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REVIEW ARTICLE

Terpenes: Multifunctional roles for plant survival and sustainable farming

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Abstract

Terpenes are the largest class of plant secondary metabolites which play a major role in plant-environmental interactions and serve vital ecological and agricultural functions. Their volatile nature plays a crucial role in pollination and insect attraction by emitting chemical signals that lure pollinators and seed dispersers, while simultaneously repelling herbivores and attracting the predators of the pests. Terpenes exhibit strong antimicrobial and antiviral activities, making them highly effective against pathogens. The insecticidal activity of terpenes offers an effective and eco-friendly alternative to synthetic pesticides, helping to kill pests in an environmentally sustainable manner. Allelopathic interactions of terpenes suppress the germination and growth of weeds and offer sustainable weed management. Besides, terpene biosynthesis in plants is influenced by abiotic stresses such as drought, elevated temperature, light stress and UV radiation highlighting the critical role in defense and adaptation mechanisms in relation to environmental changes. β-caryophyllene, a sesquiterpene is crucial for pollination, pest management, pathogen resistance, allelopathy and stress tolerance, enhancing survival and sustainability of plants. Modulation of terpene levels due to climate change emphasize their role in improving plant resilience to changing environments. The involvement of terpenes in diverse biotic and abiotic interactions underscores the need for continued research to harness their sustainable applications in agriculture, ecology and beyond.

Keywords: abiotic stress; allelopathy; β-caryophyllene; pathogens; pollination; terpenes

Introduction

Terpenes are the natural compounds produced by plants, with more than 30000 distinct structures and serving as an essential building blocks in numerous biological and ecological processes. Terpenes and their oxygenated compounds are the major constituents of essential oils, playing pivotal roles in regulating cell growth and maintaining membrane fluidity and permeability (1). In addition to their physiological roles, terpenes perform multifunctional ecological roles including attracting pollinators, repelling herbivores, acting as natural insecticides and suppressing weed growth.

Field pests are often managed using synthetic insecticides, which pose significant risks to human health, the environment and other non-target species. The overuse of these chemicals disrupts the ecosystem by leaving behind harmful residues. This has driven a search for safe, natural alternatives such as terpenes found in essential oils (2). As eco-friendly insecticides, terpenes are naturally synthesized by the plants help to repel herbivorous insects and playing an important role in ecological pest regulation (3). Unlike synthetic insecticides, terpenes are biodegradable, leaves no toxic residues and degrade rapidly in the environment. Their application in the integrated pest management offers a sustainable and long-term solution for agricultural pest control (4).

Pollination in plants is often hindered by habitat fragmentation, loss of foraging resources and the decline of pollinators. These limitations can cause failure in seed production, adaptability of plant species and long-term survival (5). Floral scent comprising terpenoids and aromatics are crucial for attracting pollinators. These volatile profiles vary across plant species and even in the same species at different times of day, a challenge for the recognition of pollinators (6). However, higher emissions of terpenoids have been shown to correlate with increased seed health, indicating that these compounds directly influence reproductive success by attracting pollinators (7).

Weeds pose significant threats to the crops by competing for resources like light, nutrients, water and space leading to the reduced growth and yield of crops. Additionally, weeds serves as a host for various pests and pathogens (8). The indiscriminate use of herbicides resulted in herbicide-resistant weeds causing environmental issues such as contamination of groundwater and ecosystem disruption and degradation of soil health. This has raised public awareness of health risks associated with herbicide overuse to the humans, animals and the environment (9). The allelochemical activity of terpenes act as a sustainable alternative for weed control. By suppressing weed germination and growth, terpenes act as natural herbicides and replace synthetic herbicides. Thus, forms a promising tool for sustainable weed management (10).

Pathogens such as bacteria, fungi, virus and mycoplasma impact crop health and reducing the yield productivity. These pathogens interrupt the regular physiological and metabolic processes of plants. Terpenes inhibit the pathogenic microorganisms which pose a serious threat to the plant survival (11). Plants have evolved to produce antimicrobial compounds like terpenes that inhibit the growth of pathogenic microorganisms by blocking bacterial DNA synthesis, inhibiting biofilm formation and maintaining membrane integrity (12). The presence of these bioactive metabolites not only helps in the growth of plants but also helps for the plants in adapting to the pathogenic attacks (13).

Temperature stress, whether due to extreme heat or cold, adversely affects the plant growth and metabolism. High temperature causes cellular disruption, protein denaturation, lipid liquefaction and membrane damage, while cold stress alters membrane lipids, leading to a gel like consistency that restricts membrane functionality (14). UV-B radiation induces oxidative stress and cellular damage, reducing protein content and overall cellular function (15). Terpenes play a vital role in mitigating these stresses by stabilizing membranes, reducing proton leakage and maintaining cellular integrity, which helps in protecting cell structures and chloroplasts. In high-light conditions, terpenes protect the photosynthetic machinery from photo-oxidative damage, enhancing the plant's resilience against light stress (16). Additionally, terpenes scavenge ROS during UV-B radiation stress, helping to maintain protein content and cellular function (15). Terpenes possess therapeutic attributes such as antifungal, antiviral, antihyperglycemic, analgesic, anti-inflammatory and antiparasitic effects contributing to disease prevention, immune system support and overall well-being (17). Through genetic engineering, plant derived terpenes can be refined into biofuels, reducing reliance on fossil fuels and lowering carbon emissions (17). Their antioxidant and anti-inflammatory properties make them valuable in the cosmetic industry, particularly in skincare, perfumes and therapeutic cosmetics (18). This review explores the diverse and multifunctional roles of terpenes, emphasizing their potential in agriculture and ecological resilience (Fig. 1).

Biosynthetic pathways of terpenes

The biosynthetic pathways responsible for terpenoid production include the mevalonate (MVA) pathway and methylerythritol phosphate (MEP) pathway (Fig. 2). These pathways produce essential isoprenoid precursors, isopentenyl pyrophosphate (IPP) and dimethylallyl pyrophosphate (DMAPP), which serve as building blocks for various terpenoids (17).

The MVA pathway begins with Acetyl-CoA condensation. Acetyl-CoA acetyltransferase catalyzes the formation of acetoacetyl-CoA, which is then converted into HMG-CoA by HMG-CoA Synthase (18). The rate-limiting step of this pathway involves HMG-CoA reductase, which reduces HMG

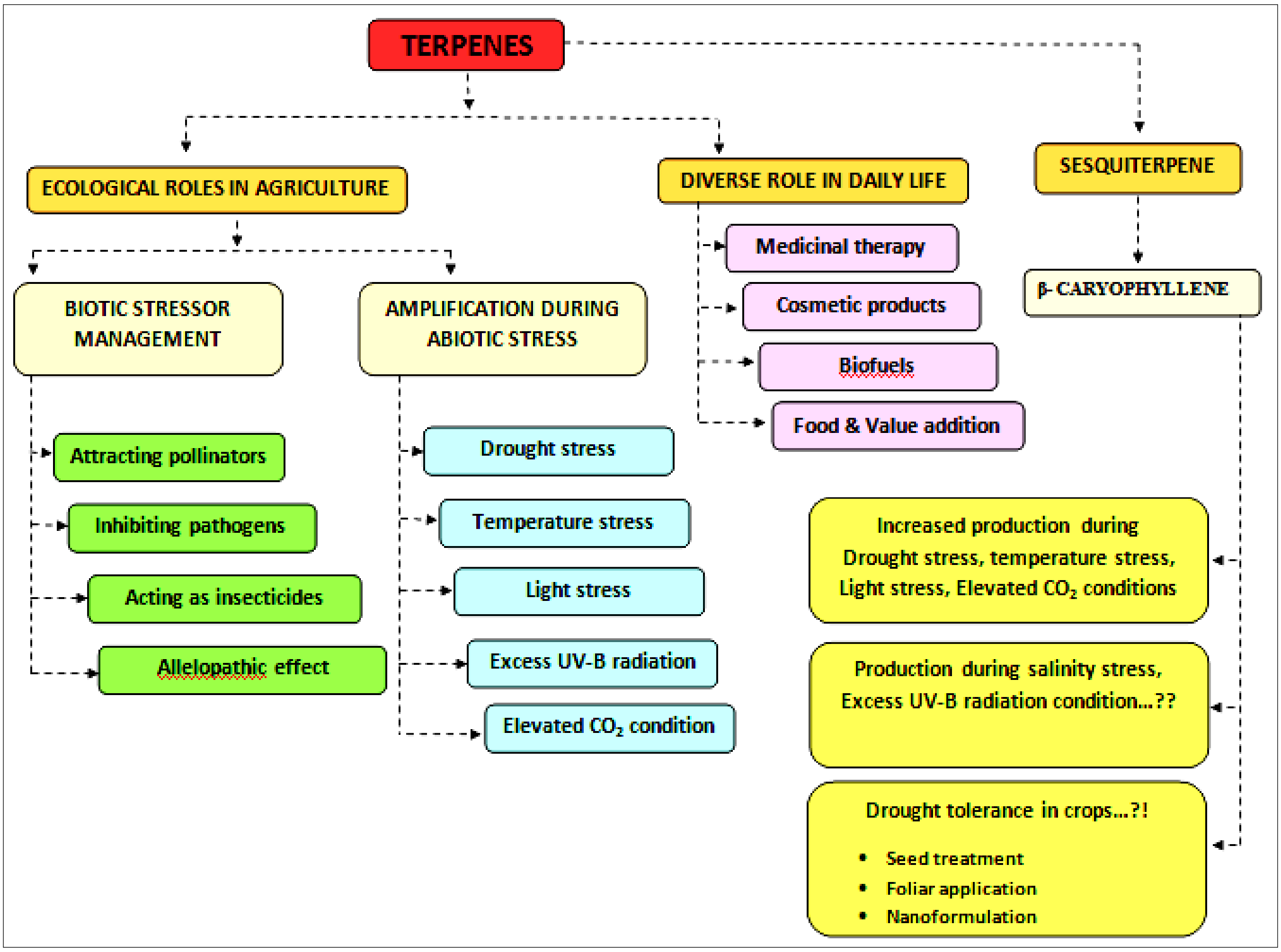

Fig. 1. Multifunctional role of terpenes.

