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Insect-plant interaction and defense strategies mediated by chemicals: A review

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Abstract

Plant-Insect relationships are constantly evolving as the morphology of plants and insects is shaped by natural selection in order to optimizing their defenses for the sake of enhancing propagation and ensuring the survival of the species. Plants usually coexist with one another, while herbivores and their natural enemies may respond to characteristics of the plant and the result of interactions. Plants have two types of defense: direct and indirect. Direct defense comes from their own naturally produced defenses, while indirect defense involves attracting other insects that will kill or impede herbivore activity. Some chemical defense mechanisms in plants against herbivorous insects include binding to protein to reduce the quality of the food, making the food unpalatable for the insects, changing the gut pH, causing the insect to rot, becoming unable to function correctly, having a bad taste to a particular insect, and reducing the growth rate of the insect that allows potential predators to parasitize, or eat the prey. Toxins in the gut of herbivore insects may be either increased by changing the pH or, in the case of insects, condensed harmlessly by secreting special enzymes, degraded by eating a lot of plant material, or absorbed by adding the toxins to their defense strategies.

Keywords: herbivorous insects, induced resistance, plant defense, plant-insect interaction'; Insect defense strategies; secondary metabolites

Introduction

Interaction is always going in the living environment. Herbivores and plants have developed highly specialized defense strategies in the struggle for survival. Plants and herbivores express many types of defenses. Plant communities employ chemical defenses to ward off herbivory. An herbivore kills plants or reduces their capabilities when they encounter toxins produced by the plants. Plants can also call on their parasitoids to help enhance their defenses, reducing herbivory from their opponents [1]. Direct chemical defenses come in the form of toxins and do not need to be induced. They protect many insect species [2].

Insects are not defenceless. It is being developed and used a variety of strategies and behavioral techniques to counteract the effects of plant defenses to enhance their effectiveness. Adapting insect populations to toxic chemicals in plants is one of the techniques, since it allows herbivorous insects to become specialists and exploit no longer toxic plants [3]. The plants' chemical defense has been sequestered by herbivorous insects so that they can use it against predatory insects [4].

Insect-Plant Interaction

Insect-plant interaction can be defined as the activities of insects that have several beneficial activities like defense and pollination and plants that provide shelter, food, and oviposition sites [5]. The interaction between plants and insects can be beneficial for both as illustrated in pollination. In other types of interactions, it can be injurious to plants but beneficial to insects. Plants can be also damaged not only by herbivorous insects but also by pathogenic microorganisms transmitted by these insects.

Various defense mechanisms are developed in plants to reduce insect attack, including the production of defensive proteins, volatiles that attracts insect herbivores, secondary metabolites, and dense trichomes [6]. In contrast, insect strategies have evolved to overcome plant barriers, such as detoxifying toxic compounds, avoiding them, sequestering poison, and altering gene expression [7].

Plants and insects have coevolved to assist each other in a symbiotic relationship such as pollination. Gymnosperms rely primarily on scents to attract insects; angiosperms utilize both visual and aromatic communication. In doing so, they depend upon the use of petal iridescence and floral perfumes composed of volatile organic compounds (VOCs) to attract pollinating insects to advance their reproductive cause [8].

As the temperature is unfavorable for other insect pollinators such as bees at high altitudes, many plants rely on butterflies for pollination. Likewise, butterfly larvae are dependent on plants for food. Especially at high altitudes, these relationships are crucial [9].

The interaction between butterflies and plants can be hostile just like in caterpillars and their host plants or have a mutual relationship with each other, butterflies transfer pollen from
one plant or flower to another. This in turn allows for the propagation of more plants and more food for butterflies [9]. Insects rely on plant mimicry for protection and hunting but not to exploit them. They camouflage themselves from potential predators and prey [10].

Plant Defence Strategies

The number of herbivorous insect species is far greater than the diversity of plant species. Plants survive by developing new ways to protect themselves against insects so that they can survive and reproduce. The emergence of substances that are not essential for essential processes such as photosynthetic and metabolic functions has been connected to the evolution of chemical defenses in plants [11]. Plants are natural laboratories in which a great number of chemicals are biosynthesized. Many plants have developed natural, biochemical mechanisms to defend themselves from insect attacks. Some of these chemicals discourage feeding by insects. Others provide protection or even immunity from diseases. Others help plants compete for resources by discouraging competition among different plant species. Therefore, by studying the diverse chemistries of many different plant species, many useful compounds that can be used as biopesticides have been discovered. Indirect defenses have received increasing attention because the ecological implication for the plant and its arthropod community is different from those that derive from purely constitutive defenses.

