Idrus et al., 2025
J. Basic Appl. Res. Biomed. 11(1): 8-19

JBAAR
Journal of Basic and Applied Research in Biomedicine
ISSN 2413-7014

Review Article

Discovering the Therapeutic Potential of *Piper* Essential Oils: Chemistry and Bioactivities

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Received: 26-01-2025
Revised: 26-04-2025
Published: 01-05-2025

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

Abstract: The genus *Piper*, a prominent member of the Piperaceae family, encompasses over 2,000 species and is widely distributed, particularly in Southeast Asia. Known for its medicinal and economic significance, several *Piper* species have been traditionally utilized in their native regions for various purposes. These species thrive in tropical areas, primarily as aromatic shrubs and trees that produce essential oils in significant quantities. Widely valued for their therapeutic properties, these oils are extensively used in the food, pharmaceutical, and cosmetic industries. Recent studies on Malaysian *Piper* species have highlighted notable pharmacological activities associated with their essential oils. This review provides an in-depth overview of the medicinal applications, chemical composition, and bioactivities of essential oils from key *Piper* species. Data were gathered through comprehensive searches of electronic databases, including Scopus, PubMed, ScienceDirect, SciFinder, and Google Scholar, along with a library search for peer-reviewed articles. The review focuses on the chemical constituents of *Piper* essential oils, offering insights into selecting species with optimal chemical profiles for diverse applications.

Cite this article as: Idrus, S.N.W., Salleh, W.M.N.H.W, Salihu, A.S., Ghani, N.A., Abed, S.A. (2025) Discovering the Therapeutic Potential of *Piper* Essential Oils: Chemistry and Bioactivities. Journal of Basic and Applied Research in Biomedicine, 11(1): 8-19.

1. INTRODUCTION

The Piperaceae family, often referred to as the pepper family, represents a highly diverse group of flowering plants comprising five primary genera: *Piper*, *Peperomia*, *Zippelia*, *Manekia*, and *Verhuellia*. Among these, *Piper* and *Peperomia* are the most prominent, known for their widespread distribution and multifaceted uses. This family is characterized by its ecological adaptability, predominantly thriving in tropical and subtropical regions, particularly in Central and South America. They range in form from small trees and shrubs to herbaceous plants. One of the defining features of Piperaceae plants is their strong aromatic scent, which is derived from essential oils stored within their tissues. These essential oils not only contribute to the characteristic fragrances of these plants but also play crucial roles in their interactions with herbivores and pollinators (Salehi et al., 2019). Most Piperaceae plants exhibit simple leaves that are typically heart-shaped or oval, serving both as identifiers and as sources of bioactive compounds that have significant medicinal properties. The flowers are generally small and arranged in spikes or clusters, lack a perianth, which is an adaptation that aids in attracting specific pollinators such as flies and beetles. This floral structure reflects the evolutionary strategies to maximize pollination efficiency while minimizing energy expenditure on elaborate floral displays (Valentin-Silva, 2023).

Structurally, the Piperaceae family displays several unique adaptations that enhance its ecological success. Many species grow from underground stems known as rhizomes, allowing them to thrive in diverse environments. By spreading laterally through rhizomes, these plants can efficiently colonize new areas while maintaining genetic continuity. The fruits produced by Piperaceae plants are typically small and stone-like, containing a single seed, this trait aids in efficient reproduction by ensuring successful dispersal mechanisms. The small size and hard texture of the fruits allow them to be easily dispersed by animals or water, increasing the likelihood of germination in suitable habitats. Some species exhibit adaptations such as fleshy fruit coverings that attract frugivorous animals, further enhancing seed dispersal (Smith et al., 2008).

The Piperaceae family is essential to multiple economic sectors, including agriculture, food, medicine, and cosmetics. Its most notable economic contribution lies in the spice industry. Members of the Piperaceae family, such as black pepper, are essential culinary ingredients used globally to enhance the flavor of foods. They are among the most traded spices in the world, with substantial demand in international markets. The global popularity of these spices has made them important agricultural commodities, supporting economies in major producing regions (Salehi et al., 2019). In addition to their culinary use, plants from the Piperaceae family are also valued for their medicinal properties, contributing to the pharmaceutical and nutraceutical industries. Many species in this family have been used in traditional medicine for their anti-inflammatory, antimicrobial, and antioxidant properties. The bioactive compounds found in these plants, including alkaloids, flavonoids, and essential oils, are the focus of ongoing research aimed at identifying novel therapeutic compounds. This growing body of research highlights the potential for these plants to provide new solutions for treating a range of health conditions, making them economically significant in modern drug development (Biswas et al., 2022).

The Piperaceae family also plays a role in the cosmetics and personal care industries. Essential oils derived from specific species are valued for their fragrance and therapeutic benefits. Due to their antibacterial and anti-inflammatory properties, these oils are widely incorporated into skincare products, perfumes, and toiletries. With increasing consumer demand for natural, plant-based products, the role of Piperaceae plants in the cosmetics industry is expected to continue growing, further increasing their economic value (Michalak, 2022).

Furthermore, Piperaceae plants have cultural and social importance, especially in many regions of Southeast Asia. Some plants from this family are used in traditional practices, rituals, and social gatherings, which provides economic opportunities for local communities engaged in the cultivation and trade of these plants. The cultural significance of these plants further underscores their economic importance, as they support livelihoods and sustain cultural traditions (Salehi et al., 2019). In addition to their economic uses, Piperaceae plants play important roles in maintaining biodiversity and ecosystem services. Many species in this family contribute to the health of tropical ecosystems by providing food and habitat for various animal and insect species. The conservation of these plants is crucial for preserving biodiversity and supporting industries that rely on healthy ecosystems. Therefore, the economic significance of the Piperaceae family extends beyond immediate financial benefits to include broader ecological contributions that sustain industries and communities (Thorn et al., 2020).

In recent years, interest in essential oils and plant-derived aromatic compounds used in alternative medicine has significantly increased. As a result, a review focusing on *Piper* essential oils is essential to consolidate and simplify existing knowledge. This review is based on data collected through electronic searches across databases such as Scopus, PubMed, ScienceDirect, SciFinder, and Google Scholar. Its aim is to provide a comprehensive summary of the published studies on the chemical composition, biological activities, and medicinal applications of *Piper* essential oils.

2. MORPHOLOGICAL CHARACTERISTICS AND TRADITIONAL MEDICINAL USES OF THE *Piper* GENUS

The Piperaceae family exhibits a remarkable diversity of medicinal applications, with various *Piper* species traditionally used across different cultures. The data in **Table 1** highlights the extensive ethnomedicinal significance of these plants, emphasizing their role in treating a broad spectrum of ailments. Among the plant parts utilized, leaves are the most frequently employed, often for their anti-inflammatory (*P. marginatum, P. ovatum*, *P. aduncum*), respiratory (*P. sarmetosum, P. kadsura, P. guineense*), analgesic (*P. amalago, P. regnellii, P. ovatum*), and antimicrobial (*P. angustifolium, P. caninum, P. elongatum*) properties. This suggests that bioactive compounds responsible for these therapeutic effects are likely concentrated in the foliage, making them a sustainable resource compared to roots or stems (Salehi et al., 2019; Sheti et al., 2019).

The fruits of several *Piper* species, including *P. longum, P. nigrum, P. chaba*, and *P. umbellatum*, are predominantly used for respiratory disorders, digestive issues, and even as antidotes for venomous bites. Their widespread use in traditional medicine aligns with modern pharmacological findings, particularly in digestive health and metabolic regulation. Roots and stems, though less frequently cited, play essential medicinal roles, such as antidotes for snake venom (*P. sylvaticum, P. tuberculatum*), pain relief (*P. mikanianum*), and respiratory treatments (*P. sarmetosum*), indicating the presence of potent bioactive compounds with specific pharmacological actions (Mbadiko et al., 2023). The medicinal properties of *Piper* species encompass a wide range of biological activities, including anti-inflammatory, antimicrobial, analgesic, and antimalarial effects. Notably, *P. aduncum* and *P. angustifolium* are recognized for their wound-healing and antiseptic properties, supporting their potential for developing topical treatments. Meanwhile, species such as *P. methysticum* and *P. capense* demonstrate efficacy in treating respiratory conditions, which aligns with their traditional use in managing asthma and bronchitis. Interestingly, several *Piper* species (*P. piscatorum, P. macedoi, P. divaricatum*) exhibit insecticidal or pesticidal properties, highlighting their potential for biopesticide development as natural alternatives to synthetic chemical pesticides (Lima et al., 2020).

Additionally, certain species, such as *P. umbellatum* and *P. wallichii*, have been traditionally used for treating conditions like dysmenorrhea, filariasis, and even as stimulants, suggesting the presence of bioactive alkaloids or flavonoids that may warrant further phytochemical investigation. The extensive applications of *Piper* species in traditional medicine reinforce their significance not only in ethnopharmacology but also in modern drug discovery. Further phytochemical and pharmacological studies are essential to validate these traditional claims, potentially leading to the discovery of novel therapeutic agents that can contribute to modern medicine and healthcare solutions (Kamsu et al., 2024).