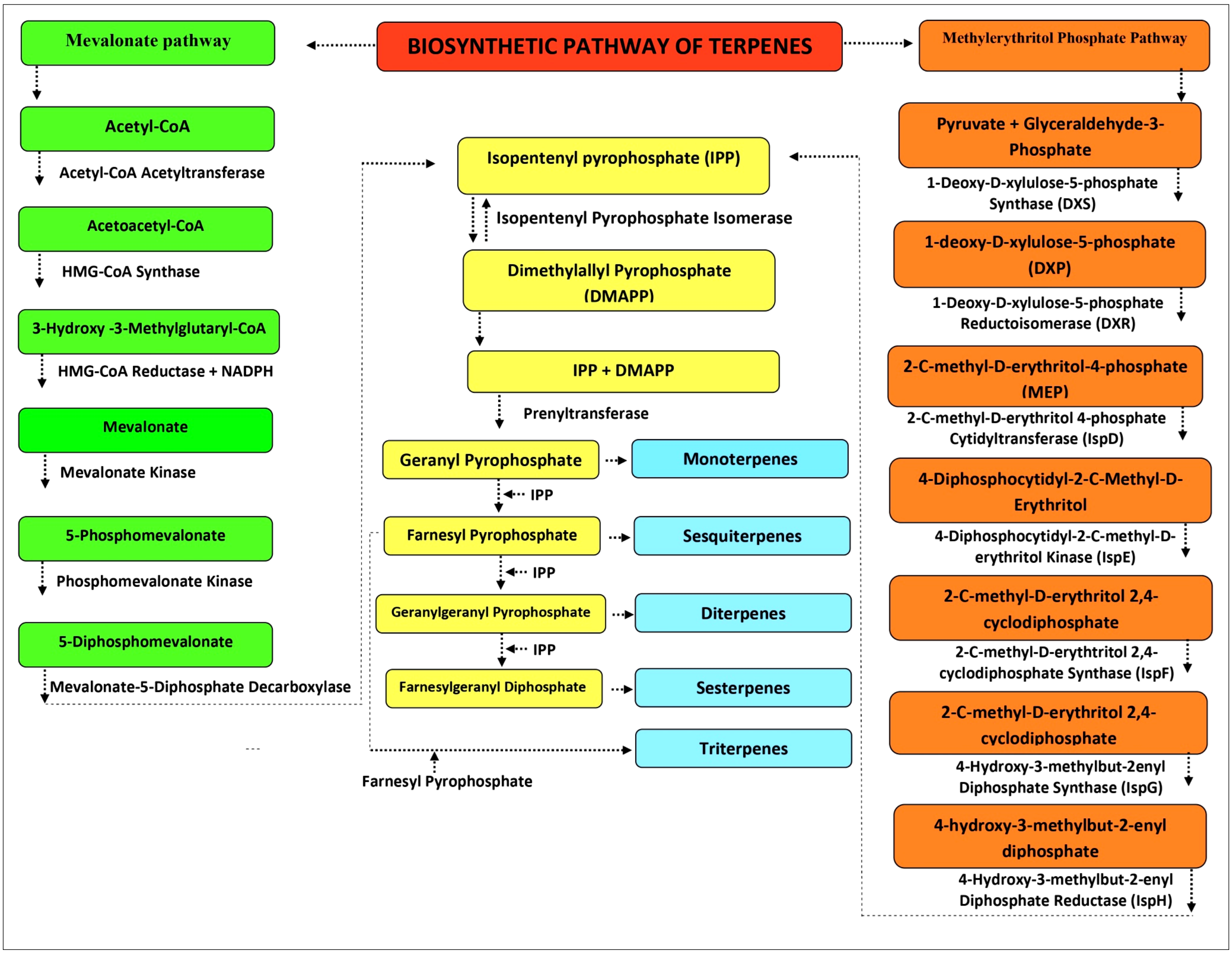

Fig. 2. Biosynthetic pathways responsible for terpenoid production.

-CoA to mevalonate using NADPH. Mevalonate undergoes sequential phosphorylation by mevalonate kinase and phosphomevalonate kinase to form 5-diphosphomevalonate (19). Mevalonate-5-diphosphate decarboxylase then converts this intermediate to IPP, releasing CO_2. Isopentenyl Pyrophosphate Isomerase catalyzes the isomerization of IPP to DMAPP (20).

The MEP pathway, located in the plastids of plants and many bacteria, begins with the condensation of pyruvate and glyceraldehyde-3-phosphate. This reaction, catalyzed by 1-Deoxy-D-xylulose-5-phosphate Synthetase (DXS), produces 1-deoxy-D-xylulose-5-phos-phate (DXP), which is subsequently converted by 1-Deoxy-D-xylulose-5-phosphate reductoisomerase (DXR) into 2-C-methyl-D-erythritol-4-phosphate (MEP) (17). A series of enzymatic steps then lead to the formation of 4-hydroxy-3-methylbut-2-enyl diphosphate, which is finally reduced to both IPP and DMAPP (21, 22).

DMAPP and IPP condense to form geranyl pyrophosphate (GPP, C10), a precursor for monoterpenes (21). GPP condenses with IPP to form farnesyl pyrophosphate (FPP, C15), which serves as a precursor for sesquiterpenes (22). FPP undergoes further condensation with IPP to form geranylgeranyl diphosphate (GGPP, C20), leading to diterpenes (23). Additional condensation reactions result in the formation of sesterterpenes (C25), triterpenes (C30) and tetraterpenes (C40) (24).

Role of terpenes in pollinator attraction

Pollinators such as bees, butterflies, moths, flies and birds facilitate cross-pollination by transferring pollen from the anther to the stigma, drawn by the colors and fragrances of flowers (25). Lilac aldehyde, the main monoterpene of White campion, *Silene latifolia* attracts noctuid moth, *Hadena bicruris* (26). In Pineapple zamia (*Macrozamia lucida*), obligate pollination mutualism with *Cycadothrips* involves thermogenic male cones release β-myrcene, β-ocimene and allo-ocimene which prompt thrips to transfer pollinaria to female cones (27). Similarly, the fig wasp, *Ceratosolen solmsi marchali* is attracted to the receptive flowers of *Ficus hispida*, which emit monoterpenes such as linalool, limonene and β-pinene to lurepollinators (28).

Monkey flowers (*Mimulus lewisii*) use D-limonene, β-myrcene and E-β-ocimene to attract bumblebees (*Bombus* spp.) (29), while sweet rocket (*Hesperis matronalis)* emits linalool and β-ocimene to lure syrphid flies (6). Radiator plant (*Peperomia macrostachya)* releases geranyl linalool to attract arboreal ants (*Camponatus femoratus)* for seed dispersal (30). *Citrus reticulata* and *Citrus limon* with linalool are highly attractive to *Tetragonula laeviceps* (31).

Lavendar oil, rich in linalool and linalyl acetate, attracts honeybees for pollination and enhances oil quality. Pollinated lavender plants exhibit higher levels of these compounds compared to non-pollinated ones (32). *Philodendron fragmentissimum* secretes (Z)-jasmone to attract *Cyclocephala* *simulatrix* Hohne for pollination (33). *Tetragonula angustula* is attracted to terpenes emitted by *Piper mollicomum* Kunth, which exhibits higher linalool concentrations during the flowering stage, with levels decreasing during fruiting (34).

