	Brazil (Inflorescence)	24 (88.7)	1.0	Linalool (50.2%), (*E*)-nerolidol (22.7%)[120]
P. variabile	Guatemala (Leaf)	36 (96.5)	0.7	Camphor (28.4%), camphene (16.6%), limonene (13.9%), *o*-cymene (6.3%)[54]
P. jacque-montianum	Guatemala (Leaf)	34 (99.5)	0.8	Linalool (69.4%), (*E*)-nerolidol (8.0%)[54]
P. krukoffii	Brazil (Leaf)	44 (97.6)	2.0	Myristicin (40.3%), apiole (25.4%)[121]
	Brazil (Twig)	44 (96.8)	0.8	Myristicin (26.7%), apiole (34.1%), *epi*-*α*-muurolol (5.7%)[121]
P. xylosteoides	France (Leaf)	11 (98.9)	2.3	Safrole (84.1%), *α*-pinene (7.7%)[122]
	Brazil (Leaf)	8 (99.8)	3.2	Safrole (75.8%), *α*-pinene (15.3%)[122]
P. klotzschianum	Brazil (Seed)	18 (99.3)	13.0	1-Butyl-3,4-methylenedioxy-benzene (37.0%), limonene (17.8%), *α*-phellandrene (17.0%)[113]
P. pedicellatum	India (Leaf)	84 (96.7)	0.1	Germacrene D (41.0%), *β*-caryophyllene (7.5%)[123]
P. angustifolium	Brazil (Leaf)	25 (93.0)	0.4	Spathulenol (23.8%), caryophyllene oxide (13.1%), α-pinene (5.9%)[124]
P. vicosanum	Brazil (Leaf)	60 (95.9)	0.8	*γ*-Elemene (14.2%), *α*-alaskene (13.5%), limonene (9.1%)[125]
P. ilheusense	Brazil (Leaf)	22 (80.6)	0.9	*β*-Caryophyllene (11.8%), patchouli alcohol (11.1%), gleenol (7.5%), germacrene B (7.2%)[126]
P. sarmentosum	India (Leaf)	8 (98.4)	0.7	Myristicin (83.4%), *β*-caryophyllene (4.2%)[127]
	India (Fruit)	10 (98.2)	0.5	Myristicin (84.2%), *β*-caryophyllene (5.7%)[127]
	India (Root)	6 (97.5)	0.02	Myristicin (81.2%), apiole (5.6%)[127]
P. acre	Vietnam (Leaf)	45 (99.4)	0.2	(*E*)-Nerolidol (22.7%), sabinene (19.5%), *δ*-cadinene (12.4%), *β*-eudesmol (7.5%)[128]
P. acre	Vietnam (Stem)	52 (89.4)	0.1	Sabinene (19.9%), (*E*)-nerolidol (15.6%), *δ*-cadinene (13.5%), benzyl benzoate (7.0%)[128]

Table 2. (cont.)

Species	Locality (Parts)	Total (No. %)	Yield (%)	Major components
P. laosanum	Vietnam (Leaf)	57 (85.7)	0.2	α-Curcumene (12.0%), germacrene D (6.3%), sabinene (6.1%), spathulenol (5.1%)[128]
P. laosanum	Vietnam (Stem)	44 (89.0)	0.1	Sabinene (14.9%), benzyl salicylate (14.3%), (*E*)-nerolidol (9.3%)[128]
P. mollicomum	Brazil (Leaf)	15 (98.0)	0.9	Camphor (39.9%), camphene (25.3%), (*E*)-nerolidol (7.5%)[129]
P. carpunya	USA (Leaf)	42 (96.2)	0.7	Piperitone (26.2%), limonene (9.5%), elemicin (7.2%)[130]
P. subscutatum	Ecuador (Leaf)	66 (96.9)	0.2	β-Caryophyllene (25.3%), β-chamigrene (10.3%)[131]

5. Chemical composition of *Piper* essential oils from Malaysia

Table 3 presents the essential oil compositions of 18 *Piper* species native to Malaysia, with oils extracted primarily from leaves, stems, and rhizomes.[132-143] These plant parts offer distinct chemical profiles, reflecting the influence of organ-specific biosynthesis and environmental interactions. The data reveal a consistent richness in sesquiterpenes across the studied species, positioning them as central to the chemical identity of Malaysian *Piper* essential oils. Among these, β-caryophyllene emerges as a dominant compound, widely distributed across multiple species and plant parts.