Table 1: Traditional uses of several *Piper* species

Species	Part	Traditional uses
P. aequale	Leaves	It effectively treats urinary and prostate ailments (Sánchez-Aguirre et al., 2024)
P. amalago	Leaves	It helps treat chest pain and gastrointestinal issues and effective in alleviating inflammation (Martha et al., 2013)
P. aduncum	Leaves	It is used to treat inflammation and effectiveness against general urinary, throat, and venereal diseases (Orjala et al., 1994)
P. angustifolium	Leaves	It acts as a disinfectant for wounds and sores. (Tirillini et al., 1996)
P. auritum	Leaves	It is used to treat asthma, counteract scorpion stings, reduce fever, alleviate rheumatism and sores, manage gout, act as a diuretic, and address chronic laryngitis (Domínguez & Alcorn, 1985)
P. betle	Leaves	It is used as a mouthwash for swollen gums, bleeding, or bad breath (Depi et al., 2020)
P. caninum	Leaves	It is used to treat throat ache and acts as an antiseptic (Salleh et al., 2011)
P. chaba	Fruits	It is used to treat a variety of conditions, including asthma, fever, bronchitis, and abdominal pain (Prasad et al., 2005)
P. capense	Fruits	It helps with diarrhea and cough (Rojas et al., 2006)
P. divaricatum	Leaves	It is used as an insecticidal against fire ant (Souto et al., 2012)
P. elongatum	Leaves	It is used to treat the symptoms of cutaneous leishmaniasis (Terreaux et al., 1998)
P. guineense	Leaves	It acts as a flavoring agent and is used to treat bronchitis, gastrointestinal diseases, and rheumatism (Colvard et al., 2006)
P. hispidum	Leaves	It acts as a poultice to heal wounds and symptoms of cutaneous leishmaniasis (Terreaux et al., 1998)
P. jaborandi	Leaves	Commonly used as a local anesthetic (Urbina & Docampo, 2003)
P. kadsura	Leaves	Treating arthritic conditions and asthma (Martha et al., 2013)
P. longum	Fruits	It is used for treating bronchitis, coughs, colds, snakebites, and scorpion stings (Biswas et al., 2024).
	Roots	It provides a cooling effect and is used as a stomachic, antidiarrhoeic, and laxative (Biswas et al., 2024)
P. lanatum	Aerial	It is used to treat fever, toothache, influenza, rheumatism, ulcer, malaria and acts as a deworming (Salleh et al., 2014a)
P. lanceaefolium	Fruits	It helps in treating skin infections (Martha et al., 2013)
P. macedoi	Leaves	It is used as an insecticide (Lima et al., 2024)
P. marginatum	Leaves	It is used to treat inflammation, snake bites, liver and bile duct diseases, and toothaches (Ma et al., 2004)
P. mikanianum	Roots	It effectively treats stomach disorders (Soares et al., 2022)
P. methysticum	Fruits	It is used to treat bronchitis, asthma, and fever (Prasad et al., 2005)
P. nigrum	Fruits	It is used to enhance glucose uptake and to treat abdominal tumors (Chaveerach et al., 2006).
	Leaves	It relieves pain, atropic arthritis, influenza, fever, and aids digestion, and treatment for coughs (Bagheri et al., 2014)
P. ovatum	Leaves	Treating inflammation and acts as an analgesic (Silva et al., 2009)
P. piscatorum	Leaves	It is a remedy for toothache and a substitute for tobacco chewing (Holetz et al., 2002)
	Roots	It is used as a poison for fish, a remedy for toothache, and a substitute for chewing tobacco (Holetz et al., 2002)
P. regnellii	Leaves	It helps in treating wounds and reducing swelling and skin irritation (Silva et al., 2009)
P. ribesoides	Stem	It acts as a carminative, tonic element, and antiflatulent (Martha et al., 2013)
P. sarmentosum	Leaves	It treats conditions like fever, cough, rheumatism, diarrhea, toothache, and traumatic injuries (Sun et al., 2020)
	Roots	It is used to treat toothache, headache, asthma, cough, pleurisy, and fungal dermatitis (Chan et al., 2014)
P. sylvaticum	Roots	It is used as an antidote to snake venom (Chahal et al., 2011)
P. tuberculatum	Leaves	It acts as a sedative and is used as an antidote for snake bites (Holetz et al., 2002)
P. tricuspe	Fruits	It is used to treat snake bites and acts as an antimalarial (Pino et al., 2005)
P. umbellatum	Fruits	It is used to treat poisoning, fetal malpresentation, pitting edema, rheumatism, filariasis, hemorrhoids, and dysmenorrhea (Ampofo et al., 1987)
P. wallichii	Stems	It helps in treating influenza, asthma, and flatulence, and acts as a stimulant (Chaveerach et al., 2006)

3. ESSENTIAL OILS COMPOSITION

Essential oils have been used for over 3,000 years, dating back to ancient civilizations like Egypt, China, and India, primarily for medicinal and religious purposes. Their applications evolved through the Renaissance in Europe, leading to the development of aromatherapy by René-Maurice Gattefossé in the early 20th century (Elshafie et al., 2017). In Malaysia, essential oils are deeply rooted in traditional practices, such as "jamu," where oils from native plants like *Pandanus* and *Cinnamomum* are used for therapeutic purposes. These oils, valued for their antimicrobial, anti-inflammatory, and antioxidant properties, have diverse applications in cosmetics, healthcare, food preservation, and aromatherapy (Salleh et al., 2012a). The chemical complexity of essential oils, rich in terpenes and functional groups like alcohols and ketones, underpins their biological effects. Extraction methods, including steam distillation and cold pressing, preserve their therapeutic properties, while analytical techniques like GC-MS ensure precise chemical profiling. The versatility of essential oils across industries reflects their growing demand for natural, eco-friendly solutions (de Sousa et al., 2023).

Table 2 provides an overview of the major components identified in *Piper* species, illustrating their significance in defining the chemical and biological properties of these plants. This data highlights the global diversity and distribution of *Piper* essential oils while also identifying common patterns in their chemical composition. The most common country is Brazil indicating its prominence in the production and study of *Piper* essential oils (da Silva et al., 2016; Carvalho et al., 2022; Genderen et al., 1999). The country's rich biodiversity and favorable climate for *Piper* species cultivation contribute to this status. Other significant contributors include Colombia (Caballero-Gallardo et al., 2014; Colorado et al., 2019), Peru (Ruiz-Vásquez et al., 2022; Genderen et al., 1999), Vietnam (Hieu et al., 2014; Vu et al., 2021), and Ecuador (Guerrini et al., 2009; Gilardoni et al., 2020), emphasizing the tropical and subtropical regions as hotspots for essential oil production. Certain chemical components repeatedly appear as dominant constituents across various *Piper* species and locations.

Essential oils from *Piper* species commonly contain sesquiterpenes like β-caryophyllene (Carmo et al., 2012), germacrene D (Lima et al., 2024), and bicyclogermacrene (Soares et al., 2022), as well as monoterpenes such as α-pinene (Carvalho et al., 2022) and β-pinene (Sales et al., 2018). These compounds not only contribute to their medicinal properties but also play a crucial role in their chemotaxonomic classification. Chemo-types, or chemical variations within a species, further distinguish *Piper* species based on their dominant phytochemical constituents. The sesquiterpene-rich chemo-type, found in species such as *P. nigrum* (Al-Sayed et al., 2021), *P. betle* (Efdi et al., 2023), and *P. aduncum* (Monzote et al., 2017), is characterized by high levels of β-caryophyllene and germacrene D. The monoterpene-rich chemo-type, present in *P. auritum* (Caballero-Gallardo et al., 2014), *P. guineense* (Oyemitan et al., 2015), and *P. hispidum* (Colorado et al., 2019), is marked by significant amounts of α-pinene, β-pinene, and limonene. Another important classification is the phenylpropanoid chemo-type, which includes species like *P. hispidinervum* (Mendonça et al., 2024), *P. marginatum* (Carvalho et al., 2022), and *P. sanctum* that produce safrole, eugenol, and methyl eugenol. **Figure 1** shows the chemical structures of several major components of *Piper* essential oils.

Other frequently reported components include safrole that is found in *P. auritum* (Colombia and Brazil) (Lam- Gutiérrez et al., 2024) and *P. hispidinervum* (Brazil) (Colorado et al., 2019), notable for its use in fragrance and flavor industries. Besides, limonene also identified in oils from Egypt (*P. nigrum*) (Al-Sayed et al., 2021), Vietnam (*P. boehmeriaefolium*) (Hieu et al., 2014), and Peru (*P. soledadense*) (Ruiz-Vásquez et al., 2022), often used for its refreshing citrus aroma and cleaning properties. α-Pinene and β-pinene commonly found in essential oils from Brazil. Among the frequent utilized part for essential oil extraction, aerial parts often yield higher percentages of essential oils. For instance, *P. aduncum* (Brazil) (Monzote et al., 2017) shows a yield of 3.0% from aerial parts, primarily rich in dillapiol. *P. marginatum* (Brazil) (da Silva et al., 2016) yields 0.7% essential oil from aerial parts, with 3,4-methylenedioxypropiophenone as a significant component. In contrast, leaf oils, though widely studied, generally show lower yields, such as 0.58% in *P. hispidum* (Colombia) (Colorado et al., 2019) and 0.6% in *P. arboreum* (Brazil) (Lima et al., 2024). Fruit oils tend to have moderate yields, such as 1.01% in *P. cubeba* (Egypt) (Al-Sayed et al., 2022). This analysis highlights Brazil as a key player in *Piper* essential oil production, with leaves being the most used plant part, despite aerial parts often yielding higher percentages. The frequent occurrence of β-caryophyllene, safrole, and α-pinene derivatives across regions underscores their significance as common constituents, demonstrating the chemical consistency and therapeutic potential of *Piper* essential oils worldwide.