Manihot violacea secretes geraniol and limonene to attract stingless bees (*Partamona cupira*), while *Manihot oligantha* emits myrcene and pinene to lure kleptoparasitic flies of *Chloropidae* family (35). *Nicotiana attenuate* releases (E)-β-ocimene and (E)-α- bergamotene to attract its pollinator *Manduca sexta* (36). Unpollinated flowers of *Ficus carica* emit more volatile organic compounds, including β-citral and geranial, attracting black fig fly, *Silba adipate* (37). *Citrus mangshanensis* produces high levels of β-myrcene, attracting bees (38). During blooming, *Lavandula angustifolia* increases the emission of (+)-R-limonene, β-trans-ocimene, linalool and linalyl acetate, attracting *Apis mellifera*, *Apis cerana* and other pollinators such as *Macroglossum pyrrhosticum*, *Pieris rapae, Sarcophaga* spp. and *Calliphora vicina* (39). The various terpenes involved in attracting pollinators are listed in Table 1.

Antimicrobial properties of terpenes against plant pathogens

Terpenoids provide resistance to various microorganisms by inhibiting their metabolic actions and eliminating them from plants by employing various mechanisms. Bacterial strains such as *Enterobacter aerogenes*, *Acinetobacter baumannii*, *Pseudomonas aeruginosa* are susceptible to antibiotics which are enhanced by geraniol (47). When geraniol is combined with an efflux pump inhibitor such as phenylalanine-arginine naphthylamide (PAN), it renders the organism fully susceptible to chloramphenicol, completely reversing its initial resistance (47).

Thymol and (+)-menthol exhibit antimicrobial activity against *Staphylococcus aureus* ATCC 6538P and *Escherichia coli* ATCC 15221 by exhibiting strong membrane disrupting effects on liposomes. But, linalyl acetate shows less detrimental effects on *Staphylococcus aureus* ATCC 6538P and *Escherichia coli* ATCC 15221 (48). Menthol possessing higher relative lipophilicity (Rm) values have the ability to penetrate lipid membranes and thereby shows the antimicrobial activity against pathogens (48).

Thymol and carvacrol make the cell membranes more permeable by increasing the NPN (N-Phenyl-1-naphthylamine) uptake. They effectively inhibit *E. coli* and *Salmonella typhimurium*. They make bacteria more sensitive to detergents like SDS and triton X-100 (49). Thymol and carvacrol reduce the viral inoculum of Tobacco Mosaic Virus (TMV) and Cucumber Mosaic Virus (CMV) (50). α-Terpinene, γ-Terpinene and α-Pinene shows the complete eradication of Herpes Simplex Virus Type 1 (HSV-1) (51).

Xanthorrhizol, a sesquiterpene acts against *Streptococcus mutans* by reducing its adherence to the cells. This mode of action reduces the adhesion phase of bacteria which is critical for the dental plaque formation. Xanthorrhizol also effectively reduces the colony forming units of *Mycobacterium smegmatis* and prevents the bacterial adherence and biofilm formation (52). Salvipisone shows both the bacteriocidal and bacteriostatic activity. Salvipisone acts as an antimicrobial agent against *S. aureus* and *S. epidermidis* (53). The terpenes possessing antimicrobial activities against plant pathogens are listed in Table 2.

Allelopathic interactions mediated by terpenes

Allelopathy is the process wherein plants release chemicals to affect the growth of neighbouring plants. Allelopathic plants suppress weed germination and growth through the release of compounds such as terpenes, offering a natural means of weed control. The triterpenoids in *Praxelis clematide* are identified by colour changes such as brown, red or purple in the visible light and also under UV with the use of Liebermann-Burchard reagent (53). These compounds act as bioherbicides against *Asystasia gangetica* (54). The allelopathic activity exhibited by wheat against redroot pigweed demonstrates the suppression effect of terpenes such as linalool, borneol, terpinen-4-ol, linalyl acetate, geraniol and thymol (55).

The inoculation of *Solanum nigrum* with *Rhizoglomus intraradices* have resulted in the increased terpenoid levels in its fruits. The association of *Ipomoea purpurea* with *Funneliformis mosseae* showed enhanced terpenoid content in its flowers, which is likely inhibiting root or seedling growth in competing vegetation. When *Digitaria sanguinalis* got associated with both *F. mosseae* and *R. intraradices*, it showed limited allelopathic potential from the terpenoids in its seeds (56). The aqueous extract of fleagrass (*Adenosma buchneroides Bonati*) contains terpenoids such as ursolic acid and asiatic acid, which inhibit the germination and seedling growth of weed species including *Bidens pilosa*, *Boehmeria japonica* and *Pseudodonia thunbergii* (57).

The aqueous extract and powdered form of *Solanum linnaeanum* contain terpenoids such as cis- geranylacetone, trans-β-ionone and linalool oxide, which inhibit the germination and growth of *Lolium multiflorum*, *Sinapis alba* and *Trifolium incarnatum* (58). *Mikania micrantha* which possesses terpenoids such as α-terpineol, β-ocimene, β-myrcene and α-pinene, exhibits allelopathic effects against *Bidens pilosa* by reducing its germination rate, shoot and root length and chlorophyll content (59). *Parthenium hysterophorus* shows allelopathic effects on *Cyperus iria* through terpenoids including parthenin, dehydroleucodine, rishitin, gaillardilin and hymenoxynin (60). The aqueous extract of *Artemesia vulgaris* contains 1,8-cineole and vulgarin, which acts as a potential bioherbicide for controlling *Amaranthus retroflexus* L. (61), a common weed in *Zea mays* cultivation (62).

The essential oil of *Euphorbia mauritanica* contains monoterpene hydrocarbons (limonene, α-Pinene), oxygenated monoterpenes (eucalyptol, camphor), sesqui-terpene hydrocarbons (γ-muurolene, cadalene), oxygenated sesquiterpenes (hexahydrofarnesyl acetone, butylated hydroxytoluene), diterpene hydrocarbons (cembrene, kaur-16-ene) and oxygenated hydrocarbons (verticiol), which exhibit allelopathic potential against *Dactyloctenium aegyptium* and *Urospermum picroides* (63). Rainfed cotton intercropped with pearl millet results in improved weed control due to the presence of terpenes such as squalene and neophytadiene, which exhibit alleopathic potential towards *Echinochloa crus-galli*, lettuce and leafy spurge (64). The terpenes involved in

Table 1. Terpenes produced by plants for attracting the pollinators

Terpene	Plant source	Pollinators	Reference
Lilac aldehyde	White campion	*Hadean bicruris*	(26)
β-Myrcene	*Macrozamia lucida* *Mimulus lewisii*	*Cycadothrips chadwicki* *Bombus* spp.	(27, 29)
β-Ocimene	*Macrozamia lucida*	*Cycadothrips chadwicki*	(27)
	Ficus hispida	*Ceratosolen solmsi marchali*	(28)
	Hesperis matronalis	Syrphid flies	(29)
	Mimulus lewisii	*Bombus* spp.	(29)
	Lavandula angustifolia	*Apis mellifera* *Apis cerana* *Macroglossum pynhostictum* *Pieris rapae* *Sarcophaga* spp. *Calliphora vicina*	(40)
Allo-ocimene	*Macrozamia lucida*	*Cycadothrips chadwicki*	(27)
Linalool	*Ficus hispida*	*Ceratosolen solmsi marchali*	(28)
	Hesperis matronalis	Syrphid flies	(6)
	Peperomia macrostacya	*Camponotus femoratus*	(30)
	Citrus reticulate	*Tetragonula laeviceps*	(41)
	Piper mollicomum Kunth	*Tetragonisca angustula*	(34)
	Lavandula angustifolia	*Apis mellifera, Apis cerana, Macroglossum pynhostictum, Pieris rapae, Sarcophaga* spp, *Calliphora vicina*	(40)
Limonene	*Ficus hispida*	*Ceratosolen solmsi marchali*	(28)
	Mimulus lewisii	*Bombus* spp.	(29)
	Manihot violacea	*Partamona cupira*	(35)
D-Limonene	*Mimulus lewisii*	*Bombus* spp.	(29)
Geranyl linalool	*Peperomia macrostachya*	*Camponotus femoratus*	(30)
Linalyl acetate	*Lavandula angustifolia*	*Apis mellifera,* *Apis cerana,* *Macroglossum pynhostictum,* *Pieris rapae,* *Sarcophaga* spp. *Calliphora vicina*	(32) (42)
(Z)- Jasmone	*Philodendron fragrantissimum*	*Cyclocephala simulatrix* Hohne	(43)
Geraniol	*Manihot violacea*	*Partamona cupira*	(35)
Myrcene Pinene	*Manihot oligantha*	Kleptoparasitic flies	(35)
α –Humulene	*Passiflora sexocellata*	*Colletus* spp.	(44)
β -Caryophyllene	*Passiflora sexocellata*	*Colletus* spp.	(41)
	Salvia verticillata	*Apis mellifera, Bombus lapidaries, Bombus terrestris, Bombus pascuorum*	(45)
(E)-β-Ocimene (E)-α-Bergamotene	*Nicotiana attenuata*	*Manduca sexta*	(46)
β –Citral Geranial	*Ficus carica*	*Silpa adipata*	(37)
(+) –R-limonene β –Trans-Ocimene	*Lavandula angustifolia*	*Apis mellifera, Apis cerana, Macroglossum pynhostictum, Pieris rapae, Sarcophaga* spp., *Calliphora vicina*	(42)
Germacrene D	*Salvia verticillata*	*Apis mellifera, Bombus lapidaries, Bombus terrestris, Bombus pascuorum*	(45)

