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# Insect Plant Interaction with Reference to Secondary Metabolites: A Review

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## ABSTRACT

Plant and herbivorous insect share a contradictory but everlasting relationship. To cope with the herbivores, plant invested its energy in the production of various defensive chemicals which are known as plant secondary metabolites (PSMs). During coevolution with plants, insects also adapted themselves to counter plant defensive mechanisms. The secreted saliva and ovipositional fluids of insects induce the production of secondary metabolites in plants. Plants also produce compounds constitutively in the tissues that are susceptible to insect attack. These compounds reduce insect growth and development of insects through interfering with the developmental phases, acting as feeding deterrent, reducing nutritive value, affecting protein digestion and the production of substances toxic to them. On the contrary, insect's adaptations to PSMs include the detoxification of plant toxins, conversion of the toxic compounds into conducible form for its growth and development, development of feeding choice based on the concentration of PSMs, quicker absorption and elimination as feces and obtaining the help of symbiotic intestinal microorganism to inactivate toxic materials. Furthermore, insects also utilize PSMs as chemical cues mediated through their chemoreceptive systems. The selection of host plants by monophagous insect is sometimes concentrated on the production of particular PSMs. Secondary metabolites also act as attractant to insect pollinators by exhibiting distinctive odors. Insects also store toxic PSMs which are used by them against their predators and in giving protection to eggs. However, this intrinsic capability of plants to produce defensive chemicals in response to insect attack should be explored to a wide extent to optimize the performance of PSMs.

**Key words:** Chemoreceptor, Feeding deterrent, Herbivorous insects, Insect adaptations, Plant secondary metabolites.

The conflicting relationship between plants and herbivorous insects is mainly regulated by the way plants develop direct and indirect defensive mechanisms against insects (Fig 1) and insects produce counter-adaptation in themselves in addition with some indirect defense Plants produce a wide array of specialized chemicals against insect herbivores called as secondary metabolite-based defense chemicals which can be induced upon attack or are constitutive (Yactayo-Chang *et al.,* 2020). Plant secondary metabolites (PSMs) include different nitrogen- and sulfur-containing metabolites namely alkaloids, amines, cyanogenic glucosides, glucosinolates, non-protein amino acids, organic acids, terpenoids, phenolics, quinones, polyacetylenes and peptides (War *et al.,* 2020). Instead of producing a single compound for defense, plants usually produce a complex mixture of secondary metabolites of different structural classes with multiple molecular targets at the same time (Mason and Singer, 2015; Wink, 2015). This strategy of plant impedes the adaptation and resistance of herbivores against the chemical defense (Wink, 2018).

Depending on the host plant range, insects can be categorized as generalists and specialists where generalists have a broad host range and specialists have a more limited specialized range of hosts. Specialists are recognized as to be more adapted to deal with their specialized host defenses (Douglas, 2017). On the contrary, it is said that insects utilize plant produced secondary metabolites as a feeding stimulus (Wink, 2018). In its addition, it is found that monophagous insects prefer to feed on individual species or species groups which produce similar PSMs (Ali and Agrawal, 2012; Mason and Singer, 2015).

There are a number of molecules produced by plants that exhibit toxic and defensive action against insect and more than 2000 plant species containing insecticidal properties have been identified (Benayad, 2008). Through the evolutionary process, the structures of PSMs underwent several rounds of selection to give them such structures which could interfere with the metabolism, neuronal transmission or reproduction of an herbivore (Wink, 2003). Meanwhile, insects also developed strategies to exploit their hosts by obtaining specific adaptations in them. Moreover, these defense chemicals are not always effective against all insect pests as specialized insects can detoxify specific chemicals (Yactayo-Chang *et al.,* 2020). These phenomena lead to an impressive plant insect interaction to sustain their

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coexistence. Therefore, the purpose of this article is to provide an overview on plant produced secondary metabolites as an interaction factor to deter and attract the insect and to induce counter-adaptations in them.