Notably, *Piper nigrum* fruit oil stands out with an exceptionally high β-caryophyllene content of 39.7%, in addition to δ-3-carene (10.9%) and myrcene (9.1%).[109] This suggests a potential link to the plant's well-documented pharmacological properties. Similarly, the stem oil of *P. caninum* contains 20.6% β-caryophyllene, alongside significant levels of α-bergamotene (13.7%) and (E)-isoeugenol (13.4%),[136] while the leaf oil of *P. magnibaccum* features 19.7% β-caryophyllene and germacrene D (10.7%).[138] These findings underscore the prominent role of β-caryophyllene as a chemotaxonomic marker and a key contributor to the biological efficacy of *Piper* essential oils.

In addition to sesquiterpenes, monoterpene hydrocarbons are important constituents in several Malaysian *Piper* species. For example, *P. baccatum* leaf oil is characterized by high levels of camphene (22.1%), together with β-caryophyllene (30.7%) and eucalyptol (14.9%).[142] Similarly, *P. ribesioides* leaf oil contains 16.3% camphene and 20.0% β-caryophyllene,[19] indicating the co-occurrence of monoterpenes and sesquiterpenes in meaningful proportions. The stem oil of *P. porphyrophyllum* is also notable for its sabinene content (15.5%), a monoterpene valued for its fragrance and antimicrobial properties.[32] These monoterpenes contribute to the essential oils' aromatic complexity and may also enhance synergistic biological activities.

Oxygenated sesquiterpenes represent another significant class of bioactive compounds in Malaysian *Piper* oils. *Piper miniatum* leaf oil, for example, is rich in caryophyllene oxide (20.3%), followed by α-cubebene (10.4%) and β-caryophyllene (8.5%).[132] Likewise, *P. ornatum* leaf oil contains 31.5% caryophyllene oxide and spathulenol (5.9%),[140] further highlighting this oxygenated sesquiterpene's relevance. *Piper penangense* leaf oil features humulene epoxide II as its major component (31.9%), which may be associated with specific antimicrobial or anti-inflammatory properties.[141] The occurrence of these oxygenated compounds enriches the pharmacological potential of the oils and suggests specialized roles in plant defense mechanisms.

Hence, the essential oils of Malaysian *Piper* species exhibit a rich and varied chemical makeup, dominated by sesquiterpenes such as β-caryophyllene, monoterpenes like camphene and sabinene, and oxygenated sesquiterpenes including caryophyllene oxide and humulene epoxide II. The diversity and abundance of these compounds not only define the aromatic and sensory attributes of the oils but also contribute to their functional properties, such as antimicrobial, anti-inflammatory, and antioxidant activities. This distinct chemical profile highlights the therapeutic potential of Malaysian *Piper* species and supports further exploration for pharmaceutical, nutraceutical, and cosmetic

applications. Figure 2 provides a visual summary of the most frequently identified major components across the studied species.