Table 2. Terpenes and their role in the inhibition of pathogenic microorganisms

Terpenoid	Pathogen	Mechanism of action	Minimum inhibitory concentration (MIC)	References
Geraniol	*Enterobacter aerogenes*	Enhances susceptibility to antibiotics; when combined with PAN, reverses resistance to chloramphenicol	1.02 mg/mL	(47)
Thymol	*Staphylococcus aureus*	Exhibits antimicrobial activity and disrupts membrane	0.31 mg/mL	(48)
	Tobacco mosaic virus (TMV)		1 mmol/L	
	Cucumber mosaic virus (CMV)		1 mmol/L	
(+)- Menthol	*Escherichia coli*	Higher lipophilicity, facilitating penetration of lipid membranes	2.50 mg/mL	(48)
Carvacrol	*Escherichia coli*	Increases cell membrane permeability; enhances sensitivity to detergents like SDS	3 mM	(49)
	Salmonella typhimurium		1 mM	
α-Terpinene γ-Terpinene α-Pinene	Herpes Simplex Virus Type 1 (HSV-1)	Complete eradication of HSV-1 at low concentrations	25 μg/mL	(50)

Table 3. Allelopathic potential of terpenes against weeds

Plant source	Terpenoids	Target species	References
Triticum aestivum	Linalool, borneol, terpinen-4-ol, linalyl acetate, geraniol, thymol	*Amaranthus retroflexus*	(65)
Adenosma buchneroides Bonati	Ursolic acid Asiatic acid	*Bidens pilosa, Boehmaria japonica, Pseudodonia thunbergii*	(66)
Solanum linnaeanum	Cis-Geranylacetone, trans- β-ionone, linalool oxide	*Bidens pilosa*	(59)
Mikania micrantha	α-Terpineol, α-Pinene, β-Ocimene, β-Myrcene		
Parthenium hysterophorus	Parthenin, dehydroleucidine, rishitin, gaillardilin, hymenoxynin	*Cyperus iria*	(60)
Litsea pungens	α-Pinene,camphene, bicyclo(3,1,0)hexane, β-pinene, myrcene, limonene, eucalyptol, linalool, citronellal, cis-verbenol, α-terpineol, neral, β-caryophyllene, humulene, caryophyllene oxide	*Lolium perenne,* *Bidens pilosa*	(67)
Euphorbia mauritanica	Limonene, α-pinene, eucalyptol, camphor, cadalene, hexahydrofarnesyl acetone, butylated hydroxytoluene, cembrene, kaur-16-ene, verticiol	*Dactyloctenium aegyptium,* *Urospermum picroides*	(63)
Pennisetum glaucum	Squalene, neophytadiene	*Echinochloa crus-galli,* *Lactuca sativa,* *Euphorbia esula*	(64)

weed suppression through allelopathic effects are listed in Table 3.

Terpenes as eco-friendly insecticides

Terpenes play a significant role in pest management due to their insecticidal and repellant properties. The monoterpenes pose a threat to the insect pests. Carvacrol shows strong toxicity towards *Helicoverpa armigera* and *Drosophila suzukii* (68, 69). *Chilo partellus* and *Bemisia tabaci* are effectively controlled by 1,8-cineole (70, 71), while linalool is effective against *Plutella xylostella* and *Ceratitis capitata* (72, 73). Thymol exhibits its efficacy against *Chilo partellus* (70).

In the category of triterpenes, swietenitin O shows significant insecticidal activity against *Achea janata* and *Spodoptera litura*, showcasing its potential as an ecofriendly pest control solution (74). Methyl angolensate causes a remarkable mortality rate in *Spodoptera frugiperda* indicating its effectiveness as pesticide (75). Khayasin effectively targets *Brontispa longissima*, demonstrating its potential in managing this pest species (76).

Among sesquiterpenes, 9β-hydroxy-1βH, 11αH-guaia-4,10(14)-dien-12,8α-olide exhibits potent insectcidal activity against *Plutella xylostella* and *Bradysia odoriphaga*, highlighting its potential in agricultural pest management (77). 6b-acetoxy-9 oxofuranoeremophilane/dehydrodecompostin showed a notable selectivity index against *Myzus persicae*, indicating its potential as a targeted pest control agent (78). 6-hydroxyeuryopsin demonstrates effective feeding inhibition against *Leptinotarsa decemlineata*, suggesting its utility in reducing pest populations (79). Also, 10α-hydroxy-1-oxoeremophilia-7(13), 8(9)-dien-12,8-olide achieved high feeding inhibition in *S. littoris*, further supporting its role in pest management strategies (78). The various terpenes involved in controlling pests are listed in Table 4.

Adaptation to abiotic stress through terpenes

Plants respond to various abiotic stresses, such as extreme temperature, elevated CO_2 levels, light and UV radiation by increasing the emission of terpenes and terpenoids. This serves as an adaptive and protective mechanism against environmental stressors. Cold stress poses a problem of decreasing the membrane fluidity. At 0 °C, *Pyrus communis* L. emitted higher levels of farnesene showcasing the plants ability to adapt to cold stress (82). *Daucus carota* L. responded to a milder cold stress of 9 °C by enhancing α-terpinolene emission to adapt for cold tolerance (83). In *Daucus carota* L. the increased emission of β-farnesene, α-humulene, α-pinene and γ-terpinene at 21 °C (83) and in *Hypericum brasiliense,* increased production of betulinic acid in heat stress at 36 °C reflects the metabolic flexibility of plants in response to heat stress (84).

Elevated CO_2 concentrations influence the terpenoid emission across various plant species which is linked to the

Table 4. Insecticidal potential of terpenes

Terpenes		Insect species	Activity	References
Monoterpenes	Carvacrol	*Helicoverpa armigera*	LC_{50} = 51.5 µg mL^{-1}	(68)
		Drosophila suzukii	LD_{50} = 1.30 µg $male^{-1}$ fly	(69)
	1,8-Cineole	*Chilo partellus*	LD_{50} = 412.1 µg $larva^{-1}$	(70)
		Bemisia tabaci	M = 91.2 % (1000 mg/L)	(71)
	Linalool	*Plutella xylostella*	LC_{50} = 3.37 ppm	(80)
		Ceratitis capitata	LD_{50} = 10.37 nL male fly^{-1}	(73)
	Thymol	*Chilo partellus*	LD_{50} = 189.7 µg $larva^{-1}$	(70)
Triterpenes	Swietenitin O	*Achaea janata*	LC_{50} = 0.65 µg/cm^2	(74)
		Spodoptera litura	LC_{50} = 0.75 µg/cm^2	
	Methyl angolensate	*Spodoptera frugiperda*	40 % mortality at 50 mg kg^{-1}	(75)
	Khayasin	*Brontispa longissima*	LC_{50} = 7.28 µg/mL	(76)
	Piscidinol I	*Achea janata*	LC_{50} = 40.83 mg/cm^2	(81)
		Spodoptera litura	LC_{50} = 46.55 mg/cm^2	
	Piscidinol L	*Achea janata*	LC_{50} = 20.00 mg/cm^2	
		Spodoptera litura	LC_{50} =22.02 mg/cm^2	
Sesquiterpenes	9β-hydroxy-1βH,11αH-guaia-4,10(14)-dien-12,8α-olide	*Plutella xylostella*	EC_{50} = 19.84 mg/L	(77)
		Bradysia odoriphaga	LD_{50} = 18.71 mg/L	
	6b-Acetoxy-9-oxofuranoeremophilane/ Dehydrodecompostin	*Myzus persicae*	SI = 74 %	(78)
	6b-Tigloyl-9-oxofuranoeremophilane			
	6-Hydroxyeuryopsin	*Leptinotarsa decemlineata*	FI = 72.2 %	(79)
	1,10-Epoxy-6-hydroxyeuryopsin		FI = 83.9 %	
	10a-Hidroxy-1-oxoeremophila-7(13),8(9)-dien-12,8-olide	*Spodoptera littoris*	FI = > 80 %	(78)

EC=Effective concentration causing 50 % mortality, **SI** = Susceptibility Index, **FI**= Feeding Inhibition, **LD** = Dose causing 50 % mortality, **LC** = Concentration causing 50 % mortality, **M** = Mortality.

changes in plant metabolism and stress signaling. Under elevated CO_2, *Quercus ilex*, shows an increased emission of limonene and *Zingiber officinale* produced more gingerol, which is known for its antioxidant and stress-mitigating properties (85). The native and Bt. transgenic varieties of *Gossypium hirsutum* showed elevated production of gossypol under higher CO_2 levels, reflecting the plant's adaptive mechanism to changing environmental conditions (86).

Light induced the stress in plants due to its variable intensities and spectral composition influencing the production of terpenoids. Under high light conditions, *Fluorensia cernua*, showed an increased emission of camphene, α-thujene and limonene (16) while *Brassica juncea* L. showed an elevated production of α- and β-carotenes, violaxanthin and lutein, which contributed to enhanced photoprotection and stress adaptation (87).