## Response of plants to produce secondary metabolites

Insect-inducible production of secondary metabolites in plants can be variable and dependent on the specific plant-insect interaction, however, some common defense metabolites are given in Fig 2 with mentioning some examples. A primary benefit of insect-inducible PSMs is their direct feeding deterrent action against herbivory (Yactayo-Chang *et al.,* 2020).

Several mechanisms have been identified by which plants perceive the insect attack and develop defense against them. The secreted saliva of insects while feeding and ovipositional fluid secreted while egg-laying to deter the attack of other insects or to glue the egg to the plant surface can be sensed by plants to initiate the production of defensive chemicals (Hilker and Meiners, 2006; Wu *et al*., 2007; Howe and Jander, 2008). The first reported elicitor of an insect is from the oral secretion of *Spodoptera exigua* which is volicitin (N-(17-hydroxylinolenoyl)-L-glutamine) (Alborn *et al*., 1997).

The delay for the synthesis of new compounds is the main disadvantage of inducible defense systems. On the other hand, constitutive defense of plants enables them to produce defensive compounds from before in the tissues that are susceptible to attack. This also possesses several disadvantages, such as, the loss of the metabolic energy required to produce compounds even in the absence of the insect threat and the toxicity of active form of certain compounds not only to the insects, but also to the plant itself. To avoid this toxic effect, the compounds are stored as readily activated non-toxic forms and activate them upon insect attack (Yactayo-Chang *et al.,* 2020). An example of this strategy is to the storage of the defensive compound glucosinolates and its activating enzyme myrosinases separately in specialized S-cells and specific myrosin cells, respectively (Koroleva *et al.,* 2010; Shirakawa and Hara-Nishimura, 2018). Rupture of the plant tissue during herbivory leads to the mixing of the components of the two cell types and the cleavage of the glucosinolates by the