Table 3. Major components identified from Malaysian *Piper* essential oils

Species	Parts	Total (No. %)	Yield (%)	Major components
P. miniatum	Leaf	64 (89.2)	0.4	Caryophyllene oxide (20.3%), *α*-cubebene (10.4%), *β-caryophyllene* (8.5%), *α-muurolene* (5.8%), *guaiazulene* (3.8%)[132]
P. aduncum	Leaf	35 (67.9)	NM	Apiole (38.0%), methyl isobutyl ketone (8.2%), piperitone (3.3%)[133]
P. aborescens	Leaf	36 (97.5)	0.2	*β*-Phellandrene (24.3%), sabinene (16.3%), *α*-pinene (10.4%), terpinen-4-ol (7.2%)[134]
	Stem	46 (90.5)	0.1	*β*-Phellandrene (20.4%), methyl eugenol (11.0%), *β*-caryophyllene (9.0%)[134]
P. abbreviatum	Aerial	33 (70.5)	0.2	Spathulenol (11.2%), (*E*)-nerolidol (8.5%), *β*-caryophyllene (7.8%), ar-curcumene (5.8%), caryophyllene oxide (5.5%)[16]
P. erecticaule	Aerial	35 (63.4)	0.1	*β*-Caryophyllene (5.7%), spathulenol (5.1%), *β*-cadinene (3.8%)[16]
P. lanatum	Aerial	39 (78.2)	0.2	Borneol (7.5%), *β*-caryophyllene (6.6%), *α*-amorphene (5.6%), *α*-cubebene (5.0%)[16]
P. muricatum	Whole plant	40 (90.8)	0.4	Aromadendrene (16.2%), *β*-caryophyllene (8.8%), germacrene D (7.9%), *γ*-cadinene (7.9%), elemol (5.4%), *γ*-elemene (4.9%)[135]
P. caninum	Stem	57 (98.4)	0.4	*β*-Caryophyllene (20.6%), *α*-bergamotene (13.7%), (*E*)-isoeugenol (13.4%), (*E, Z*)-3,6-nonadien-1-ol (9.3%)[136]
	Leaf	36 (77.9)	0.4	Safrole (17.1%), *β*-pinene (8.9%), linalool (7.0%), *β*-caryophyllene (6.7%)[137]
P. magnibaccum	Leaf	25 (93.5)	0.2	Germacrene D (40.8%), *α*-caryophyllene (8.5%), *α*-cadinol (6.1%)[138]
	Stem	33 (87.6)	0.09	*β*-Caryophyllene (19.7%), germacrene D (10.7%), *α*-cadinol (8.2%)[138]
P. stylosum	Leaf	50 (89.2)	0.08	Aromadendrene (26.6%), *β*-caryophyllene (11.5%), sabinene (13.8%)[19]
	Stem	45 (88.8)	0.07	Aromadendrene (18.8%), *β*-caryophyllene (17.9%), sabinene (6.7%)[19]
P. officinarum	Leaf	40 (85.6)	0.2	*β*-Caryophyllene (11.2%), *α*-pinene (9.3%), sabinene (7.6%), *β*-selinene (5.3%) limonene (4.6%)[139]
	Stem	41 (93.0)	0.2	*β*-Caryophyllene (10.9%), *α*-phellandrene (5.4%)[139]
P. ornatum	Leaf	27 (79.6)	0.3	Caryophyllene oxide (31.5%), spathulenol (5.9%) aromadendrene (4.9%)[140]
P. penangense	Leaf	12 (84.5)	0.5	Humulene epoxide II (31.9%), caryophyllene oxide (9.9%), muurola-4,10(14)-dien-1-ol (9.1%), *β*-ionone (8.3%)[141]

Table 3. (cont.)

