Zoo Botanica
ISSN: 3007-2050 (E), 3007-2042 (P)

Review Article

The critical functions of plant secondary metabolites in mediating insect host selection and defence strategies: a comprehensive review

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ABSTRACT

Plants produce secondary metabolites (SMs), which are bioactive compounds produced as an adaptive defense against herbivorous insect attacks. These compounds include alkaloids, terpenes, phenolics, and glucosinolates, which deter insects' feeding, disrupt their digestive systems, and kill them. Insects have olfactory and gustatory receptors, which help them select or reject the plant hosts. Plant secondary metabolites (SMs) can either cause direct toxicity by acting as toxins for the insects or cause indirect toxicity by attracting parasitoids of pests. Plants use complex biosynthetic 3 pathways such as the shikimic acid pathway for phenolic and flavonoids, the Methylerythritol phosphate (MEP) and mevalonate pathway for terpenoids, and the acetate-malonate pathways for polyketide synthesis. These pathways are specifically regulated, upon tissue damage or stress, by plant hormones such as jasmonic acid and salicylic acid. Alkaloids such as nicotine and caffeine interfere with the insects' nervous system, causing death. Azadirachtin, a terpenoid from neem, disrupts moulting and reproduction in insects, while tannins and flavonoids inhibit the digestive enzymes of insects. Although these compounds are plants' natural defence, many insects of the families Nocutidae, Lepidoptera, Aphididae, Danainae, and Chrysomelidae have evolved certain molecular mechanisms, such as cytochrome P450 mono-oxygenase-based oxidation, sequestration, target insensitivity, and microbial symbiont-mediated detoxification, to protect themselves against SMs. This review discusses the biosynthesis of different plant SMs, their direct or indirect toxicity, and insects' adaptations against these SMs, and Implications of SMs in modern research to explore their role as biopesticides.

Keywords: Detoxification mechanisms; insect herbivory; insect host selection; secondary metabolites (SMs); plant defence mechanisms.

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Article History
Received: November 16, 2025
Accepted: December 20, 2025
Published: December 31, 2025

INTRODUCTION

Plants are complex living organisms that rely on an arrangement of biochemical strategies to survive under environmental and biotic challenges (Zhang et al., 2020). As per Darwin's theory of natural selection, there is always survival of the fittest. Plants are immobile and constantly exposed to stresses like herbivory, pathogen attack, drought, and other extreme conditions (Koyro et al., 2011). Phytophagous herbivores alone are responsible for about 20% loss of global crop annually (Divekar et al., 2022). The complex biochemical pathways of plants produce metabolites to cope with their needs. Primary metabolites such as carbohydrates, lipids, amino acids, and nucleotides are responsible for growth, development, and reproduction, while the secondary metabolites (SMs such as alkaloids, phenolics, and terpenes are responsible for the communication and defence of plants against pests and

https://doi.org/10.55627/zoobotanica.003.03.1721

pathogens (Salam et al., 2023). Plant SMs are regulated through several biosynthetic pathways, like shikimic acid pathway produces aromatic amino acids, the precursors of phenolics, flavonoids, and alkaloids in plants (Kabera et al., 2014). The malonate pathway synthesizes phenolic compounds, such as tannins and flavonoids, through polyketide intermediates derived from malonyl-CoA. Mevalonate pathways synthesise isoprenoids using acetyl-CoA as a precursor (Vranová et al., 2013). The SMs exhibit species-specific distributions; glucosinolates are predominantly produced in Brassicaceae species and deter insects from feeding. Nicotine, a strong alkaloid, is produced by the Solanaceae family of plants. Artemisinin is specifically present only in Artemisia annua (sweet wormwood) of the Asteraceae family. Caffeine is present in coffee and tea plants, and azadirachtin, a limonoid, is produced in the Meliaceae family (Jan et al., 2025; Tlak Gajger & Dar, 2021). These SMs pose serious harm to insects either directly, i.e., by acting as neurotoxins, antifeedants, and digestive inhibitors, or indirectly by attracting parasitoids which kill the pests. When attacked by insects, plants release green leaf volatiles (GLVs) and herbivore-induced plant volatiles (HIPVs) as signaling compounds to attract predators (Gebreziher, 2018). These plant defences are valuable; however, some species of insects have evolved adaptations via mutations, gene duplication, and selection-driven expression changes. These genetic modifications enable insects to metabolise, tolerate, and resist toxic SMs, exhibiting microevolution under strong plant-insect co-evolutionary pressure (Jermy, 1976; Mujiono & Witjaksono, 2025). Plant SMs, being natural compounds, have several advantages over synthetic and harmful pesticides. In agriculture, azadirachtin, pyrethrins, and nicotine serve as natural insecticides as an integral part of sustainable pest management (Al-Khayri et al., 2023; Lyubenova et al., 2023). Recent research focuses on improving the yield, potency, and specificity of these SMs via genetic engineering and CRISPR-Cas9 gene editing. Moreover, genomic and transcriptomic studies of plants integrated with metabolomics engineering in microbes can also serve as a potent way to upscale the production of these SMs (Yan Li et al., 2021; Xia et al., 2021). This review discusses the biosynthesis pathways involved in the production of plant SMs and how they defend plants against herbivorous insects. How do they play a role in insect host selection and insect detoxification adaptation? And the effective implications of these SMs in eco-environment and cost-effective strategies to ensure sustainable agriculture.

This review aims to discuss current knowledge on the roles of plant SMs in mediating insect host selection, plant defence strategies and adaptive responses, with prime emphasis on the mechanistic link between chemical diversity or plant-based organic compounds and their ecological function. The review not only focuses on individual classes of SMs or isolated plant or insect responses, but also on the chemical, ecological, and applied perspectives. It particularly compares how different SMs classes shape the host choice, defence efficiency and detoxification strategies across diverse plant-insect systems. Hence, the review provides a structural framework to guide future research of bio-pesticide development by identifying common patterns, knowledge gaps, and translational challenges.

LITERATURE SEARCH AND REVIEW METHODOLOGY

The literature for this review was collected through a comprehensive search of major scientific databases, including Google Scholar, Scopus and Web of Science. Searches were conducted using a combination of keywords such as "Plans Secondary Metabolites", "Insect-Host selection", "Plant-Insect Interactions", "Chemical defence", "Biopesticides", along with specific classes of SMs where relevant. While searching for literature, the duration was set to 2018 to 2025 to retrieve recent and up-to-date data. Articles were selected based on their relevance to the roles of SMs in insect behaviour, plant defence mechanisms and insect adaptive responses. Preference was given to studies providing mechanistic insights, comparative perspectives or clarifying implications of pest management and applied biopesticide development. Moreover, PubChem and ChemDraw were used to retrieve and draw chemical structures of SMs.

CLASSIFICATION OF PLANT SECONDARY METABOLITES

Plants synthesize a wide variety of SMs, which play a crucial role in the growth and survival of plants under different ecological and environmental factors (Tiwari & Rana, 2015). These SMs are basically the derivatives of primary metabolites produced in plants during several metabolic reactions, such as the methylerythritol phosphate (MEP) pathway, shikimate, and mevalonate (MVA) pathways (Umalatha et al., 2025). It is estimated that different taxonomic groups of the Kingdom Plantae collectively contain about 100,000 SMs, which exert long-lasting effects on plants' survival under unfavorable conditions (Zandalinas et al., 2017). There are four major groups of plant SMs (Figure 1). These include Terpenes, Phenolic compounds, Nitrogen-containing SMs, and sulphur-containing compounds. These compounds have diverse chemical properties, biosynthetic origins, and roles in plants' direct or indirect defence systems, as summarized in table (1).

