RSC Advances

REVIEW

View Article Online
View Journal | View Issue

Cite this: *RSC Adv.*, 2021, **11**, 37767

An overview of the chemical composition and biological activities of essential oils from *Alpinia* genus (Zingiberaceae)†

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Received 4th October 2021
Accepted 5th November 2021

DOI: 10.1039/d1ra07370b

rsc.li/rsc-advances

Alpinia Roxb. is the largest genus of the Zingiberaceae family. A large number of *Alpinia* species has been used as food and traditional medicines. *Alpinia* essential oils have been studied for their chemical profiles, in which 1,8-cineole, β-pinene, α-pinene, β-myrcene, camphor, γ-terpinene, *p*-cymene, geraniol, α-fenchyl acetate, ocimene, methyl cinnamate, and β-caryophyllene have been found to be the major compounds. Essential oils isolated from *Alpinia* plants have been reported to have antimicrobial, cytotoxic, antioxidant, anti-inflammatory, anti-asthmatic, tyrosinase inhibitory, insecticidal, and larvicidal activities and slimming aromatherapy. In this review, the comprehensive information regarding the volatile components of various *Alpinia* plants, the bioactivities of *Alpinia* essential oils and their major compounds are provided.

1. Introduction

Alpinia Roxb. is a large genus belonging to the Zingiberaceae family with around 230 species. This genus is widely distributed in tropical and subtropical regions, including Andamans, Australia, Burma, the Carolines, China, Fiji, India, Indochina, Indonesia, Japan, New Guinea, New Hebrides, New Caledonia, Malaysia, Philippines, Sri Lanka, Solomons, Samoa and Thailand.[1,2] The *Alpinia* species are herbal plants, usually 2–4 meters, but sometimes up to 12 meters in height.[1] Many *Alpinia* species are considered ethnomedicinal and spice plants in several countries such as China, India, Japan and Vietnam.[3,4] For instance, the plant parts of *Alpinia* species are commonly used to cure digestion, gastralgia, vomiting, and enterozoa.[5,6] The classes of chemical components generally found in *Alpinia* plants are terpenes, phenylpropanoids, diarylheptanoids, flavonoids, volatile oils, and lignins.[4] In addition, this genus has been reported to possess various bioactivities such as antitumor,[7,8] antiulcer,[9] antimicrobial,[10,11] hypoglycemic,[12] antiemetic,[13,14] cardioprotection,[15] neuroprotection,[16,17] and antianxiety activities.[18]

Alpinia plants, which are also known as aromatic herbs, have many parts that contain essential oils such as fruits, seeds, leaves, rhizomes, roots, shoots, stems, pseudostems, inflorescences, flowers, petals and seeds. *Alpinia* essential oils have been reported to contain oxygenated monoterpenes, monoterpene hydrocarbons and oxygenated sesquiterpenes as the major compounds.[19,20] They also exhibit a wide variety of medicinal properties, such as antimicrobial, antioxidant, cytotoxic, anti-inflammatory, larvicidal, anti-asthmatic, tyrosinase inhibitory activity and slimming aromatherapy.[21,22] In addition, the compounds in *Alpinia* essential oils have a wide variety of pharmacological resources.[23–25] However, to date, there is no overall review on the chemical profiles and bioactivities of *Alpinia* essential oils. Therefore, this review aims to provide comprehensive information on the chemical composition and biological activities of the essential oils and their major components isolated from various parts of *Alpinia* plants.

2. Volatile compounds of *Alpinia* spp.

In many studies, the gas chromatography-mass spectrometry method has been routinely used for the identification of the volatile compounds of *Alpinia* spp. Table S1† presents the chemical compositions of the essential oil isolated from different parts of *Alpinia* plants, including rhizomes, leaves, pseudostems, stems, roots, seeds, fruits, flowers, inflorescences and petals.[25,26]

2.1. *Alpinia zerumbet* (Pers.) B.L.Burtt & R.M.Sm. Synonym: *A. speciosa* (J.C.Wendl.) K.Schum., *A. cristata* Griff., *A. fimbriata* Gagnep., *A. fluvitialis* Hayata, *A. schumanniana* Valeton, *A. nutans* var. *longiramosa* Gagnep.

A. zerumbet, commonly known as "shell ginger" and the synonym "*A. speciosa* (J.C.Wendl.) K.Schum.", is an endemic species to India and also found in the subtropical and tropical areas of South America, Oceania and Asia.[27] *A. zerumbet* is one of the large species in the Zingiberaceae whose height can reach

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† Electronic supplementary information (ESI) available. See DOI: 10.1039/d1ra07370b

up to 2 or 3 meters.[28] This species is known for its traditional medicine to treat inflammation, hypertension, colds, and cardiovascular disorders and as an antispasmodic agent.[29,30] Also, several plant parts of *A. zerumbet* are used as food. Notably, the leaves and rhizomes of this species are commonly used as herbal tea and spices, respectively.[31]

The major components of *A. zerumbet* essential oils are mainly composed of oxygenated monoterpenes, followed by monoterpene hydrocarbons and oxygenated sesquiterpenes. The leaf is the most common part used in the studies of the essential oil of *A. zerumbet*. Accordingly, the major components of the leaf essential oils of *A. zerumbet* collected from Okinawa, Japan at different times of the year included *p*-cymene, 1,8-cineole, terpinen-4-ol, α-pinene, limonene, sabinene and camphor.[32,33] Meanwhile, the leaf oils from Nishieue, Japan had 3,4-dimethyl-3-cyclohexen-1-carboxaldehyde and α-humulene as their main constituents.[34] The leaf oil samples from Maja and Toyohara, Japan contained 3,4-dimethyl-3-cyclohexen-1-carboxaldehyde and camphor as their major compounds.[34] The leaf oils from Futami, Japan,[34] Fiji,[35] Rio de Janeiro, Brazil,[36,37] Ceara, Brazil,[38] and São Cristóvão, Brazil[26] were identified as a mixture of terpinen-4-ol and 1,8-cineole, whereas that from Kushi, Japan possessed caryophyllene oxide and 3,4-dimethyl-3-cyclohexen-1-carboxaldehyde as their major constituents.[34] Moreover, linalool has been reported as the most constituent in the leaf oils collected from Higashieue and Nago, Japan,[34] while that from Rio de Janeiro, Brazil had terpinen-7-al, sabinene hydrate and *p*-mentha-1,3,8-triene as the major compounds.[37]

The essential oils of *A. zerumbet* flowers collected from three different regions of France, including São Cristóvão, Morne Rouge and François have been reported to contain 1,8-cineole and terpinen-4-ol as their major components.[39] These compounds were also the main constituents in the rhizome oils from Fiji.[35] Meanwhile, terpinen-4-ol and α-terpineol were the major constituents in the petal and rhizome oils collected from São Cristóvão, Brazil.[26] Furthermore, the leaf essential oil from *A. zerumbet* var. *variegata* from Rio de Janeiro, Brazil was reported to contain 1,8-cineole, β-pinene, and β-caryophyllene as its main constituents.[40]

Alpinia speciosa (J.C.Wendl.) K.Schum., also known as *Alpinia zerumbet*, has been also reported for its phytochemical composition of essential oils. Accordingly, the leaf and seed oils of *A. speciosa* from Chu-Tung, Taiwan were mainly composed of camphor and sabinene, followed by ocimene and 1,8-cineole,[41] while terpene-4-ol and 1,8-cineole were the major constituents in the rhizome and leaf oils of this species from Amazonas, Brazil[42] and Dehradun, India.[43] The major constituents of the essential oil of the *A. speciosa* leaves from Martinique, France were terpinen-4-ol, 1,8-cineole and *p*-cymene,[24] while β-pinene and 1,8-cineole were the major compounds in the leaf oils from Mexico[44] and Egypt.[45] Finally, the leaf essential oil of *A. speciosa* from Japan was found to be rich in (*E*)-methyl cinnamate, camphor and camphene.[46]

2.2. *Alpinia galanga* (L.) Willd. Synonym: *Alpinia alba* (Retz.) Roscoe, *A. bifida* Warb., *A. carnea* Griff., *A. pyramidata* Blume, *A. rheedei* Wight, *A. viridiflora* Griff., *A. galanga* var. *galanga*, *A. galanga* var. *pyramidata* (Blume) K.Schum.

Alpinia galanga is commonly known as "galangal" in English and "Riêng nếp" in Vietnamese. It is widely cultivated in subtropical and tropical regions, including Sri Lanka, India, Malaysia, Philippines, Indonesia, Thailand, India, China and Vietnam.[3,47] Several parts of the galangal plant are broadly used as a condiment for foods and as traditional medicine in some Asian countries.[3,48] Notably, in traditional Vietnamese medicine, the dried fruits, rhizomes and seeds of *A. galanga* are used for treating abdominal aches, dysentery, diarrhea, flatulence, vomiting, coughs, intoxication and sore throat. Rhizomes soaked in salt have been used as anti-thirst agent and remedy for tiredness. People in Thai Nguyen Province, Vietnam use rhizome of this plant soaked in alcohol to treat ringworm.[3] In addition, this plant has been reported to possess many pharmacological effects such as antioxidant, antiplatelet, antidiabetic, hypolipidemic, antiprotozoal, antibacterial, antifungal and antiviral activities.[49,50]

Furthermore, the chemical profiles of the essential oils isolated from various parts of the galangal plant have been reported in previous studies. Accordingly, the main constituents of *A. galanga* essential oils are composed of relatively equal amounts of monoterpene hydrocarbons and oxygenated monoterpenes, followed by sesquiterpene hydrocarbons. The major compounds are 1,8-cineole, α-fenchyl acetate, β-myrcene, β-ocimene, camphor, and limonene. Some galangal rhizome essential oils from several locations of India contained 1,8-cineole as the most abundant compound, followed by α-terpineol, germacrene D,[51] α-fenchyl acetate, camphor,[52] chavibetol acetate[53] (Kerala, India), geranyl acetate, β-caryophyllene[54] (New Delhi, India), β-sesquiphellandrene, chavicol, (*E*)-β-farnesene and eugenol acetate[55] (Imphal, India). Furthermore, the leaf and stem essential oils of galangal from Kerala, India mainly contained 1,8-cineole, camphor, β-pinene and (*E*)-methyl cinnamate, while its root oil was found to be rich in α-fenchyl acetate and 1,8-cineole.[52] The essential oil isolated from the galangal oil of the whole plant from Tamil Nadu, India contained 1,8-cineole, β-farnesene, and β-sesquiphellandrene as the main compounds.[52]