Species	Parts	Total (No. %)	Yield (%)	Major components
P. baccatum	Leaf	14 (98.1)	NM	*β*-Caryophyllene (30.7%), camphene (22.1%), eucalyptol (14.9%), *γ*-muurolene (6.9%), *α*-pinene (5.3%)[142]
P. porphyro-phyllum	Leaf	34 (97.3)	0.2	Bicyclogermacrene (14.7%), *α*-copaene (13.2%), *β*-phellandrene (9.5%), *α*-cubebene (7.4%), *β*-caryophyllene (6.4%)[32]
	Stem	38 (95.5)	0.1	Sabinene (15.5%), bicyclogermacrene (12.3%), *α*-copaene (8.1%), *α*-pinene (7.8%)[32]
P. nigrum	Fruit	14 (92.0)	NM	*β*-Caryophyllene (39.7%), *δ*-3-carene (10.9%), myrcene (9.1%), limonene (8.7%)[109]
P. maingayi	Stem	34 (83.6)	0.09	*β*-Caryophyllene (26.2%), *α*-cedrene (8.4%), caryophyllene oxide (6.7%)[143]
	Fruit	18 (78.7)	0.1	*δ*-Cadinene (22.6%), *β*-caryophyllene (18.8%), *α*-copaene (11.2%)[143]
P. ribesioides	Leaf	60 (87.0)	0.03	*β*-Caryophyllene (20.0%), camphene (16.3%)[19]
	Stem	39 (82.9)	0.04	*β*-Caryophyllene (14.4%), camphene (12.3%), *δ*-cadinene (7.8%)[19]

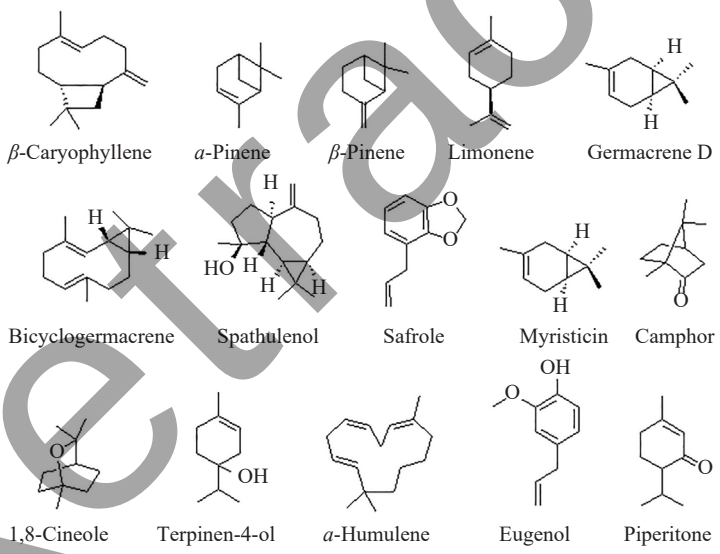

Figure 2. Common major components of *Piper* essential oils

6. Biological activities of *Piper* essential oils

Piper essential oils are renowned for their remarkable biological properties, which make them highly valuable for a broad range of scientific and medicinal applications. The biological activities of these essential oils, along with the phytochemicals derived from *Piper* species, underscore their significant potential in therapeutic, agricultural, and industrial sectors. Table 4 presents an overview of the biological activities associated with *Piper* essential oils.[144-173] Several *Piper* species demonstrated robust antioxidant capacities. For instance, *P. capense* essential oil

exhibited a notable IC_{50} value of 12.5 μg/mL against DPPH radicals. This aligns with broader research on essential oils, which highlights their rich composition of phenolic and terpenoid compounds known for scavenging free radicals. Antioxidants are critical for mitigating oxidative stress, a contributor to chronic diseases such as cancer, cardiovascular disorders, and neurodegeneration. The strong activity observed in these oils suggests their potential as natural alternatives to synthetic antioxidants, which often pose toxicity concerns.

The antimicrobial activity of *Piper* essential oils is evident, with species like *P. albispicum* showing exceptional potency against *P. aeruginosa* at MIC value of 5.8 μg/mL. Essential oils generally owe their antimicrobial properties to compounds such as eugenol, safrole, and beta-caryophyllene, which disrupt microbial cell membranes. This is particularly significant in combating antibiotic-resistant bacteria and pathogenic fungi, such as *C. tropicalis* and *A. niger*. The efficacy of these oils against a wide spectrum of microorganisms positions them as promising candidates for developing plant-based antimicrobials in healthcare and food preservation.