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

Species	**Locality (Parts)**	**Total components (No., %)**	**Yield (%)**	**Major components**
P. auritum	Colombia (Leaf)	3 (97.8)	NM	Safrole (93.2%), myristicin (4.3%) (Caballero-Gallardo et al., 2014)
	Mexico (Leaf)	27 (98.9)	0.26	Safrole (51.4%), γ-terpinene (12.6%), α-terpinolene (9.6%), β-terpinene (5.9%) (Lam- Gutiérrez et al., 2024)
P. betle	Indonesia (Leaf)	46 (81.7)	1.44	β-Phellandrene (8.6%), terpinene-4-ol (7.0%), β-caryophyllene (5.4%), α-humulene (6.3%), caryophyllene oxide (5.5%) (Efdi et al., 2023)
	Vietnam (Leaf)	4 (78.4)	0.25	Eugenol acetate (38.6%), methyl eugenol (30.2%), chavicol acetate (5.7%), chavicol (3.7%) (Vu et al., 2021)
P. acutifolium	Peru (Leaf)	14 (99.9)	0.06	α-Phellandrene (38.1%), β-myrcene (29.4%), β-phellandrene (21.8%) (Cuadros-Siguas et al., 2023)
P. aduncum	Cuba (Leaf)	90 (97.4)	NM	Piperitone (23.7%), camphor (17.1%), viridiflorol (14.5%) (Monzote et al., 2017)
	Brazil (Leaf)	34 (99.9)	NM	Dillapiol (81.0%), (*E*)-β-ocimene (3.4%), germacrene D (2.7%), bicyclogermacrene (2.3%), (*Z*)-β-ocimene (1.6%) (Filho et al., 2023)
	Brazil (Aerial)	47 (97.5)	3.0	Dillapiol (73.0%), germacrene D (2.7%), β-caryophyllene (2.7%) (da Silva et al., 2016)
	Ecuador (Aerial)	45 (95.6)	0.8	Dillapiol (45.9%), (*E*)-β-ocimene (10.3%), piperitone (8.4%), 4-terpineol (3.1%), β-caryophyllene (2.5%) (Guerrini et al., 2009)
	Indonesia (Leaf)	43 (85.2)	1.93	Apiole (33.4%), β-caryophyllene (6.67%), piperitone (3.9%), δ-cadinene (3.6%), caryophyllene oxide (3.4%) (Efdi et al., 2023)
P. arboreum	Brazil (Leaf)	17 (72.7)	0.6	Germacrene D (34.4%), β-caryophyllene (12.3%), valencene (7.0%), α-copaene (6.5%), germacrene B (6.4%), β-pinene (6.0%) (Lima et al., 2024)
	Panama (Leaf)	42 (82.6)	NM	δ-Cadinene (25.8%), α-copaene (7.4%), β-pinene (6.6%), germacrene D (5.3%), (*E*)-nerolidol (5.2%) (Mundina et al., 1998)
P. amalago	Brazil (Leaf)	15 (91.1)	0.07	β-Elemene (17%), germacrene A (15.2%), linalool (15.5%), β-caryophyllene (11.5%) (Vasconcelos et al., 2024)
P. marginatum	Brazil (Leaf)	29 (95.0)	0.6	3,4-Methylenedioxypropiophenone (11.3%), germacrene D (10.8%), elemicin (9.2%), (*E*)-β-ocimene (7.7%%), β-caryophyllene (5.5%) (Carvalho et al., 2022)
	Brazil (Aerial)	58 (89.4)	0.7	3,4-Methylenedioxypropiophenone (21.8%), elemol (5.9%), β-caryophyllene (5.0%), 2-methoxy-4,5-methylenedioxy-propiophenone (4.8%) (da Silva et al., 2016)
P. guineense	Nigeria (Fruit)	44 (90.6)	NM	β-Sesquiphellandrene (20.9%), linalool (6.1%), limonene (5.8%), β-bisabolene (5.4%) (Oyemitan et al., 2015)
	Cameroon (Fruit)	21 (99.9)	0.2	Linalool (41.8%), 3,5-dimethoxytoluene (10.9%), β-pinene (9.2%), α-terpineol (4.1%) (Tankam & Ito, 2013)
P. dilatatum	Brazil (Leaf)	21 (84.2)	1.5	Germacrene D (16.7%), α-alaskene (18.9%), viridiflorol (12.5%) (Silva et al., 2014)
	Brazil (Aerial)	58 (94.4)	1.2	β-Elemene (13.8%), β-pinene (10.5%), spathulenol (9.3%), bicyclogermacrene (7.9%), δ-elemene (7.6%) (Andrade et al., 2011)