If an herbivore insect pressure can be predictable environmental factor high production of cost defenses can be advantages for the plant. Unpredictable environmental factor select for plants that can produce a defense only in the presence of herbivores. These kinds of phenotypically plastic plant responses are called induced defences [12]. Developing inducible defenses likely results from selection pressure resulting from the fitness costs associated with producing defensive compounds.

Induced Resistance

It is thought that insect herbivory-induced wounding stimulates an oxidative reaction in the plant that contributes to induced symptoms and responses. Insect herbivory can result in the production of jasmonic acid through lipoxygenation of linolenic acid. These appear to contribute to plant resistance against many insect attackers through systemic responses by the plant known as induced resistance [13]. It indicates a change in a plant that causes a decrease in any measure of herbivore performance.

Secondary Metabolites

Secondary metabolites are not primarily important for energy production; however, plants store them to improve their ecological fitness and survival. To combat herbivore damage, plants can increase the production of secondary metabolites, largely driven by volition, a component of the oral secretions of feeding insect herbivores, or defensive proteins that are categorized by their mode of action. Secondary metabolites are harmful to insects and support the plant in defense against insect attack [14].

Many plants contain compounds that function as toxins, such as alkaloids, glucosinolates, and terpenoids, such as the milkweed plant, which is toxic to many insects due to its cardenolides or cardiac glycosides. These compounds are indigestible to insects while inhibiting protein synthesis plants that elicit such defenses in response to herbivores have a lower nutritional value for subsequently arriving herbivores and can, therefore, reduce the probability of secondary attacks, i.e., reduce the quality of food by binding to proteins and preventing insects from absorbing the protein. The plant's metabolic changes may thereby not only affect insects of the same species but also may result in cross-resistance effects that affect the herbivore-community composition of the plant [16]. Qualitative secondary metabolites act by blocking specific biochemical reactions to interfere with herbivore metabolism. Qualitative allelochemicals are usually effective against non-adapted herbivores [15-16]. Plants have a large concentration of quantitative chemicals. All herbivores are equally susceptible to them. Plant cell walls become indigestible to insects when they are metabolized by quantitative metabolites. Herbivores gain less nutrition by ingesting plant tissues if they consume quantitative metabolites in large quantities. As a consequence, the amount of these chemicals in the herbivore's diet is higher. These defenses are usually large molecules, so they are expensive to synthesize and to transport; they also require an enormous amount of energy to produce.

Volatiles that attract predators of the insect herbivores

Besides producing toxic secondary metabolites that are toxic to herbivores and pathogens, the octadecanoid pathway releases volatiles produced by green leaves and herbivores. Green leafy volatiles are released directly from storage or are synthesized from intermediates and released immediately [17].

A damaged plant produces volatile organic compounds as a way of attracting natural enemies as a result of herbivore damage. This is a systemic response. Changing odor bouquets can be regarded as signals for organisms able to react to them. To be discernible by natural enemies, the signals must be clear and effective. Natural enemies should emit this signal at a time when they are foraging, so it can be relied upon to indicate when a suitable host or prey has been located [17]. During the time when the parasitoid is actively feeding, signals are emitted shortly after the damage has been caused by an herbivore and at their strongest during the daylight hours. Identified by chemical labelling studies are the volatiles that are produced after herbivores destroy the plant, especially at night. This volatile is synthesized again and is not stored, indicating they are caused by herbivore damage. In case of moth caterpillar damage to corn plants, they release odors that attract tiny parasitoid wasps. It lays its eggs inside the caterpillar of the damaged corn plant after finding the damaged plant and finding a parasitoid wasp. After hatching, the wasp larva becomes a parasite and eats the caterpillar from the inside out. Increasing the foraging success of the natural enemy and controlling the herbivore population is made possible by the volatile organic compound signal. By using indirect defenses, several plants can reduce herbivory and increase reproductive fitness and reduce the need for subsequent weapons of mass destruction [18].