Table 4. Bioacticities of *Piper* essential oils

Bioactivities	Essential oils	Description
Antioxidant	*P. cubeba*	The essential oil showed good radical scavenging activity with capacities of 28.6% and 24.1% against DPPH and ABTS free radicals, respectively.[144]
	P. capense	The essential oil demonstrated strong activity against DPPH with an IC_{50} value of 12.5 μg/mL.[91]
	P. magnibaccum	The leaf and stem oil exhibited high activity in DPPH and ABTS free radical assays, with IC_{50} values of 17.5 and 12.9 μg/mL, respectively.[138]
	P. methysticum	The root oil demonstrated strong radical scavenging activity against DPPH and ABTS free radicals, with IC_{50} values of 74.8 and 76.5 μg/mL, respectively.[145]
	P. umbellactam	The essential oil exhibited potent activity against DPPH, with an IC_{50} value of 17.4 μg mL.[146]
	P. betle	The leaf oil had strong activity against DPPH with an IC_{50} value of 114.3 g/mL.[146]
	P. caninum	The stem oil demonstrated the highest inhibitory activity against lipid peroxidation, reaching 114.9%.[18]
	P. aleyreanum	The essential oil had strong activity against DPPH with 412.2 mg TE/mL.[147]
	P. maingayi	The stem and leaf oils exhibited strong activity against DPPH, with IC_{50} values of 14.9 and 20.8 μg/mL, respectively.[143]
Herbicidal	*P. cubeba*	The fruit oil exhibited an inhibition effect on the shoot growth of *Bidens pilosa* with an IC_{50} value of 1.9 mg/mL.[144]
Anti-trichomonal	*P. nigrum*	The fruit oil caused 100% mortality of *Trichomonas vaginalis* by inducing cell lysis at a minimum lethal concentration (MLC) of 12.5 μg/mL and reduced trophozoite viability at a sub-MLC level of 6.2 μg/mL.[148]
Anti-hyperuricemia	*P. cubeba.*	The essential oil exhibited strong inhibitory effects on xanthine oxidase with an IC_{50} value of 54.8 μg/mL.[144]
	P. methysticum	The essential oil exhibited strong inhibitory effects on xanthine oxidase with an IC_{50} value of 50.0 μg/mL.[145]

Table 4. (cont.)