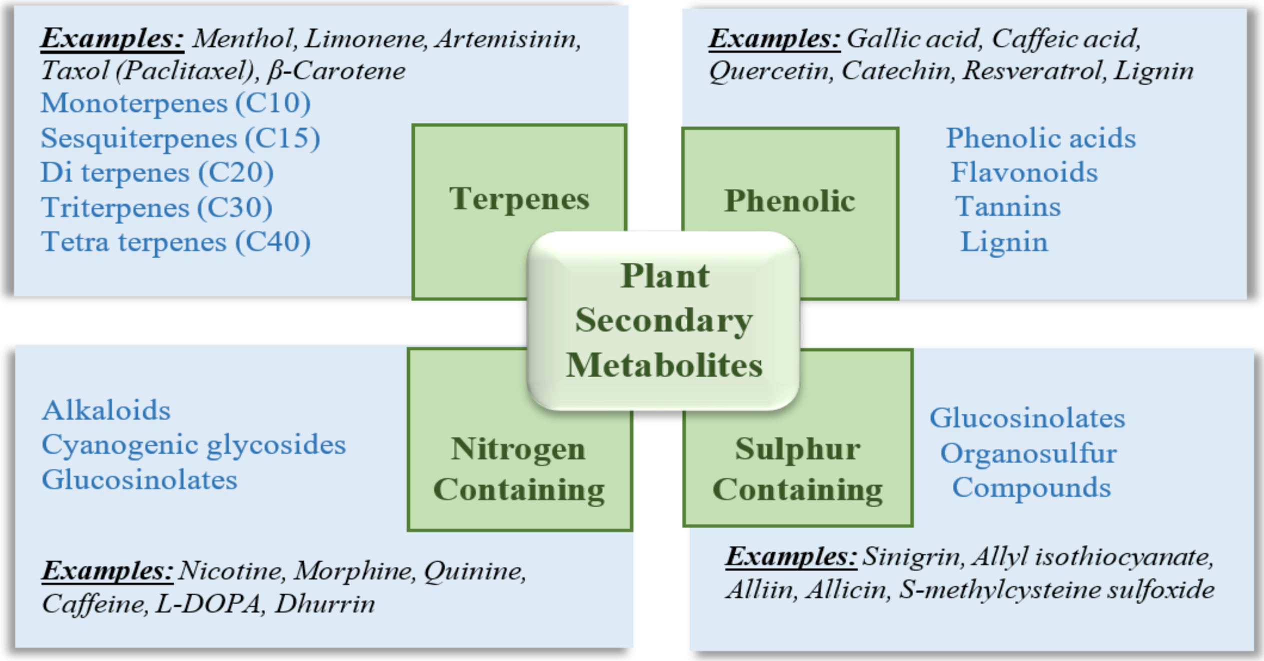
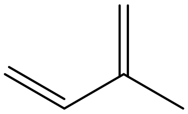
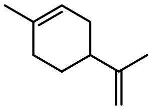
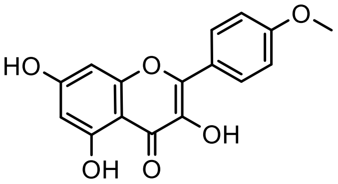
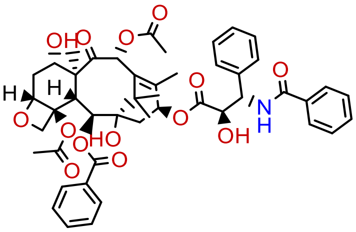
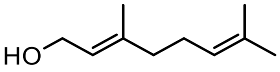
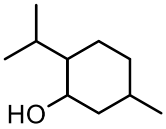
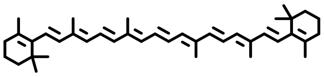
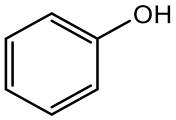
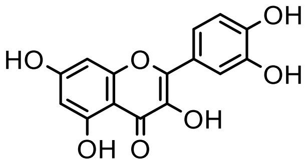
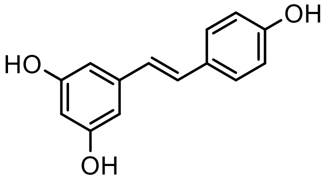
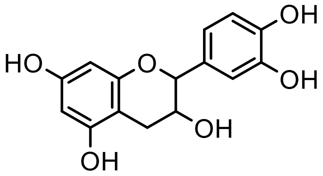
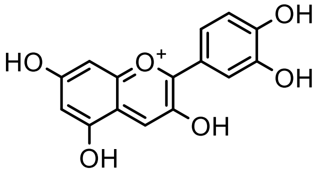
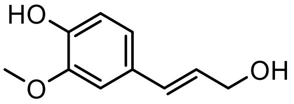
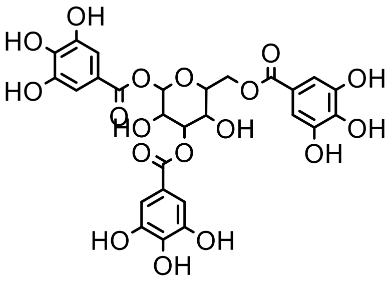
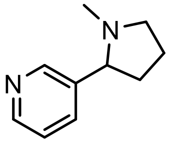
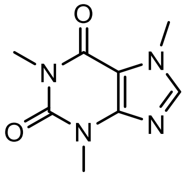
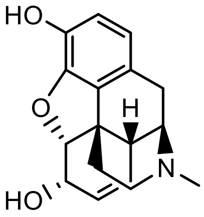
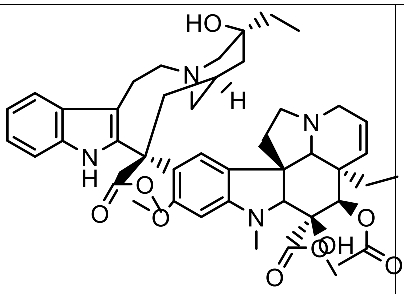
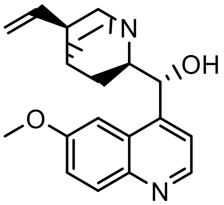
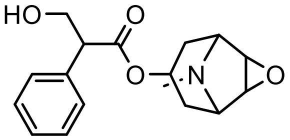
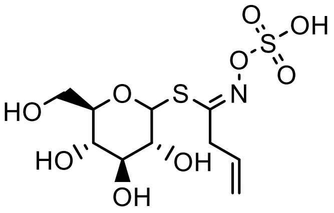
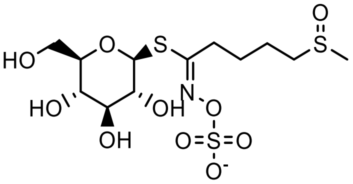
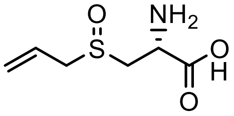
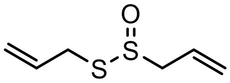
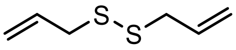


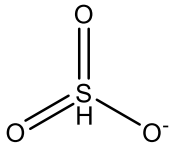
Figure 1: Four major classes of plant secondary metabolites: Terpenes, Phenolics, nitrogen-containing compounds, and sulphur-containing compounds, along with their subclasses, and specific representative compounds.

Table 1. Major classes of plant secondary metabolites in terms of their biosynthetic pathway, key examples, and plant sources.

Major Classes of Plant Secondary Metabolites	Biosynthetic Pathway	Plant Secondary Metabolites	Chemical structures	Plant species	References
Terpenes (Terpenoids) Basic unit of Terpenes is isoprene units (C_5), which could either be linear or cyclic. Main functional groups in terpene SMs are alcohols, ketones, esters, and epoxides. 	Methylerythritol phosphate (MEP) pathway in plastids and Mevalonate pathway in cytosol, producing IPP and DMAPP as common intermediates.	Limonene		Peels of Citrus spp. fruits.	(Alqahtani et al., 2019; Siddiqui et al., 2022; Stephane, 2020)
		Artemisinin (sesquiterpene lactone)		*Artemisia annua*	
		Paclitaxel (taxane diterpene)		*Taxus* spp.	
		Geraniol		*Pelargonium/* roses	
		Menthol		*Mentha* spp.	
		β-Carotene (tetraterpene)		carrot/green plants	