The rhizome and leaf essential oils of *A. galanga* from Alabama, United States were characterized by the predominance of β-myrcene, β-ocimene and β-pinene.[56] The rhizome oil of galangal from Thailand contained a mixture of 1,8-cineole, chavicol, α-bisabolene, 5-*t*-butyl-hexa-3 and DL-limonene.[57,58] Moreover, 1,8-cineole, 4-allylphenyl acetate and α-farnesene were the main constituents of the rhizome oils of galangal from Indonesia,[59] while sample from China was found to be rich in 1,8-cineole, β-pinene and α-pinene.[60] The chemical compositions of the rhizome and seed essential oils of *A. galanga* from Malaysia were reported in a study by Jantan *et al.*[61] in which 1,8-cineole, β-bisabolene, (*Z*,*E*)-farnesol (leaf), β-bisabolene, (*E*)-β-farnesene, and (*E*,*E*)-farnesyl acetate (seed) were present as the major constituents.[61] The rhizome essential oil of galangal from

Nawinna, Sri Lanka mainly contained zerumbone, *p*-cymene and camphene,[62] whereas the samples from Indonesia were characterized by the predominance of β-bisabolene and *trans*-caryophyllene.[63] In addition, the whole plant oil of galangal from Phu Tho, Vietnam mainly contained limonene, borneol and geranyllinelol as the major constituents,[64] while the rhizome oil from Ha Noi, Vietnam was found to be rich in 1,8-cineole, neral and geranial.[65]

2.3. *Alpinia malaccensis* (Burm.f.) Roscoe. Synonym: *Alpinia malaccensis* var. *malaccensis*, *A. nutans* var. *sericea* Baker

A. malaccensis is commonly known as "Kha Pa" in Thai and "Riêng Malacca" in Vietnamese. It is a medicinal plant native to both Indonesia and Malaysia. In addition, it is widely distributed in other tropical and subtropical such as Bangladesh, Bhutan, India, Myanmar, Thailand and Vietnam.[3,66,67] Several plant parts of *A. malaccensis* were used to treat sores and wounds as well as make the voice clear.[66,67] In Vietnam, the rhizome extract of *A. malaccensis* is used to cure intestinal diseases and scabies.[3]

The main constituents of *A. malaccensis* essential oils belong to monoterpene hydrocarbons and non-terpenoid, followed by oxygenated monoterpenes. The major constituents in the essential oil of *A. malaccensis* rhizomes from Thailand mainly contained 1,8-cineole, linalool and fenchyl acetate,[58] while the rhizome oils from Kerala, South India possessed α-phellandrene, *p*-cymene and β-pinene as their major compounds.[53] In addition, α-phellandrene was found as the most abundant constituent in the leaf oil of *A. malaccensis* from Chittagong, Bangladesh and Orissa, India, followed by notable amounts of 1,8-cineole, *O*-cymene, β-cymene and β-pinene.[67,68] Other essential oils extracted from different plant parts of *A. malaccensis* grown in Vietnam such as leaves, stems and fruits had β-pinene as the most abundant constituent, followed by α-pinene, δ-3-carene and β-phellandrene, whereas (*E*)-methyl cinnamate, β-pinene and β-phellandrene were the main constituents in the root oil.[69] Furthermore, *A. malaccensis* var. *nobilis*, a variant of *A. malaccensis* endemic to Peninsular Malaysia[70] has been reported for its essential oil compositions. Accordingly, the essential oils extracted from the fruits, leaves and rhizomes of this variant contained (*E*)-methyl cinnamate as the highest percentage, followed by notable amounts of 1,8-cineole, *p*-cymene, β-pinene and β-phellandrene.[70] Furthermore, the leaf oil of *A. malaccensis* var. *nobilis* from Janda Baik, Malaysia contained methyl cinnamate, α-terpineol and 1,8-cineole as their major compounds.[22]

2.4. *Alpinia officinarum* Hance. Synonym: *Languas officinarum* (Hance) Farw., *L. officinarum* (Hance) P.H. Hộ

A. officinarum is also known as "Gaoliangjiang" in Chinese and "Riêng" in Vietnamese. It is a rhizomatous perennial herb widely distributed in India, southeast Asia and China.[3,71,72] In Chinese pharmacopoeia, dried rhizomes of *A. officinarum* are used to treat several diseases such as colds, stomachaches, and vomiting, invigorate the circulatory system, and alleviate swelling.[73] Juice from boiled *A. officinarum* rhizomes is used to cure intestinal diseases and treat scabies in Vietnamese traditional medicine.[3] Notably, various important bioactive compounds belonging to flavonoids, diarylheptanoids, phenylpropanoids and glycosides extracted from the rhizome essential oils of *A. officinarum* have been recorded in several previous studies.[74,75]

The major constituents of *A. officinarum* essential oils are mainly composed of oxygenated monoterpenes, followed by sesquiterpene hydrocarbons. For instance, dozens of chemical components have been identified in the essential oils of *A. officinarum* rhizomes collected from several regions of China, including Sanming, Guilin, Yulin, Guigang, Qiandongnan, Panzhihua, Xishuangbanna and Bozhou. Notably, the most abundant constituent was 1,8-cineole, followed by notable amounts of γ-cadinene, α-farnesene, α-terpineol, α-bergamotene and globulol.[73] In addition, the rhizome oils of *A. officinarum* collected from Gaozhou, China were found to contain *trans*-β-farnesene, α-bergamotene and linalool as dominant constituents, while α-farnesene, γ-cadinene and δ-cadinene were the major compounds in the sample from Xuwen, China.[73] Moreover, the main compounds of *A. officinarum* rhizome essential oil from Hainan island were found to be 1,8-cineole, *trans*-carveol and piperitol,[76] while the major constituents of the rhizome oil of this species collected from Imphal, India were 1,8-cineole, α-fenchyl acetate, carotol and β-pinene.[55,77] Finally, the essential oil of *A. officinarum* rhizomes from Thailand possessed α-bisabolene, α-*trans*-bergamotene and β-sesquiphellandrene as its major constituents,[58] whereas 1,8-cineole, *exo*-2-hydroxy-1,8-cineole acetate and β-caryophyllene were the main constituents in the sample from Vietnam.[78]

2.5. *Alpinia calcarata* (Haw.) Roscoe. Synonym: *Alpinia alata* A.Dietr., *A. bracteata* Roscoe, *A. calcarata* var. *compacta* Gagnep., *A. cernua* Sims, *A. erecta* Lodd. ex Steud., *A. roscoeana* Steud., *A. simsii* Gasp., *A. spicata* Roxb.

A. calcarata is known as an economic and medicinal plant. It is a slender and perennial rhizomatous herb, reaching a height of 60–120 cm. This species is widely distributed in tropical and subtropical regions such as India, Myanmar, Indonesia, Thailand and Sri Lanka.[79] In traditional medicine, this species is used to cure rheumatism, diabetes, and fever and stomach aches.[79] Notably, its rhizomes have been widely used to treat several diseases, such as bronchitis, throat inflammation, colds and asthma.[80] Furthermore, this species was also reported to have some pharmacological properties such as anti-emetic, antibacterial, antispasmodic, antifungal, antiulcer, antioxidant and anti-inflammatory activities.[81]

The major constituents of *A. calcarata* are mainly composed of oxygenated monoterpenes, followed by monoterpene hydrocarbons, oxygenated sesquiterpenes and non-terpenoids. Accordingly, the rhizome and leaf oils of *A. calcarata* collected from Sri Lanka contained 1,8-cineole and α-terpineol as their main compounds,[23] while 1,8-cineole and β-fenchyl acetate were found as the major constituents in the rhizome oils from Kerala, India.[51] The leaf oil of *A. calcarata* from Tamil Nadu, India was mainly composed of 1,8-cineole, camphor and α-myrcene,[82] while the whole plant oil of this species grown in Karnataka,

India was composed of α-fenchyl acetate, 1,8-cineole and (*E*)-methyl cinnamate.[82] Rout *et al.*[83] reported the chemical constituents of the essential oils of *A. calcarata* collected from Bhubaneswar and Bangalore, India. Accordingly, the root oils from these two locations contained α-fenchyl acetate, 1,8-cineole and camphene as their major constituents, while β-pinene, 1,8-cineole, camphor and camphene were the major compounds in the leaf oils. The rhizome oil from Bhubaneswar region was found to be rich in α-fenchyl acetate, 1,8-cineole, and camphene, whereas the sample from Bangalore mainly contained geraniol, 1,8-cineole and α-fenchyl acetate.[83]

The leaf and rhizome essential oils of *A. calcarata* grown in Pantnagar, India had 1,8-cineole as their most abundant constituent, followed by camphor, β-pinene (leaf), α-fenchyl acetate, and camphene (rhizome).[84] The rhizome and root essential oils of this plant from south India were dominated by α-fenchyl acetate and 1,8-cineole, followed by camphene (root) and α-terpineol (rhizome), while 1,8-cineole, α-fenchyl acetate and camphor were the major compounds in the shoot oil of the same species.[81] In addition, the major components of the rhizome, leaf and root essential oils of *A. calcarata* from Veyangoda, Sri Lanka were 1,8-cineole, α-fenchyl acetate, β-pinene, camphene and camphor.[85]

2.6. *Alpinia mutica* Roxb. Synonym: *Alpinia korthalsii* K.Schum., *A. laxiflora* Gagnep., *Catimbium muticum* (Roxb.) Holttum, *Languas korthalsii* (K.Schum.) Merr. *L. laxiflora* (Gagnep.) Merr., *L. mutica* (Roxb.) Merr., *Renealmia mutica* (Roxb.) Salisb.

A. mutica is a herbaceous perennial species, which is endemic to the southern regions of Malaysia and also found in Borneo, Singapore, India and Vietnam.[3,86] Several plant parts of this species are used to treat flatulence and diarrhea by local people in southern India.[87] In Malaysia, *A. mutica* is cultivated as ornamental trees, while its rhizomes are used as a stomachic.[88] Vietnamese people use crushed rhizomes mixed with water to cure stomachaches and abdominalaches.[3] Furthermore, *A. mutica* has been reported to possess some biological activities. For examples, its crude extract had a cytotoxic effect against human cancer cells, including KB, MCF7 and CaSki cells[89] and CEMss (human T4 lymphoblastoid) cancer cells.[90] The hexane extract of *A. mutica* showed antibacterial activity against *Staphylococcus aureus* and *Pseudomonas aeruginosa*,[91] while its dichloromethane extract presented an antibacterial effect against *Bacillus subtilis* and *Staphylococcus aureus*.[90] Moreover, the ethyl acetate fractions isolated from *A. mutica* rhizome have been reported to exhibit antioxidant activity.[91,92]

The chemical composition of the essential oils from *A. mutica* is characterized by the predominance of monoterpene hydrocarbons and oxygenated monoterpenes, followed by sesquiterpene hydrocarbons, and oxygenated sesquiterpenes. The major volatile components of *A. mutica* unripe and ripe fruits from Peninsular, Malaysia included camphor, camphene and β-pinene.[93] Furthermore, the main components of the essential oils of the young and mature fruits of *A. mutica* from Johor, Malaysia were (*E*,*E*)-farnesol and α-farnesene, followed by α-humulene and 1,8-cineole,[94] while the rhizome oil from the same location possessed camphor, 1,8-cineole and borneol as the major compounds.[95] The rhizome and fruit essential oils of this plant from Kerala, India were characterized by large quantities of β-pinene, camphor and 1,8-cineole.[96] In addition, the diversity of the chemical composition in the essential oils from different plant parts of *A. mutica* collected from Phong Nha-Ke Ban National Park, Vietnam has been reported.[86] Accordingly, the quantitatively significant constituents of the leaf and root essential oils were β-pinene, 1,8-cineole and α-pinene, while the other plant parts were found to be rich in 1,8-cineole, β-pinene, and α-pinene (pseudostem) and β-caryophyllene, β-cadinol, and camphor (fruit).[86]

2.7. *Alpinia nigra* (Gaertn.) Burtt. Synonym: *Alpinia allughas* (Retz.) Roscoe, *Amomum bifidum* Stokes, *A. nigrum* (Gaertn.) Raeusch., *A. taraca* Horan., *Hellenia allughas* (Retz.) Willd., *Heritiera allughas* Retz., *Languas allughas* (Retz.) Burkill, *L. aquatica* J. König, *Zingiber nigrum* Gaertn.