UV-B radiation triggers the increment in the terpenoid content in plants and strengthens their natural defense systems. *Coleus forskohlii* and *Withania somnifera* Dunal exhibited increased emissions of β-carotene, with the latter also emitting higher levels of lycopene under UV-B, preventing the tissues from radiation induced damage (88, 89). *Zea mays* demonstrated enhanced emissions of β-carotene and lutein (90). These protective mechanisms show the role of terpenes in mitigating abiotic stress by enhancing plant adaptation and tolerance. The terpenes involved in plant responses to various abiotic stresses are listed in Table 5.

β- Caryophyllene: A multifunctional terpene

β- Caryophyllene, a bicyclic sesquiterpene, is one of the twelve most common volatile compounds in floral scents, occurring in over 50 % of angiosperm families and present in many essential oils (93). *Passiflora sexocellata* secretes G- caryophyllene and α-humulene to attract *Colletus* spp. for pollination (44). *Salvia verticillata* contains high levels of β- caryophyllene, germacrene D and bicyclegermacrene, which attract pollinators like *Apis mellifera* and several *Bombus* species (45). In maize, (E)-β-caryophyllene released by roots attracts the ento-mopathogenic nematode *Heterorhabditis megidis*, which kills pests like *Galleria mellonella* and *Diabrotica virgifera*. Maize leaves attacked by *Spodoptera littoris* emit β-caryophyllene, which attracts the parasitic wasp, *Cotesia marginiventris* thereby contributing to pest population control (94, 95). Genes encoding β-caryophyllene synthase, such as QHS1 in *Artemisia annua*, have been utilized for heterologous production of β-caryophyllene, which exhibited the inhibitory effects against pathogens such as *Sclerotinia sclerotiorum* and *Fusarium oxysporum* (96).

At low concentrations, β-caryophyllene promoted

Table 5. Role of plant-derived terpenes in adaptation to abiotic stresses

Abiotic stress	Plant	Terpenoids	Environmental conditions under which modulations in terpene concentrations are observed	References
Cold stress	*Pyrus communis* L.	Farnesene	0 °C	(91)
	Daucus carota L.	α-Terpinolene	9 °C	(83)
	Hypericum brasiliense	Betulinic acid	36 °C	(84)
Heat stress	*Daucus carota* L.	β-Farnesene, α-Humulene, g-Terpinene, α-Pinene, ocimene, camphene, caryophyllene, β-Myrcene	21 °C	(83)
Elevated CO_2	*Quercus ilex* L.	Limonene	700 ± 250 ppm of CO_2	(92)
	Zingiber officinale roscoe	Gingerol	800 ppm of CO_2	(85)
	Gossypium hirsutum	Gossypol	750 µl/L of CO_2	(86)
Light stress	*Flourensia cernua*	Camphene, Tricyclene, α-Thujene, β-Pinene, myrcene, 1,8-cineole, Limonene, γ-Terpinene, trans-sabinene hydrate, bornyl acetate, caryophyllene oxide, β-Cubebene	70 µmol $m^{-2} s^{-1}$ light condition	(16)
	Brassica juncea L. 'Red Lion'	α-Carotene, β-Carotene, Violaxanthin, Lutein/Zeaxanthin	100 µmol $m^2 s^{-1}$ light condition	(87)
	Brassica rapa var *chinensis*		440 µmol $m^2 s^{-1}$ light condition	
	Brassica rapa var. rosularis		330 µmol $m^2 s^{-1}$ light condition	
UV-B radiation	*Coleus forskohlii*	β-carotene	UV-B radiation of 9.6 kJ m^{-2} d^{-1}	(88)
	Withania somnifera Dunal	β-carotene Lycopene	UV-B radiation of 9.6 kJ m^{-2} d^{-1}	(88)
	Zea mays	β-carotene Lutein	UV-B radiation of 8.35 kJ m^{-2} per day	(90)

growth in some plants, but at higher concentrations, it inhibited the germination and growth of species like *Amaranthus retroflexus* and *Echinochloa crus-galli*. *Mikania micrantha* emits β-caryophyllene, showing allelopathic effects on weeds like *Brassica campestris*, promoting growth at low concentrations but inhibiting germination at higher levels (97). Stress conditions like cold, drought and heat significantly increase β- caryo-phyllene production. In holy basil, cold stress and drought stress increased β-caryophyllene levels (98). Heat stress in *Polygonum minus* enhances emission of terpenoids like β-caryophyllene (14). Increased light intensity boosts β-caryophyllene emissions in *Citrus sinensis* (99). Under water stress, *Origanum vulgare* shows elevated β- caryo-phyllene levels (100).

Conclusion

Terpenes are the essential secondary metabolites that play diverse and beneficial roles in plant biology. The characteristic volatile nature enables them to create a communication signal, which is involved in direct defenses like deterring pests, attracting beneficial insects for pollination and indirect defences such as attracting predatory insects that reduce the population of pests. By eliminating the pest and pathogen community, terpenes strengthen the plants' resilience and eliminate the weed community by suppressing their growth through their allelopathic potential. Additionally, terpenes alleviate abiotic stresses, stabilizing the plant's cellular structures and modulating stress related processes. The terpenes will be used to enhance sustainable agricultural practices in future. Terpene-based biocontrol agents will reduce the need for synthetic pesticides and support the eco-friendly pest management. Crops can be genetically modified to produce higher amounts of terpenes thereby directly enhancing their resistance to pests and environmental stresses. Future research on terpenes should focus on developing crop varieties better suited to changing climatic conditions, while also contributing to the sustainability and resilience of agricultural ecosystems.

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Authors' contributions

SKJ conducted the literature review, drafted and edited the manuscript. NS and MD assisted in the final editing of the manuscript. GSK and SM performed plagiarism checking and made necessary corrections.

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References

1. Roberts SC. Production and engineering of terpenoids in plant cell culture. Nature Chemical Biology. 2007;3(7):387–95. https://doi.org/10.1038/nchembio.2007.8
2. Seiber JN, Coats J, Duke SO, Gross AD. Biopesticides: state of the art and future opportunities. Journal of Agricultural and Food Chemistry. 2014;62(48):11613–9. https://doi.org/10.1021/jf504252n
3. Langenheim JH. Higher plant terpenoids: a phytocentric overview of their ecological roles. Journal of Chemical Ecology. 1994;20:1223–80. https://doi.org/10.1007/BF02059809
4. El-Gaied L, Mahmoud A, Salem R, Elmenofy W, Saleh I, Abulreesh HH, et al. Characterization, cloning, expression and bioassay of vip3 gene isolated from an Egyptian *Bacillus thuringiensis* against whiteflies. Saudi Journal of Biological Sciences. 2020;27(5):1363–7.https://doi.org/10.1016/j.sjbs.2019.12.013
5. Wilcock CC, Neiland MR, editors. Reproductive characters as priority indicators for rare plant conservation. Planta Europa: Proceedings of the second European conference on the conservation of wild plants; Swedish Threatened Plants Unit & Plantlife Uppsala, Sweden/London: UK. 1998. p. 221–30.
6. Majetic CJ, Raguso RA, Ashman TL. The sweet smell of success: floral scent affects pollinator attraction and seed fitness in *Hesperis matronalis*. Functional Ecology. 2009;23(3):480–7. https://doi.org/10.1111/j.1365-2435.2008.01517.x
7. Anderson JA, Padhye SR. Protein aggregation, radical scavenging capacity and stability of hydrogen peroxide defense systems in heat-stressed *Vinca* and sweet pea leaves. Journal of the American Society for Horticultural Science. 2004;129(1):54–9. https://doi.org/10.21273/JASHS.129.1.0054
8. Chauhan BS. Grand challenges in weed management. Frontiers in Agronomy. 2020;1:3. https://doi.org/10.3389/fagro.2019.00003
9. Poudyal S, Cregg BM. Irrigating nursery crops with recycled run-off: a review of the potential impact of pesticides on plant growth and physiology. HortTechnology. 2019;29(6):716–29. https://doi.org/10.21273/HORTTECH04302-19
10. Cheng F, Cheng Z. Research progress on the use of plant allelopathy in agriculture and the physiological and ecological mechanisms of allelopathy. Frontiers in Plant Science. 2015;6:1020. https://doi.org/10.3389/fpls.2015.01020
11. González-Vega J, Walk C, Murphy M, Stein H. Requirement for digestible calcium by 25 to 50 kg pigs at different dietary concentrations of phosphorus as indicated by growth performance, bone ash concentration and calcium and phosphorus balances. Journal of Animal Science. 2016;94(12):5272–85. https://doi.org/10.2527/jas.2016-0751
12. Kannappan A, Sivaranjani M, Srinivasan R, Rathna J, Pandian SK, Ravi AV. Inhibitory efficacy of geraniol on biofilm formation and development of adaptive resistance in *Staphylococcus epidermidis* RP62A. Journal of Medical Microbiology. 2017;66(10):1506–15. https://doi.org/10.1099/jmm.0.000570
13. Condon AG, Richards R, Rebetzke G, Farquhar G. Improving intrinsic water-use efficiency and crop yield. Crop Science. 2002;42(1):122–31. https://doi.org/10.2135/cropsci2002.1220
14. Goh HH, Khairudin K, Sukiran NA, Normah M, Baharum S. Metabolite profiling reveals temperature effects on the VOCs and flavonoids of different plant populations. Plant Biology. 2016;18:130–9. https://doi.org/10.1111/plb.12403
15. Wang X, Xu X, Cui J. The importance of blue light for leaf area expansion, development of photosynthetic apparatus and chloroplast ultrastructure of *Cucumis sativus* grown under weak light. Photosynthetica. 2015;53(2):213–22. https://doi.org/10.1007/s11099-015-0083-8