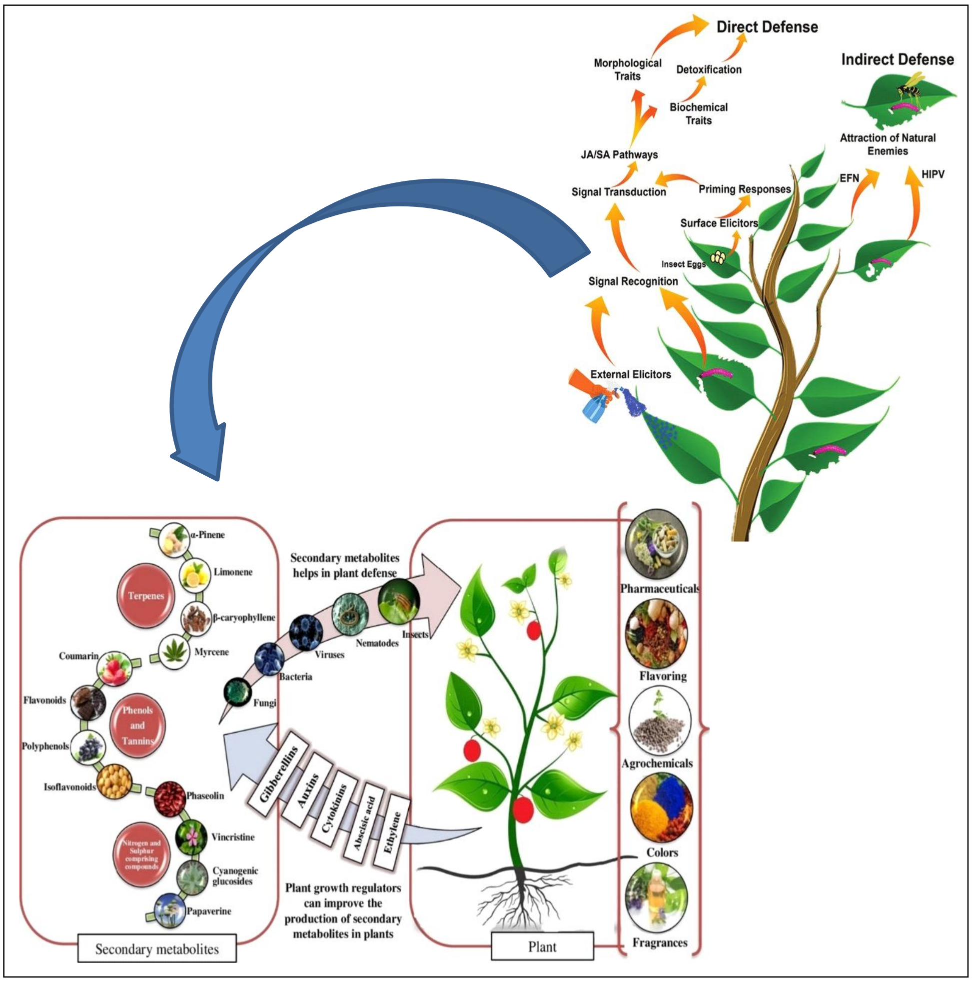
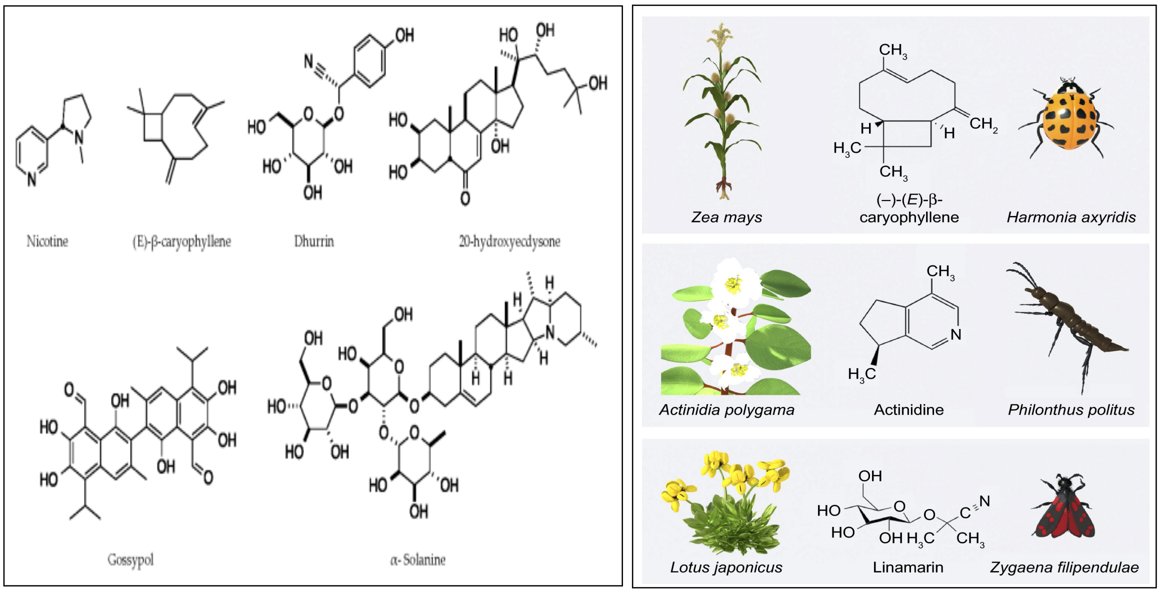


**Fig 1:** Thematic diagram representing the plant defense mechanism against insect pests. (EPF = Extrafloral nectar; HIPV = Herbivore induced plant volatiles; JA = Jasmonic acid; SA = Salicylic acid) (modified from War *et al*., 2018 and Jamwal *et al.,* 2018)



(A) (B)

**Fig 2:** (A) Representative chemical structures of plant defense compounds. (B) with examples (modified from Yactayo-Chang *et al.*, 2020 and Beran *et al.*, 2019).

myrosinases to produce unstable aglycones. The aglycones are responsible for the production of variety of toxic products including isothiocyanates, thiocyanates, nitriles and epithionitriles (Halkier and Gershenzon, 2006; Burow and Halkie, 2017). Sorghum (*Sorghum bicolor*) accumulates the cyanogenic glucoside dhurrin in the cytoplasm (Maag *et al.*, 2015), whereas the activating enzyme of it the dhurrinase (endogenous β-glucosidase) remains in the chloroplasts (Campos *et al.*, 1988). Upon cell rupture during herbivory, cyanogenic glucosides become exposed to their activating hydrolases, which converts them to toxic cyanohydrin aglycones (Yactayo-Chang *et al.*, 2020).