A. nigra is a perennial and aromatic plant widely distributed in Bhutan, China, India, Sri Lanka and Thailand. This species is used as a spice and medicinal agent. In Thai folk remedies, *A. nigra* was used to cure stomachicum, gastric diseases, bronchitis, jaundice, dyspepsia, gastric ulcers and insect bites and as antibacterial and antifungal agents.[97] In addition, the aerial parts of *A. nigra* were used in curry as a flavour and anthelmintics by the native tribes of Tripura, northeast India.[98] Studies showed that the leaf extract of *A. nigra* has analgesic, antibacterial and cytotoxic activities,[99,100] while its rhizome extract possesses anti-inflammatory and analgesic effects.[101]

The chemical profiles of the essential oils isolated from *A. nigra* have been reported in previous studies. For instance, the essential oils obtained from four plant parts such as the leaves, rhizomes, flowers and seeds of *A. nigra* grown in Guwahati, India contained β-caryophyllene, β-pinene and α-humulene as their major compounds.[102] The rhizome and leaf essential oils from Kalimpong, India were characterized by the presence of β-pinene as the most abundant compound, followed by myrtenol, α-humulene and α-farnesene,[103] whereas β-pinene, α-caryophyllene and α-farnesene were the major constituents in the leaf oil from West Bengal, India.[104] In addition, β-pinene was the most abundant component in the leaf and rhizome essential oils of *A. allughas* (a synonym of *Alpinia nigra*) from Terai, India, followed by α-pinene, 7-*epi*-α-eudesmol (rhizome), 1,8-cineole, α-humulene (leaf).[105]

2.8. *Alpinia hainanensis* K.Schum. Synonym: *Alpinia katsumadai* Hayata, *A. henryi* K.Schum., *A. henryi* var. *densihispida* H.Dong & G.J.Xu, *A. kainantensis* Masam., *Languas hainanensis* (K.Schum.) Merr., *L. henryi* (K.Schum.) Merr., *L. katsumadai* (Hayata) Merr.

Alpinia hainanensis K.Schum. is commonly known as "Riêng Hải Nam" in Vietnamese and the synonym "*Alpinia katsumadai* Hayata". This species is distributed in several locations in China (Guangdong, Guangxi, Hainan) and northern Vietnam.[3] *A. hainanensis* is extensively used in traditional Chinese medicine to

treat emesis and gastric disorders.[25] Also, Vietnamese people use *A. hainanensis* to cure abdominal aches and bloating diseases by drinking juice extract from its fruits.[3] The extracts of *A. katsumadai* and its fractions have been reported to possess *in vitro* antiviral effects against influenza virus type A, especially human A/PR/8/34 (H1N1) and avian A/Chicken/Korea/MS96/96 (H9N2).[106] Moreover, the antioxidant[107] and antibacterial[108] activities of *A. katsumadai* extracts have been also reported.[107]

The chemical composition of the essential oils isolated from *A. hainanensis* were reported in previous studies. For example, the leaf and flower essential oils of *A. hainanensis* collected from Hainan island, China were found to be rich in ocimene and β-pinene, followed by octadecenoic acid and terpinene.[109] Furthermore, the components of the oils from *A. katsumadai*, a synonym of *A. hainanensis*, have been recorded. Accordingly, the leaf oil of *A. katsumadai* from Hainan island, China contained *p*-menth-1-en-ol, terpinen and 4-carene as its major compounds, while *p*-menth-1-en-ol, 1,8-cineole and terpinen were the prominent constituents in its flower oil.[109] The seed oil of *A. katsumadai* from Guangxi, China contained methyl cinnamate, *cis*-4-decen-1-ol and octahydro-*cis*-2*H*-inden-2-one as its major constituents.[25] Furthermore, the essential oil of *A. katsumadai* from Vietnam was mainly composed of geraniol, fenchone and 1,8-cineole. The major constituents of the stem essential oil were fenchone, geraniol and 1,8-cineole, while the seed oil was dominated by geraniol, linalool and decanol.[110]

2.9. *Alpinia conchigera* Griff. Synonym: *Alpinia laosensis* Gagnep., *A. humilis* Teijsm. & Binn., *A. sumatrana* (Miq.) K.Schum., *Languas conchigera* (Griff.) Burkill, *L. sumatrana* (Miq.) Merr., *Strobidia conchigera* (Griff.) Kuntze, *S. oligosperma* Kuntze, *S. sumatrana* Miq.

A. conchigera is commonly known as "Lengkuas ranting" in Malay, "Riêng rừng" in Vietnamese and the synonym "A. laosensis Gagnep."[3] This species is a native plant in Malaysia and also found in Bangladesh and Vietnam.[67,111] Several plant parts of this species have been used as a food flavour and Malaysian traditional remedies for rheumatism, arthritis, stimulation, diaphoretic and regulatory in uterine hemorrhage.[112] In Vietnam, boiled juice from its leaf and rhizome is traditionally used as a folk remedy to cure spleen and abdominal pain.[3] In addition, *A. conchigera* has been reported to possess anti-inflammatory,[113] antifungal and antibacterial[67] activities. Previous studies showed that *A. conchigera* extracts contained various bioactive compounds such as β-sitosterol, 1′-acetoxychavicol acetate, 1′-acetoxyeugenol acetate,[114] chavicol, chavicol acetate, 1-hydroxychavicol acetate, 4-acetoxycinnamyl alcohol and 4-acetoxycinnamyl acetate.[114]

There have been several studies investigating the chemical composition of the essential oils isolated from *A. conchigera*. For example, the rhizome oil of *A. conchigera* from Penang, Malaysia had β-bisabolene, 1,8-cineole and β-caryophyllene as its main compounds,[114] while the rhizome oil collected from Pagoh, Malaysia was characterized by the predominance of β-sesquiphellandrene, β-bisabolene and 1,8-cineole.[115] The leaf essential oil of *A. conchigera* from Chittagong, Bangladesh was obviously dominated by 1,8-cineole, chavicol and β-pinene.[67] In addition, the phytochemical profiles of the essential oil of Alpinia laosensis Gagnep., a synonym of *A. conchigera*, have been reported. Accordingly, the essential oil isolated from A. laosensis rhizomes grown in northern Vietnam was mainly composed of 1,8-cineole, caryophyllene oxide and methyl eugenol.[111]

2.10. *Alpinia latilabris* Ridl. Synonym: *Alpinia hookeriana* Valeton, A. sericea Ridl., *Catimbium latilabre* (Ridl.) Holttum, *Languas hookeriana* (Valeton) Merr., *L. sericea* (Ridl.) Merr.

A. latilabris is commonly known as "Ry" in Vietnamese and the synonym "Catimbium latilabre (Ridl.) Holttum". It is a herbaceous plant, reaching a height of 3 meters and usually found in lowland forests in Borneo, Malaya, Myanmar and Vietnam.[3,116,117] In Vietnam, the rhizome extract of *A. latilabris* is traditionally used as a folk remedy to cure gastrointestinal diseases.[3]

The components of the essential oils of three plant parts of *A. latilabris* such as rhizomes, unripe and ripe fruits collected from Peninsular, Malaysia have been identified. Accordingly, 1,8-cineole, β-pinene and α-pinene were the dominant compounds in the unripe fruit and ripe fruit oils,[93] while the oil obtained from its rhizome was dominated by camphor, 1,8-cineole and β-pinene.[114] The leaf essential oil of this plant from Janda Baik, Malaysia possessed phytol, carvone and β-sesquiphellandrene as its major compounds.[22] In addition, the leaf, stem and root essential oils of *A. latilabris* grown in Pu Mat National Park, Vietnam were characterized by the predominance of α-cadinol, γ-terpinen and β-pinen.[118] Catimbium latilabre (Ridl.) Holttum, a synonym of *A. latilabris*, collected from Hue, Vietnam has been also investigated for the components of its essential oils. The rhizome oil of C. latilabre was mainly composed of 1,8-cineole, linalool and carotol, while its root oil contained citronellol, 1,8-cineole and camphene as is major compounds.[119] The major constituents in C. latilabre seed oil were β-caryophyllene, camphor and caryophyllene oxide, whereas β-pinene, 1,8-cineole and α-pinene were the main constituents in the fruit skin essential oil.[120]

2.11. *Alpinia pinnanensis* T.L.Wu & S.J.Chen

A. pinnanensis is also known as "Riêng pina" in Vietnamese. It is native to both China and northern Vietnam. This plant can reach up 1.5 meters tall and usually grows along streams, wet slopes and under forest canopies.[1,3] In traditional Vietnamese medicine, the rhizome and tuber extracts of *A. pinnanensis* are used to treat coughs, fever, abdominal aches, flatulence and stomachaches.[3] Furthermore, the extracts of this plant exhibited antimicrobial and cytotoxic effects.[121] Also, some bioactive compounds, including β-sitosterol, alpinetin, chalcones, stigmasterol, flavanones, diarylheptanoids, alpinnanins A–C (1–3), (3*S*,5*S*)-*trans*-3,5-dihydroxy-1,7-diphenyl-1-heptene, 2′,4′-dihydroxy-6′-methoxychalcone, naringenin 5-*O*-methyl ether, 4′,6′-dimethylchalconaringenin and β-sitosterol 3-*O*-β-D-glucopyranoside were isolated from *A. pinnanensis* rhizomes.[121]

The chemical compositions of the essential oils extracted from *A. pinnanensis* grown in Vu Quang National Park, Vietnam

have been reported.[122] Accordingly, the leaf oil contained 1,8-cineole, 4-phenyl-2-butanol and α-phellandrene as its major components. The rhizome oil was mainly characterized by the presence of 1,8-cineole, β-elemene and α-gurjunene. Its fruit essential oil was comprised mainly of α-cadinol, β-caryophyllene and (*E*,*E*)-farnesol, whereas (*E*,*E*)-farnesol, α-gurjunene and camphene were found to be the main compounds in its root bark oil.[122]

2.12. *Alpinia roxburghii* Sweet. Synonym: *Alpinia blepharocalyx* K.Schum., *A. blepharocalyx* var. *glabrior* (Hand.-Mazz.) T.L.Wu, *A. bracteata* Roxb., *Languas blepharocalyx* (K.Schum.) Hand.-Mazz., *Languas blepharocalyx* var. *glabrior* Hand.-Mazz.