Phenolics Basic structural units of Phenolics SMs are aromatic rings (C6) covalently bonded to one or more hydroxyl groups. Main functional groups associated with phenolics are phenol groups 	In plants, Phenolics are produced from aromatic amino acids (Phe, Tyr, Trp) via the Shikimic acid pathway.	Quercetin		*Vitis vinifera*	(X. Li et al., 2022; Singh et al., 2021; Walle, 2011)
		Resveratrol		*Vitis vinifera*	
		Catechin		Tea (*Camellia sinensis*: catechins, flavanols),	
		Cyanidin		Grape skins (anthocyanins	
		Coniferyl alcohol		woody plants (coniferyl alcohol → lignin)	
		Tannic acid			
N-Containing Secondary Metabolites Heterocyclic compounds with at least one nitrogen in either form (tertiary amines, quaternary ammonium). Main functional	In plants, N-containing compounds are primarily derived from the precursors of amino acids such as tryptamine from tryptophan, tyramine and	Nicotine		*Nicotiana tabacum*	(Ejaz et al., 2020; Hung & Hung, 2015; Le Foll et al., 2022)
		Caffeine		*Coffea arabica/Camellia sinensis*	
		Morphine		*Papaver somniferum*	

groups associated with N-containing SMs are amines and amide groups. NH_3	dopamine from tyrosine via a variety of metabolic reactions (decarboxylation, transamination, P450-mediated oxidation)	Vinblastine		*Catharanthus roseus*	
		Quinine		*Cinchona* spp.	
		Scopolamine		*Atropa/Datura* spp. (scopolamine, hyoscyamine).	
S-containing Secondary metabolites Primarily contain sulphur in the form of thiols, thioethers, thiosulfinates and sulfonates. These compounds also contain nitrogen in their chemical structures. Functional groups associated with S-containing SMs are sulfoxide, thiocyanate and isothiocyanate.	Glucosinolates are derived from amino acids, i.e., tryptophan, methionine, and phenylalanine via chain elongation and core formation (CYP79, CYP83, GSTs). Usually stored in vacuoles, released and activated upon tissue damage. Other compounds are produced via the organosulfur pathway, where cysteine sulfoxides are converted into active thiosulfinates (allicin) via a series of	Sinigrin (allyl glucosinolate)		*Brassica* spp., *Arabidopsis thaliana* (glucosinolates)	(Oyaluna et al., 2024)
		Glucoraphanin (precursor of sulforaphane		*Brassica oleracea*	
		Alliin		*Allium sativum*	
		Allicin		*Allium sativum*	
		Diallyl disulfide			

	reactions upon tissue damage.				

Terpenes

Terpenes or terpenoids are the largest group of plant SMs and are usually produced in plants' cytoplasm and plastids by the MEP and MVA pathways, respectively. Both pathways have a common universal precursor, isopentenyl diphosphate (IPP), which is formed from acetyl-CoA (Perveen & Al-Taweel, 2018). In the MEP pathway, pyruvate and glyceraldehyde-3-phosphate produce two intermediates, 1-deoxy-D-xylulose 5-phosphate (DXP) and MEP, leading to IPP and dimethylallyl diphosphate (DMAPP). While in the MVA pathway, mevalonic acid is produced from acetyl-CoA, phosphorylated, and decarboxylated to form IPP and DMAPP (Vranová et al., 2013). Further, the polymerization of IPP results in the formation of different terpenes depending upon the number of isoprene (C5) units i.e., monoterpenes with two isoprene units (C10), sesquiterpenes with three isoprene units (C15), diterpenes with four isoprene units (C20), triterpenes with six isoprene units (C30), tetraterpenes with eight isoprene units (C40), and polyterpenoids with multiple isoprene units (Boncan et al., 2020).

Terpenes produced through the MEP pathway usually include carotenoids (pigments), plant hormones (abscisic acid and gibberellins), chlorophyll precursors (phytol), tocophenols (Vitamin E), and electron carriers (plastoquinones), while the terpenes produced by the MVA pathway include sterols, plant growth hormones (Brassinosteroids), and cell signalling prenylated proteins (Tetali, 2019). Therefore, terpenes play a vital role in plant pigmentation, growth, photosynthesis, and defence. Besides these major terpenes, some exist as volatile essential oils, while others exist as toxic saponins that disrupt cellular membranes and interfere with sterol uptake in many pathogenic organisms (Kennedy et al., 2018).

Phenolics

Phenolics are the most diverse group of aromatic SMs, which are chemically characterized by a phenyl ring attached to an acidic hydroxyl group. Phenolic compounds such as flavonoids, tannins, coumarins, and lignins are important for plants' defence, maintenance of structural integrity, and pigmentation (Ahlawat et al., 2024). About 10,000 different types of phenolic compounds have been identified in plants. These are chemically heterogeneous and hence show diversity in solubility, i.e., some are polar and easily soluble in water, while others are non-polar and soluble only in organic solvents (Santos-Sánchez et al., 2019). Phenolic compounds, predominantly aromatic amino acids such as tyrosine, phenylalanine, and tryptophan, are produced via the shikimic acid pathway in plants. The shikimic acid pathway begins with the condensation of two precursors: phosphoenolpyruvate (PEP) from glycolysis and erythrose-4-phosphate from the pentose phosphate pathway, to form DAHP.

Further, a series of enzymatic reactions converts DAHP into shikimic acid, which is transformed into chorismate, leading to the synthesis of aromatic amino acids (Paul et al., 2023). Additionally, some phenolic compounds, such as aflatoxins, curcuminoids, resorcylic acids, and tetracyclines, are produced through the malonic acid pathway (MAP), also known as the polyketide pathway. In the MAP pathway, malonyl-CoA, derived from acetyl-CoA, acts as a precursor. Polyketide synthases then undergo repeated addition of malonyl-CoA from polyketide chains, resulting in the cyclisation of aromatic phenolic structures (Yu et al., 2012).

Although phenolic SMs are very diverse, but classified into two main types, i.e., phenylpropanoids and Lignin. Phenylpropanoids are the simple phenolic compounds with a phenyl ring covalently bonded to a 3C-side chain. Cinnamic acid and p-coumaric acids are the main precursors to produce major phenylpropanoids such as flavonoids, stilbenes, and coumarins (Vogt, 2010). On the other hand, lignins are complex phenolics with large, branched polymers made of phenylpropanoid monomers such as coniferyl, sinapyl, and p-coumaryl alcohols. These monomers polymerise through dehydrogenative radical-mediated pathways and form a heterogeneous and cross-linked network of lignin, which is embedded in cellulose and hemicellulose in the secondary cell walls of plants. The rigid structure of lignin provides mechanical strength and hydrophobicity to the wood and vascular system of a plant (Grabber, 2005).

Phenolic compounds, such as flavonoids and tannins, play vital roles in plants' defence against insects, pests, and pathogens. Flavonoids such as quercetin and kaempferol are antioxidants in nature and scavenge reactive oxygen species (ROS) produced during stress. These compounds have also been reported to damage the insect digestive tract by inhibiting the synthesis of proteases and amylases (Vellosa et al., 2011). The condensed tannins also affect the insect's gut by binding to digestive enzymes and impairing the digestion and nutrient absorption of the insect (Rasheed et al., 2025). Catechins, the tannin precursors, also reduce the growth and reproduction of pests. Some phenolics serve as signalling molecules, such as salicylic acid, which regulates systemic acquired resistance (SAR). Some long-lived species of plants, such as oaks, conifers, and pines, produce phenolics for their long-term defence throughout their life span (C. Li et al., 2022).

Nitrogen-containing SMs

Nitrogen-containing SMs include alkaloids, cyanogenic glycosides, and glucosinolates, which are usually derived from amino acids and possess potential toxicity and deterrent properties. N-containing compounds are widely distributed among angiosperms and exhibit strong co-evolutionary relationships with insect herbivores. Among N-containing compounds, alkaloids are the most diverse group with about 12000 known alkaloids produced in plants. These are low molecular weight compounds widely classified in various families depending upon their core structures and origins (Ejaz et al., 2020). Alkaloids are synthesized by the decarboxylation, methylation, cyclisation, and transamination of various amino acids, i.e., tyrosine, tryptophan, ornithine, phenylalanine, and lysine.