Species	Locality (Parts)	Total components (No., %)	Yield (%)	Major components
P. anonifolium	Brazil (Aerial)	87 (89.2)	0.6	Selin-11-en-4-α-ol (20.0%), β-selinene (12.7%), α-selinene (11.9%), α-pinene (8.8%) (Silva et al., 2014)
P. multiplinervium	Colombia (Leaf)	6 (28.3)	NM	β-Elemene (9.0%), β-caryophyllene (5.3%) (Caballero-Gallardo et al., 2014)
P. hispidum	Colombia (Leaf)	80 (87.8)	0.58	δ-3-Carene (9.6%), *p*-cymene (10.9%), limonene (17.2%), elemol (14.1%), γ-elemene (7.3%), β-eudesmol (5.7%) (Colorado et al., 2019)
	Cuba (Leaf)	78 (91.2)	0.17	α-Bisabolene (11.2%), β-pinene (8.2%), α-pinene (4.7%), *allo*-aromadendrene (4.9%) (Pérez et al., 2014)
	Brazil (Aerial)	87 (88.4)	1.0	β-Caryophyllene (10.5%), α-humulene (9.5%), δ-3-carene (9.1%), α-copaene (7.3%), limonene (6.9%) (Silva et al., 2014)
P. rivinoides	Brazil (Leaf)	11 (99.9)	0.14	α-Pinene (53.0%), β-pinene (18.1%), limonene (12.9%), bicyclogermacrene (6.3%) (Machado et al., 2022)
P. tuberculatum	Brazil (Leaf)	13 (96.6)	NM	β-Caryophyllene (26.3%), α-cadinol (13.7%), (*E*)-β-ocimene (9.0%), α-pinene (8.4%) (Facundo et al., 2005)
P. tuberculatum	Peru (Aerial)	16 (89.3)	0.13	β-Bisabolene (40.2%), δ-cadinene (9.8%), β-caryophyllene (9.7%), germacrene D (5.0%), (*E*)-nerolidol (4.5%) (Ruiz-Vásquez et al., 2022)
	Brazil (Fruit)	15 (98.9)	0.34	β-Pinene (27.7%), α-pinene (26.5%), β-caryophyllene (14.3%), (*E*)-β-ocimene (12.4%) (Sales et al., 2018)
P. cernuum	Brazil (Leaf)	35 (99.8)	NM	α-Pinene (16.6%), β-pinene (11.5%), bicyclogermacrene (10.7%), *p*-cymene (9.2%) (Filho et al., 2023)
P. sanctifelicis	Colombia (Leaf)	7 (86.7)	0.32	δ-3-Carene (35.3%), limonene (27.1%), β-pinene (6.9%), (*E*)-nerolidol (5.8%) (Colorado et al., 2015)
P. gorgonillense	Colombia (Leaf)	40 (99.9)	0.14	β-Caryophyllene (28.7%), α-copaene (13.5%), δ-cadinene (7.3%) (Colorado et al., 2020)
P. callosum	Brazil (Aerial)	36 (98.7)	2.3	Safrole (66.0%), methyl eugenol (10.2%), elemicin (3.7%) (da Silva et al., 2016)
	Brazil (Leaf)	27 (97.5)	0.26	α-Pinene (19.2%), β-pinene (14.3%), methyl eugenol (6.5%) (Carvalho et al., 2022)
	Peru (Leaf)	25 (96.3)	0.35	Asaricin (35.9%), safrole (20.2%), methyl eugenol (9.7%), α-asarone (7,8%) (Genderen et al., 1999)
P. lindbergii	Brazil (Leaf)	44 (99.5)	NM	α-Pinene (61.7%), α-copaene (6.4%), limonene (5.3%), caryophyllene oxide (3.4%) (Filho et al., 2023)
P. trioicum	India (Leaf)	45 (96.7)	0.28	δ-Cadinene (19.5%), germacrene D (8.5%), β-caryophyllene (6.8%), epicubenol (4.8%), α-pinene (4.5%) (Jena et al., 2023)
P. permucronatum	Brazil (Leaf)	33 (69.5)	0.23	δ-Cadinene (12.7%), γ-muurolene (7.4%), α-cadinol (6.9%), β-caryophyllene (6.8%), t-muurolol (3.2%) (Torquilho et al., 1999)
P. retrofractum	Vietnam (Leaf)	60 (92.0)	0.2	Benzyl benzoate (14.4%), β-myrcene (14.4%), bicycloelemene (9.9%), bicyclogermacrene (7.0%), β-caryophyllene (5.3%) (Hieu et al., 2014)
P. boehmeriaefolium	Vietnam (Leaves)	50 (92.2)	0.2	α-Copaene (28.3%), α-pinene (7.4%), 1,8-cineole (5.7%), limonene (4.4%) (Hieu et al., 2014)
P. sarmentosum	Vietnam (Aerial)	19 (98.4)	0.25	Benzyl benzoate (49.1%), benzyl alcohol (17.9%), 2-hydroxybenzoic acid phenyl-methyl ester (10.0%), 2-butenyl-benzene (7.9%) (Hieu et al., 2014)
P. maclueri	Vietnam (Leaf)	40 (97.1)	0.25	(*E*)-Cinnamic acid (37.4%), (*E*)-nerolidol (19.4%), bicyclogermacrene (3.4%) (Hieu et al., 2014)
	Vietnam (Stem)	21 (98.4)	0.20	(*Z*)-9-Octadecanoic acid methyl ester (28.0%), (*E*)-cinnamyl acetate (17.2%), phytol (12.2%), (*E*)-cinnamaldehyde (8.8%) (Hieu et al., 2014)
P. duckei	Brazil (Leaf)	25 (90.1)	0.5	β-Caryophyllene (27.1%), γ-eudesmol (17.9%) germacrene D (14.7%), 1,8-cineole (5.8%), bicyclogermacrene (5.2%) (Carmo et al., 2012)
P. demeraranum	Brazil (Leaf)	25 (92.9)	0.6	β-Elemene (33.1%), limonene (19.3%), bicyclogermacrene (8.8%), germacrene D (5.2%) (Carmo et al., 2012)
P. brachypetiolatum	Brazil (Leaf)	28 (99.4)	0.06	(*E*)-Nerolidol (44.2%), caryophyllene oxide (10.0%), α-cadinol (8.9%) (Araujo et al., 2021)
P. cubataonum	Brazil (Leaf)	57 (96.8)	1.96	Dillapiol (65.3%), apiole (24.1%) (Santos et al., 2014)
	Brazil (Branch)	66 (98.5)	0.44	Dillapiol (66.0%), apiole (23.2%), *n*-pentadecane (5.3%) (Santos et al., 2014)
P. mikanianum	Brazil (Leaf)	26 (99.8)	0.1	Bicyclogermacrene (26.3%), β-myrcene (17.2%), β-caryophyllene (9.5%), limonene (6.6%), germacrene D (6.6%) (Soares et al., 2022)
P. gaudichaudianum	Brazil (Leaf)	26 (97.4)	0.1	β-Selinene (14.0%), viridiflorene (10.5%), caryophyllene oxide (9.3%), (*E*)-nerolidol (9.0%), humulene epoxide II (6.8%) (Soares et al., 2022)
P. mollipilosum	Brazil (Leaf)	39 (93.7)	0.02	β-Selinene (32.4%), spathulenol (8.2%), selin-11-en-4-α-ol (6.8%), 14-hydroxycaryophyllene (5.0%) (Araujo et al., 2021)
P. glandulosissimum	Brazil (Leaf)	25 (91.2)	0.11	β-Caryophyllene (19.1%), α-selinene (8.3%), germacrene D (7.5%), α-humulene (7.1%) (Araujo et al., 2021)
P. madeiranum	Brazil (Leaf)	21 (90.6)	0.05	Caryophyllene oxide (16.9%), selin-11-en-4-α-ol (9.2%), α-copaene (9.1%), β-selinene (8.7%) (Araujo et al., 2021)
P. nigrum	Egypt (Fruit)	19 (99.9)	0.905	Limonene (35.6%), δ-3-carene (17.5%), β-pinene (15.8%), β-caryophyllene (9.4%), α-pinene (6.6%) (Al-Sayed et al., 2021)
P. ramipilum	Indonesia (Leaf)	42 (94.9)	1.11	β-Phellandrene (7.7%), β-caryophyllene (14.7%), caryophyllene oxide (5.3%), α-pinene (6.0%), linalool (9.4%), β-selinene (6.6%) (Efdi et al., 2023)
P. coruscans	Peru (Aerial)	26 (89.9)	0.47	β-Bisabolene (33.4%), (*E*)-nerolidol (10.2%), β-caryophyllene (8.0%), β-selinene (4.9%), α-bisabolol (Ruiz-Vasquez et al., 2022)
	Ecuador (Leaf)	52 (91.3)	0.26	β-Caryophyllene (24.1%), α-humulene (11.6%), caryophyllene oxide (10.9%), linalool (5.2%) (Gilardoni et al., 2020)
P. casapiense	Peru (Aerial)	18 (81.3)	0.13	Caryophyllene oxide (10.2%), β-caryophyllene (4.7%), humulene epoxide (3.8%), guaiol (2.9%), α-humulene (2.5%) (Ruiz-Vasquez et al., 2022)
P. obliquum	Peru (Aerial)	31 (90.6)	0.13	Bicyclogermacrene (7.9%), elemol (7.3%), β-caryophyllene (6.3%), α-pinene (6.0%), β-pinene (5.1%) (Ruiz-Vásquez et al., 2022)
	Ecuador (Aerial)	33 (99.2)	0.16	Safrole (45.8%), γ-terpinene (17.1%), α-terpinolene (11.4%), α-terpinene (6.2%) (Guerrini et al., 2009)
	Panama (Leaf)	31 (81.3)	NM	β-Caryophyllene (27.6%), spathulenol (10.6%), caryophyllene oxide (8.3%) (Mundina et al., 1998)
P. reticulatum	Peru (Aerial)	24 (80.0)	1.26	Germacrene D (12.6%), bicyclogermacrene (8.1%), δ-cadinene (6.0%), α-copaene (4.6%) (Ruiz-Vásquez et al., 2022)
P. soledadense	Peru (Aerial)	18 (89.9)	0.54	Limonene (38.5%), apiole (15.0%), caryophyllene oxide (8.4%), eudesma-3,7-(11)-diene (5.8%) (Ruiz-Vásquez et al., 2022)
P. aleyreanum	Brazil (Aerial)	87 (89.9)	0.8	β-Elemene (16.3%), bicyclogermacrene (9.2%), δ-elemene (8.2%), germacrene D (6.9%), β-caryophyllene (6.2%), spathulenol (5.2%) (Silva et al., 2014)
P. sanctifelicis	Peru (Aerial)	14 (91.2)	0.88	Apiole (76.1%), β-caryophyllene (4.1%) (Ruiz-Vasquez et al., 2022)
P. mituense	Peru (Aerial)	23 (94.5)	0.11	Apiole (51.6%), bicyclogermacrene (9.0%), germacrene D (6.7%), myristicin (4.6%), (Ruiz-Vasquez et al., 2022)
P. divaricatum	Colombia (Leaf)	11 (99.9)	NM	Eugenol (37.5%), methyl eugenol (36.3%), γ-elemene (10.7%), α-asarone (4.6%) (Colorado et al., 2015)
	Brazil (Leaf)	14 (67.4)	0.99	Valencene (11.1%), γ-cadinene (11.0%), germacrene D (9.4%) (Silva et al., 2014)
P. mollicomum	Brazil (Leaf)	63 (98.3)	0.86	1,8-cineole (34.1%), α-pinene (15.2%), β-pinene (12.1%), linalool (7.3%) (Ramos et al., 2022)
P. cubeba	Egypt (Fruit)	22 (99.9)	1.01	Methyl eugenol (47.4%), β-myrcene (21.1%), eugenol (10.6%), 1,8-cineole (6.4%) (Al-Sayed et al., 2022)
	Saudi Arabia (Fruit)	24 (98.1)	1.0	Methyl eugenol (41.3%), eugenol (33.9%), (*E*)-β-caryophyllene (5.6%) (Alminderej et al., 2020)
P. longum	Egypt	38	0.285	*n*-Heptadecane (11.9%), β-caryophyllene (11.8%), heptadecene (11.0%), α-humulene (6.2%), γ-himachalene (5.0%) (Al-