Alpinia roxburghii is commonly known as "*Alpinia blepharocalyx* K.Schum." This species usually grows on wet slopes and is native to both China and Vietnam.[3] *A. blepharocalyx* is a pseudostem, reaching a height of up to 3 meters and used as a flavor and fragrance.[123] In Chinese traditional medicine, *A. blepharocalyx* rhizomes are used to treat abdominal pain and abdominal distension.[123] The juice obtained from the fruits, rhizomes and seeds of this plant has been used as Vietnamese traditional remedies to cure stomachache digestive disorders and abdominal aches due to the cold.[3] Moreover, studies demonstrated that this plant contains diarylheptanoids and phenolic compounds.[124,125]

The chemical profiles of the essential oils isolated from *A. blepharocalyx* have been investigated. Accordingly, the rhizome essential oils of *A. blepharocalyx* collected from Xishuangbanna, China were mainly characterized by the presence of camphor, sabinene and α-pinene,[123] while the rhizome oil of this plant grown in Pu Hoat Natural Reserve, Vietnam contained δ-cadinene, τ-muurolol and α-cadinol as its major components.[20] Also, the principal compounds in the pseudostem oil from Pu Hoat Natural Reserve were (*E*,*E*)-α-farnesene, β-pinene, τ-muurolol and α-cadinol, whereas δ-cadinene, β-pinene and γ-cadinene constituted the bulk of the leaf oil.[20]

2.13. *Alpinia purpurata* (Vieill.) K.Schum. Synonym: *Alpinia grandis* K.Schum., *A. purpurata* var. *albobracteata* K.Schum., *A. purpurata* var. *anomala* Gagnep., *A. purpurata* var. *grandis* (K.Schum.) K.Schum.

A. purpurata is commonly known as an ornamental plant. This species is native to the Pacific islands.[37,126] There is little information about the medicinal use of *A. purpurata*, only that this species was used in Venezuelan traditional medicine to cure coughs.[127] The major constituents of *A. purpurata* essential oils were mainly characterized by the predominance of monoterpene hydrocarbons, followed by oxygenated monoterpenes and sesquiterpene hydrocarbons. The inflorescence essential oils of the red variant and pink variant of *A. purpurata* collected from Paulista, Brazil contained β-caryophyllene and β-pinene, respectively as the most dominant constituents, followed by notable amounts of linalool, α-pinene, bornyl acetate and 7-*epi*-selinene.[128] Similarly, β-pinene was found as the major constituent in the essential oil from the leaf, rhizome and flower oils of the red variant and pink variant of *A. purpurata* grown in Fiji.[35] Meanwhile, the leaf oil of *A. purpurata* from Rio de Janeiro, Brazil had β-pinene, α-pinene and *trans*-β-guaiene as its major compounds.[37]

2.14. *Alpinia breviligulata* (Gagnep.) Gagnep. Synonym: *Alpinia calcarata* var. *breviligulata* Gagnep., *Catimbium breviligulatum* (Gagnep.) P.H.Hô

A. breviligulata is commonly known as "Riêng lưỡi ngắn" in Vietnamese. This species usually grows along the streams in secondary forests. *A. breviligulata* is native to both China and Vietnam.[3] In traditional Vietnamese medicine, the rhizome of *A. breviligulata* is used to treat abdominal aches by drinking water with it or topically on the abdomen.[3] Several studies also reported the compositions of the essential oils of *A. breviligulata* collected from Hue, Vietnam. Accordingly, the seed oil of *A. breviligulata* contained (*E*,*E*)-farnesol, geranyl acetate and α-humulene as its major compounds.[19] The fruit peel oil was mainly characterized by the presence of β-pinene, α-terpineol and caryophyllene oxide.[19] The flower oil was made of β-pinene, β-caryophyllene and α-pinene,[129] while caryophyllene oxide, α-pinene and α-copaene were found to be the main compounds in its leaf oil.[130]

2.15. Other *Alpinia* species

Other *Alpinia* species have been reported much less due to their limited distribution and commercial interest. The rhizome oil of *A. aquatica* (Retz.) Roscoe from Kuching, Malaysia had β-pinene, α-humulene and aromadendrene as its dominant compounds, while its leaf oil contained notable amounts of germacrene D, β-pinene and sabinene. Also, α-humulene, germacrene D and β-caryophyllene were the main constituents in the pseudostem oil of this species.[131] The leaf oil of *A. murdochii* Ridl. from Pahang, Malaysia was composed of β-pinene, sabinene and terpinene-4-ol, while the rhizome oil of this plant possessed γ-selinene, (*E*,*E*)-farnesyl acetate and terpinen 4-ol as its main components.[132] The fruit and rhizome essential oils obtained from *A. rafflesiana* Wall. ex Baker grown in Selangor Darul Ehsan, Malaysia contained tetracosane as the most abundant constituent, followed by τ-cadinol, α-terpineol and (2*E*,6*E*)-farnesol. The leaf oil of this species was found to be rich in β-caryophyllene, caryophyllene oxide and (2*E*,6*E*)-farnesol, while the pseudostem oil was made of 1,8-cineole, β-myrcene and α-terpineol.[133] In addition, the major volatile components of *A. scabra* (Blume) Náves leaves collected from Pahang, Malaysia contained β-pinene, α-pinene and borneol as their major constituents, whereas the rhizome oil was obviously dominated by γ-selinene, α-selinene and α-terpineol.[132]

A. polyantha D. Fang, an *Alpinia* species collected from Nghe An, Vietnam, has been reported to possess a diverse chemical composition in the essential oils from its different plant parts. The leaf oil contained camphor, α-pinene and β-agarofuran as its main constituents. The stem oil was found to be rich in α-pinene, β-cubebene and β-agarofuran. The major compounds of the root oil were found to be β-cubebene, fenchyl acetate and β-maaliene, whereas the fruit oil was characterized by the

predominance of δ-cadinene, β-caryophyllene and β-pinene.[134] The chemical constituents of *A. macroura* K.Schum. essential oils, another *Alpinia* species from Nghe An, Vietnam, was also investigated. Accordingly, γ-terpinene, β-pinene and 1,8-cineole were found in its root and stem oils as their major compounds. The leaf oil of this species was mainly composed of 1,8-cineole, γ-terpinene and β-pinene. Meanwhile, β-caryophyllene was the most abundant constituent in the fruit and flower oils of *A. macroura*, followed by β-pinene, 1,8-cineole and sabinene.[135] In addition, the essential oil obtained from the fruits, leaves, stems and roots of *A. menghaiensis* S.Q.Tong & Y.M.Xia grown in Nghe An, Vietnam was dominated by β-pinene and α-pinene,[136,137] whereas γ-terpinene, 1,8-cineole and α-terpinene were the major compounds in the leaf, stem and root essential oils of *A. nantoensis* F.Y.Lu & Y.W.Kuo from Pu Mat National Park, Vietnam.[138] Meanwhile, the leaf and rhizome oils of *A. nantoensis* collected from Nantou County, Taiwan were dominated by camphor, camphene and β-pinene.[139]

The leaf, pseudostem and stem essential oils of *A. strobiliformis* T.L.Wu & S.J.Chen collected from Pu Hoat Natural Reserve, Vietnam consisted mainly of 1,8-cineole, γ-terpinene and β-pinene.[20] The leaf and stem oils of *A. maclurei* Merr. from Bach Ma National Park, Vietnam were dominated by β-pinene and α-pinene, whereas its root oil contained β-pinene, β-phellandrene and fenchyl acetate.[137] The diversity of the chemical compositions in the essential oils from different plant parts of *A. chinensis* (Retz.) Roscoe collected from Hue, Vietnam has been reported. Accordingly, the leaf oils of the species mainly comprised β-bisabolene, (*E*,*E*)-farnesylacetate and β-pinene. The root oil was found to be rich in caryophyllene oxide, γ-selinene and α-humulene, while (*E*,*E*)-α-farnesene, α-humulene and β-bisabolene constituted the bulk of the flower oil.[140] In addition, β-pinene was the most abundant compound in the leaf essential oils of *A. tonkinensis* Gagnep. and *A. globosa* (Lour.) Horan. collected from Ben En National Park, Vietnam, followed by (*E*)-β-ocimene and γ-terpinene (*A. tonkinensis*), α-gurjunene and (*Z*)-13-docosenamide (*A. globosa*).[141] Finally, the rhizome oil of *A. henryi* K.Schum. from Vinh Phuc, Vietnam contained 1,8-cineole, α-terpineol and β-pinene as its major compounds.[142]

The major volatile components of *A. kwangsiensis* T.L.Wu & S.J.Chen rhizome from Xishuangbanna, China included camphor, 1,8-cineole and β-pinene as their major constituents.[143] The leaf oil of *A. vittata* W.Bull from Rio de Janeiro, Brazil was mainly composed of β-pinene, *epi*-cubebol and α-pinene.[36] The essential oil from the aerial parts of *A. nutans* (L.) Roscoe from Uttarakhand, India possessed sabinene, 1,8-cineole and terpinen-4-ol as its major compounds, while the flower oil was mainly composed of terpinen-4-ol, γ-terpinene and sabinene.[144] Moreover, β-caryophyllene was found to be the most abundant constituent in the leaf and rhizome oils of *A. smithiae* M.Sabu & Mangaly from Kerala, India, followed by sabinene, β-myrcene and β-pinene.[145] Finally, the leaf oil of *A. carinata* Valeton collected from Gorakhpur, India consisted mainly of β-pinene, terpinen-4-ol and *p*-cymene.[146]

According to Table S1† with the major chemical patterns of *Alpinia* essential oils, the oils can be classified into the following groups.

(1) Oils dominated by monoterpenes and their oxygenated derivatives;

(2) Oil mainly with monoterpenes and sesquiterpenes; and

(3) Oils with an ester of carboxylic acid as the main compound.