The alkaloids such as nicotine, caffeine, and morphine interfere with the metabolic and neurophysiological processes of insects and hence facilitate plants' defence (Kukula-Koch & Widelski, 2017). Nicotiana tabacum produces nicotine, which acts like acetylcholine and binds to nicotine acetylcholine receptors of the insect nervous system, causing paralysis and mortality of the insect (Lewis, 2020). Caffeine is produced by Coffea and Camellia spp. acts as a reproductive inhibitor of insects. Morphine, produced from *Papaver somniferum*, has a bitter taste and has toxic effects in higher concentrations. Some alkaloids play important roles as drugs (Rahul et al., 2018). The terpenoid indole alkaloids, such as vinblastine and camptothecin, are potent anticancer agents (Dhyani et al., 2022). Ajmaline, produced by *Rauwolfia sepentina*, and quinine, produced from *Chinchona spp*, act as antiarrhythmic and antimalarial drugs, respectively (Thawabteh et al., 2019). Benzylisoquinoline alkaloids (BIAs), mostly derived from tyrosine, include morphine, codeine, and papaverine, which also show analgesic, antimicrobial, and antiparasitic properties. Tropane alkaloids such as hyoscyamine and scopolamine, derived from ornithine, are widely synthesised in the Solanaceae family of plants. These alkaloids act as competitive antagonists of muscle receptors and are hence used in surgery and motion sickness. The hydroxylated non-tropane alkaloids are calystegines, found in the Convolvulaceae and Solanaceae family, has beneficial implications in managing diabetes (Adamski et al., 2020).

Cyanogenic glycosides are usually synthesised by amino acids tyrosine, leucine, valine, and phenylalanine via the shikimic acid pathway. Cytochrome P450 monooxygenases convert an amino acid to aldoxime and then cyanohydrin, which is stabilized by glycosylation to ultimately form cyanogenic glycosides such as amygdalin, linamarin, and dhurrin (Vetter, 2000). These are stored in the plant’s vacuoles under normal conditions. In case of any invasion and tissue disruption, these cyanogenic glycosides are hydrolysed by β-glucosidases and produce hydrogen cyanide (HCN). HCN interferes with the electron transport chain and blocks oxidative phosphorylation, leading to the death of the insect. It has been observed in plant families such as Fabaceae, Rosaceae, and Poaceae (Naveena et al., 2021). Glucosinolates are sulphur and nitrogen-containing SMs which are predominantly present in the Brassicaceae family of plants, such as *Arabidopsis thaliana*, *Brassica oleracea* (Halkier & Gershenzon, 2006). Upon cell damage, glucosinolates are hydrolysed and produce toxic isothiocyanate, thiocyanate, and nitriles, leading to the alkylation of DNA and protein, ultimately disrupting gut membranes.

However, some species of insects have evolved resistance against this system by producing nitrile-specifier proteins (NSPs) and glucosinolate sulfatases, which prevent the formation of toxic cyanides. On the other hand, some insects, such as flea beetles, avoid it by minimizing tissue disruption during feeding. This co-evolutionary phenomenon indicates the evolutionary arms race in plant-insect interactions (Bischoff, 2021).

Sulphur-containing compounds

As the name indicates, sulphur-containing SMs contain sulphur-containing functional groups in their structure, such as thiols, thioesters, thiosulfinates, and sulfoxides. In plants, S-containing SMs are primarily derived from cysteine and methionine, the S-containing amino acids. Major S-containing SMs are glucosinolates and organosulfur compounds. Glucosinolates are abundantly present in the Brassicaceae family, such as cabbage, mustard, and broccoli. Glucosinolates are produced by the catalysis of methionine via CYP79 and CYP83 (Mitreiter & Gigolashvili, 2021). When tissues are ruptured, glycosinolates stored in vacuoles are released and hydrolysed to produce isothiocyanates, thiocyanates, and nitriles, which distort proteins and DNA. Some isothiocyanates, such as mustard oil, are highly volatile and trigger the defence system of neighbouring plants or attract parasitoid wasps (Bischoff, 2021). Organosulfur compounds are produced by cysteine sulfoxide pathways in Allium spp, such as onion and garlic. In garlic, alliin is produced by cysteine sulfoxide through the S-alkylation pathway and is activated (allicin) upon tissue damage (Miękus et al., 2020). Allicin further reacts with the thiol group of enzymes in insects and kills them. Other organosulphur compounds, such as diallyl disulphide and methyl allyl trisulfide, contribute to the characteristic strong odour of garlic. These compounds provide direct chemical defence and volatile signalling in plants. The volatile nature of these compounds makes them easily diffusible through air, enabling both the local defence and long-distance signalling among plants (Borlinghaus et al., 2014).

Across four major classes of plant SMs, defence function is usually linked to the chemical structure and biosynthetic origin. Both these factors influence the mode and extent of plant defence along with the degree of insect adaptation. Terpenes commonly contribute to defence through their volatile and lipophilic nature, making terpenes direct toxins and signalling compounds. On the other hand, phenols often function by binding proteins, modulating oxidative processes and strengthening plant tissues. Nitrogen-containing SMs generally exhibit strong effects on insect physiology, specifically targeting insect’s neural and metabolic processes. However, Sulphur-containing systems, particularly glucosinolates and their hydrolysis products, represent inducible defences that are activated upon tissue damage and produce compounds lethal to herbivores. Importantly, Individual classes of SMs can contribute to both direct and indirect defence responses, with defensive outcomes shaped more by ecological context, tissue localization, and inducibility than by a single chemical class. However, key gaps remain in understanding how multiple metabolites interact within plant tissues and how environmental factors influence these interactions, highlighting the need for comparative studies to support effective SM based biopesticide development.

DEFENCE MECHANISMS OF PLANTS AGAINST INSECTS

Plants are well-organized living organisms with a well-developed defence system against insect herbivory. Their defence includes both direct as well as indirect approaches (Figure 2). Direct defence includes the physical structures, such as thorns, rigid cell walls, and trichomes, and chemical compounds, primarily SMs, to prevent invasion or tissue damage by insects. Indirect defence system refers to the release of volatile organic compounds and herbivore-induced plant volatiles (HIPVs) that attract parasitoids and predators of insects toward them (Belete, 2018).

Direct defence

In plants, direct toxicity or direct chemical defence refers to the release of SMs that reduce the feeding of insects or cause severe damage, leading to mortality. In direct defence, the chemical compound directly repels or kills the pest by either producing a strong and pungent smell or by interfering with the digestion of insects, respectively (Harborne, 2007). SMs such as tannins, alkaloids, and terpenes are more important in posing direct toxicity. Tannins reduce herbivore performance by irreversibly binding to the insect's digestive enzymes. Tannins bind to free amino acids and the peptide backbone, inhibiting digestive proteases (Bule et al., 2020). It reduces nitrogen assimilation, leading to stunted growth, prolonged developmental time, and reduced fecundity in insects. Alkaloids such as nicotine, pyrrolizidine, and isoquinoline, produced from *Nicotiana tabacum*, *Senecio jacobaea*, and *Berberis vulgaris*, respectively, act as neurotoxins (Murch, 2006).

Terpenes are central to both direct and indirect defence of plants. For example, limonene, a monoterpene, has a very intense scent that repels aphids from citrus plants. Caryophyllene, a sesquiterpene widely present in cloves, provides insecticidal and antimicrobial properties. Azadirachtin, a tetranortriterpenoid present in *Azadirachta indica*, interferes with ecdysteroids, the moulting hormones of insects, and disrupts reproduction in species like *Helicoverpa armigera*. Azadirachtin acts as a potent botanical insecticide for *Spodoptera frugiperda* (Yu et al., 2023). It inhibits ecdysis in larvae by suppressing the expression of nuclear hormone receptor HR3, a key regulator of 20-hydroxyecdysone signalling (Fan et al., 2023).

Indirect defence

Indirect defence of plants includes herbivore-induced plant volatiles (HIPVs), the volatile SMs, which are released upon a plant’s damage and attract predators or parasitoids that kill the pest (Turlings et al., 2012). HIPV typically includes a blend of aldehydes, alcohols, terpenoids, aromatic benzoids, and their derivatives. Their biosynthesis is upregulated by the jasmonic acid pathway and the lipoxygenase (LOX2) pathway (Toomey, 2021). When *Zea mays* leaves are attacked by caterpillars, jasmonic acid pathway is activated in plant, which releases a blend of volatiles, sesquiterpenes and indoles, (Z)-3-hexenol, (E)-2-hexenal acting as plant’s indirect defence system, when invaded by insects, which act as kairomones and attract parasitoid wasp (*Cotesia marginiventris*) to lay eggs inside caterpillars. With the passage of time, the wasp larvae consume the caterpillar from inside and protect the plant (Zitzelsberger & Buchbauer, 2015).