Bioactivities	Essential oils	Description
Antimicrobial	*P. longum*	The essential oil demonstrated activity against clinical urine isolates of *C. tropicalis*, with an MIC value of 31.2 µg/mL.[38]
	P. albispicum	The leaf oil exhibited activity against *P. aeruginosa*, with an MIC value of 5.8 µg/mL.[149]
	P. ovatum	The essential oil demonstrated significant activity, with MIC values of 15.6 and 31.2 µg/mL against *B. subtilis* and 3.9 µg/mL against *C. tropicalis.*[38]
	P. ecuadorense	The essential oil displayed strong activity against *S. aureus*, *T. rubrum*, and *T. mentagrophytes*, with MIC values of 250, 62.5, and 62.5 µg/mL, respectively.[150]
	P. arborescens	The leaf oil demonstrated significant activity against *S. aureus*, with an MIC value of 250 µg/mL, while the stem oil exhibited activity against *P. aeruginosa* and *A. niger*, each with an MIC value of 500 µg/mL.[134]
	P. ribesioides	The essential oils exhibited strong activity against *B. cereus* and *S. aureus*, with both having an MIC value of 62.5 µg/mL.[19]
	P. porphyrophyllum	The leaf and stem oils demonstrated MIC values of 125, 250, and 250 µg/mL against *B. subtilis*, *S. aureus*, and *E. coli*, respectively.[32]
	P. pendulispicum	The leaf and stem oils exhibited strong growth inhibition against *E. faecalis*, *S. aureus*, and *B. cereus*, with MIC values of 16, 64, and 64 µg/mL, respectively.[151]
	P. erecticaule	The essential oil demonstrated the highest activity against *A. niger*, with an MIC value of 31.3 µg/mL.[16]
	P. lanatum	The essential oil exhibited strong activity against *A. niger*, with an MIC value of 62.5 µg/mL.[16]
	P. abbreviatum	The essential oil demonstrated activity against *B. cereus*, *S. aureus*, and *E. faecalis*, with an MIC value of 250 µg/mL for each.[16]
	P. magnibaccum	The essential oil exhibited strong activity against *P. aeruginosa*, with an MIC value of 250 µg/mL.[138]
	P. officinarum	The leaf and stem oils demonstrated activity against *E. coli* and *P. aeruginosa*, with MIC values of 250 µg/mL for each.[139]
	P. stylosum	The leaf and stem oils exhibited strong activity against *B. cereus* and *S. aureus*, with MIC values of 125 µg/mL for both.[152]
	P. muricatum	The leaf oil demonstrated activity against *B. cereus*, *S. mutans*, and *P. aeruginosa*, with an MIC value of 250 µg/mL for each[135]
Insecticidal	*P. auritum*	The essential oil was active with a RC_{50} value of 0.002 µL/cm^2 against *T. castaneum*.[153]
	P. marginatum	The essential oil caused over 80% mortality in *Artemia salina* larvae with an LC_{50} value of 17.4 µg/mL.[154]
	P. retrofractum	The fruit oil exhibited toxicity against BPH nymphs, with LC_{50} and LC_{95} values of 0.02% and 0.19%, respectively.[155]
Anti-helicobacter	*P. longum*	The fruit oil exhibited inhibitory effects on *Helicobacter pylori*, with an MIC value of 1.95 µg/mL.[156]
Antifungal	*P. divaricatum*	The leaf oil demonstrated significant activity against *Fusarium solani*, with an MIC value greater than 2.50 mg/mL and an inhibition rate exceeding 90%.[101]
	P. auritum	The essential oil inhibited the radial growth of *Fusarium oxysporum*, with an MIC value of 9 mg/mL.[157]
	P. borbonense	The leaf and branch oils demonstrated strong efficacy against *Coniophora puteana* with MIC value 1/5,000 and against *Poria placenta*, with MIC value 1/3,000 (v/v).[92]
	P. macedoi	The leaf oil effectively inhibited the mycelial growth of *Colletotrichum musae* with an IC_{50} value of 0.804 mL/L.[158]
Anti-proliferative	*P. trioicum*	The leaf oil exhibited significant cell growth inhibition in HCT-116, HT-29, PC-3, and HepG2 cell lines with IC_{50} values of 95.2, 33.1, 74.9, and 63.0 µg/mL, respectively.[159]
	P. chaudocanum	The leaf oil inhibited HepG2 cell with an IC_{50} value of 22.9 µg/mL.[160]
Xanthine oxidase	*P. lolot*	The essential oil displayed an IC_{50} value of 28.4 µg/mL.[90]

Table 4. (cont.)