It can be seen that, the oils dominated by monoterpenes and their oxygenated derivatives are from *A. allughas*, *A. aquatica*, *A. breviligulata*, *A. calcarata*, *A. chinensis*, *A. conchigera*, *A. galanga*, *A. hainanensis*, *A. katsumadai*, *A. laosensis*, *A. malaccensis*, *A. macroura*, *A. maclurei*, *A. menghaiensis*, *A. murdochii*, *A. mutica*, *A. nantoensis*, *A. nutans*, *A. pinnanensis*, *A. polyantha*, *A. purpurata*, *A. rafflesiana*, *A. scabra*, *A. speciosa*, *A. tonkinensis*, *A. strobiliformis*, *A. vittata* and *A. zerumbet*. The oils rich in both

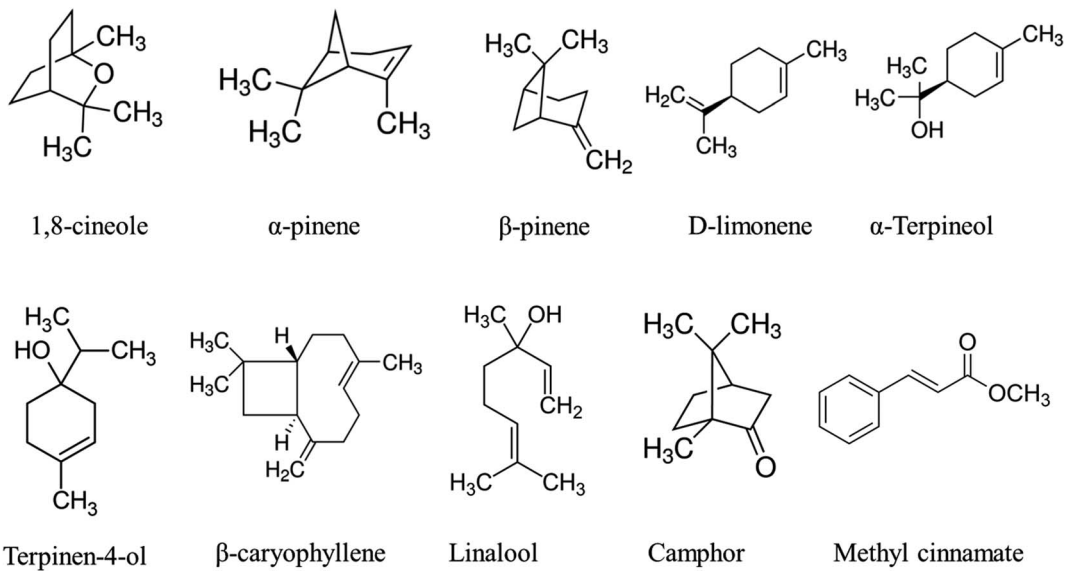

Fig. 1 Major chemical compounds isolated from the essential oils of *Alpinia* spp. exhibiting biological activities.

monoterpenes and sesquiterpenes are from *A. aquatica*, *A. blepharocalyx*, *A. globosa*, *A. nigra*, *A. officinarum*, *A. smithiae* and *A. zerumbet* var. *variegata*. The oils consisting of carboxylic acid as the main compound are from *A. malaccensis* var. *nobilis*. The chemical patterns of the *Alpinia* oils including their chemical composition and the number of major compounds vary significantly depending on the part of the plant and its habitat (Fig. 1).

3. Biological activities of *Alpinia* oils

Table S2† presents a summary of the biological activities of the various *Alpinia* essential oils. Generally, the *Alpinia* oils possess some important bioactivities such as antifungal, antibacterial, cytotoxic, anti-inflammatory, antioxidant, insecticidal, and larvicidal activities and slimming aromatherapy. This information gives evidence for the future applications of the species from the genus *Alpinia* in medicine and other relevant fields.

3.1. Antimicrobial activity

The essential oils isolated from *A. galanga* rhizomes grown in Samut Sakhon, Thailand could inhibit the growth of *Escherichia coli*, *Staphylococcus aureus* and *Salmonella typhimurium* with MIC values of 0.78, 1.56 and 0.78 μL mL^{-1}, respectively.[57] The rhizome oil of *A. galanga* from Central Java, Indonesia exhibited an antibacterial effect against *Bacillus subtilis*, *Escherichia coli*, *Staphylococcus aureus*, *Salmonella typhimurium* and *Vibrio cholera* with MIC values ranging from 62.5 to 1000 μg mL^{-1}.[59] The essential oils extracted from *A. galanga* grown in Phu Tho, Vietnam had an inhibitory effect on *Salmonella typhimurium*, *Bacillus cereus*, *Staphylococcus aureus* and *Escherichia coli*.[64] In addition, the essential oil from the leaf of *A. malaccensis* was reported to have antimicrobial activity against oral bacteria and fungi, including *Staphylococcus aureus*, Pseudomonas *aeruginosa*, *Candida albicans* and *Aspergillus niger* with MIC values of 1.95, 7.81, 5.5, 6.7 μL mL^{-1}, respectively.[68] The rhizome essential oil of *A. galanga* from Vietnam showed antimicrobial activity against *Staphylococcus aureus*, *Bacillus subtilis*, *Streptococcus faecalis*, *Escherichia coli*, *Proteus vulgaris*, *Salmonella enteritidis* and *Saccharomyces cerevisiae* with MIC values ranging from 2.5 to 20 μL mL^{-1}.[65]

The essential oils from the unripe fruit of *A. mutica* showed strong antimicrobial activities against *Staphylococcus aureus*, *Escherichia coli*, *Trichophyton mentagrophytes* and *Trichophyton rubrum*, followed by *Bacillus subtilis*, *Pseudomonas aeruginosa*, *Candida glabrata* and *Microsporum canis*.[93] Meanwhile, the ripe fruit oil of *A. mutica* had a potent antimicrobial effect against *S. aureus*, *Escherichia coli*, *M. canis*, *T. mentagrophytes* and *T. rubrum*, followed by *B. subtilis*, *P. aeruginosa* and *Candida glabrata.*93 Furthermore, the rhizome and fruit essential oils of *A. mutica* from southern India also exhibited moderate antibacterial activity against *Bacillus subtilis*, *Staphylococcus aureus*, *Staphylococcus epidermis*, *Staphylococcus simulans*, *Escherichia coli*, *Pseudomonas aeruginosa*, *Proteus mirabilis*, *Vibrio cholerae*, *Klebsiella pneumonia* and *Salmonella typhi*.[96] Similarly, the unripe and ripe fruit oils extracted from another *Alpinia* species grown in Peninsular Malaysia, *A. latilabris*, showed strong antimicrobial effects against *Staphylococcus aureus*, *Trichophyton mentagrophytes* and *Candida glabrata*, followed by *Escherichia coli*, *Bacillus subtilis*, *Pseudomonas aeruginosa*, *Microsporum canis*, *Trichophyton mentagrophytes* and *Trichophyton rubrum*.[93] In addition, the leaf oil of *A. latilabris* from Pahang, Malaysia possessed potent antibacterial activity against *Klebsiella pneumonia* and *Staphylococcus aureus*, followed by *Bacillus subtilis*, *Acinetobacter baumannii*, *Pseudomonas aeruginosa* and *Salmonella typhii*.[22]

Additionally, the essential oil from the flower of *A. zerumbet* from Martinique island, France showed potent antibacterial activity against *Pseudomonas aeruginosa*, *Staphylococcus aureus*, *Bacillus cereus*, *Escherichia coli*, *Listeria innocua* and *Salmonella arizonae*. It also showed strong antifungal effects against *Aspergillus niger* and *Candida albicans*.[39] Meanwhile, the leaf oil of *A. zerumbet* grown in Rio de Janeiro, Brazil presented interesting antimicrobial activity against *Escherichia coli*, *Staphylococcus aureus*, *S. epidermidis*, *Candida albicans* and *Cryptococcus neoformans*.[147] In addition, the leaf oil of *A. zerumbet* collected from Ceara, Brazil was active against many bacterial strains, including *Staphylococcus aureus*, *Bacillus cereus*, *Escherichia coli*, *Pseudomonas aeruginosa*, *Aeromonas caviae*, *Klebsiella pneumonia*, *Shigella flexneri*, *Vibrio cholerae* and *Listeria monocytogenes* with MIC values of 32, 512, 128, 1024, 256, 256, 512, 1024 and 256 μL mL^{-1}.[38]

The essential oil from the rhizomes of *A. officinarum* collected from ten different habitats in China, including Sanming, Guilin, Yulin, Guigang, Qiandongnan, Panzhihua, Xishuangbanna, Gaozhou, Xuwen and Bozhou possessed antimicrobial activity. Accordingly, all ten samples showed potent antibacterial activity against two Gram positive bacteria, *Staphylococcus aureus* and *Bacillus subtilis*, while the oils from Yulin and Xishuangbanna could inhibit *Escherichia coli*, and only the oil sample from Yulin was found to be effective against *Pseudomonas aeruginosa*. Furthermore, four oil samples also showed strong antifungal effects against *Candida albicans*.[73] The inflorescence oil of *A. purpurata* also showed strong antibacterial activity against Gram-positive and Gram-negative bacteria such as *Staphylococcus aureus* and *S. epidermis* with MIC values of 10 μg mL^{-1}, while this sample presented weak inhibition against *Pseudomonas aeruginosa*, *Escherichia coli*, *Salmonella* sp., *Shigella* sp., *Klebsiella* sp. and *Proteus* sp. with MIC values of 1000 μg mL^{-1}.[128] The leaf, pseudostem, rhizome and fruit oils of *A. rafflesiana* grown in Selangor, Malaysia have been reported to possess antimicrobial and antifungal activities by using the MIC test.[133] Accordingly, the leaf oil showed strong antimicrobial activity against *Staphylococcus aureus* and *Escherichia coli* with MIC values of 7.81 and 15.63 μg mL^{-1}, respectively, and weak effects against *Pseudomonas putida* and *C. albicans* with MIC values of 125 μg mL^{-1}. The pseudostem oil possessed potent antimicrobial activities against *S. aureus* and *Bacillus subtilis* (MIC = 31.25 μg mL^{-1}), moderate effects against *E. coli* (MIC = 62.5 μg mL^{-1}) and low activities against *Pseudomonas aeruginosa*, *P. putida*, *Candida albicans* and *Aspergillus niger* (MICs = 125 μg mL^{-1}). The fruit oil was moderately active against *S. aureus* (MIC = 31.25 μg mL^{-1}), *E. coli*, *B. subtilis*, *P.*

aeruginosa, *P. putida*, *C. albicans* and *A. niger* (MICs = 125 μg mL^{-1}). Finally, the rhizome oil showed weak antifungal activity against *A. niger* (MIC = 125 μg mL^{-1}), while it was inactive against all the tested bacteria and *C. albicans*.[133]

The seed and leaf oils from *A. speciosa* grown in Taiwan exhibited strong broad-spectrum antimicrobial activity against *Malassezia pachydermatis*, *Candida albicans*, *Staphylococcus aureus* and *Escherichia coli*.[41] The rhizome oil of *A. speciosa* collected from Dehradun, India exhibited strong antibacterial activity against *Bacillus subtilis* and *Salmonella typhimurium*, followed by *Micrococcus luteus*, *Streptococcus mutans*, *Staphylococcus aureus* and *Pseudomonas aeruginosa*.[43] The leaf and rhizome essential oils of *A. scabra* were also demonstrated to exhibit potent antimicrobial effects against *Staphylococcus aureus* ATCC 29213, *S. aureus* ATCC 33591, *S. aureus* ATCC 700699, *S. aureus* VISA24, *S. aureus* VRSA156, *Candida albicans*, *C. glabrata*, *Microsporum canis* and *Trichophyton rubrum*.[132] Moreover, the leaf oil of *A. speciosa* grown in Martinique, France showed potent antibacterial effects against *Staphylococcus aureus*, *Escherichia coli* and *Mycobacterium smegmatis* and moderate effects against *Streptococcus faecalis* and *Pseudomonas aeruginosa*, whereas this sample presented strong antifungal activity against *Candida albicans*, *Aspergillus niger*, *Cylindrocarpon mali*, *SotIyfis cinerea*, *Stereum purpureum* and *Sclerotinia sclerotiorum*.[24]