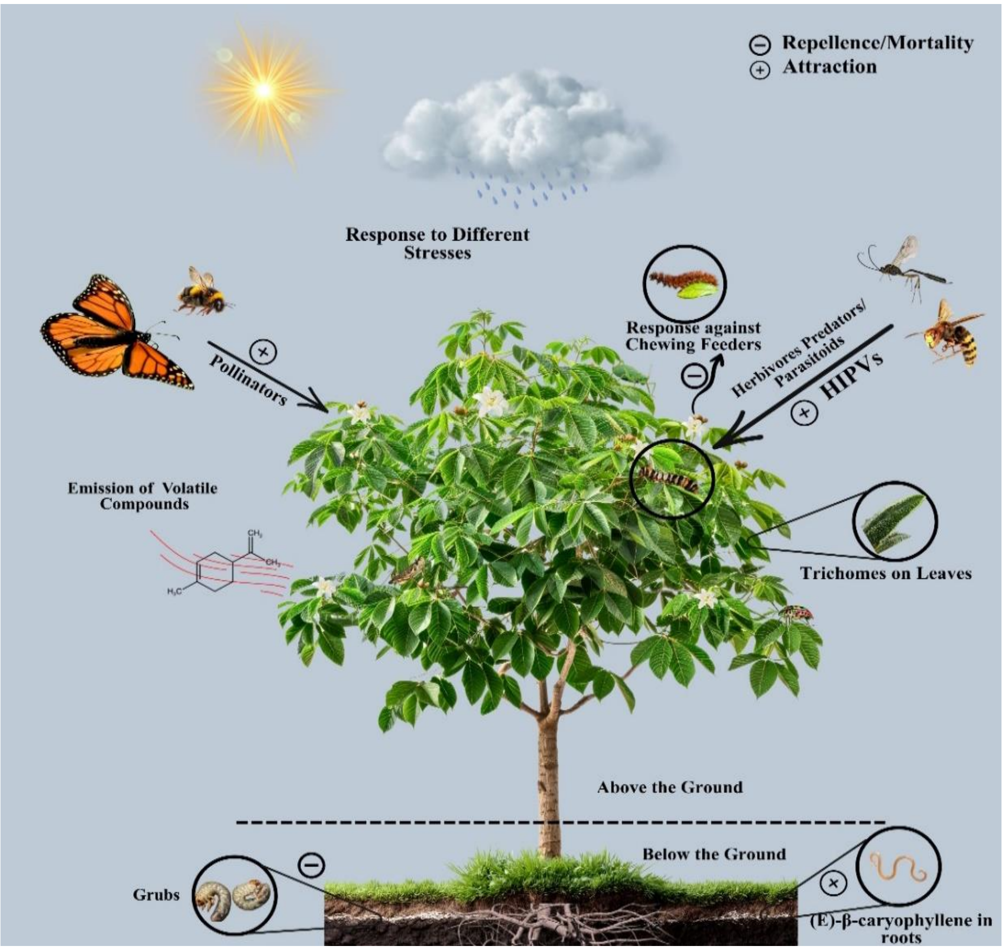


Figure 2. Systemic induction of VOC emission occurs in response to multitrophic stress. Plant defence signalling and VOC biosynthesis are activated upon herbivory. Chewing by herbivores leads to the emission of specific volatiles, including HIPVs and GLVs. This above-ground defence mechanism is coordinated with below-ground responses. Herbivory or damage to roots prompts the release of signalling VOCs like (E)-β-caryophyllene, which aids in attracting nematodes for indirect defence. The dashed arrow indicates systemic signalling, such as jasmonic acid, that integrates the plant's defence mechanisms against multifaceted stressors.

Behavioural assays reveal that the olfactory receptors of parasitoids are tuned to detect HIPVs, enabling them to distinguish between host and non-host volatiles (Menzel & Feldmeyer, 2021). If these HIPVs are genetically induced in plants, they can act beneficially against several pests. In a study, genetically engineered maize was used to produce (E)-β-caryophyllene in its roots, attracting entomopathogenic nematodes and preventing the plant from being infested by *Diabrotica virgifera*, a major underground pest of maize (Turlings et al., 2012). The concentration of these HIPVs also affects the extent of parasitoid attraction. In *A. thaliana* mutants lacking LOX2, lower concentrations of volatile blends were released, which resulted in less parasitoid attraction toward the plant (He et al., 2022). HIPVs are used to facilitate biological control of pests. Xu and their colleagues placed synthetic dispensers, releasing methyl salicylate, in a wheat field. It attracted parasitic wasps in the wheat fields, and hence an increase in the parasitism of aphids was recorded (Xu et al., 2018). Table (2) describes specific SMs of different plants, facilitating direct or indirect defence in plants.

Other defence mechanisms

There are several other ways by which plants ensure their defence against insects, i.e., protease inhibitors, antimicrobial peptides, and cysteine-rich peptides. Some plants produce protease inhibitors (PIs) as direct defence against chewing herbivores (Divekar et al., 2023). These PIs interfere with serine, cysteine, and metalloproteases of the insect digestive tract, reducing the insect's ability to digest amino acids, leading to nutritional stress and slow growth. Plant PIs such as Kunitz trypsin inhibitor and Bowman-Birk inhibitors primarily affect the insects relying on serine or cysteine proteases, such as Lepidoptera (e.g., *Helicoverpa armigera*), Coleoptera (e.g., *Callosobruchus maculatus*), and some Hemiptera (Divekar et al., 2023; Liu, 2024). The overexpression of PIs in transgenic crops such as legumes, corn, and soybeans has shown increased resistance to lepidopteran and coleopteran pests (Sultana et al., 2023; Sultana et al., 2022).

Plants also produce small antimicrobial peptides and induce insecticidal compounds such as phytoalexins and furanocoumarins. These compounds produce localised responses at the site of damage. Phytoalexins such as resveratrol, daidzein, and camalexin rapidly accumulate in the damaged tissue right after the insect invasion. These chemical compounds induce oxidative stress, interfere with nucleic acid synthesis, and inhibit respiratory enzymes of the insect for plant defence (Nguyen et al., 2022). Furanocouramines such as psoralen and bergapten are the photoactivated toxins widely present in the Apiaceae and Rutaceae families. When plant tissues are damaged, furanocouramines are exposed to UV rays and get activated. The activated form of these compounds binds strongly with DNA and proteins of insects, causing their death (Wu et al., 2021). Plant defensins are 4-5 kDa cysteine-rich peptides that are produced when plant tissues are wounded. Defensins can disrupt insects' midgut lining and cause membrane permeability, along with ion flux perturbation (Pastierovič et al., 2024). Plant defence systems are not passive but highly regulated via an internal communication system called a signaling cascade. The jasmonic acid pathway is activated against chewing insects, while the salicylic acid pathway is activated in case of microbial infection in plants (X. Li et al., 2022). Some signals involve the production of reactive oxygen species (ROS), while others include the expression of transcription factors such as MYC and ERF families to regulate defensive genes (Singh et al., 2022; Song et al., 2022).

It indicates that plant defence is an integrated system in which direct chemical toxicity, indirect recruitment of natural enemies, and inducible protein and peptide-based defences are coordinated through a regulated signalling pathway. Where direct defences such as tannins and alkaloids reduce herbivore performance by impairing digestion, the indirect defences rely on the controlled release of herbivore-induced plant volatiles that act as cues for predators and parasitoids. Defence effectiveness depends on metabolite concentration, volatile blend composition, and signalling intensity, while protease inhibitors, phytoalexins, furanocoumarins and defensins provide layered protection by targeting insect digestion. Individual compounds may contribute to both direct and indirect defence and are regulated by hormonal pathways such as jasmonic acid signalling. However, certain areas such as defence interactions within the whole plant, field reliability of volatile-mediated responses, and insect adaptations and need to be researched and studied more concisely.