Species	Locality (Parts)	Total components (No., %)	Yield (%)	Major components
	(Fruit)	(99.0)		Sayed et al., 2022)
P. macedoi	Brazil (Leaf)	15 (73.5)	1.56	Piperitone (21.9%), bicyclogermacrene (14.1%), sylvan (11.2%), germacrene D (10.4%), linalool (9.6%) (Lima et al., 2024)
P. anisum	Brazil (Leaf)	33 (97.5)	0.09	1-Butyl-3,4-methylenedioxy-benzene (58.3%), α-phellandrene (7.5%), α-terpinene (8.3%) (Moreira & Pereira, 2021)
P. diospyrifolium	Brazil (Leaf)	47 (95.4)	0.02	β-Elemene (9.5%), *β*-caryophyllene (7.6%), germacrene D (9.7%), (*E*)-nerolidol (9.0%) (Moreira & Pereira, 2021)
P. lepturum	Brazil (Leaf)	29 (96.1)	0.56	β-Caryophyllene (22.4%), bicyclogermacrene (17.6%), γ-bisabolene (17.3%), α-zingiberene (7.3%) bicycloelemene (6.9%) (Moreira & Pereira, 2021)
P. vicosanum	Brazil (Leaf)	17 (99.9)	0.03	α-Eudesmol (17.3%), α-copaene (12.3%), β-selinene (8.9%), β-caryophyllene (7.6%), β-bisabolene (6.8%) (Moreira & Pereira, 2021)
P. ecuadorense	Ecuador	44 (98.6)	0.23	Bicyclogermacrene (12.9%), 3-thujopsanone (11.5%), α-phellandrene (6.8%), (*E*)-nerolidol (6.8%), δ-elemene (6.8%), shyobunol (5.7%) (Valarezo et al., 2021)
P. amplum	Brazil (Leaf)	27 (96.6)	0.06	Germacrene D (9.7%), (*E*)-nerolidol (10.0%), β-caryophyllene (7.6%), β-elemene (9.5%), α-bergamotene (5.5%) (Moreira & Pereira, 2021)
P. dumosum	Peru (Aerial)	29 (89.2)	0.078	Bicyclogermacrene (16.5%), germacrene D (10.4%), apiole (8.9%), β-caryophyllene (6.8%), β-pinene (6.3%) (Ruiz-Vasquez et al., 2022)
P. fimbriulatum	Panama (Leaf)	52 (79.8)	NM	Germacrene D (12.8%), β-caryophyllene (11.3%), linalool (5.3%), linalyl acetate (5.3%) (Mundina et al., 1998)
P. crassinervium	Brazil (Leaf)	23 (79.6)	NM	7-*epi*-α-Eudesmol (11.1%), β-selinene (10.4%), β-caryophyllene (8.4%), α-amorphene (5.9%), germacrene B (5.2%) (de Souza et al., 2020)
P. hispidinervum	Brazil (Leaf)	63 (98.8)	2.61	Safrole (98.8%) (Mendonça et al., 2024)
	Brazil (Aerial)	27 (98.6)	0.95	Safrole (85.0%), α-terpinolene (5.4%) (Sauter et al., 2012)
P. glabratum	Brazil (Leaf)	67 (99.9)	0.37	β-Pinene (12.7%), longiborneol (12.0%), α-pinene (9.6%), β-caryophyllene (7.9%), viridiflorene (7.3%) (Branquinho et al., 2017)
P. corcovadense	Brazil (Root)	38 (86.3)	NM	*trans*-Sesquisabinene hydrate (24.9%), β-caryophyllene (10.7%), β-pinene (5.6%), β-farnesene (5.2%) (Fontoura et al., 2024)

NM – not mentioned

Table 3: Major components identified from several Malaysian *Piper* essential oils

Species	Locality (Parts)	Total components (No., %)	Yield (%)	Major components
P. betle	N.Sembilan (Leaf)	38 (94.1)	0.14	Eugenol (18.9%), germacrene D (11.6%), chavibetol acetate (9.3%), β-caryophyllene (7.4%), bicyclogermacrene (7.3%) (Ahmad et al., 2024)
P. ornatum	Johor (Leaf)	27 (79.6)	0.35	Caryophyllene oxide (31.5%), spathulenol (5.9%), alloaromadendrene (4.9%), β-caryophyllene epoxide (4.5%) (Azman et al., 2024)
P. baccatum	Perak (Leaf)	14 (98.1)	0.18	β-Caryophyllene (30.7%), camphene (22.1%), eucalyptol (14.9%), γ-muurolene (6.9%) α-pinene (5.3%) (Salihu et al., 2024)
P. aduncum	Selangor (Leaf)	30 (86.4)	1.30	Dillapiol (64.5%), (*E*)-α-ocimene (2.3%), β-caryophyllene (5.1%), α-humulene (4.6%), β-selinene (5.2%) (Jantan et al., 1994)
P. caninum	Perak (Leaf)	36 (77.9)	0.46	Safrole (17.1%), β-pinene (8.9%), linalool (7.0%), β-caryophyllene (6.7%) (Salleh et al., 2011)
	Perak (Stem)	37 (87.0)	0.31	Safrole (25.5%), β-caryophyllene (9.8%), germacrene D (7.8%), β-pinene (4.9%) (Salleh et al., 2011)
P. crassipes	Perak (Leaf)	22 (97.8)	0.15	Chavibetol (59.8%), chavibetol acetate (10.4%), γ-muurolene (5.4%), germacrene D (4.6%) (Rezod et al., 2024)
P. abbreviatum	Sarawak (Aerial)	33 (70.5)	0.22	Spathulenol (11.2%), (*E*)-nerolidol (8.5%), β-caryophyllene (7.8%) (Salleh et al., 2014a)
P. erecticaule	Sarawak (Aerial)	35 (63.4)	0.18	β-Caryophyllene (5.7%), spathulenol (5.1%), β-cadinene (3.8%), α-amorphene (3.8%) (Salleh et al., 2014a)
P. lanatum	Sarawak (Aerial)	39 (78.2)	0.25	Chavibetol (42.7%), borneol (7.5%), caryophyllene oxide (6.6%), α-amorphene (5.6%) (Salleh at al., 2014a)
	Selangor (Leaf)	32 (90.4)	1.34	Chavibetol (42.7%), β-caryophyllene (6.8%), α-cadinene (6.6%), α-muurolene (6.2%) (Jantan et al., 1994)
P. arborescens	Sarawak (Leaf)	36 (97.5)	0.24	β-Phellandrene (24.3%), sabinene (16.3%), α-pinene (10.4%), 4-terpineol (7.2%) (Salleh et al., 2016)
	Sarawak (Stem)	46 (90.5)	0.16	β-Phellandrene (20.4%), methyl eugenol (11.0%), β-caryophyllene (9.0%) (Salleh et al., 2016)
P. sarmentosum	Sarawak (Leaf)	31 (96.2)	1.10	Spathulenol (20.9%), myristicin (18.7%), β-caryophyllene (18.1%), (*E,E*)-farnesol (10.5%) (Chieng et al., 2008)
P. nigrum	Sarawak (Seed)	40 (99.87)	2.16	β-Caryophyllene (24.3%), limonene (15.8%), sabinene (15.0%), δ-3-carene (9.4%), β-pinene (9.2%), α-copaene (4.5%) (Bagheri et al., 2014)
	Sarawak (Fruit)	35 (89.86)	1.00	α-Terpinene (22.2%), (*Z*)-β-ocimene (13.7%), β-farnesene (10.5%), isolimonene (8.1%), β-pinene (7.5%) (Rezvanian et al., 2016)
P. officinarum	Sarawak (Leaf)	41 (85.6)	0.26	β-Caryophyllene (11.2%), α-pinene (9.3%), sabinene (7.6%), β-selinene (5.3%), limonene (4.6%) (Salleh et al., 2012a)
	Sarawak (Stem)	41 (93.0)	0.22	β-Caryophyllene (11.2%) α-phellandrene (9.3%), linalool (6.9%) limonene (6.7%), α-pinene (5.0%) (Salleh et al., 2012a)
P. maingayi	Perak (Fruit)	18 (78.7)	1.17	δ-Cadinene (22.4%), β-Caryophyllene (18.8%), δ-copaene (11.2%) (Hashim et al., 2016)
	Perak (Stem)	34 (83.6)	0.09	β-caryophyllene (26.2%), α-cedrene (8.4%), calamenene (6.2%), δ-cadinene (5.2%) (Hashim et al., 2016)
P. magnibaccum	Perak (Leaf)	25 (93.5)	0.20	Germacrene D (40.8%), β-caryophyllene (8.5%), α-cadinol (6.1%), elemicin (5.5%) (Hashim et al., 2017)
	Perak (Stem)	33 (87.6)	0.09	β-Caryophyllene (19.7%), germacrene D (10.7%), α-cadinol (8.2%), γ-cadinene (6.4%) (Hashim et al., 2017)
P. penicellosum	Selangor (Leaf)	39 (96.1)	1.11	Eugenol (17.2%), β-phellandrene (21.9%), β-caryophyllene (7.5%), 4-terpineol (4.1%) (Jantan et al., 1994)
P. porphyrophyllum	Sarawak (Leaf)	34 (97.3)	0.20	Bicyclogermacrene (14.7%), α-copaene (13.2%), β-phellandrene (9.5%), β-caryophyllene (6.4%), α-cadinol (6.1%) (Salleh et al., 2012b)
	Sarawak (Stem)	38 (95.5)	0.18	Sabinene (15.5%), bicyclogermacrene (12.3%), α-copaene (8.1%), α-pinene (7.8%), β-caryophyllene (7.1%) (Salleh et al., 2012b)
P. miniatum	Selangor (Leaf)	64 (89.2)	0.45	Caryophyllene oxide (20.3%), α-cubebene (10.4%), β-caryophyllene (8.5%), α-muurolene (5.8%) (Salleh et al., 2015)
P. muricatum	Terengganu (Aerial)	40 (90.8)	0.46	Alloaromadendrene (16.2%), β-caryophyllene (8.8%), germacrene D (7.9%) (Salleh et al., 2014b)
P. stylosum	Terengganu (Leaf)	50 (89.2)	NM	Alloaromadendrene (26.6%), sabinene (13.8%), β-caryophyllene (11.5%) (Salleh et al., 2014c)
	Terengganu (Stem)	45 (88.8)	NM	Alloaromadendrene (18.8%), β-caryophyllene (17.9%), sabinene (6.7%) (Salleh et al., 2014c)
P. ribesioides	Terengganu (Leaf)	60 (87.0)	NM	β-Caryophyllene (20.0%), camphene (16.3%), α-pinene (4.4%) (Salleh et al., 2014c)
	Terengganu (Stem)	39 (82.9)	NM	β-Caryophyllene (14.4%), camphene (12.3%), δ-cadinene (7.8%) (Salleh et al., 2014c)
P. penangense	Selangor (Leaf)	33 (93.5)	0.23	(*E*)-Nerolidol (17.5%), cedrol (14.8%), β-eudesmol (8.1%), palustrol (8.0%), δ-elemene (7.4%) (Jantan et al., 1994)
	Kedah (Leaf)	12 (84.5)	0.12	Humulene epoxide II (31.9%), caryophyllene oxide (9.9%), muurola-4,10(14)-dien-1β-ol (9.1%), β-ionone (8.3%) (Salleh et al., 2024)