Some pathways have a combined approach, where the pathway to produce the compounds is constitutive and the last activating step is inducible. For instance, maysin, a C-glycosyl flavone, is produced by maize constitutively at high levels in its silks and correlates with increased resistance to insect pests including corn earworm (Elliger *et al.*, 1980). Maysin itself does not have anti-insect properties directly; rather it is activated by conversion into quinones by polyphenol oxidases induced during tissue damage (Byrne *et al.*, 1996). Quinones formed from maysin and related compounds render plants less nutritive to insect larvae by reducing the availability of proteins and amino acids as a food source as they bind to their -SH and $-NH_2$ groups (Wiseman and Carpenter, 1995).

## Aptitude of PSMs to modify insect attack

The primary metabolites of plants don't directly help in countering the insect attacks; rather serve as precursors for the synthesis of secondary metabolites. These secondary metabolites are involved in the plant defense against a variety of stresses and don't take part in normal growth and development of the plant. PSMs can be directly toxic to insect pests or can mediate signaling pathways of the production of plant toxins. Among the plant defensive traits, both the inducible and constitutive chemical barriers and the nutritional content in a plant are considered to have significant effect on reducing the insect growth and development (Peters and Constabel, 2002).

For example, the plant produced compounds phytoecdysteroids are analogues of the insect hormone ecdystreroid, which controls developmental phases on insects from larva to adult. These compounds have been identified in asparagus (*Asparagus* spp.), spinach and quinoa (*Chenopodium quinoa*) (Graf *et al.*, 2012; Bokov *et al.* 2020). Phytoecdysteroids such as 20-hydroxyecdysone binds to the ecdysone receptor and disrupt insect development (Chaubey, 2018).

Terpenes, flavonoids, tannins, alkaloids, cyanogenic glucosides, nonprotein amino acid, *etc.* as PSMs play important role in defending plants against insect herbivory. One such class is the cyclopentanoid monoterpene-derived compounds known as iridoids. These compounds are considered as a powerful defense against insect pests due to their bitter taste which leads to their deterrent effect (Biere *et al.*, 2004). Iridoid glycosides lead to the denaturation of amino acids, proteins and nucleic acids through the formation of covalent bonds with the nucleophilic side chains of them *via* imine formation (Park *et al.*, 2010). Thus, the destruction of protein and nucleic acids reduces the nutrient quality of the plant tissues. Some terpenoids such as amide derivatives interfere with the growth and development of insect by mimicking as insect juvenile hormone analogs (War *et al.*, 2020).

The products of the oxidative reactions include quinones reduce the nutritive value and palatability of the plant tissues to insect pests by cross-linking with the nucleophilic side chains of proteins and free amino acids. Quinones also act as directly toxic to insect pests (War *et al.,* 2020). A higher induction of phenols was reported in groundnut plants when attacked by *Helicoverpa armigera* and by exogenous application of jasmonic acid (War *et al*., 2015).

Generally, tannins affect protein digestion in insects because they have an affinity with the midgut proteins and digestive enzymes of insect pests (Peters and Constabel, 2002; Barbehenn and Constabel, 2011). Tannins bind with gut proteins through hydrogen or covalent bonds which lead to the chelation of metal ions, precipitation of proteins and the development of gut lesions in insect herbivores (Barbehenn and Constabel, 2011).

In Arabidopsis, higher production of flavonoids confers high levels of resistance to *Spodoptera frugiperda* by overexpressing of transcription factor controlling production (Johnson and Dowd, 2004). Glucosides are one of the important groups of sulfur-containing secondary metabolites present in Brassicaceae and Capparales. The glucosides are derived from amino acids and contain about 120 structures (Hopkins *et al*., 2009).