Depending on the type of herbivore cue, the amount and composition of volatile signals produced by the plant can be variable. For example, mechanical wounding or infestation with insects like aphids causes a medium response, whereas Spodoptera larvae cause a strong response [17]. Volition, which forms in the larval gut and is introduced into leaves during larval feeding, is one of the elicitors that increase volatile production [19]. Due to the absence of volatility induced in lima bean (*Phaseolus lunatus* L.), volition appears to be relatively specific for induction of maize and other grasses [20]. Volatile organic compounds' responses are specific. For example, parasitoid wasps can use the specificity of the signal to locate particular hosts or even particular instars of their hosts. A diverse range of herbivore species is also frequently known to produce volatile organic compounds (VOCs) upon attack, which can attract generalist herbivores [14].

Volatile organic compounds can also function as direct defenses by repelling ovipositing herbivores or by involved in plant–plant interactions [14, 18]. The chemicals released in the oviposition process, produce unique volatiles which is an attractant to egg-parasitoids resulting in greater predation and decreased herbivory from hatched larvae [21]. Plant volatiles may also act as signals between plants, where volatiles from damaged tissue induce a defense response in neighboring undamaged plants. For example, Corn plants under attack from insect pests use chemical signals not only to interact with beneficial insects but also to stimulate early defense responses in nearby plants [22].

The caution signs are chemical compounds are known as green leafy volatiles. When the corn plant becomes attack by the pest, corn plants release green leafy volatiles into the air to appeal support from the pest's natural enemies. The volatile, which smells like cut grass, attract caterpillar predators and parasitoids [23].

In addition to helping plants defend themselves, volatiles from plants such as maize have also been demonstrated to evoke responses in surrounding plants. Plants can respond more quickly and vigorously to herbivore attacks as a result of this phenomenon, known as priming. It was the green leaf volatiles, which was produced by the lipoxygenase pathway in maize that elicited this interaction. As a result of prolonged exposure to this volatile, maize plants' herbivory-induced genes become primed in order to respond more efficiently to subsequent damage by herbivores. A primed plant that has suffered herbivore damage is better able to defend itself and will then release volatiles, which will attract parasitic wasps [24].

Against herbivorous insects, plants have the option of developing direct chemical defenses or relying on indirect defenses that are more energy-efficient. Both *Salix phylicifolia* and *Salix myrsinifolia* are willow species native to Europe that have developed different mechanisms for dealing with a similar problem of defoliation caused by foraging insects. The herbivorous insects that attack *Salix phylicifolia* (Linnaeus) are chemically weak. Birds that feed on insects are used to assess foliage damage and recognize high populations of insects. By concentrating their feeding, they reduce defoliation threats. When birds pass over *Salix myrsinifolia* (Salisb), it is because the plants are actively defending themselves with chemicals designed to reduce insect herbivory [25]. Therefore, the choice for either direct defense or indirect defense seems to be ecologically determined [25].

Inducible defenses are more cost-efficient in the long run than constitutive ones because they are only synthesized whenever needed, especially when herbivory is variable. The plant can produce large quantities of volatile chemicals during damage or when it is vulnerable, leading to an influx of insects that will parasitize herbivores or predators that are tuned into the combination of chemicals.

Variability of plant volatiles

Odor blends emitted by herbivore-infested plants are complex mixtures, composed of more than one hundred different volatile organic compounds [26].

It has been shown that the volatile compound blends released by herbivores vary both quantitatively and qualitatively depending on the soil, genotype or cultivar, the growth stage of the leaf, and the tissue attacked by the herbivore, as well as abiotic factors such as the time of year and the intensity of the light. Beyond that, the time of the day also influences the composition of the emitted volatile blend. For example, *Nicotiana tabacum* (Linnaeus) releases several herbivore-induced plant volatiles exclusively at night. In addition to repelling moths (*Heliothis virescens*) (Fabricius), these compounds were also repellant to female moths (*Heliothis virescens*) who find oviposition sites at night. In addition, the proportion of herbivorous feeding in the blend is significantly affected by the type of damage caused by oviposition versus herbivorous feeding, as well as by the time between leaf damage [27]. The emitted blend also varies with the herbivore species, and dissimilar ontogenetic stages of the same herbivore may influence the headspace composition. Nevertheless, differences between volatile blends seem to be highest among different plant species and lowest among plants of the same species infested by variable herbivores [26].