On the other hand, this study provides a detailed account of the major components of essential oils extracted from *Piper* species specifically found in Malaysia. These species are known for their unique chemical profiles, which can vary depending on the geographical location and environmental conditions of the regions within Malaysia (Salleh et al., 2016). **Table 3** summarizes the major components of essential oils derived from various *Piper* species found across Malaysia. The data highlights the diversity of chemical compositions, regional variations, and plant parts used for oil extraction. Sarawak emerges as the most common state for *Piper* essential oil production in Malaysia, with numerous species. *P. arborescens* (Salleh et al., 2016), *P. porphyrophyllum* (Salleh et al., 2012b), *P. sarmentosum* (Chieng et al., 2008), and *P. officinarum* (Salleh et al., 2012a), identified in the region. This prevalence is likely due to Sarawak's tropical climate and rich biodiversity, which create ideal conditions for the growth of *Piper* species. Selangor and Perak also feature prominently, with significant contributions to the study of local *Piper* species and their chemical compositions.

β-Caryophyllene stands out as a common component across multiple *Piper* species and regions in Malaysia. Found in essential oils from Sarawak (*P. sarmentosum*) (Chieng et al., 2008), Selangor (*P. penangense*) (Jantan et al., 1994), and Perak (*P. magnibaccum*) (Hashim et al., 2017), this compound is known for its anti-inflammatory, antimicrobial, and analgesic properties. Other frequently identified components include spathulenol found in *P. lanatum* (Sarawak) and *P. abbreviatum* (Sarawak), often noted for its anti-inflammatory and antimicrobial effects (Salleh at al., 2014a). Germacrene D present in *P. betle* (Negeri Sembilan) (Ahmad et al., 2024) and *P. magnibaccum* (Perak) (Hashim et al., 2017), valued for its aromatic and therapeutic properties. Safrole a significant component in *P. caninum* (Perak), known for its use in fragrances and flavoring (Salleh et al., 2011). The table reveals that the leaves are the most used plant part for essential oil extraction in Malaysia, yielding moderate percentages of oil. For example, *P. sarmentosum* from Sarawak (Chieng et al., 2008) yields 1.10% essential oil from its leaves. For *P. penicellosum* (Jantan et al., 1994) from Selangor produces 1.11% from its leaves. Besides, stems and aerial parts are also utilized but generally yield lower percentages of essential oils. For instance, the stem of *P. arborescens* from Sarawak (Salleh et al., 2016) yields 0.16% essential oil. The aerial parts of *P. abbreviatum* from Sarawak yield 0.22% (Salleh et al., 2014a).

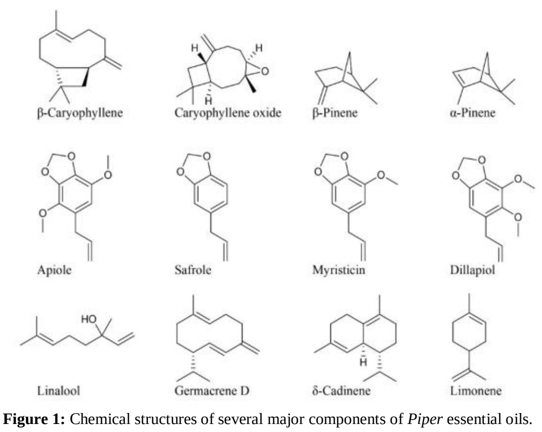

Figure 1: Chemical structures of several major components of *Piper* essential oils.

4. PHARMACOLOGICAL STUDIES OF *Piper* ESSENTIAL OIL

The bioactivity of essential oils, particularly from various *Piper* species, underscores their remarkable versatility and potential across a range of applications, including healthcare, cosmetics, and agriculture. These oils have consistently demonstrated powerful antioxidant, antimicrobial, cytotoxic, and insecticidal properties, making them effective tools in addressing some of the most pressing global challenges. What sets these essential oils apart is their natural origin and broad-spectrum effectiveness, positioning them as safer, more environmentally friendly, and sustainable alternatives to synthetic chemicals (Chouhan et al., 2017). Unlike synthetic counterparts, which often pose risks of toxicity and environmental harm, essential oils from *Piper* species align with the growing demand for green and sustainable solutions. Their multi-target action enhances their effectiveness across diverse applications, reducing the need for multiple chemical agents. Strong evidence, supported by detailed bioactivity metrics, highlights the significant potential of these oils for future research and innovation (Ferraz et al., 2022). They represent a promising avenue not only for therapeutic and industrial advancements but also for addressing environmental and public health concerns. As research continues to uncover their mechanisms and broader applications, *Piper* essential oils are paving the way for sustainable and effective natural solutions that align with global needs for safer, eco-conscious innovations (Salleh et al., 2016). **Table 4** shows biological activities of several *Piper* essential oils.

The table categorizes these activities into antioxidant, anti-tyrosinase, cytotoxicity, antibacterial, antifungal, insecticidal, antileishmanial, antiparasitic, anticholinesterase, and toxicological effects. The antioxidant properties of these oils are particularly notable, as evidenced by their effectiveness in DPPH, ABTS, and FRAP assays. For instance, *P. longum* demonstrates substantial radical scavenging ability with IC_{50} values as low as 0.97 µg/mL, suggesting its potential in oxidative stress mitigation (Biswas et al., 2024). Other species, like *P. chaba and P. auritum,* also exhibit significant activity, albeit with varying potency (Rahman et al., 2024).

Anti-tyrosinase activity is another critical focus, particularly for its applications in treating hyperpigmentation disorders. Species like *P. maingayi* and *P. magnibaccum* have shown promising tyrosinase inhibition percentages of 65.5% and 57.0%, respectively (Hashim et al., 2016). Similarly, their cytotoxic effects against various cancer cell lines, such as the 95.4% inhibition of MCF-7 breast adenocarcinoma cells by *P. imperiale* position these oils as promising candidates for developing anticancer therapies (Setzer et al., 2008).

The antibacterial and antifungal properties extend their utility to combating microbial infections. For instance, *P. longum* exhibits a MIC value of 1.95 µg/mL against *Helicobacter pylori*, showcasing its potential in managing gastric ulcers (Al-Sayed et al., 2021). Similarly, *P. diospyrifolium's* antifungal activity, with MIC values against *Candida* species as low as 8.3 µg/mL, emphasizes its role in antifungal treatments (Bernuci et al., 2016). These findings highlight the essential oils' broad-spectrum antimicrobial activities, addressing critical needs in medicine and food safety.

Piper essential oils also exhibit potent insecticidal and larvicidal properties, such as *P. marginatum's* effectiveness against *Aedes aegypti* larvae with LC_{50} value of 19.9 µg/mL (Torquilho et al., 1999). Such activities indicate their potential as eco-friendly alternatives to synthetic pesticides. Additionally, anti-leishmanial and anti-parasitic activities, like the IC_{50} value of 3.4 µg/mL exhibited by *P. hispidum* against *Leishmania amazonensis*, open avenues for treating neglected tropical diseases (Houël et al., 2016).