Bioactivities	Essential oils	Description
α-Amylase	*P. lolot*	The essential oil displayed an IC_{50} value of 130.6 μg/mL.[90]
α-Glucosidase	*P. lolot*	The essential oil displayed an IC_{50} value of 59.1 μg/mL.[90]
Anti-cholinesterase	*P. abbreviatum*	The essential oil showed high selective inhibition for AChE with percentage values ranged from 24.2 to 58.2%.[161]
	P. ornatum	The essential oil showed activity against AChE and BChE with inhibition of 70.2% and 75.8% respectively.[140]
	P. erecticaule	The essential oil demonstrated the highest inhibitory activity against AChE and BChE, with inhibition rates of 22.9% and 70.9%, respectively.[16]
Insecticidal	*P. septuplinervium*	The essential oil induced high mortality rates in *Spodoptera frugiperda* instar larvae with an LC_{50} value of 9.4 μL/L in air.[112]
	P. subtomentosum	The inflorescence oil led to high mortality rates in *Spodoptera frugiperda* instar larvae with an LC_{50} value of 13.2 μL/L in air.[112]
	P. macedoi	The leaf oil exhibited a high mortality rate (> 91%) against the aphid *Cerosipha forbesi.*[162]
	P. aduncum	The essential oil exhibited high efficacy against *C. felis*, resulting in 100% egg mortality.[163]
Acaricidal	*P. marginatum*	The leaf oil caused 100% mortality of *Suidasia pontifica* after 72 hours of exposure with LC_{50} values between 1.1 and 2.1 μL/L in air.[164]
	P. callosum	The essential oils induced 100% mortality in *Suidasia pontifica* with LC_{50} values between 1.2 and 3.4 μL/L air.[164]
	P. tuberculatum	The leaf oil demonstrated high toxicity against *Tetranychus urticae* with an LC_{50} value of 0.50 μL/L in air.[165]
Larvicidal	*P. capense*	The essential oil resulted in over 80% mortality of *Anopheles gambiae* after 24 h of exposure with an LC_{50} value of 34.9 ppm.[166]
	P. marginatum	The inflorescence oil exhibited strong activity against *Aedes aegypti* with LC_{10} and LC_{50} values of 14.8 and 20.0 ppm, respectively.[114]
Antifeedant	*P. hispidinervum*	The essential oil demonstrated high effectiveness against *Leptinotarsa decemlineata* with an EC_{50} value of 0.4 μg/cm^2.[167]
	P. capitarianum	The leaf oil exhibited strong deterrent activity, reducing the feeding of *Plutella xylostella* with an AC_{50} value of 0.07 mg/mL.[168]
	P. sarmentosum	The stem and leaf oils produced significant effects on *Brontispa longissima* resulting in antifeedant rates of 50.32%, 61.29%, 74.08%, 86.15%, and 92.26%, respectively.[169]
Adulticidal	*P. capitarianum*	The essential oil was active against *A. aegypti* and *A. albopictus* with LC_{50} values of 126.2 and 124.5 μg/mL, respectively.[86]
Anti-leishmanial	*P. auritum*	The essential oil effectively inhibited the growth of intracellular amastigotes of *Leishmania donovani*, achieving an IC_{50} value of 22.3 μg/mL.[170]
	P. angustifolium	The leaf oil showed high activity against intracellular amastigotes of *Leishmania infantum,* with an IC_{50} value of 1.43 μg/mL.[124]
	P. claussenianum	The leaf oil effectively inhibited the growth of *Leishmania amazonensis* achieving a 31.2% reduction.[119]
Cytotoxic	*P. artanthe*	The essential oil exhibited strong toxicity against *Artemia salina,* with an LC_{50} value of 107.1 μg/mL.[105]
	P. boehmeriifolium	The essential oil showed activity against HepG2 and MCF-7 cell lines with IC_{50} values of 51.5 and 14.3 μg/mL, respectively.[171]
	P. klotzschianum	The leaf oil demonstrated inhibitory effects on HepG2 and HL-60 cell lines, with IC_{50} values of 27.3 and 33.8 μg/mL, respectively.[107]

Table 4. (cont.)

Bioactivities	Essential oils	Description
Anti-parasitic	*P. claussenianum*	The leaf oil effectively inhibited the growth of *Leishmania amazonensis*, with MIC and IC_{50} values of 57.6 and 30.4 μg/mL, respectively.[119]
	P. diospyrifolium	The branch oil significantly reduced the growth of *Leishmania braziliensis,* achieving a 35.3% inhibition rate.[172]
	P. cubeba	The leaf oil displayed activity against *Trypanosoma cruzi* with IC_{50} values of 45.5 μg/mL for trypomastigotes and 87.9 μg/mL for amastigotes.[173]