Behavioral responses to herbivore-induced plant volatiles

Behavioural assays are important on the ability of insects to discriminate different odor blends. Researchers have examined the role of plant-derived volatiles in determining the ability of parasitoid or carnivore species to detect their herbivorous hosts or prey due to their initial descriptions of the production of herbivore-induced plant volatiles because such plants have been used as a source of host-location cues by parasitic wasps. A growing number of studies on tritrophic plant-herbivore-carnivore systems have found that carnivores and parasitoids can discriminate between different odor blends according to the degree of their dietary specialization, the degree of deprivation they experience, and the level of experience they have had [28]. Whether an herbivore or carnivore is attracted, repelled, or reacts neutrally to a specific blend of herbivore-induced plant volatiles can be depends on the level of plant induction [29].

Plants also interact with entomopathogenic nematodes. The nematode, *Heterohabditis megidis* (Larvanem) are attracted yet unidentified chemicals that are released from roots of a coniferous plant (*Thuja occidentalis*) (Thuj) when weevil larvae, *Otiorhynchus sulcatus* (Fabricius) attack. Furthermore, systemically released HIPVs have been shown to attract the specialist parasitoids of root-feeding larvae [30].

Elicitation of plant responses

A compound that comes from herbivores and interacts with the plant on a cellular level is called elicitor. For example, a series of herbivore-derived elicitors have been isolated from the oral secretion of lepidopteran caterpillars & the oviposition fluid of weevil beetles. The elicitors characterize three groups of compounds: lytic enzymes, fatty-acid–amino-acid conjugates, and bruchins from the oviposition fluid of *Callosobruchus maculatus* (Fabricius) [31].

Both herbivore feeding and mechanical damage induce plant responses that are systemically propagated throughout the plant or remain locally restricted to the wound site. Consequently, the plant’s response to herbivore damage must integrate the responses to the herbivore-unspecific mechanical wounding and the herbivore-specific application of insect-derived chemical elicitors [32].

As a byproduct of the octadecanoid pathway, wound-induced resistance is largely mediated by compounds derived from linolenic acids, such as 12-oxophytodienoic acid, jasmonic acid, and methyl jasmonate [32]. The plant response to herbivores, however, involves at least two other signaling pathways: ethylene and salicylic acid. Although it has become increasingly apparent that single signal cascades, such as oxylipins, can produce an amazing array of secondary signal molecules with a diverse range of functions [32], it has also become clear that herbivore attacks are frequently the product of a variety of communication cascades. 'Signaling crosstalk' is the interaction between these different communication pathways which may explain the specificity of responses. The Crosstalk of Jasmonic Acid, Salicylic Acid, and Ethylene Signal Pathways was proposed by Raymond and Farmer [38] as a system to regulate defensive gene expression. Studies on the fine-tuning of responses to minimize vulnerability to attack by specific herbivore species and guilds have been published recently. Kessler and Baldwin [19] modelled crosstalk as a Boolean network with circuits and logical links.

Currently, such models are limited by our incomplete understanding of all the signaling cascades that are involved. In addition, we have sketchy knowledge about the biochemical consequences of the expression and interactions of these pathways. Understanding the functional implications of signal crosstalk and the corresponding expression of plant defenses requires an in-depth knowledge of the whole plant ecosystem and the natural history of the involved multitrophic interactions in the native habitats of the plants [34].

Defensive Function of Plant Secondary Metabolites

The biosynthetic pathways involved in the production of secondary metabolites have been discovered with impressive speed. This exploratory process will be enhanced as genetic mechanisms and transcriptional processes are identified. Plant-insect interactions are complex and we are not yet fully aware of the ecological implications of induced direct and indirect defenses.

Only experimental manipulations and comparative tests in natural habitats, where defensive traits can be manipulated and tested in comparative experiments, can be used to evaluate the defensive function of secondary metabolites, as well as their physiological and ecological costs. Chemical elicitors are used to induce specific plant responses and mutants and transgenic plants that cannot produce or overexpress certain defenses can be used [35].

This approach is largely restricted to a few model plant species, such as *Arabidopsis thaliana* (Linnaeus) [36] or a limited number of crops such as tomato, maize, and rice. Accordingly, recent widespread introductions of genetically modified crop plants with defense compounds, such as *Bacillus turingiensis*-toxins, to natural arthropod communities may provide a means of elucidating patterns in the plant-insect co-evolutionary process (E.g. the evolution of insect resistance to plant toxins). Although research on agro ecosystems may produce limited conclusions, often neither the crop plants nor their herbivores are studied in their native habitats where co-evolution has occurred. Similar limitations apply to the study of single native species [26].