16. Estell RE, Fredrickson EL, James DK. Effect of light intensity and wavelength on concentration of plant secondary metabolites in the leaves of *Flourensia cernua*. Biochemical Systematics and Ecology. 2016;65:108–14. https://doi.org/10.1016/j.bse.2016.02.019
17. Banerjee A, Sharkey T. Methylerythritol 4-phosphate (MEP) pathway metabolic regulation. Natural Product Reports. 2014;31(8):1043–55. https://doi.org/10.1039/C3NP70124G
18. Re EB, Brugger S, Learned M. Genetic and biochemical analysis of the transmembrane domain of *Arabidopsis* 3-hydroxy-3-methylglutaryl coenzyme A reductase. Journal of Cellular Biochemistry. 1997;65(4):443–59. https://doi.org/10.1002/(SICI)1097-4644(19970615)65:4<443::AID-JCB1>3.0.CO;2-O
19. Lluch MA, Masferrer A, Arró M, Boronat A, Ferrer A. Molecular cloning and expression analysis of the mevalonate kinase gene from *Arabidopsis thaliana*. Plant Molecular Biology. 2000;42:365–76. https://doi.org/10.1023/A:1006325630792
20. Henry LK, Thomas ST, Widhalm JR, Lynch JH, Davis TC, Kessler SA, et al. Contribution of isopentenyl phosphate to plant terpenoid metabolism. Nature Plants. 2018;4(9):721–9. https://doi.org/10.1038/s41477-018-0220-z
21. Calisto BM, Perez-Gil J, Bergua M, Querol-Audi J, Fita I, Imperial S. Biosynthesis of isoprenoids in plants: Structure of the 2C-methyl-d-erithrytol 2, 4-cyclodiphosphate synthase from *Arabidopsis thaliana*. Comparison with the bacterial enzymes. Protein Science. 2007;16(9):2082–8. https://doi.org/10.1110/ps.072972807
22. Seemann M, Wegner P, Schünemann V, Bui BT, Wolff M, Marquet A, et al. Isoprenoid biosynthesis in chloroplasts via the methylerythritol phosphate pathway: the (E)-4-hydroxy-3-methylbut-2-enyl diphosphate synthase (GcpE) from *Arabidopsis thaliana* is a [4Fe–4S] protein. JBIC Journal of Biological Inorganic Chemistry. 2005;10:131–7. https://doi.org/10.1007/s00775-004-0619-z
23. Kamran S, Sinniah A, Abdulghani MA, Alshawsh MA. Therapeutic potential of certain terpenoids as anticancer agents: a scoping view. Cancers. 2022;14(5):1100. https://doi.org/10.3390/cancers14051100
24. Mewalal R, Rai DK, Kainer D, Chen F, Kulheim C, Peter GF, et al. Plant- derived terpenes: A feedstock for speciality biofuels. Trends in Biotechnology. 2017;35(3):227–40. https://doi.org/10.1016/j.tibtech.2016.08.003
25. Herman A, Herman AP. Essential oils and their constituents as skin penetration enhancer for transdermal drug delivery: a review. Journal of Pharmacy and Pharmacology. 2015;67(4): 473–85. https://doi.org/10.1111/jphp.12334
26. Dötterl S, Jürgens A, Seifert K, Laube T, Weißbecker B, Schütz S. Nursery pollination by a moth in *Silene latifolia*: the role of odours in eliciting antennal and behavioural responses. New Phytologist. 2006;169(4):707–18. https://doi.org/10.1111/j.1469-8137.2005.01509.x
27. Terry I, Walter GH, Moore C, Roemer R, Hull C. Odor-mediated push-pull pollination in cycads. Science. 2007;318(5847):70. https://doi.org/10.1126/science.1145147
28. Chen C, Song Q. Responses of the pollinating wasp *Ceratosolen solmsi marchali* to odor variation between two floral stages of *Ficus hispida*. Journal of Chemical Ecology. 2008;34:1536–44. https://doi.org/10.1007/s10886-008-9558-4
29. Byers KJ, Bradshaw Jr H, Riffell JA. Three floral volatiles contribute to differential pollinator attraction in monkey flowers (*Mimulus*). Journal of Experimental Biology. 2014;217(4):614–23. https://doi.org/10.1242/jeb.092213
30. Youngsteadt E, Baca JA, Osborne J, Schal C. Species-specific seed dispersal in an obligate ant-plant mutualism. PloS one. 2009;4(2):e4335. https://doi.org/10.1371/journal.pone.0004335
31. Nurdiansyah MA, Abduh MY, Ono H, Permana AD. Attractiveness of *Tetragonula laeviceps* (Hymenoptera: Apidae) to citrus volatile compounds and flower colors in indoor microclimate conditions. Sociobiology. 2024;71(3):e10395-e. https://doi.org/10.13102/sociobiology.v71i3.10395
32. Radev Z. Honey Bee (*Apis mellifera* L.) Pollination as an ecological method to increase the quality of lavender essential oil. Agriculturae Conspectus Scientificus. 2023;88(1):85–8.
33. Gibernau M, Gomes Gonçalves E, Do Amaral Navarro DM, Dália Maia A. Chemical diversity of floral scents in 9 species of Philodendron (Araceae) from French Guiana. Botany Letters. 2023;170(1):53–64. https://doi.org/10.1080/23818107.2022.2144445
34. de Brito-Machado D, Ramos YJ, Defaveri ACAe, de Queiroz GA, Guimarães EF, de Lima Moreira D. Volatile chemical variation of essential oils and their correlation with insects, phenology, ontogeny and microclimate: *Piper mollicomum* Kunth, a case of study. Plants. 2022;11(24):3535. https://doi.org/10.3390/plants11243535
35. Farinasso HC, Consolaro H, Gomes SM, Aguiar AJ. From generalization to pollination syndromes: filtering and dependency on functional-group of pollinators in two cassava wild relatives. Arthropod-Plant Interactions. 2021;15(2):235–47. https://doi.org/10.1007/s11829-021-09811-x
36. Xu S, Kreitzer C, McGale E, Lackus ND, Guo H, Köllner TG, et al. Allelic differences of clustered terpene synthases contribute to correlated intraspecific variation of floral and herbivory-induced volatiles in a wild tobacco. New Phytologist. 2020;228(3):1083–96. https://doi.org/10.1111/nph.16739
37. Nawade B, Shaltiel-Harpaz L, Yahyaa M, Kabaha A, Kedoshim R, Bosamia TC, et al. Characterization of terpene synthase genes potentially involved in black fig fly (*Silba adipata*) interactions with *Ficus carica*. Plant Science. 2020;298:110549. https://doi.org/10.1016/j.plantsci.2020.110549
38. Zhang H, Liu C, Yao JL, Deng CH, Chen S, Chen J, et al. *Citrus mangshanensis* pollen confers a xenia effect on linalool oxide accumulation in pummelo fruit by enhancing the expression of a cytochrome P450 78A7 gene CitLO 1. Journal of Agricultural and Food Chemistry. 2019;67(34):9468–76. https://doi.org/10.1021/acs.jafc.9b03158
39. Li Y, Zhu N, Liang X, Zheng L, Zhang C, Li YF, et al. A comparative study on the accumulation, translocation and transformation of selenite, selenate and SeNPs in a hydroponic-plant system. Ecotoxicology and Environmental Safety. 2020;189:109955. https://doi.org/10.1016/j.ecoenv.2019.109955
40. Lin BY, Chan PP, Lowe TM. tRNAviz: explore and visualize tRNA sequence features. Nucleic Acids Research. 2019;47(W1):W542–W7. https://doi.org/10.1093/nar/gkz438
41. Kasali AA, Lawal OA, Eshilokun AO, Olaniyan AA, Opoku AR, Setzer WN. Citrus essential oil of Nigeria part V: Volatile constituents of sweet orange leaf oil (*Citrus sinensis*). Natural Product Communications. 2011;6(6):1934578X1100600629. https://doi.org/10.1177/1934578X1100600629
42. Li H, Li J, Dong Y, Hao H, Ling Z, Bai H, et al. Time-series transcriptome provides insights into the gene regulation network involved in the volatile terpenoid metabolism during the flower development of lavender. BMC Plant Biology. 2019;19:1–17. https://doi.org/10.1186/s12870-019-1908-6
43. Gibernau M, Maia AC, Amaral Navarro DM. Pollination ecology and floral scent chemistry of *Philodendron fragrantissimum* (Araceae). Botany Letters. 2021;168(3):384–94. https://doi.org/10.1080/23818107.2021.1909497
44. della Cuna FS, Giovannini A, Braglia L, Sottani C, Grignani E, Preda S. Chemical composition of the essential oils from leaves and flowers of *Passiflora sexocellata* and *Passiflora trifasciata*. Natural