Insecticidal activity is another noteworthy aspect, with *P. retrofractum* fruit oil exhibiting LC_{50} values as low as 0.02% against brown planthopper nymphs. The larvicidal properties of *P. capense* against *Anopheles gambiae* (LC_{50} value of 34.9 ppm) reinforce their utility in controlling disease vectors like malaria mosquitoes. Such properties are linked to monoterpenes and sesquiterpenes in essential oils, which act as neurotoxins to pests. These findings play a critical role in advancing sustainable pest management approaches, minimizing the reliance on synthetic pesticides that negatively impact non-target species and the broader environment. The cytotoxicity of *Piper* oils, including *P. boehmeriifolium*, against HepG2 and MCF-7 cell lines (with an IC_{50} value of 14.3 μg/mL), highlights their promising anticancer potential. Essential oils are increasingly studied for their ability to induce apoptosis, inhibit cell proliferation, and target multiple cancer pathways. For example, terpenoids like limonene and linalool, often found in *Piper* oils, have demonstrated these effects. These natural agents have the potential to complement conventional cancer treatments, offering the possibility of reducing side effects and enhancing patient outcomes The herbicidal activity of *P. cubeba* fruit oil against *Bidens pilosa* (IC_{50} value of 1.9 mg/mL) highlights its application in sustainable agriculture. Similarly, the anti-parasitic properties, like those of *P. cubeba* oil against *Trypanosoma cruzi* (IC_{50} value of 45.5 μg/mL), suggest utility in neglected tropical diseases. These findings align with global efforts to reduce chemical residues in agriculture and develop affordable treatments for parasitic infections.

The biological implications of this chemical diversity are particularly noteworthy, with sesquiterpene hydrocarbons such as *β*-caryophyllene, nerolidol, and bicyclogermacrene demonstrating promising anti-inflammatory, antimicrobial, and antioxidant properties. However, comparative bioassays are necessary to determine their pharmacological potency relative to synthetic or natural alternatives. Oxygenated monoterpenes like linalool and camphor contribute to antimicrobial and sedative effects, but their efficacy compared to commercially available compounds remains unclear. Furthermore, the presence of phenylpropanoids such as myristicin, safrole, and apiole adds another layer of complexity, as these compounds are associated with potent biological activity but also raise concerns regarding toxicity, potentially limiting their medicinal or industrial applications.

From an industrial and pharmacological perspective, the study highlights the commercial potential of *Piper* essential oils, yet further research is needed to identify which species offer the highest value for pharmaceutical, cosmetic, or fragrance industries. Synergistic interactions between major and minor constituents may enhance therapeutic benefits, but these effects require further validation. Regulatory concerns surrounding compounds like safrole and myristicin, which are subject to restrictions due to potential toxicity, could pose challenges in large-scale applications. Additionally, methodological variations in extraction techniques and analytical procedures, such as differences in gas chromatography-mass spectrometry (GC-MS) parameters, may influence the reported compositions, raising questions about standardization and reproducibility.

7. Conclusion

This review provides a comprehensive analysis of the medicinal applications, chemical profiles, and bioactivity of *Piper* essential oils. The studies examined highlight that these oils are predominantly composed of monoterpenes and sesquiterpenes, which exhibit significant antioxidant, antimicrobial, and other pharmacological effects. The variability in their chemical composition is largely influenced by genetic and environmental factors, emphasizing the need for further investigation into their biosynthetic pathways. While existing research underscores the therapeutic potential of *Piper*

essential oils, additional pharmacological studies are required to explore their broader medicinal applications.

Future research should focus on identifying the most relevant bioactive compounds, assessing their mechanisms of action, and conducting preclinical and clinical studies to validate their efficacy and safety. Expanding investigations to *Piper* species from underexplored regions and diverse environmental conditions could uncover novel chemotypes with unique bioactivities. Advanced technologies, such as metabolomics and genomics, can provide deeper insights into the genetic and environmental factors influencing oil composition. Furthermore, interdisciplinary collaboration with the pharmaceutical and cosmetic industries could facilitate the commercialization of *Piper* essential oils, enhancing their economic value and broadening their application as bioactive agents in drug development and product formulation. By addressing these research gaps, *Piper* essential oils could emerge as valuable resources for natural therapeutics and industrial applications.

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Conflict of interest

Authors declare that there is no conflict of interest.

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