Table 2. Plant secondary metabolites and their defensive mode of action against insects.

Plant SMs	Defensive Mode of Action	References
Nicotine	Direct defence: Nicotine, present in the tobacco plant, has a similar mode of action to synthetic neonicotinoids. It acts as an agonist of insects' nicotinic acetylcholine receptors (nAChRs) in *Coleoptera, Lepidoptera*, and *Hemiptera*. It poses neurotoxicity by causing neural depolarization, convulsions, paralysis, and even death in insects.	(Edde, 2018; Sarker & Lim, 2018)
Azadirachtin	Direct defence: Azadirachtin interferes with the moulting and metamorphosis of sap feeders and chewing insects such as *Spodoptera frugiperda, Callosobruchus maculatus,* and *Myzus persicae* by disrupting ecdysteroids and juvenile hormone signalling. It acts as a feeding deterrent and oviposition inhibitor. Indirect defence: Sometimes reduces the herbivore population in the ecosystem. For example, *Spodoptera* frugiperda, when exposed to azaradachtin-treated maize, their feeding behaviour switched from maize-to-maize aphids *(Rhopalosiphum maidis)*.	(Kilani-Morakchi et al., 2021; Lin et al., 2021)
Pyrethrins or pyrethroids	Direct defence: Pyrethrins in *Chrysanthemum* spp. reduces a range of insect populations such as *Aedes aegypti*, *Plutella xylostella, and Tribolium castaneum.* Pyrethrins bind to the voltage-gated Na+ channels of an insect's nervous system, leading to prolonged opening and conduction failure, resulting in rapid knockdown and death of the insect.	(Shimira et al., 2021)
Rotenone	Direct defence: Rotenone, present in *Derris*, *Lonchocarpus* spp**,** also targets *Coleoptera, Lepidoptera*, and *Diptera sp*. by causing metabolic poisoning**.** Rotenone inhibits the NADH-Ubiquinone oxidoreductase complex of	(Zubairi et al., 2016)

	mitochondria and halts the electron transport chain, depleting ATP production. It results in neuromuscular dysfunction and death of the insect.	
Cyanogenic glycosides (dhurrin and linamarin)	Direct defence: Cyanogenic glycosides present in bean (*Phaseolus vulgaris*), almond, and cherry protect plants against generalist chewing herbivores and beetles. On tissue damage, these compounds react with beta-glucosidases, releasing HCN, which inhibits cytochrome c oxidase by binding to Cu containg groups. It results in rapid respiratory arrest in insects and ultimately death.	(Wari et al., 2022)
Glucosinolate	Direct defence: Sinigrin and glucoraphanin present in cabbage protect the plant against diamond back moth (*Plutella xylostella).* Upon tissue damage, myrosinase hydrolyzes these glucosinolates to form reactive isothiocyanates and nitriles, which disrupt the gut lining of insects. Indirect defence: The volatile ITCs attract parasitoids. For example, when a large white butterfly (*Pieris brassicae)* eats cabbage, volatile ITCs attract *Cotesia glomerata* wasps to eat the butterfly.	(Robin et al., 2017)
Allicin	Direct defence: *Allium sativum* (garlic) contains alliin. Upon tissue damage, alliin is converted to allicin, the active form, by alliinases. Allicin reacts with the thiol group of enzymes and disturbs the redox balance in insects. Indirect defence: Allicin repels insects due to its pungent smell.	(Batiha et al., 2020)
Proanthocyanidins	Direct defence: Proanthocyanidins, the condensed tannins in woody plants such as oak and eucalyptus, deter chewing insects. Upon tissue damage, these tannins produce quinone and semiquinolones radicals. These radicals induce oxidative stress in the midgut of insects.	(Marsh et al., 2017)
Caffeine	Direct defence: Caffeine in coffee, tea, and cacao plants affects various insects, including *Drosophila* (Diptera) and *Lepidoptera larvae*. It disrupts neuronal signalling through modulating adenosine receptors and inhibiting phosphodiesterases. It results in impaired larval growth and increased mortality in insects	(Maguire et al., 2017)

INSECT HOST SELECTION

In insects, the selection of suitable host plants depends on a combination of several chemical, visual, and tactile cues. Particularly, plants' SMs play major fundamental roles in host selection. As the insects move in their environment for feeding, they come across a variety of volatile and non-volatile compounds that either attract or deter the insect from the plant (Finch & Collier, 2000). It is very important to note that only the presence or absence of a specific SM is not responsible for host acceptance or rejection; however, the concentration of SMs and their combination with other metabolites also act as limiting factors. Moreover, insects' physiological and evolutionary characteristics also influence host selection. These behaviours are largely driven by the olfactory and gustatory systems of insects (Pettersson et al., 2017).

Attraction and repellence

The volatile organic compounds (VOCs) released by plants are primary attractants or deterrents for the insects. VOC blends often contain terpenoids, phenolics, GLvs, and nitrogen or sulphur-containing compounds. These compounds are detected by insects' olfactory receptors, sensory neurons, and antennae, and influence host-insect interaction. A specific SM may have opposite effects on different insects (Romero et al., 2023). The pyrrolizidine alkaloids (PAs), commonly produced by the plants of the Asteraceae and Boraginaceae families, are useful for the cinnabar moth (Tyria jacobaeae), which stores PAs in its tissues by sequestration and becomes toxic for its predators. On the other hand, the generalist herbivore insects, such as grasshoppers, locusts, and caterpillars, are negatively affected by PAs because they lack the PAs detoxification pathways. The bitter taste and toxic nature of PAs damage the gut cells of insects and kill them (Tamariz et al., 2018). Some herbivore-induced plant volatiles and green leaf volatiles, such as (Z)-3-hexenol, (E)-2-hexenal, act as the plant's indirect defence system when invaded by insects. Additionally, some cereals (wheat and maize) release benzoxazinoids for conditional defence. In iron-deficient conditions, these volatiles act as antifeedants against rootworms, while in surplus of iron, they enhance larval growth. Hence, the duality of volatile SMs can either act as repellents or attractants based on insect specialization, plant ontology, abiotic factors, and the relative effect of other SMs released at the same time (Tamariz et al., 2018).

Olfactory and gustatory receptors

Insects' host selection highly depends on olfactory (smell) and gustatory (taste) systems. The sensory organs of insects perceive the chemical signals from plants and respond accordingly (Wicher, 2015). Volatile chemicals act as olfactory cues and guide insects in long-distance host location. The olfactory receptor neurons of insects present in the sensilla of antennae sense these chemical signals. The presence of certain compounds, along with their specific concentration, determines both the extent of attractiveness and repellence to the plant (Jacquin-Joly & Merlin, 2004). The tobacco releases different ratios of volatile terpenoids, such as linalool, beta-ocimene, and alpha-bergamotene, in different ecological conditions (Halitschke et al., 2000). The variation in this ratio affects the host-recognition capacity of the special moth *Manduca sexta*. Similarly, a parasitoid wasp, *Cotesia vestalis*, detects the host plants by a specific blend of terpenes and isothiocyanates emitted only when the plant is attacked by herbivores (Stutz et al., 2017).