The diverse bioactivities of *Piper* essential oils highlight their immense potential to address various challenges across healthcare, cosmetics, and agriculture. With demonstrated antioxidant, antimicrobial, cytotoxic, anti-tyrosinase, and insecticidal properties, these oils offer promising natural solutions for pressing global issues. It has shown significant efficacy in their respective domains, supporting their use in developing new therapies, eco-friendly pesticides, and cosmetic formulations (Sharifi-Rad et al., 2017). These evidence-backed bioactivities not only reflect the therapeutic value of these oils but also their environmental and economic benefits.

Table 4: Biological activities of several *Piper* essential oils

Bioactivity	Essential oils	Description
Antioxidant	*P. longum*	The essential oil exhibited moderate radical scavenging activity against DPPH and ABTS, with IC_{50} values of 0.97 and 0.78 μg/mL, respectively (Biswas et al., 2024)
	P. chaba	The leaf oil exhibited DPPH radical scavenging activity with IC_{50} value of 17.03 mg/mL (Rahman et al., 2024)
	P. auritum	The essential oil exhibited ABTS assay with EC_{50} value ranging from 3.02 to 4.86 g/mL (Luján -Hidalgo et al., 2017)
	P. nigrum	The essential oil exhibited DPH free radical scavenging against DPPH with IC_{50} value of 22.8 mg/mL (Abukawsar et al., 2018)
	P. boehmeriifolium	The essential oil exhibited ABTS assay with IC_{50} value of 7.36 μg/mL (Wang et al., 2020)
	P. umbellatum	The essential oil exhibited DPPH radical scavenging assay with IC_{50} value of 32.3 μg/mL (Rodriguez et al.,2013)
	P. corcovadense	The essential oil exhibited FC, DPPH and ABTS with value of 5.4 mg GAE/mL, 2.8 and 6.2 μmol TE/mL respectively (Fontoura et al., 2024)
	P. ecuadorense	The essential oil gave IC_{50} value of 1.81 mg/mL in ABTS assay (Valarezo et al., 2021)
	P. acutifolium	The essential oil gave IC_{50} values of 160.1, 138.1 and 450.1 μg/mL in DPPH, ABTS and FRAP assay, respectively (Cuadros-Siguas et al., 2023)
	P. madeiranum	The essential oil gave EC_{50} values of 66.8 and 242.6 μg/mL in DPPH and ABTS assay, respectively (Araujo et al., 2021)
	P. mollipilosum	The essential oil gave EC_{50} values of 79.0 and 280.5 μg/mL in DPPH and ABTS assay, respectively (Araujo et al., 2021)
	P. glabratum	The essential oil gave IC_{50} value of 17.98 μg/mL in DPPH assay (Santos et al., 2019)
	P. maingayi	The essential oil gave IC_{50} values of 14.9 and 12.6 μg/mL in DPPH and ABTS assay, respectively (Hashim et al., 2016)
	P. miniatum	The essential oil gave IC_{50} value of 240.5 μg/mL in DPPH assay (Salleh et al., 2015)
	P. stylosum	The essential oil gave IC_{50} value of 623.2 μg/mL in DPPH assay (Salleh et al., 2014c)
	P. ribesioides	The essential oil gave IC_{50} value of 692.4 μg/mL in DPPH assay (Salleh et al., 2014c)
	P. brachypetiolatum	The essential gave EC_{50} values of 64.8 and 159.7 μg/mL in DPPH and ABTS assay, respectively (Araujo et al., 2021)
	P. gladulosissimum	The essential oil gave EC_{50} values of 104.4 and 200.9 μg/mL in DPPH and ABTS assay, respectively (Araujo et al., 2021)
	P. magnibaccum	The essential oil gave IC_{50} values of 20.5 and 11.7 μg/mL in DPPH and ABTS assay, respectively (Hashim et al., 2017)
Anti-tyrosinase	*P. maingayi*	The essential oil demonstrated 65.5% tyrosinase inhibition activity, as assessed using the modified dopachrome method (Hashim et al., 2016)
	P. magnibaccum	The essential oil demonstrated 57.0% tyrosinase inhibition activity, as assessed using the modified dopachrome method (Hashim et al., 2017)
	P. ribesioides	The essential oil demonstrated 30.0% tyrosinase inhibition activity, as assessed using the modified dopachrome method (Salleh et al., 2014)
Cytotoxicity	*P. arborescens*	The essential oil gave LC_{50} value of 57.9 μg/mL against *Artemia salina* (Daniel et al., 2019)
	P. caninum	The essential oil gave LC_{50} value of 249.7 μg/mL against *Artemia salina* (Daniel et al., 2019)
	P. aequale	The essential oil gave IC_{50} value of 8.69 μg/mL against HCT-116 human colorectal carcinoma cells (da Silva et al., 2016)
	P. aleyreanum	The essential oil gave IC_{50} value of 7.40 μg/mL against SKMel19 human melanoma cells (da Silva et al., 2014)
	P. longum	The essential oil gave IC_{50} value of 5.27 μg/mL against HeLa cells (Yadav et al., 2019)
	P. regnellii	The essential oil gave IC_{50} values from 11.0 to 17.0 μg/mL against HeLa cells (Anderson et al., 2018)
	P. klotzschianum	The essential oil gave IC_{50} value of 27.3 μg/mL against HepG2 cells (Lima et al., 2019)
	P. rivinoides	The essential oil gave IC_{50} value of 59.0 μg/mL against oral squamous cell carcinoma and non-tumoral gingival fibroblasts (Machado et al., 2022)
	P. trioicum	The essential oil gave IC_{50} value of 33.1 μg/mL against HT-29 cells (Jena et al., 2023)
	P lindbergii	The essential oil gave CC_{50} value of 41.3 μg/mL against taxoplasmosis (Filho et al., 2023)
	P. imperiale	The essential oil showed 95.4% inhibition against MCF-7 human breast adenocarcinoma cells (Setzer et al., 2008)
Antibacterial	*P. eriopodon*	The essential oil MIC value of 16.0 μg inhibits the growth of *S. aureus*, *E. coli*, and *L. monocytogenes* (Acevedo et al., 2023).
	P. corcovadense	The essential oil gave MIC value ranging from 10.0 to 0.16 μg/mL against *B. subtilis*, *E. coli*, *L. monocytogenes* and *S. typhimurium* (Fontoura et al., 2024)
	P. cubeba	The essential oil gave MIC value of 7.81 μg/mL against *Helicobacter pylori* (Al-Sayed et al., 2021)
	P. longum	The essential oil gave MIC value of 1.95 μg/mL against *Helicobacter pylori* (Al-Sayed et al., 2021)
	P. diospyrifolium	The essential oil gave MIC value of 125 μg/mL against *Mycobacterium tuberculosis* $H_{37}Rv$ bacillus, with a by REMA plate method (Bernuci et al., 2016)
	P. abutiloides	The essential oil gave MIC value of 700.0 μg/mL against *E. coli* (Duarte et al., 2007)
	P. boehmeriifolium	The essential oil gave MIC values ranging from 0.07-1.25 mg/mL against *B. subtilis*, *S. aureus*, *E. coli* and *P. aeruginosa* (Wang et al., 2020)
	P. corcovadense	The essential oil gave MIC and MBC values of 10.4 μg/mL against *B. subtilis*, *L. monocytogenes*, and *S. typhimurium* (Fontoura et al., 2024)
	P. betle	The essential oil gave MIC value of 64.0 μg/mL strongly controlled the growth of *Clostridium sporogenes* NCTC 12935 (Dai et al., 2023)
	P. rivinoides	The essential oil gave MIC value of 125 μg/mL against *Mycobacterium tuberculosis* $H_{37}Rv$ bacillus (Bernuci et al., 2016)
	P. cernuum	The essential oil gave MIC value of 125 μg/mL against *Mycobacterium tuberculosis* $H_{37}Rv$ bacillus (Bernuci et al., 2016)
	P. mosenii	The essential oil gave MIC value of 250 μg/mL against *Mycobacterium tuberculosis* $H_{37}Rv$ bacillus (Bernuci et al., 2016)
Anti-leishmanial	*P. diospyrifolium*	The essential oil gave IC_{50} value of 13.5 μg/mL against amastigote forms of *Leismania amazonensis* (Bernuci et al., 2016)
	P. lanceifolium	The essential oil gave IC_{50} value of 37.8 μg/mL against promastigote form of *Leismania infantum* (Leal et al., 2013)
	P. obrutum	The essential oil gave IC_{50} value of 35.9 μg/mL against promastigote form of *Leismania infantum* (Leal et al., 2013)
	P. mosenii	The essential oil gave IC_{50} value of 17.4 μg/mL against *Leismania amazonensis* promastigotes (Bernuci et al., 2016)
	P. aduncum	The essential oil gave IC_{50} value of 25.9 μg/mL against amastigote forms of *Leismania amazonensis* (Bernuci et al., 2016)
	P. hispidum	The essential oil gave IC_{50} value of 3.4 μg/mL against amastigote forms of *Leismania amazonensis* (Houël et al., 2016)
Antifungal	*P. betle*	The essential oil gave MIC value of 64.0 μg/mL strongly controlling the growth of the fungus *Aspergillus niger* (Dai et al., 2023)
	P. diospyrifolium	The essential oil gave MIC values of 10.7, 9.3, and 8.3 μg/mL against *Candida albicans*, *C. parapsilosis* and *C. tropicalis* respectively (Vieira et al., 2011)
	P. bogotense	The essential oil gave MIC value of 79.0 μg/mL against *Trichophyton rubrum* (Castaño et al., 2014)
	P. hispidum	The essential oil gave MIC value of 500.0 μg/mL against *Fulsarium oxysporum* (Castaño et al., 2014)
	P. bredemeyeri	The essential oil gave MIC value of 125.0 μg/mL against *Trichophyton mentagrophytes* (Castaño et al., 2014)
	P. gaudichaudianum	The essential oil gave MIC value of 32.2 μg/mL against *Candida krusei* (Giannetti et al., 2010).
	P. auritum	The essential oil gave MIC values of 364.7 and 254.4 μg/mL against *Colletotrichum acutatum* and *Botryodiplodia theobromae* respectively by bioautographic assay (Pineda et al., 2012)
	P. solmsianum	The essential oil gave MIC value of 62.5 μg/mL against *Cryptococcus neoformans* (Giannetti et al., 2010)
	P. marginatum	The essential oil shows moderate activity with a detection limit value ranging from 10 to 100 μg against *C. cladosporioides* and *C. sphareospermum* determined by TLC bioautography (da Silva et al., 2016)
Insecticidal	*P. auritum*	The essential oil exhibited repellent activity against *Tribolium castaneum* with RC_{50} value of 0.002 μL/cm² (Caballero-Gallardo et al., 2014)
	P. marginatum	The essential oil exhibited repellent activity against *Solenopsis saevissima* with an IC_{50} value of 240.0 μg/mL (Souto et al., 2012)
Larvicidal	*P. klotzschianum*	The essential oil gave LC_{50} value of 122.4 μg/mL against *Aedes aegypti* larvae (Lima et al., 2019)
	P. marginatum	The essential oil gave LC_{50} value of 19.9 μg/mL against *Aedes aegypti* larvae (Torquilho et al., 1999)
	P. longispicum	The essential oil gave LC_{50} value of 250.0 μg/mL against *Aedes aegypti* larvae (Santana et al., 2016)
	P. permucronatum	The essential oil gave LC_{50} value of 36.0 μg/mL against *Aedes aegypti* larvae (de Morais et al., 2007)
Anti-parasitic	*P. eriopodon*	The essential oil demonstrates a repellent effect against *Sitophilus zeamais* with an IC_{50} value of 0.5 μg/mL (Acevedo et al., 2023).
	P. lanceifolium	The essential oil exhibited IC_{50} value of 7.48 μg/mL against *Trypanosoma cruzi* (Leal et al., 2013)
	P. obrutum	The essential oil gave IC_{50} value of 29.3 μg/mL against *Trypanosoma cruzi* (Leal et al., 2013)
	P. septuplinervium	The essential oil gave IC_{50} value of 14.0 μg/mL against *Trypanosoma cruzi* (Leal et al., 2013)
	P. mikanianum	The essential oil gave LC_{50} value of 33.1 μg/mL against *L. braziliensis* (Gomez et al., 2021)
	P. diospyrifolium	The essential oil gave LC_{50} value of 30.1 μg/mL against *L. braziliensis* (Gomez et al., 2021)
	P. tuberculatum	The essential oil gave EC_{50} value of 133.9 and 143.5 μg/mL against *L. infantum* and *L. braziliensis* respectively (dos Santos et al., 2018)
Anti-proliferative	*P. lindbergii*	The essential oil gave EC_{50} value of 0.83 μg/mL against *Toxplasma gondii* (Filho et al., 2023)
Anti-cholinesterase	*P. capitarianum*	The essential oils showed activity on AChE with IC_{50} value of 14.2 μg/mL (França et al. 2020)
	P. ornatum	The leaf oil showed significant inhibitory activity on AChE (70.2%) (Azman et al. 2022)
	P. arboreum	The leaf oil showed high selective inhibition for BuChE with IC_{50} value of 29.3 μg/mL (Espinoza et al. 2023)
Toxicity	*P. hispidinervum*	The essential oil concentration ranging from 140.0 to 1000.0 μL/kg against 11 *Sitophilus zeamais* determined by concentration-mortality bioasssays (Lopes et al., 2024)
	P. retrofractum	The essential oil gave LC_{50} and LC_{95} value of 0.02% and 0.19% respectively against botanical insecticide brown plant hopper (BPH) (Nuryanti et al., 2020)
	P. corcovadensis	The essential oil gave LD_{50} and LD_{90} value of 3.58 and 6.34 mg/g respectively against *Spodoptera frugiperda* (Dutra et al., 2020)
	P. marginatum	The essential oil gave LD_{50} and LD_{90} value of 4.18 and 18.1 mg/g respectively against *Spodoptera frugiperda* (Dutra et al., 2020)
	P. arboreum	The essential oil gave LD_{50} and LD_{90} value of 10.9 and 54.8 mg/g respectively against *Spodoptera frugiperda* (Dutra et al., 2020)
	P. aduncum	The essential oil, at a concentration of 40.0 mg/mL, caused the LT_{50} to be 10.7 days and 16.8 days for the first and second instar respectively against *Helicoverpa armigera* (Dos Santos et al., 2017)
Anti-inflammatory	*P. glabratum*	The leaf oil significantly inhibited leukocyte migration at doses of 100, 300, and 700 mg/kg with a maximal inhibition of 92% (Branquinho et al. 2017)
	P. miniatum	The leaf oil gave an inhibition of 73.6% in the TPA-induced mouse ear edema assay and 76.0% in the in vitro lipoxygenase assay (Salleh et al. 2015)
	P. rostratum	The essential oil demonstrated moderate activity in lipoxygenase inhibition with IC50 value of 77.2 μg/mL (Ramin et al., 2025)
	P. gaudichaudianum	The essential oil showed ability to inhibit neutrophil chemotaxis in vitro when stimulated by *Escherichia coli* lipopolysaccharide with reduction in migration of 0–72.2% (Soares et al., 2022)
	P. mikanianum	The essential oil showed ability to inhibit neutrophil chemotaxis in vitro when stimulated by *Escherichia coli* lipopolysaccharide with reduction in migration of 8.6-100% (Soares et al., 2022)