Product Communications. 2021;16(4):1934578X211007691. https://doi.org/10.1177/1934578X211007691

45. Giuliani C, Ascrizzi R, Lupi D, Tassera G, Santagostini L, Giovanetti M, et al. *Salvia verticillata*: Linking glandular trichomes, volatiles and pollinators. Phytochemistry. 2018;155:53–60. https://doi.org/10.1016/j.phytochem.2018.07.016

46. Xu C, Luo J, Wang L, Zhu X, Xue H, Huangfu N, et al. Gut bacterial community and gene expression alterations induced by transgenic Bt maize contribute to insecticidal activity against *Mythimna separata*. Journal of Pest Science. 2024;97(2):685–700. https://doi.org/10.1007/s10340-023-01671-z

47. Lorenzi V, Muselli A, Bernardini AF, Berti L, Pages JM, Amaral L, et al. Geraniol restores antibiotic activities against multidrug-resistant isolates from gram-negative species. Antimicrobial Agents and Chemotherapy. 2009;53(5):2209–11. https://doi.org/10.1128/AAC.00919-08

48. Trombetta D, Castelli F, Sarpietro MG, Venuti V, Cristani M, Daniele C, et al. Mechanisms of antibacterial action of three monoterpenes. Antimicrobial Agents and Chemotherapy. 2005;49(6):2474–8. https://doi.org/10.1128/AAC.49.6.2474-2478.2005

49. Smid E, Koeken J, Gorris L. Fungicidal and fungistatic action of the secondary plant metabolites cinnarnaldehyde and carvone. 1996.

50. Dunkić V, Bezić N, Vuko E, Cukrov D. Antiphytoviral activity of *Satureja montana* L. ssp. *variegata* (Host) PW Ball essential oil and phenol compounds on CMV and TMV. Molecules. 2010;15(10):6713–21. https://doi.org/10.3390/molecules15106713

51. Astani A, Reichling J, Schnitzler P. Comparative study on the antiviral activity of selected monoterpenes derived from essential oils. Phytotherapy Research. 2010;24(5):673–9. https://doi.org/10.1002/ptr.2955

52. Jin J, Guo N, Zhang J, Ding Y, Tang X, Liang J, et al. The synergy of honokiol and fluconazole against clinical isolates of azole-resistant *Candida albicans*. Letters in Applied Microbiology. 2010;51(3):351–7. https://doi.org/10.1111/j.1472-765X.2010.02900.x

53. Oleszek W, Kapusta I, Stochmal A. 20TLC of triterpenes (including saponins). Thin Layer Chromatography in Phytochemistry; CRC Press/Taylor & Francis Group: New York, NY, USA. 2008:519. https://doi.org/10.1201/9781420046786.ch20

54. Wardini TH, Afifa IN, Esyanti RR, Astutiningsih NT, Pujisiswanto H. The potential of invasive species *Praxelis clematidea* extract as a bioherbicide for *Asystasia gangetica.* Biodiversitas Journal of Biological Diversity. 2023;24(9). https://doi.org/10.13057/biodiv/d240914

55. Abdullah S, Zahoor I. Biopesticides: A green substitute to chemical pesticide.International Journal of Chemical and Biochemical Sciences. 2023;24(4):141–56.

56. Rashidi S, Yousefi AR, Pouryousef M, Goicoechea N. Effect of arbuscular mycorrhizal fungi on the accumulation of secondary metabolites in roots and reproductive organs of *Solanum nigrum*, *Digitaria sanguinalis* and *Ipomoea purpurea*. Chemical and Biological Technologies in Agriculture. 2022;9(1):23. https://doi.org/10.1186/s40538-022-00288-1

57. Wang D, Poss J, Donovan T, Shannon M, Lesch S. Biophysical properties and biomass production of elephant grass under saline conditions. Journal of Arid Environments. 2002;52(4):447–56. https://doi.org/10.1006/jare.2002.1016

58. Garcia CR, Malik MH, Biswas S, Tam VH, Rumbaugh KP, Li W, et al. Nanoemulsion delivery systems for enhanced efficacy of antimicrobials and essential oils. Biomaterials Science. 2022;10(3):633–53. https://doi.org/10.1039/D1BM01537K

59. Ma H, Chen Y, Chen J, Ji J, He H. Identification and comparison of allelopathic effects from leaf and flower volatiles of the invasive plants *Mikania micrantha*. Chemoecology. 2021;31(6):355–65. https://doi.org/10.1007/s00049-021-00356-2

60. Motmainna M, Juraimi AS, Uddin MK, Asib NB, Islam AM, Ahmad-Hamdani MS, et al. Phytochemical constituents and allelopathic potential of *Parthenium hysterophorus* L. in comparison to commercial herbicides to control weeds. Plants. 2021;10(7):1445. https://doi.org/10.3390/plants10071445

61. Pannacci E, Masi M, Farneselli M, Tei F. Evaluation of mugwort (*Artemisia vulgaris* L.) aqueous extract as a potential bioherbicide to control *Amaranthus retroflexus* L. in maize. Agriculture. 2020;10(12):642. https://doi.org/10.3390/agriculture10120642

62. Sheibany K, Baghestani meybodi MA, Atri A. Competitive effects of redroot pigweed (*Amaranthus retroflexus*) on the growth indices and yield of corn. Weed Biology and Management. 2009;9(2):152–9. https://doi.org/10.1111/j.1445-6664.2009.00333.x

63. Essa AF, El-Hawary SS, Abd-El Gawad AM, Kubacy TM, AM El-Khrisy EE, Elshamy AI, et al. Prevalence of diterpenes in essential oil of *Euphorbia mauritanica* L.: Detailed chemical profile, antioxidant, cytotoxic and phytotoxic activities. Chemistry & Biodiversity. 2021;18(7):e2100238. https://doi.org/10.1002/cbdv.202100238

64. Verma P, Blaise D, Sheeba JA, Manikandan A. Allelopathic potential and allelochemicals in different intercrops for weed management in rainfed cotton. Current Science. 2021;120(6):1035. https://doi.org/10.18520/cs/v120/i6/1035-1039

65. Alizadeh Z, Motafakkerazad R, Salehi-Lisar SY, Zarrini G. Evaluation of the allelopathic effect of wheat and redroot pigweed on growth indices and antioxidant system activity in intercropping. Journal of Plant Protection Research. 2023:97–112. https://doi.org/10.24425/jppr.2023.144508

66. Wang C, Qi J, Liu Q, Wang Y, Wang H. Allelopathic potential of aqueous extracts from fleagrass (*Adenosma buchneroides* Bonati) against two crop and three weed species. Agriculture. 2022;12(8):1103. https://doi.org/10.3390/agriculture12081103

67. Kong Q, Zhou L, Wang X, Luo S, Li J, Xiao H, et al. Chemical composition and allelopathic effect of essential oil of *Litsea pungens*. Agronomy. 2021;11(6):1115. https://doi.org/10.3390/agronomy11061115

68. Gong X, Ren Y. Larvicidal and ovicidal activity of carvacrol, p-cymene and γ-terpinene from *Origanum vulgare* essential oil against the cotton bollworm, *Helicoverpa armigera* (Hübner). Environmental Science and Pollution Research. 2020;27:18708–16. https://doi.org/10.1007/s11356-020-08391-2

69. Park CG, Jang M, Yoon KA, Kim J. Insecticidal and acetylcholinesterase inhibitory activities of Lamiaceae plant essential oils and their major components against *Drosophila suzukii* (Diptera: Drosophilidae). Industrial Crops and Products. 2016;89:507–13. https://doi.org/10.1016/j.indcrop.2016.06.008

70. Singh R, Koul O, Rup PJ, Jindal J. Toxicity of some essential oil constituents and their binary mixtures against *Chilo partellus* (Lepidoptera: Pyralidae). International Journal of Tropical Insect Science. 2009;29(2):93–101. https://doi.org/10.1017/S1742758409990087

71. Araújo EC, Silveira ER, Lima MA, Neto MA, de Andrade IL, Lima MA, et al. Insecticidal activity and chemical composition of volatile oils from *Hyptis martiusii* Benth. Journal of Agricultural and Food Chemistry. 2003;51(13):3760–2. https://doi.org/10.1021/jf021074s

72. Wattam AR, Davis JJ, Assaf R, Boisvert S, Brettin T, Bun C, et al. Improvements to PATRIC, the all-bacterial bioinformatics database and analysis resource center. Nucleic Acids Research. 2017;45(D1):D535–42. https://doi.org/10.1093/nar/gkw1017