Gustatory receptors are present in the mouthparts; labial and maxillary palps, as shown in figure 3(A-C), and tarsi or feet of insects, which detect plants' gustatory cues, plant signals that affect the feeding and oviposition of insects. The sensory organs of insects detect tannins, flavonoids, and alkaloids, which either stimulate or inhibit their feeding (Xu et al., 2016). GRs vary by species within phytophagous insects; however, these can be broadly categorized into five main types. Sugar GRs respond to glucose, fructose, and sucrose; Bitter GRs detect toxic, bitter, and unpalatable phytochemicals (alkaloids, phenolics, terpenoids, and glucosinolates). Gases and organic acid GRs detect CO2 and

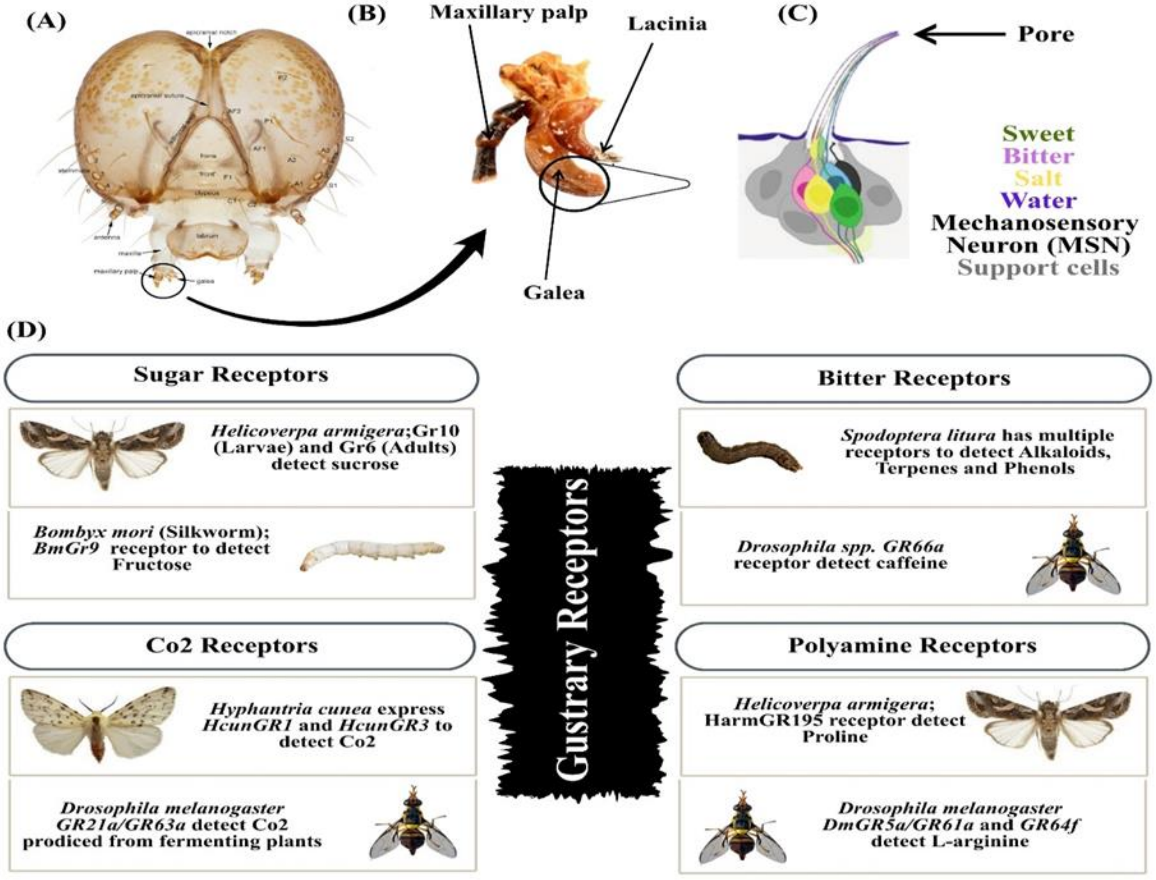


Figure 3. Gustatory receptor in herbivore insects and its types (A) Schematic of an insect head and the abbreviations are A: anterior setae; AF: adfrontal setae; C: clypeal setae; F: frontal setae; L: lateral setae; P: posteriodorsal setae; S: stemmatal setae. (B) Close-up view of a typical sensillum on a gustatory organ, illustrating the porous tip that allows tartans to enter. (C) Diagram of a single sensillum, showing the innervation by dendrites of multiple chemosensory neurons (e.g., tuned to sweet, bitter, salt, water) and a mechanosensory neuron (MSN), all surrounded by support cells. (D) Main types of gustatory receptors in herbivore insects: Sugar receptors in *Helicoverpa armigera* (cotton bollworm) and *Bombyx mori* (silk worm)detects sucrose and fructose respectively; Bitter receptors in *Spodoptera littoralis* (Cotton leaf worm) and *Drosophila sp.* (flies) detect several bitter plant SMs; CO_2 receptors in *Hyphantria cunea* (fall webworm) and Drosophila melanogaster (fruit fly) detects CO_2 and some other gasses produced in fermenting plants; Polyamine receptors in *H. armigera* and D. melanogaster detects proline and L-arginine respectively. This panel underscores the species-specific adaptations of the gustatory system that underpin feeding behaviors and host plant selection.

organic acids released by plants; Polyamine GRs are responsible for the detection of polyamines and stimulate feeding in senescent plant tissues, as indicated in Figure 3(D). Some other oviposition-related GRs detect SMs such as glucosinolates or cardenolides, important in oviposition (Kasubuchi et al., 2018; Kent & Robertson, 2009; Schmelz et al., 2012). Flavonoids (kempferol and quercetin) deter feeding in lepidopterans such as *Spodoptera littoralis*, while certain flavonoids (glucosinolate) stimulated specific oviposition in some butterflies such as *Pieris rapae* (Su et al., 2018). Similarly, tropane alkaloids in *Datura stramonium* deter non-adapted herbivores via post-ingestive toxicity but may not affect adapted Manduca species. Some SMs of plants also modulate post-ingestive feedback to influence host selection in the future. Insects that experience reduced digestion and toxicity avoid the plant in future encounters. When *Spodoptera litura* caterpillars feed on tannin-rich leaves of *Quercus spp*, the tannin binds to the digestive enzymes of the insect and reduces nitrogen assimilation, causing slower growth rates (Murray, 2008). This negative nutritional feedback leads to the avoidance of *S. litura* from feeding on these leaves. Similarly, some locusts ingesting high concentrations of nicotine exhibit reduced feeding rate on tobacco plants in future trials (Ikechi-Nwogu & Oluchi, 2023).

Insect-host selection operates as an integrated process in which volatile cues guide long-distance directions while non-volatile metabolites influence close-range acceptance through gustatory evaluation and post-ingestive feedback. Host choice depends on metabolic concentration, volatile blend composition and insect ecological strategy. Olfactory and gustatory receptor systems jointly shape attraction, feeding and ovipositional decisions. However, predicting host selection under field conditions remains challenging due to complex metabolite mixtures and several insect adaptations, highlighting the need for integrative studies linking sensory mechanisms with ecological outcomes.

DETOXIFICATION ADAPTATIONS IN INSECTS

Plant SMs serve as a great defence for plants against invading predators; however, many insects have evolved adaptations to tolerate the toxic SMs via several behavioural, physiological, and molecular strategies (Heidel-Fischer & Vogel, 2015).

Behavioural and physiological adaptations

Many insects exhibit behavioural and physiological resistance against plant SMs by sequestering the toxic compounds. Monarch butterflies sequester cardenolides from milkweed plants, making the larvae and even adults toxic to their predators. These insects also present target-site insensitivity by mutating Na^+/K^+ ATPase and preventing sequestered cardenolides from causing damage to the insect's own body. The sequestered compounds perform dual function in insects, i.e., defence and sexual signalling (Agrawal et al., 2024). Arctiid moth (Utetheisa ornatrix) sequesters PAs and transfers them to females in a spermatophore, hence maintains sequestration in all life stages, i.e., eggs, larvae, pupae, and adults. Furthermore, male moths produce hydroxydaniadal, a pheromone derived from sequestered PAs. The more PA load in the insect, the more chances of successful mating. It indicates evolutionary links between ecological adaptation and reproductive success (Iyengar & Conner, 2016).

Molecular adaptations

Several molecular mechanisms that insects use to protect themselves from SMs are described in table (3). In oxidative detoxification, cytochrome P450 monooxygenases modify hydrophobic toxins such as furanocouramines and make them soluble (Lu et al., 2021). In conjugation pathways, enzymes such as glycosyltransferases and glutathione S-transferases render flavonoids, phenolics, and isothiocyanates to make them less reactive and easier to excrete. Other strategies include the hydrolysis of plant SMs by esterases, target site insensitivity by receptor mutation, and microbial symbiont-mediated degradation of tannin-rich compounds. Some insect lineages exhibit gene duplication and divergence in their detoxification genes which ultimately enhance their capacity to feed on chemically defended plants (BK et al., 2022). Horizontal gene transfers of the β-cyanoalanine synthase (CAS) gene, in aphids, enables them to neutralize cyanide from cyanogenic plants. These adaptations indicate dynamic co-evolution between plants and insects. As plants evolve more potent SMs to protect themselves, insects also evolve their detoxification capabilities, leading to reciprocal selection pressure, the driving force to shape biodiversity in an ecosystem (Yinghui Li et al., 2021).