The oils from the leaf and rhizome of *A. murdochii* showed antifungal activity against *Candida albicans*, *C. glabrata*, *Microsporum canis* and *Trichophyton rubrum* with MIC values of 2.5 mg mL^{-1}, while MIC values of 2.5 and 0.63 mg mL^{-1}, 2.5 and 2.5 mg mL^{-1}, 2.5 and 0.63 mg mL^{-1}, 1.25 and 0.08 mg mL^{-1}, 0.31 and 0.04 mg mL^{-1} were recorded for the leaf and rhizome oils towards five *S. aureus* strains (ATCC 29213, ATCC 33591, ATCC 700699, VISA24, VRSA156), respectively.[132] Furthermore, the rhizome, leaf, seed and flower oils of *A. nigra* from India showed antibacterial activity against 3 Gram positive bacteria (*Staphylococcus aureus*, *Bacillus cereus* and *Listeria monocytogenes*) and 4 Gram negative bacteria (*Escherichia coli*, *Salmonella paratyphi*, *E. coli* enterotoxic and *Yersinia enterocolitica*) with MIC and MBC values ranging from 3.12 to 6.25 μL mL^{-1}.[102] The rhizome oil of *A. nigra* from India also possessed potent antimicrobial effects against *Pseudomonas aeruginosa*, followed by *Escherichia coli*, *Staphylococcus aureus*, *Candida albicans* and *Aspergillus niger*.[104]

The aerial part and flower essential oils of *A. nutans* from India showed strong antibacterial activities against *Staphylococcus aureus*, *Pasteurella multocida*, *Salmonella enterica enterica*, *Shigella flexneri* and *Escherichia coli*.[144] Moreover, the leaf oil of *A. malaccensis* var. *nobilis* from Malaysia showed strong inhibition of the growth of *Cryptococcus neoformans* and *Candida tropicalis* with IC_{50} values of 1.97 and 1.75 mg mL^{-1}, respectively. Meanwhile, this sample possessed moderate antibacterial effects against *Bacillus subtilis*, *Staphylococcus aureus*, *Escherichia coli*, *Klebsiella pneumonia*, *Pseudomonas aeruginosa*, and *Salmonella typhii*.[22] Finally, the leaf essential oils of two *Alpinia* species from Vietnam, including *A. globosa* and *A. tonkinensis*, had an inhibitory effect on *Escherichia coli*, *Staphylococcus aureus* subsp. *aureus*, *Fusarium oxysporum* and *Saccharomyces cerevisiae*.[141]

The antimicrobial activities of the essential oils obtained from different parts of *Alpinia* plants are established by the following major compounds, including α-pinene, 1,8-cineole, β-pinene, terpinen-4-ol, β-caryophyllene, linalool, D-limonene, β-myrcene, *p*-cymene and camphor. Among them, α-pinene, 1,8-cineole and linalool possess strong antimicrobial activities. It has been reported that α-pinene isolated from the leaf oil of *A. speciosa* grown in Martinique, France showed a strong antimicrobial effect against *Escherichia coli* (MIC = 2 mg mL^{-1}), *Candida albicans*, and *Sclerotinia sclerotiorum* (MICs = 0.25-0.5 mg mL^{-1}), followed by *Mycobacterium smegmatis*, *Cylindrocarpon mali*, *Staphylococcus aureus*, *Streptococcus faecalis*, *Pseudomonas aeruginosa*, *Aspergillus niger* and *Stereum purpureum* with MIC values of more than 4 mg mL^{-1}.[24] Furthermore, α-pinene showed antibacterial activities against Staphylococcus *aureus* (MIC = 20 μL mL^{-1}), *S. epidermidis* (MIC = 5 μL mL^{-1}), Streptococcus *pyogenes* (MIC = 10 μL mL^{-1}) and *S. pneumonia* (MIC = 5 μL mL^{-1}).[148] Additionally, α-pinene had antifungal activities against *Candida albicans*, Cryptococcus *neoformans* and Rhizopus *oryzae* with MIC values of 3.13, 117 and 390 μg mL^{-1}, respectively.[149] 1,8-Cineole isolated from the leaf oil of *A. speciosa* grown in Martinique, France showed potent antimicrobial activity against *Mycobacterium smegmatis* (MIC = 2–4 mg mL^{-1}) and *Cylindrocarpon mali* (MIC = 0.5–1 mg mL^{-1}), followed by *Staphylococcus aureus*, *Escherichia coli*, *Streptococcus faecalis*, *Pseudomonas aeruginosa*, *Candida albicans*, *Aspergillus niger*, *SotIyfis cinerea*, *Stereum purpureum* and *Sclerotinia sclerotiorum* with MIC values of more than 4 mg mL^{-1}.[24] Furthermore, 1,8-cineole had antimicrobial activity against microorganisms grown in suspension and biofilm. Accordingly, 1,8-cineole showed the potent antimicrobial properties against *Staphylococcus aureus*, *Pseudomonas aeruginosa*, *Escherichia coli* and *Candida albicans* grown in suspension and biofilm with MIC values of 16 and 512 mg L^{-1}, 256 and 512 mg L^{-1}, 64 and 128 mg L^{-1}, and 8 and 4 mg L^{-1}, respectively whereas MBC values of 256 and 512 mg L^{-1}, 256 and 512 mg L^{-1}, 64 and 256 mg L^{-1}, 64 and 8 mg L^{-1} respectively were shown by 1,8-cineole towards the same microorganisms grown in suspension and biofilm.[150] Linalool has been reported to possess strong antibacterial and antifungal activities. This compound can inhibit the growth of Staphylococcus *aureus*, Pseudomonas *aeruginosa*, *Escherichia coli* and *Candida albicans*.[151] Also, linalool displayed activity against many periodontopathogens, including *Porphyromonas gingivalis*, *Prevotella intermedia*, *P. nigrescens*, *Fusobacterium nucleatum* subsp. *nucleatum*, *F. nucleatum* subsp. *polymorphum*, *F. nucleatum* subsp. *vincentii*, *F. nucleatum* subsp. *fusiforme*, *F. nucleatum* subsp. *animalis*, *Streptococcus mutans*, *S. sobrinus* and *Aggregatibacter actinomycetemcomitans*.[152] In addition, linalool showed strong activity against *Pasteurella multocida*[153] and *Listeria monocytogenes*.[154]

In addition, β-pinene, terpinen-4-ol, β-caryophyllene, D-limonene, β-myrcene, *p*-cymene and camphor also contribute to the antimicrobial properties of *Alpinia* essential oils. Namely, β-pinene has been shown to exhibit antibacterial activity against Gram-positive bacteria that cause the potential infectious

endocarditis, including Staphylococcus *aureus*, *S. epidermidis*, Streptococcus *pyogenes* and *S. pneumonia* with MIC values of 20 μL mL^{-1}.[148] Also, β-pinene exhibited antifungal activity against *Candida albicans*, Cryptococcus *neoformans* and Rhizopus *oryzae* with MIC values of 187, 234 and 780 μg mL^{-1}, respectively.[149] Terpinen-4-ol has been shown to be an antibacterial and antibiofilm agent against *Staphylococcus aureus*. It showed potent antibacterial activity against ten *S. aureus* strains, including ATCC-25923, ATCC-13150, LM-02, LM-40, LM-45, LM-116, LM-222, LM-232, LM-297 and LM-314 with MIC and MBC values of 0.25% and 0.5% (v/v), respectively.[155] β-caryophyllene has been reported to possess antimicrobial activities against *Bacillus cereus*, *B. subtilis*, *Staphylococcus aureus*, *Escherichia coli*, Klebsiella *pneumonia*, Pseudomonas *aeruginosa*, Aspergillus *niger*, *Penicillium citrinum*, Rhizopus *oryzae* and Trichoderma *reesei* with MIC values ranging from 4 to 14 μM.[156] D-Limonene, a bioactive component, has been shown to be biologically active against a wide range of microorganisms. This compound was active against *Escherichia coli*, *Staphylococcus aureus*, *Bacillus subtilis* and *Saccharomyces cerevisiae* with MIC values of 12.5, 3.2, 12.5 and 6.3 μg mL^{-1}, respectively.[157] β-myrcene has been reported to possess antibacterial activities against *Enterococcus faecalis*, *Streptococcus salivarius* and *S. sanguinis* with MIC values of 2.0, 0.4 and 1.5 mg mL^{-1}, respectively.[158] Finally, *p*-cymene and camphor isolated from the leaf oil of *Alpinia speciosa* grown in Martinique, France showed antimicrobial activity against many bacterial and fungal strains, including *Escherichia coli*, *Mycobacterium smegmatis*, and *Cylindrocarpon mali* followed by *Staphylococcus aureus*, *Streptococcus faecalis*, *Pseudomonas aeruginosa*, *Candida albicans*, *Sclerotinia sclerotiorum*, *Aspergillus niger*, *SotIyfis cinerea* and *Stereum purpureum*.[24]

The antimicrobial mechanisms of the above-mentioned compounds can be attributed to their lipophilicity and/or hydrophobicity and the presence of a hydroxyl group (–OH), playing a key role in the sequential inhibition of common biochemical pathways, inhibition of protective enzymes and the use of cell wall active agents to enhance the uptake of other antimicrobials.[159,160] Although several components isolated from *Alpinia* essential oil were found to be effective against various microorganisms, the mechanism of the antimicrobial activity using the initial *Alpinia* essential oil is still unclear.