Specific mechanisms for regulating plant defenses may vary between species depending on factors including internal components, such as signals perceived and transduced (elicitation), as well as external components, such as the highly complex web of interacting species on multiple trophic levels and abiotic factors. A comprehensive survey of the diversity of internal and external factors influencing the plant-insect interaction, utilizing additional, natural study systems, will ultimately reveal the general underlying mechanisms, providing a more sustainable method of utilizing plant defences [37].

Insect Defence Strategies

Insects are not weapon less. Insects have established varies forms of host plant associations coupled with different life histories and feeding approaches essential for the exploitation of their hosts [5]. Insects are continuously developing new methods to overcome plant defenses.

Detoxification of Toxic Compounds

Insects have developed induced defense in response to plant toxins. Detoxification is a means for dealing with a wide variety of toxic chemicals from a diversified diet. Insects possess a powerful assemblage of enzymes that constitute their defense against toxicants. Detoxification of defense chemicals can be carried out by oxidation, reduction, hydrolysis, or conjugation of molecules [38]. Herbivorous insects and host plants have an interesting interaction as variation in how plants produce furanocoumarins is accompanied by variations in how the insects metabolize them. *Papilio polyxenes* (Fabricius) is adapted to feed on toxins-containing host plants by studying its monooxygenase gene. In some cases, detoxification can be induced by environmental conditions [38].

Sequestration of Poison

One way that insects avoid plant poisons is by sequestering the poisons in their pheromone system and defense mechanisms [4]. Lepidoptera sequesters plant secondary metabolites such as some terpenes, phenols, and many nitrogen-containing compounds and uses them as toxic or unpalatable to predators [4]. As an example, swallowtail caterpillars feed on toxic mulberry plants. They can then use these chemicals to defend themselves against predators. When frightened, a swallowtail caterpillar will eject a red, forked organ or osmeterium from its head, which releases a nasty odor. The caterpillar can produce this odor only when it feeds on mulberry plants because the plant produces a chemical that the caterpillar needs [39].

Heliconiine butterflies, for example, have developed mechanisms to take advantage of plant chemicals. Adult heliconiine butterflies lay their eggs on passionflower vines. The young caterpillar emerges and feeds upon the leaves. As adults, butterflies produce and store chemicals in their bodies, causing some birds to become poisonous when they feed on them [14].

Another example is shown by the tobacco hornworm. Insects that accumulate nicotine produced from tobacco plants accumulate poison in their bodies, which deters parasitic insects [40]. On the other hand, the presence of caffeine, the major alkaloid in coffee, is not effective against the *Perileucoptera coffeella* (Guérin-Méneville) larvae. This proposes that insect adaptation to this potentially toxic compound can be due to a resistance mechanism41. An interesting mechanism of avoiding toxic substances was observed in *Helicoverpa zea* (Boddie). It was determined that glucose oxidase, suppresses induced resistance in tobacco plants. They infer that this enzyme may prevent nicotine induction by inhibiting the signalling pathway [42].

Protein inhibitors are significant plant chemical barriers that should be circumvented by herbivore insects. The *Helicoverpa armigera* (Hubner) larvae can overcome the effect of various host plant protein inhibitors by altering their mid-gut composition after protein inhibitors ingestion [43]. Compared to trypsin derived from *Heliothis virescens* (Fabricius), trypsin synthesized from *Heliothis virescens* forms oligomers that bind tightly to the substrate and may reduce the affinity of Protein inhibitors. Lepidopteran insects have constitutive trypsin in addition to trypsins that are produced after consuming Protein inhibitors that are resistant to these inhibitors, as demonstrated by Mazumdar-Leighton and Broadway [43]. A-amylase and chymotrypsin produced similar results. Additionally, the production of proteinases that digest inhibitor proteins helps the insect to overcome plant defenses and to use the digestion of the inhibitor as an amino acid source [44].

Filtration

Insects can consume toxic plants by filtering out the toxins and excreting them. By breaking down toxic chemicals from plants, the cabbage white butterfly can be able to feed on plants that would most likely kill other insects [45].

Insect Diet

It was earlier thought that the prey species consumed by most generalist predators contained quite equivalent nutritional value [46]. In recent years, it has been shown that some predacious generalists may also consider the quality of food when they hunt wolf spiders *Schizocosa stridulans* (Mello-Leitao). The energy content, nutrients, and toxins of different prey species may be variable. These factors must be considered when determining the overall nutritional value available to even the most opportunistic predatory arthropods such as spiders. Some opportunistic spiders predict the food value of prey based on species-specific behavior and nutritional requirements. An optimal diet would consist of a mixture of species, especially when key prey is in short supply [47].