APPLICATIONS OF PLANT SMS

Plant SMs, being eco-friendlier than synthetic chemical compounds, have numerous applications in the field of agriculture, medicine, and industry. In agriculture and plant management, alkaloids, terpenes, and phenolics can be used to protect crops from several pests. Many SMs have antimicrobial, anti-inflammatory, antioxidant, and even anti-

https://doi.org/10.55627/zoobotanica.003.03.1721

cancerous properties, and hence are being used in medicine. In the food industry, plant SMs are used as natural preservatives, food colourants, and flavour enhancers.

Role of plant secondary metabolites (SMs in pest management)

Several studies have demonstrated that integrating SMs into crop management, either as botanical extracts or as signalling compounds, can reduce the use of synthetic pesticides by up to 61% (Ediagbonya et al., 2025). Azaridactin and many saponins act as antifeedants and growth disruptors of many insects, such as aphids, caterpillars, and white flies (Qasim et al., 2020). Pyrethrins, caffeine, and nicotine act as neurotoxic insecticides. Essential oils such as thymol, carvacrol, and eugenol are used in stored foods to control pests (Campolo et al., 2018). However, their use at the commercial level still requires field-based studies. Some studies reported that salinity stress (1.5%) can potentially enhance azadirachtin production in *Azadirachta indica* (Omar et al., 2024). In another study, Bae developed nano-formulated azadirachtin biopesticide using whey proteins (Bae et al., 2022). Their approach showed significant insecticidal activity against *Spodoptera frugiperda*. Gudeta reported a significant control over cabbage aphids using emulsified nicotine (3.26%) (Gudeta et al., 2021). Another study showed similar results in *Zea mays*, i.e., preventing it from pests using nicotine as a biopesticide (Nurhidayah et al., 2022). In a recent study, a water-based nano system delivering SMs based biopesticide has shown potential insecticidal effects against *Aphis gossypii* and *Ostrinia*

Table 3. Different detoxification adaptation mechanisms in insects against Plant SMs.

Detoxification mechanism	The biosynthetic pathway involved	Example	Reference
Oxidation	Hydrophobic plant SMs are oxidized by Cytochrome P450 monooxygenases (e.g., *CYP6B*, *CYP321A*), resulting in an increase in their solubility and a decrease in their activity.	In *Helicoverpa zea* (corn earworm) and *Papilio polyxenes* (black swallowtail), furanocoumarins present in *Pastinaca sativa* (parsnip) and *Apium graveolens* (celery) are detoxified through oxidation, neutralizing their phototoxicity and enabling feeding on these plants.	(Li et al., 2007)
Conjugation	In the glycosylation-based pathway, sugar residues are conjugated to toxic aglycones by UDP-glycosyltransferases to reduce the toxicity.	*Helicoverpa armigera* (cotton bollworm) detoxifies flavonoids and phenolic acids of alfalfa (*Medicago sativa)* and tea (*Camellia sinensis*) by glycosylation.	(Ahn et al., 2012)
	In the glutathione pathway, electrophilic compounds are conjugated with glutathione via Glutathione S-transferases (GSTs).	Diamondback moths (*Plutella xylostella)* rely on the plants of the Brassicaceae family, such as *Brassica oleracea* (cabbage) and *Arabidopsis thaliana,* by detoxifying isothiocyanate via enzymatic conjugation.	(Sathya & Kumar, 2022)
Sequestration	Sequestration is the accumulation of intact plant SMs in specialized tissues of the insect.	*Tyria jacobaeae*, the cinnabar moth, sequesters pyrrolizidine alkaloids present in ragwort plants. The insect uses these sequestered alkaloids for its defence against predators, and it also acts as a pheromone during mating.	(Crowley et al., 2023; Quicke et al., 2023)
Hydrolysis	Esterases disrupt ester bonds in toxic compounds	*Chrysanthemum cinerariifolium* (pyrethrum daisy) produces pyrethrins as antifeedants against green peach aphids, *Myzus persicae.* However, aphids neutralize these SMs via hydrolysis and continue to feed.	(Souto et al., 2021; Tang et al., 2017)
Target site insensitivity	Mutations in target proteins reduce the binding of PSMs	*M. persicae* detoxifies nicotine in tobacco plant (*Nicotiana tabacum)* via structural modifications and hence tolerates its neurotoxic effects	(Troczka et al., 2021)
Microbial symbiont-mediated detoxification	The symbiotic microbes present in the gut of insects degrade plant SMs and prevent the insects from their harmful impact.	In *Hyphantria cunea* (fall webworm), toxic tannins are present in *Quercus* spp. (oak) are detoxified via symbiotic gut bacteria.	(Chen et al., 2020; Hammer et al., 2017)

furnacalis. This nonsystem-based biopesticide application has promising implications for commercial use (Zhang et al., 2025).

Plant secondary metabolites (SMs enhanced engineered crops)

With the advancement in molecular biology, crops can now be engineered to enhance the expression of specific SMs as an intrinsic pest resistance. Maize and other cereals naturally produce a benzoxazinoid, DIMBOA (2,4-dihydroxy-7-methoxy-1,4-benzoxazin-3-one). Xie et. al. reported that high concentration of DIMBOA in seedlings confers resistance against corn rootworms (Xie et al., 1990). Recent genetic studies have identified SSR markers and gene loci responsible for varied DIMBOA concentration in different maize lines. It can act as a molecular tool to incorporate these alleles into breeding lines, enabling the development of DIMBOA-expressing crops, providing a heritable pest control system (Niu et al., 2023). CRISPR/Cas9 is the most promising molecular editing technique to up- or downregulate SMs at the genetic level. Recently, a project supported by Cotton Board is using transgene-free CRISPR/Cas9 to modify terpene biosynthesis in *Gossypium hirsutum*. The goal is to upregulate terpenes as a pest control strategy, without introducing an external gene.

CONCLUSION AND FUTURE PROSPECTS

Plant secondary metabolites (SMs have potential roles in pest management; however, several challenges are still associated with their upregulation in plants, i.e., high concentration of a specific SM may reduce the yield of the crop or reduce its quality. It can also interfere with the ecological distribution of insects, putting pressure on the food chain. Therefore, there is a huge scope of research in this regard. Besides this, high-throughput metabolomics tools such as GC-MS and NMR can provide insights into plant defence. Coupling metabolomics with genomics and transcriptomics can provide valuable insights. Other cutting-edge gene editing techniques, such as base editing and prime editing, can also be used to fine-tune the genes that code for specific enzymes involved in the biosynthetic pathway of secondary metabolites (SMs. Further, plant secondary metabolites (SMs producing pathways can be rebuilt in different expression systems, such as E. coli and yeast, to produce more valuable secondary metabolites (SMs, having better potential to be used as biopesticides. For example, instead of extracting azadirachtin, producing it in fermenters, using an engineered expression system can upscale the production. These advancements can mark a transformative step toward sustainable agriculture, replacing the harmful pesticides with engineered plant defences and bio-based solutions.

AUTHOR’S CONTRIBUTION

Mayozadi Ainan Saleem led the literature review and writing of the original draft, while Hassan Anjam was responsible for conceptualization, designing tables and figures, and revising and finalizing the manuscript. Soban Tahseen and Sundas Sharif provide critical revision and editing of the manuscript. All the authors have revised the manuscript diligently and agree to the submission.

FUNDING

No funding was received for the present study.

AVAILABILITY OF DATA AND MATERIAL

This article presents all of the data that was created or examined for this study as tables and figures.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

The study was approved by the relevant forum.

CONSENT FOR PUBLICATION

The publishing was approved by all of the authors.

CONFLICT OF INTERESTS

The authors declare there is no conflict of interest.

ACKNOWLEDGEMENT

Figures were designed using Canva (https://www.canva.com/), and the structures of all compounds were created with ChemDraw 6.0. software.

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