73. Papanastasiou SA, Bali EM, Ioannou CS, Papachristos DP, Zarpas KD, Papadopoulos NT. Toxic and hormetic-like effects of three components of citrus essential oils on adult Mediterranean fruit flies (*Ceratitis capitata*). PloS One. 2017;12(5):e0177837. https://doi.org/10.1371/journal.pone.0177837

74. Yadav PA, Suresh G, Rao MS, Shankaraiah G, Rani PU, Babu KS. Limonoids from the leaves of *Soymida febrifuga* and their insect antifeedant activities. Bioorganic & Medicinal Chemistry Letters. 2014;24(3):888–92. https://doi.org/10.1016/j.bmcl.2013.12.077

75. Sarria AL, Soares MS, Matos AP, Fernandes JB, Vieira PC, Silva MF. Effect of triterpenoids and limonoids isolated from *Cabralea canjerana* and *Carapa guianensis* (Meliaceae) against *Spodoptera frugiperda* (JE Smith). Zeitschrift Für Naturforschung C. 2011;66(5–6):245–50. https://doi.org/10.1515/znc-2011-5-607

76. Li MY, Zhang J, Feng G, Satyanandamurty T, Wu J. Khayasin and 2′ S-methylbutanoylproceranolide: Promising candidate insecticides for the control of the coconut leaf beetle, *Brontispa longissima*. Journal of Pesticide Science. 2011;36(1):22–6. https://doi.org/10.1584/jpestics.G10-52

77. Wu HB, Wu HB, Wang WS, Liu TT, Qi MG, Feng JC, et al. Insecticidal activity of sesquiterpene lactones and monoterpenoid from the fruits of *Carpesium abrotanoides*. Industrial Crops and Products. 2016;92:77–83. https://doi.org/10.1016/j.indcrop.2016.07.046

78. Reina M, Santana O, Domínguez DM, Villarroel L, Fajardo V, Rodríguez ML, et al. Defensive sesquiterpenes from *Senecio candidans* and *S. magellanicus* and their structure activity relationships. Chemistry & Biodiversity. 2012;9(3):625–43. https://doi.org/10.1002/cbdv.201100236

79. Burgueño-Tapia E, González-Coloma A, Martín-Benito D, Joseph-Nathan P. Antifeedant and phytotoxic activity of cacalolides and eremophilanolides. Zeitschrift für Naturforschung C. 2007;62(5–6):362–6. https://doi.org/10.1515/znc-2007-5-608

80. Webster A, Manning P, Sproule J, Faraone N, Cutler G. Insecticidal and synergistic activity of two monoterpenes against diamondback moth (Lepidoptera: Plutellidae). The Canadian Entomologist. 2018;150(2):258–64. https://doi.org/10.4039/tce.2017.63

81. Rao AR, Rao PK, Jyotsna KP. Efficacy of certain natural insecticides against Citrus leaf miner, *Phyllocnistis citrella* Stainton as prophylactic and curative measures on Sathgudi Sweet Orange. Pest Management in Horticultural Ecosystems. 2015;21(1):11–5.

82. Rupasinghe H, Murr D, Paliyath G, DeEll J. Suppression of alpha-Farnesene synthesis in delicious' Apples by Aminoethoxyvinylglycine (AVG) and 1-Methylcyclopropene (1-MCP). Physiology and Molecular Biology of Plants. 2000;6:195–8.

83. Rosenfeld HJ, Aaby K, Lea P. Influence of temperature and plant density on sensory quality and volatile terpenoids of carrot (*Daucus carota* L.) root. Journal of the Science of Food and Agriculture. 2002;82(12):1384–90. https://doi.org/10.1002/jsfa.1200

84. de Abreu IN, Mazzafera P. Effect of water and temperature stress on the content of active constituents of *Hypericum brasiliense* Choisy. Plant Physiology and Biochemistry. 2005;43(3):241–8. https://doi.org/10.1016/j.plaphy.2005.01.020

85. Ghasemzadeh A, Jaafar HZ, Karimi E, Ashkani S. Changes in nutritional metabolites of young ginger (*Zingiber officinale* Roscoe) in response to elevated carbon dioxide. Molecules. 2014;19(10):16693–706. https://doi.org/10.3390/molecules191016693

86. Gao M, Li R, Dai S, Wu Y, Yi D. Diversity of *Bacillus thuringiensis* strains from soil in China and their pesticidal activities. Biological Control. 2008;44(3):380–8. https://doi.org/10.1016/j.biocontrol.2007.11.011

87. Brazaitytė A, Sakalauskienė S, Samuolienė G, Jankauskienė J, Viršilė A, Novičkovas A, et al. The effects of LED illumination spectra and intensity on carotenoid content in Brassicaceae microgreens. Food Chemistry. 2015;173:600–6. https://doi.org/10.1016/j.foodchem.2014.10.077

88. Takshak S, Agrawal S. Defence strategies adopted by the medicinal plant *Coleus forskohlii* against supplemental ultraviolet-B radiation: Augmentation of secondary metabolites and antioxidants. Plant Physiology and Biochemistry. 2015;97:124–38. https://doi.org/10.1016/j.plaphy.2015.09.018

89. Takshak S, Agrawal Sá. Secondary metabolites and phenylpropanoid pathway enzymes as influenced under supplemental ultraviolet-B radiation in *Withania somnifera* Dunal, an indigenous medicinal plant. Journal of Photochemistry and Photobiology B: Biology. 2014;140:332–43. https://doi.org/10.1016/j.jphotobiol.2014.08.011

90. Carletti P, Masi A, Wonisch A, Grill D, Tausz M, Ferretti M. Changes in antioxidant and pigment pool dimensions in UV-B irradiated maize seedlings. Environmental and Experimental Botany. 2003;50(2):149–57. https://doi.org/10.1016/S0098-8472(03)00020-0

91. Schnepf E, Crickmore N, Van Rie J, Lereclus D, Baum J, Feitelson J, et al. *Bacillus thuringiensis* and its pesticidal crystal proteins. Microbiology and Molecular Biology Reviews. 1998;62(3):775–806. https://doi.org/10.1128/MMBR.62.3.775-806.1998

92. Loreto F, Fischbach RJ, Schnitzler JP, Ciccioli P, Brancaleoni E, Calfapietra C, et al. Monoterpene emission and monoterpene synthase activities in the Mediterranean evergreen oak *Quercus ilex* L. grown at elevated CO2 concentrations. Global Change Biology. 2001;7(6):709–17. https://doi.org/10.1046/j.1354-1013.2001.00442.x

93. Knudsen JT, Eriksson R, Gershenzon J, Ståhl B. Diversity and distribution of floral scent. The Botanical Review. 2006;72(1):1–20. https://doi.org/10.1663/0006-8101(2006)72[1:DADOFS]2.0.CO;2

94. Chiriboga X, Campos-Herrera R, Jaffuel G, Röder G, Turlings TC. Diffusion of the maize root signal (E)-β-caryophyllene in soils of different textures and the effects on the migration of the entomopathogenic nematode *Heterorhabditis megidis*. Rhizosphere. 2017;3:53–9. https://doi.org/10.1016/j.rhisph.2016.12.006

95. Kollner TG, Held M, Lenk C, Hiltpold I, Turlings TC, Gershenzon J, et al. A maize (E)-β-caryophyllene synthase implicated in indirect defense responses against herbivores is not expressed in most American maize varieties. The Plant Cell. 2008;20(2):482–94. https://doi.org/10.1105/tpc.107.051672

96. Hilgers F, Habash SS, Loeschcke A, Ackermann YS, Neumann S, Heck A, et al. Heterologous production of β-caryophyllene and evaluation of its activity against plant pathogenic fungi. Microorganisms. 2021;9(1):168. https://doi.org/10.3390/microorganisms9010168

97. Wang R, Peng S, Zeng R, Ding LW, Xu Z. Cloning, expression and wounding induction of β-caryophyllene synthase gene from *Mikania micrantha* HBK and allelopathic potential of β-caryophyllene. Allelopathy Journal. 2009;24(1):35–44.

98. Nguyen CT, Nguyen NH, Choi WS, Lee JH, Cheong JJ. Biosynthesis of essential oil compounds in *Ocimum tenuiflorum* is induced by abiotic stresses. Plant Biosystems. 2022;156(2):353–7. https://doi.org/10.1080/11263504.2020.1857870

99. Hansen U, Seufert G. Temperature and light dependence of β-caryophyllene emission rates. Journal of Geophysical Research: Atmospheres. 2003;108(D24). https://doi.org/10.1029/2003JD003853

100. Morshedloo MR, Craker LE, Salami A, Nazeri V, Sang H, Maggi F. Effect of prolonged water stress on essential oil content, compositions and gene expression patterns of mono-and sesquiterpene synthesis in two oregano (*Origanum vulgare* L.) subspecies. Plant Physiology and Biochemistry. 2017;111:119–28. https://doi.org/10.1016/j.plaphy.2016.11.023

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