Gossypol is a sesquiterpene aldehyde that was originally extracted from cotton (*Gossypium* spp.). It can deactivate enzymes by the production of crosslink to proteins with its two central aldehyde groups via the amino acid lysin (Krempl *et al*., 2016). For instance, it can affect the larval weight gain of African eafworm (*Spodoptera littoralis*) by inhibiting protease and amylase activities in larvae (Meisner *et al*., 1978). Another such compound is the sesquiterpene 7-epizingiberene that is present in wild tomato (*Solanum habrochaites*) but absent in domesticated tomato. The domesticated tomato showed improved herbivore resistance when the genes responsible for producing sesquiterpene 7-epizingiberene were expressed in it (Bleeker *et al.,* 2012). Many non-crop species have extensive defense chemicals, some of which have provided the hope for insecticide development (Yactayo-Chang *et al*., 2020).

## Counter-adaptation to PSMs by insects

Insects are not without their defenses against PSMs and so they adapted themselves to counter plant defense mechanisms. Various insects have developed specialized methods to overcome defense chemicals of their host plant. They had and still have to cope with the PSMs in their food plants (Linde and Wittstock, 2011). These methods include suppressing host defense responses via the use of secreted effector proteins (Hogenhout and Bos, 2011) and avoidance, target site insensitivity, detoxification, degradation, disarming, sequestering, or excretion of host defense chemicals (Pentzold *et al*., 2015).

The detoxifying enzymes glycosylation, glutathionation, sulfation, or deacylation may involve in insect adaptation to plant toxins depends on host diet composition and insect species (Schramm *et al*., 2011). The intracellular glutathione-S-transgerase (GST) detoxification of plant toxins occurs by binding of lipophilic compounds to the reduced glutathione (GSH) and is then removed easily from the cells (Enayati *et al*., 2005). In the midgut, the ratio of reduced to oxidized GSH is used as an oxidative stress indicator from plant toxins (Barbehenn *et al*., 2005). The greater diversity of GSTs in generalist insect pests than the specialist enables the generalists to adapt to a broader range of plant toxins (Francis *et al*., 2005).

Insect pests not only convert tannins to less toxic compounds but also utilize them for their growth and development. Thus, they have developed adaptation to plant tannins. For example, the tree locust *Anacridium melanorhodon* when fed on the tannin-containing diet, showed an increased growth by 15% (Eswaran and Jindal, 2013). The adaptation to tannins has been controlled by the presence of higher pH and lower oxygen levels in insect foregut (Appel, 1993).

The generalist insect pest such as *Spodoptera eridania* prefers feeding on plants with low glucosinolate concentrations, but the specialist *Plutella xylostella* prefers the lines with low myrosinase activity (Li *et al*., 2000). The cabbage white butterfly *Pieris rapae* has also adapted to the glucosinolates but employed different mechanism. This pest utilizes a specific gut protein to redirect toxic isothiocyanate for the formation of safe and nontoxic nitrile breakdown products (Wittstock *et al*., 2004). Brassica specialist insects, such as the larvae of the diamondback moth (*Plutella xylostella*) and the desert locust (*Schistocerca gregaria*) can feed on glucosinolate-harboring plants because of possessing sulfatases in their gut (Ratzka *et al*., 2002; Falk and Gershenzon, 2007). These sulfatases inactivate glucosinolates by disarming that does not react with myrosinases, allowing the insects to feed safely.

A strategy of insect is to feed not only on one plant, but to explore several species for low PSMs content, thus diluting any toxic effect. Often herbivores employ a fast digestion which helps in quicker absorption of nutrients than any toxins and leads to quicker elimination in the feces. For detoxification, symbiotic intestinal microorganisms of insect body often help in degradation or inactivation of toxic material (Pennisi, 2017). War and Sharma in 2014 illustrated the adaptation strategies by insect pests due to secondary metabolites, are shown in Fig 3 with slight modification.