5. CONCLUSION

This review provides a comprehensive analysis of the medicinal potential, chemical composition, and biological activities of essential oils extracted from *Piper* species. These oils are predominantly composed of monoterpenes and sesquiterpenes, compounds well-documented for their potent antioxidant and antimicrobial effects. The variation in chemical constituents among different *Piper* species is largely influenced by genetic diversity and environmental factors, including soil composition, climate, and geographical location. While these essential oils exhibit promising bioactive properties, their full therapeutic potential remains underexplored. Additional research is necessary to investigate their possible anti-inflammatory, anticancer, and antiviral effects, which could further expand their applications in medicine. To establish their efficacy and safety, rigorous preclinical studies and well-designed clinical trials are essential, paralleling the extensive research conducted on other medicinal essential oils.

Moreover, the identification of *Piper* species with optimal chemical profiles could significantly enhance their commercial value, particularly in the pharmaceutical and cosmetic industries, where natural bioactive compounds are in high demand. Future studies should prioritize the exploration of *Piper* species across diverse ecological regions, employing advanced analytical tools such as metabolomics and genomics to gain deeper insights into the influence of genetic and environmental factors on oil composition. Furthermore, fostering collaboration between academic researchers, pharmaceutical industries, and regulatory bodies can accelerate the development and commercialization of *Piper* essential oils. Such partnerships can pave the way for the formulation of innovative, plant-derived therapeutic agents, contributing not only to advancements in natural medicine but also to economic growth in regions where these plants are cultivated. By integrating multidisciplinary approaches and industry-driven innovation, *Piper* essential oils hold significant promise as valuable resources for future drug development and natural health solutions.

Funding: This research was supported by the Geran Penyelidikan Universiti (Kecemerlangan@UPSI) under grant number 2025-0012-103-01, funded by Universiti Pendidikan Sultan Idris.

Data Availability Statement: All available data are presented in this paper.

Conflicts of Interest: The authors declare no conflicts of interest.

Author Contribution: Syarifah Nadhirah Wan Idrus - Conceptualization, Investigation, and writing original draft preparation; Wan Mohd Nuzul Hakimi Wan Salleh, Nurunajah Ab Ghani and Salam Ahmed Abed - Review and editing; Abubakar Siddiq Salihu – Methodology and formal analysis.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process: The authors acknowledge that AI-assisted technologies were partially used in the preparation of this manuscript. Specifically, generative AI tools (ChatGPT and DeepSeek) were employed to support language refinement and grammar correction. All content was critically reviewed, edited, and approved by the authors to ensure accuracy, originality, and alignment with academic standards. No AI tools were used to generate data, interpret results, or replace human intellectual contribution.

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