3.2. Antioxidant effect

The antioxidant activity of the essential oil of *A. galanga* collected from Phu Tho, Vietnam was determined using 1,1-diphenyl-2-picrylhydrazol (DPPH) with a percentage inhibition of 47.15%.[64] The essential oils obtained from the leaves of *A. malaccensis* from Odisha, India showed strong radical-scavenging activities, as evaluated using the DPPH and 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) assays, with IC_{50} values of 18.26 μg mL^{-1} and 20 μg mL^{-1}, respectively.[68] Meanwhile, the antioxidant effect of the essential oil from the leaf of *A. malaccensis* var. *nobilis* from Malaysia was investigated using the DPPH radical scavenging test (IC_{50} = 32.67 mg mL^{-1}), ABTS (GAE = 26.59 mg GAE per g) and ferric reducing ability of plasma (FRAP) (TE = 24.56 M TE per g) analysis.[22] In addition, four plant parts of *A. nigra* collected from Guwahati, India showed strong radical-scavenging activities, as evaluated by the DPPH assay. Accordingly, the rhizome oil was found to be the best antioxidant with an IC_{50} value of 36.83 μg mL^{-1}, followed by the seed, leaf and flower oils with IC_{50} values of 40.11, 42.13 and 43.41 μg mL^{-1}, respectively.[102] The antioxidant effect determined using DPPH and ABTS assays was investigated for the leaf essential oil of *A. nigra* from West Bengal, India with IC_{50} values of 4.05 and 15.55 μg mL^{-1}, respectively.[104] Moreover, the seed and leaf essential oil of *A. speciose* grown in Chu-Tung, Taiwan showed potent DPPH radical-scavenging activities. At doses of 0.25%, 0.5% and 1%, the seed oil was found effective against the DPPH radical scavenger with the percentage inhibition of 58.0%, 59.9% and 63.1%, whereas that of the leaf oil was 50%, 56.4% and 67%, respectively.[41]

Kuraya *et al.*[34] showed the relationship among the antioxidant activity, chemical composition and yield of the essential oil isolated from *A. zerumbet* leaves collected from various locations in Japan. Their report demonstrated that the antioxidant activity and yield of the oils varied significantly between individuals and collecting seasons, and the yields of the essential oils and their antioxidant activity had an inverse correlation. Furthermore, the antioxidant effects of the *A. zerumbet* oils were dependent on highly polar compounds, while the chemical compounds in each plant was not affected by the season or its growth habitat. Thus, this suggests that the essential oils from different individuals of *A. zerumbet* possess different antioxidants. This can be the useful information for the selection of lineages of *A. zerumbet* to optimize the production of compounds with particular medicinal value.[34] In addition, the fruit rind and rhizome essential oils from India showed antioxidant activities, as evaluated using the DPPH radical scavenging assay. Accordingly, the fruit rind oils possessed a stronger antioxidant effect with 56.5% inhibition at a dose of 20 μg mL^{-1} (IC_{50} value of 15.17 μg mL^{-1}), while 8.9% inhibition was shown by the rhizome oil at the same oil concentration.[96] Finally, the leaf essential oil of *A. latilabris* from Malaysia was investigated using three different methods. Accordingly, the IC_{50} using the DPPH free radical scavenging assay was 54.33 mg mL^{-1}, whereas measurements by the ABTS and FRAP assays provided a GAE value of 14.47 mg GAE per g and TE value of 17.51 M TE per g, respectively.[22] The antioxidant efficacy of *Alpinia* essential oil is due to the presence of β-caryophyllene, as reported in a recent study.[156] Accordingly, β-caryophyllene showed antioxidant activities with IC_{50} values of 1.25 and 3.23 μM for the DPPH and FRAP assays, respectively. However, the antioxidant reaction mechanisms of β-caryophyllene has not been thoroughly studied to date and there is almost no literature on the transformation of this compound after it reacts with free radicals under diverse conditions.

3.3. Larvicidal activity

The flower oil of *A. zerumbet* from Le Morne Rouge, France presented repellent and irritant activities against *Aedes aegypti* at a dose of 0.1% and interesting toxic activity at 1%.[39] Similarly,

Cavalcanti *et al.*[161] demonstrated that the leaf and branch of *A. zerumbet* collected from Brazil possessed larvicidal activity against *Ae. aegypti* with an LC_{50} value of 313 ppm.[161] Moreover, the leaf essential oil of *A. speciosa* grown in Brazil had larvicidal activity against *Ae. Aegypti*. Accordingly, the oil exhibited a larvae mortality of 100% after 5 min of its application at doses of 2.0 and 2.5 μL mL^{-1}, and the lethal concentration values for 50% (LC_{50}) and 90% (LC_{90}) of 0.94 and 1.2 μL mL^{-1}, respectively.[161] The leaf and seed oils of *A. speciosa* from Chu-Tung, Taiwan have been reported to exhibit mosquito larvicidal activity. The leaf oil showed larvicidal activity against *Ae. Aegypti* with LC_{50} values of 64 and 32 ppm after 2 h and 24 h, while the LC_{50} values were 125 and 87 ppm, respectively, for the seed oil towards the same mosquito.[41] The essential oils of pink and red variants of *A. purpurata* from Paulista, Brazil showed potent larvicidal activities against *Ae. aegypti* with LC_{50} values of 71.5 and 80.7 ppm, respectively.[128] The oils isolated from different plant parts (leaf, rhizome, flower and seed) of *A. nigra* exhibited mosquito larvicidal activity. The leaf, rhizome and seed oils of *A. nigra* exhibited 100% mortality at the dose of 125 ppm. Furthermore, the oil from four plant parts also presented biting deterrent activity against female *Ae. Aegypti*. The proportion not biting for the flower, rhizome, leaf and seed oils was 49%, 52%, 58% and 62% at dose of 10 μg cm^{-2}.[102]

The larvicidal activity of *Alpinia* essential oil is ascribed to α-pinene, β-pinene, and β-caryophyllene. It has been found that α-pinene obtained from the essential oil of *Alpinia purpurata* exhibited larvicidal effects against fourth stage larvae of *Aedes aegypti*. The compound could inhibit against this mosquito with 12%, 27%, 33%, 45 and 67% mortality at doses of 150, 200, 250, 300 and 400 ppm, respectively.[128] The β-pinene from *Alpinia purpurata* oil has been shown to possess larvicidal activity against *Ae. aegypti*. At doses of 150, 200, 250, 300 and 400 ppm, β-pinene was found to be effective against this mosquito with 35%, 40%, 65%, 78% and 90% mortality, respectively.[128] β-Caryophyllene from *Alpinia purpurata* oil has been shown to possess weak larvicidal activity against *Ae. aegypti*. At doses of 150, 200, 250, 300 and 400 ppm, the compound presented larvicidal effects against this mosquito with 3.3%, 3.3%, 3.3%, 5.0% and 3.3% mortality, respectively.[128] However, to date, the mechanism of larvicidal activity of essential oils and of *Alpinia* essential oil and their constituents in particular has not been fully reported. Many researchers have supposed that the mechanism of larvicidal activity can be due to the inhibition of the acetylcholinesterase enzyme, a similar neurotoxic effect produced by organophosphorus and carbamate insecticides.[162–164]

3.4. Insecticidal activity

The essential oils derived from seeds of *A. katsumadai* grown in Guangxi, China showed insecticidal effects against *Tribolium castaneum*, *Liposcelis bostrychophila* and *Lasioderma serricorne* with LD_{50} values of 52.6, 35.6 and 17.4 μg cm^{-2}, respectively. Similarly, the essential oil of *A. kwangsiensis* rhizomes from Xishuangbanna, China was found to possess strong contact toxicity against *L. serricorne* with an LC_{50} value of 24.59 μg per adult, while the fumigant toxicity had an LC_{50} value of 9.91 μg mL^{-1} air.[143] Also, the rhizome oil of *A. galanga* from Yunnan, China showed high fumigant toxicity against *L. serricorne* adults with an LC_{50} value of 3.5 mg L^{-1}, whereas the LD_{50} value of 12.2 μg per adult was shown by the contact toxicity towards the same beetle.[60] Insecticidal activity against *Callosobruchus maculatus* has been reported in the oil of *A. calcarata* rhizome with LC_{50} values of 0.685 and 0.141 g L^{-1} for the fumigant toxicity and contact toxicity, respectively.[21]

Souza *et al.*[36] showed the insecticidal activity against *Rhodnius nasutus* (a vector of chagas disease) of the leaf oils of two *Alpinia* species grown in Rio de Janeiro, Brazil, including *A. zerumbet* and *A. vittata*. In the first 10 min of application, the *A. vittata* oil at 125 g mL^{-1} showed 73.3% of mortality, while 83.3% mortality was recorded in *A. zerumbet* oil.[36] In addition, the rhizome essential oil of *A. blepharocalyx* from China showed strong insecticidal effects against *Lasioderma serricorne* with an LD_{50} value of 15.02 μg per adult (contact toxicity) and LC_{50} value of 3.83 mg L^{-1} (fumigant toxicity).[123] Maize weevil (*Sitophilus zeamais*) is one of the most cosmopolitan pests of stored grains, including rice (*Oryza sativa*), wheat (*Triticum* spp.), triticale (*Triticum aestivum* L. and *Secale cereale*) and barley (*Hordeum vulgare*).[165] De Lira *et al.*[166] investigated the fumigant toxicity of the inflorescence essential oil obtained from *Alpinia purpurata* against *Sitophilus zeamais* adults with an LC_{50} value of 41.4 mL per L in air.[166]

The insecticidal property is mainly related to β-pinene, α-pinene, methyl cinnamate, α-terpineol and camphor as the major compounds presented in *Alpinia* essential oils. Accordingly, β-pinene isolated from *Alpinia kwangsiensis* oils displayed insecticidal effects against *Lasioderma serricorne* with an LC_{50} value of 35.69 μg mL^{-1} air for fumigant toxicity and LD_{50} value of 65.87 μg per adult for contact toxicity.[143] Similarly, β-pinene as the major compound isolated from *Alpinia galanga* oil showed insecticidal effects against *L. serricorne* with an LD_{50} value of 65.6 μg per adult for contact toxicity and LC_{50} value of 29.0 mg L^{-1} air for fumigant toxicity.[60] Souza *et al.*[36] showed that the essential oil from *Alpinia vittata* contained β-pinene as the most abundant compound, which was topically applied on *Rhodnius* nasutus fifth-instar nymphs with 100% mortality within the first 10 min of application at a dose of 44 μg mL^{-1}.[36] Similarly, α-pinene has been recorded as a major compound of *Alpinia galanga* oil. The compound had insecticidal effects against *L. serricorne* with an LD_{50} value of 76.8 μg per adult for contact toxicity and LC_{50} value of 38.1 mg L^{-1} air for fumigant toxicity.[60] Methyl cinnamate, the most abundant compound of *Alpinia katsumadai* oil, has been reported to possess potential insecticidal activities against three stored product insects, including *Tribolium castaneum*, *Liposcelis bostrychophila* and *Lasioderma serricorne*, with LD_{50} values of 5.0 μg per adult, 2.2 μg per adult and 23.5 μg cm^{-2}, respectively.[25] α-Terpineol as a major compound of *Alpinia galanga* oil exhibited insecticidal activities against *Lasioderma serricorne* with an LD_{50} value of 13.3 μg per adult for contact toxicity and LC_{50} value of 2.8 mg L^{-1} air for fumigant toxicity.[60] Camphor isolated from the essential oil of *Alpinia kwangsiensis* has been reported to possess strong insecticidal activity against *Lasioderma serricorne*

adults. This compound could inhibit by two potential contacts with an LC_{50} value of 2.91 mg L^{-1} air for contact toxicity while an LD_{50} value of 11.30 μg per adult was recorded for fumigant toxicity.[143] Several studies indicated that the above-mentioned compounds can affect the cuticle of insects, thereby favoring the insecticidal action of some synthetic compounds. In addition, they also affect the components of the epicuticular waxes of insects, which could be a mechanism of pesticidal activity.[167]