## PSMs as advantageous to insects

Insects differentiate and perceive a wide variety of plant chemicals even in very low concentrations by the chemoreceptors (gustatory and olfactory chemoreceptive systems) present on the antennae and mouthparts. Based on perceived chemical cues, insects decode the information in the central nervous system and decide whether to accept or reject the host plant (Swain, 1977). Many insects show the tendency to feed on a single or a few often phylogenetically related food plants. PSMs were observed

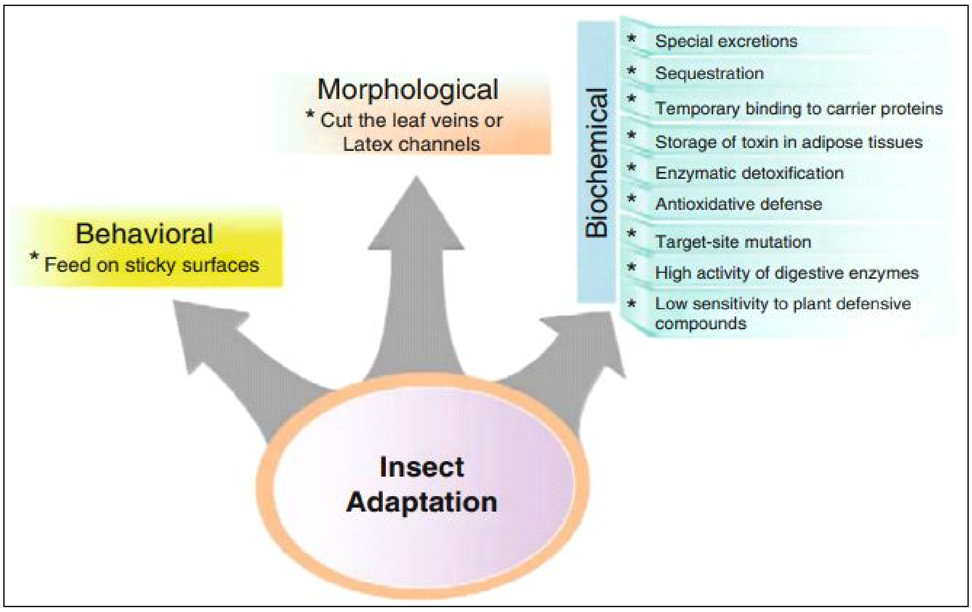


**Fig 3:** Plant defensive traits modulating the adaptation strategies to herbivore (War and Sharma 2014).

to serve as olfactory cues for insects to identify their appropriate host plants. Even a monophagous species may feed on more than a single host plant if related plants produce similar toxins, because they love these particular PSMs. But they will not feed on plants with different kinds of PSMs (Wink, 2018).

Flowering plants often employ insects as pollinators and attract them by the color or smell of their flowers. The color is usually due to the production of flavonoids, anthocyanins, or carotenoids, whereas the smell is due to the production of terpenoids, amines and phenylpropanoids which exhibit distinctive odors that are recognized by pollinators (Wink, 2018). Some specialist insects store a good amount of toxic PSMs and use them for their own defense against predators (Mason and Singer, 2015). Such specialists can store toxic cardiac glycosides, aristolochic acids, cyanogenic glucosides, iridoid glucosides and several toxic alkaloids (Kelly and Bowers, 2016; Petschenka and Agrawal, 2016).

In female larvae, pyrrolizidine alkaloids (PAs) are sequestered to some degree in the integument, but after metamorphosis into adult insects, a large part of it is transferred to the orange colored eggs to confer chemical protection (von Nickisch-Rosenegk *et al*., 1990). PAs as a nuptial gift for the defense of the eggs from male spermatophore has also been described for other arctiids *Utetheisa ornatrix* and *Cosmosoma myrodora* (Bezzerides and Eisner, 2002; Cogni *et al*., 2012).

## CONCLUSION

The production of secondary metabolites enables plants to change insect physiology and behavior which results in toxicity to insects or development of non-preference to the host. Insects are also simultaneously evolving different mechanisms to overcome this. Therefore, the capability of plant to produce defensive chemicals should be amplified as a part of pest management through optimizing the performance of PSMs against insect attack.

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