It has been illustrated that predatory insects show reduced egg production when alternative prey, such as those that only provide energy and nutrients for sustaining adults, are available. The benefits of a mixed diet have been described for predatory insects and their ability to produce eggs. Essential prey is necessary for reproductive efforts and egg production in predatory insects. The ability of generalist predators to produce eggs increases beyond the amount that would be produced with a strictly essential diet [48], when a mix of essential and alternative prey is consumed. Therefore, a mixed diet would prove to be beneficial especially when a limited amount of essentials is available. In times of resource scarcity, this feeding technique can enable species to expand their range and increase their survival. Although egg production is low when feeding on a diet of alternative prey, it is not in vain and serves a valuable purpose. For example, *Aphido phagous* (ladybirds) may use these less numbers of eggs produced on alternative diets as a timing mechanism that can exploit the short-lived colonies of aphids [48].

Plants that show induced chemical responses to herbivorous insects will be adversely affected by a mixed diet at a multitrophic level. As the level of toxic substances in its foliage increases, so will the levels of toxins in herbivores. This could diminution their nutritional value for useful predatory insects. When plants' inducible defenses are triggered, generalist predators could seek out a different food source that is more nutritious or less toxic. Taking into account the loss of some protection at higher trophic levels, the induced defense must be very effective. Insects that adapt to tolerate higher levels of toxin-induced stress are likely to suffer from increased herbivory, which would decrease generalist predation due to increased resistance. A decrease in nutritional value for predatory insects as a result of increased herbivore tolerance has resulted in a total reduction of direct and indirect defences [49].

Strategies for insect oviposition

Antennal sensilla and ovipositor sensilla contribute to the overall amount of time females spend in a particular area. Insects employ multisensory activity to locate appropriate oviposition sites [50]. A hierarchy of sensations is applied when selecting oviposition sites. Host selection is vital when determining oviposition sites. Host selection by *Melittobia digitata* (Girault) is a complex three-step process. The first and most important step is shape recognition. Once the female has identified an acceptable shape, she probes the prospective host to discover whether the host contains specific chemical cues. She probes the host with the ovipositor to ascertain whether the host contains the nutrition her larvae require for surviving. At this point, the decision for oviposition is made carefully. A single female may pass up several prospective hosts if requirements are not to her satisfaction [51].

Variation in oviposition location can also affect larval survival rates and performance in herbivorous insects. The study by Yamaga and Ohgushi [51] examined how oviposition by the lady beetle *Epilachna petulosa* (Pallas) affects the growth of two plants, *Cirsium kamtschaticum* (Ledeb), a thistle, and *Caulophyllum robustum* (Maxim), blue cohosh. The study found that oviposition preferences can be influenced both by intraspecies competition for food materials and interspecies predation pressures within a small ecosystem.

Female insects are also influenced by environmental temperature when considering fecundity and oviposition rates. The oviposition rate and total eggs laid by *Chilocorus nigritus* (Fabricius) increased as a function of temperature change. A temperature change stimulated the activity and there was no increase in constant elevated temperature within a range of 20O C to 30O C. These results suggest insects can detect temperature changes and produce more eggs when conditions become more suitable. When the temperature drops below what is suitable for larvae's growth, the insect would respond by eating fewer eggs and searching for oviposition sites, thus conserving precious energy [52].

Conclusions and Recommendations

Plant-insect interaction is an on-going process. There is a great deal of complexity to ecological responses to direct and indirect defenses. Understanding this complexity must be viewed from a co-evolutionary perspective. Herbivore specialists use indirect defenses in their war against attacking herbivores, including calling for help or providing a service to predators, as well as parasitoids. Co-evolved mutualistic relationships include complex interactions between plants, herbivores, and predators or parasitoids: plants, herbivores, and parasitoids. Insects will develop adaptations to exploit plant defenses as plants develop new methods for success. All members of an ecosystem adapt to defenses in the same way, which is a continuous process of co-evolution. More studies in agro-ecosystems and various species should be carried out where the crop plant and their herbivore's co-evolutionary processes occurred. Hence, humans can be benefited from these interactions by developing more natural means of pest control.

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