3.5. Cytotoxic activity

The essential oil isolated from the whole plant of *A. calcarata* collected from Sri Lanka has been reported to exhibit cytotoxic activities against several cell lines, including RAW264.7, HaCaT, HepG2 and IEC-6 cells. At a dose of 100 μg mL^{-1}, the oil caused a reduction in the viability of the above-mentioned cell lines.[23] In another study, Zhang *et al.*[73] showed the cytotoxic activities of *A. officinarum* essential oils collected from ten locations in China. Accordingly, the rhizome oils from different habitats such as Sanming, Guilin, Yulin, Guigang, Qiandongnan, Panzhihua, Xishuangbanna, Gaozhou, Xuwen and Bozhou showed cytotoxic activities against BV2 cells with IC_{50} values of 211.07, 269.22, 769.06, 258.08, 231.79, 552.49, 305.77, 239.95, 233.85 and 302.37 μg mL^{-1}, respectively.[73] Moreover, the rhizome and fruit rind essential oils of *A. mutica* from India showed cytotoxic activities against Dalton's lymphoma ascites (DHA). Accordingly, the fruit rind oil possessed a strong effect against DHA cells with a CD_{50} (curative dose) value of 0.06 μg mL^{-1}, while the rhizome oil showed weaker activity with a CD_{50} value of 13 μg mL^{-1}.[96] Also, at dose of 20 μg mL^{-1}, the rhizome oil of *A. nigra* from India was highly cytotoxic to MCF-7 and HeLa cells with 70.9% and 79% inhibition, while 50% and 60% inhibition, respectively, were shown by the leaf oil towards the same cells.[103]

The cytotoxic activity of *Alpinia* essential oil can be due to the presence of terpinen-4-ol, linalool, β-caryophyllene, and D-limonene. Terpinen-4-ol has been shown to exhibit moderate cytotoxicity against colorectal, pancreatic, prostate and gastric cancer cells. At a dose of 10%, this chemical component showed 90% growth inhibition towards cancer cells.[168] Besides, the cytotoxicity of linalool against human prostate cancer cells (DU145) has also been reported. At doses of 20, 40 and 80 μM, the compound induced sub-G1 cell cycle arrest, and therefore DNA damage.[169] Furthermore, linalool has been demonstrated to possess potential anti-cancer properties against some cancer cell lines, including HepG2 (IC_{50} = 290 μM), A549 (IC_{50} = 438 μM), SW620 (IC_{50} = 222 μM), T-47D (IC_{50} = 224 μM),[170] RPMI 7932 (IC_{50} = 5.60 μM),[171] HeLa (IC_{50} = 2.59 μM), U937 (IC_{50} = 11.02 μM).[172] β-Caryophyllene possessed enhanced activities based on the anticancer effects of other compounds such as α-humulene, isocaryophyllene and paclitaxel against MCF-7, DLD-1 and L-929 human tumour cells.[173] β-Caryophyllene also had cytotoxicity against some human cancer cell lines, including HCT 116, PANC-1, HT-29, ME-180, PC3, K562, MCF-7, CCD-18Co, NIH/3T3-L1 and RGC5 with IC_{50} values of 19, 27, 63, 95, 104, 105, 285, 612, 530 and 156 μM, respectively.[156] Finally, D-limonene has been proven to have bioactivity against breast cancer. After limonene intervention, cyclin D1 expression was reduced by 22% in tumor tissue, while its effect was hardly found in Ki67 tissue, cleaved caspase-3 expression, serum leptin, adiponectin, TGF-b1, insulin-like growth factor binding protein-3 (IGFBP-3) and interleukin-6 (IL-6) levels.[174] The main mechanism for the cytotoxic effects of the reported constituents includes induction of cell death by apoptosis and/or necrosis, cell cycle arrest, and loss of key organelle function.[175]

3.6. Anti-inflammatory activity

The essential oil extracted from the leaves of *A. calcarata* collected from Tamil Nadu, India exhibited a good anti-inflammatory effect in a paw edema model in albino Wistar rats. At doses of 200 mg kg^{-1} and 300 mg kg^{-1}, the oil could inhibit *in vivo* anti-inflammatory capacity with the percentage inhibition of around 75.78% and 78.15%, respectively.[82] Furthermore, the essential oils from the leaves and rhizomes of *A. calcarata* grown in Sri Lanka showed anti-inflammatory activity on COX enzymes (COX-1 and COX-2). At doses of 0.5, 5.0 and 50 μg mL^{-1}, the rhizome oil possessed the anti-inflammatory effects on COX-1 enzyme with a percentage inhibition of 19.45%, 28.5% and 76.47%, while that of 10.4%, 27.14% and 65.61%, respectively, was shown by the leaf oil towards the same enzyme. Meanwhile, the COX-2 enzyme was inhibited by the rhizome oil by about 21.4%, 36.3% and 85.7% at doses of 0.5, 5.0 and 50 μg mL^{-1}, while the leaf oil had an anti-inflammatory effect with the percentage inhibition of 5.84%, 27.92% and 70.12%, respectively.[23] The anti-inflammatory properties of the essential oils of *A. officinarum* rhizome collected from different habitats in China, including Sanming, Guilin, Yulin, Guigang, Qiandongnan, Panzhihua, Xishuangbanna, Gaozhou, Xuwen and Bozhou were determined using a 12-*O*-tetradecanoylphorbol-13-acetate (TPA)-induced mouse ear edema assay. At a dose of 100 mg kg^{-1}, the *A. officinarum* oils from these ten habitats showed anti-inflammatory activity on the TPA-induced mouse ear edema with the percentage inhibition of 72.16%, 76.20%, 91.62%, 81.14%, 64.42%, 70.96%, 82.34%, 63.17%, 79.34% and 34.43%, respectively.[73]

The anti-inflammatory properties of *Alpinia* essential oils correspond to β-caryophyllene, linalool, and γ-terpinene. It has been reported that β-caryophyllene possesses anti-inflammatory activity, which was effective in reducing platelet activating factor-, bradykinin- and ovalbumin-induced mouse paw oedema.[176] Linalool exhibited anti-inflammatory activities in LPS-stimulated RAW 264.6 cells by blocking the activation of the NF-κB pathway and the mitogen-activated protein kinase (MAPK) pathway.[177] Moreover, LPS-induced inflammation in BV2 microglia cells was suggested to be inhibited by linalool through both the NF-κB pathway and the activation of the erythroid 2-related factor/heme oxygenase-1 (Nrf2/HO-1) signaling pathway.[178] Linalool exhibited hypocholesterolemic effects in high-fat fed C57BL/6J mice and HepG2 cells. At a dose of 0.57 mg per mouse per day, linalool was sufficient to reduce plasma cholesterol levels in mice.[179] Ramalho *et al.*[180] demonstrated that γ-terpinene possessed the anti-inflammatory

effects. At a dose of 25 mg kg^{-1} or 50 mg kg^{-1}, γ-terpinene could decrease the paw edema in mice within one hour by 67.3% or 53.3%, respectively.[180]

3.7. Slimming aromatherapy

Aromatherapy, a holistic healing treatment involving the use of natural products from plants, has been recently explored as a slimming alternative medicine. Notably, the essential oils isolated from plants have high potential as slimming aromatherapy.[181,182] The essential oil of *A. galanga* grown in Indonesia and its two fractions, *n*-hexane and ethyl acetate, have been reported to exhibit a slimming aromatherapy effect through *in vivo* observation in adult male Sprague Dawley rats.[63] Accordingly, the average body weights of a male rat at pretreatment and post treatment with *A. galanga* oil and the *n*-hexane and ethyl acetate fractions were 283.2 g and 244.8 g, 287.7 g and 266.8 g, 289.0 g and 258.9 g, respectively. Additionally, the total plasma cholesterol and triglyceride concentration in Sprague Dawley rats after 5 weeks of treatment with *A. galanga* oil and *n*-hexane and ethyl acetate fractions were recorded. Consequently, the rats treated with oils had a total plasma cholesterol and triglyceride concentration of 106.6 and 47.97 mg dL^{-1}, whereas those treated with the *n*-hexane and ethyl acetate fractions had values of 79.9 and 37.83 mg dL^{-1}, 83.5 and 43.51 mg dL^{-1}, respectively.[63]

3.8. Other biological activities

Patil *et al.*[183] demonstrated that the essential oil of *A. galanga* collected from Belgaum, India showed anti-asthmatic activity in mice. Accordingly, *A. galanga* oil had a beneficial effect not only on histamine-induced bronchospasm in Guinea pigs but also on ovalbumin-induced allergic airway inflammation in a mouse model.[183] Cândido *et al.*[184] reported that the association of kinesiotherapy with *A. zerumbet* essential oils could improve the muscle recruitment of people with spasticity who needed to perform motor rehabilitation. This result showed a significant decrease in the spasticity of pathological legs during the best muscle contraction after application of essential oil at doses of 0.5 mL/2 kg and 0.05 mL/4 kg.[184] Additionally, the inhibition of mushroom tyrosinase by the oils isolated from the seeds and leaves of *A. speciosa* was evaluated. At a dose of 1000 ppm, the seed oils showed 74% inhibition of mushroom tyrosinase, while the leaf oil revealed an 81% inhibitory effect.[41] The essential oil isolated from **the** pseudostems, leaves and rhizomes of *A. aquatica* exhibited weak tyrosinase inhibitory activity with the percentage inhibition of 1.4%, 6.6% and 9.5%, repectively.[131] In a previous study, Cavalcanti and collaborators[160] also reported that the essential oil of *Alpinia zerumbet* exerted scavenging effects against DPPH radicals. Moreover, cotreatment with essential oil could increase the intracellular GSH content and decrease lipid peroxidation, oxidation of purine bases and intracellular ROS after H_2O_2 challenge.[185]

4. Conclusion and future perspectives

This overview provided a summary of the available information on the chemical compositions and biological activities of *Alpinia* essential oils. The essential oils and their major compounds isolated from different parts of the *Alpinia* plant have been found to produce dynamic biological activities, including antimicrobial, cytotoxic, antioxidant, anti-inflammatory, antiasthmatic, insecticidal, and larvicidal activities and slimming aromatherapy.

Currently, the primary focus of research is the examination of the chemical composition and biological properties of essential oils from different parts of newly found species. The chemical compositions are mainly identified using the LC-MS and GC-MS techniques. However, in many works, the *n*-alkane standard for calculating the retention indices has not been run, the retention indices have not been analyzed and compared, and a running reference standard is missing to enable a more accurate conclusion about the essential oil composition. In addition, there are not many studies related to the activities of the individual components of the *Alpinia* essential oil and their mechanisms of action. Therefore, future research should consider the correction of the composition and percentage of compounds, especially those with a low content, in the essential oils of newly discovered *Alpinia* species. Importantly, the mechanisms of action of the *Alpinia* essential oils and their individual components should be elucidated to design appropriate isolation methods for individual natural components to improve their biological properties.

Conflicts of interest

There are no conflicts to declare.

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