

The Chemistry of Plant–Insect Egg Interactions

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Abstract: Insect eggs deposited on plants constitute a threat that has led to the evolution of sophisticated defenses. The interactions between insect eggs and plants are governed by a diverse variety of chemicals that inform butterflies about suitable hosts, repel gravid females, alert plants about the presence of an egg, act as signal molecules to induce defenses, directly impair egg development, and indirectly attract egg parasitoids. In recent years, significant progress has been made on the chemical identification, perception and role of compounds associated with oviposition. Knowledge on the genetic basis of oviposition-induced responses is also accumulating. An emerging theme is that insect eggs are not passive structures on leaves but induce complex responses that result from million years of coevolution.

Keywords: Egg-associated molecular patterns · Herbivory · Oviposition · Terpenoids · Volatile organic compounds



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1. Introduction

In nature, plants are constantly exposed to a myriad of enemies, which consist of viruses, bacteria, fungi, nematodes and arthropods. During evolution, they have acquired the ability to detect and respond to these threats by mounting efficient direct defenses consisting of a vast repertoire of toxic proteins and metabolites. In addition, when facing insect herbivores, plants emit volatile organic compounds that attract predators and parasitoids, which is a fascinating example of indirect defense that relies on exchange of chemical information between trophic levels.^[1]

The strong selection pressure exerted by plant defenses on insects has generated counteradaptations, illustrated by the acquisition of detoxification genes, changes in feeding behavior or active suppression of defenses.^[2,3] The ability of some insect species to adapt to toxic molecules of plant families has led to specialization, with the need to develop chemosensory mechanisms of host selection.^[4]

Although they represent an apparent inert stage of the insect life cycle, eggs are known to induce direct and indirect defenses, which are initiated by the specific recognition of egg-associated molecules and subsequent triggering of a signaling pathway that activates transcriptional reprogramming.^[5,6] In recent years, substantial information has accumulated on the nature of egg-derived molecules and how they activate plant defenses. Also, receptors for host-associated cues that determine oviposition behavior have been identified in a few insect species. In this review, I summarize the current knowledge on chemicals and proteins that play a crucial role in plant–egg interactions.

2. Plant Responses to Oviposition

2.1 Finding a Plant Host for Oviposition

A majority of insect species are herbivorous and deposit eggs on leaves or stems. This is a no return and crucial decision since hatching larvae will start their life by consuming leaf material from the host plant. Although visual factors like shape and color constitute initial factors that help identify a suitable host, chemical characteristics of the leaf are the main drivers of oviposition.^[7]

In cruciferous plants, sulfur-containing glucosinolates (GS) are well-known defense metabolites. Upon tissue disruption, breakdown products isothiocyanates (ITCs) and related compounds are released and impair larval growth.^[8] In addition, the presence of GS and ITCs on the surface of intact plants stimulates oviposition.^[9,10] Recently, olfactory receptors P_{xyl}Or35 and P_{xyl}Or49 were identified in antennae of the crucifer specialist *Plutella xylostella*. When ectopically expressed in *Xenopus* oocytes, both receptors respond to iberverin, 4-pentenyl ITC, and phenylethyl ITC. After knocking out the two genes by CRISPR/Cas9, *Plutella* strains do not lay eggs on ITC-treated leaves.^[11] Thus, oviposition preference of *P. xylostella* for its host *Arabidopsis thaliana* depends on the specific recognition of ITCs by two olfactory receptors (Fig. 1).

Another crucifer specialist, the small white *Pieris rapae*, detects the GS sinigrin *via* the gustatory receptor PrapGr28. PrapGr28 is expressed in the female foreleg tarsus and knock-down of the gene significantly reduced the sensitivity of taste sensilla to sinigrin.^[12] Although oviposition tests were not conducted, it is known that *Pieris* butterflies probe leaf surface using contact chemosensory hairs on their tarsi and thus *P. rapae* may rely on sinigrin detection by PrapGr28 to identify its host plant. Similarly, in the butterfly *Papilio xuthus*, the gustatory receptor PxutGr1 in foreleg chemosensilla recognizes the oviposition stimulant synephrine, an alkaloid present on leaves of the Rutaceae (Fig. 1).^[13]

In the Oriental tobacco budworm, *Helicoverpa assaulta*, the odorant receptor HassOr31 in the ovipositor responds to green leaf volatiles and terpenoids, which are widely present in leaves from different plants. Oviposition tests showed that female *H. assaulta* was attracted by *Z*-3-hexenyl butyrate, one of the green leaf volatiles that stimulated HassOr31 response (Fig. 1).^[14]

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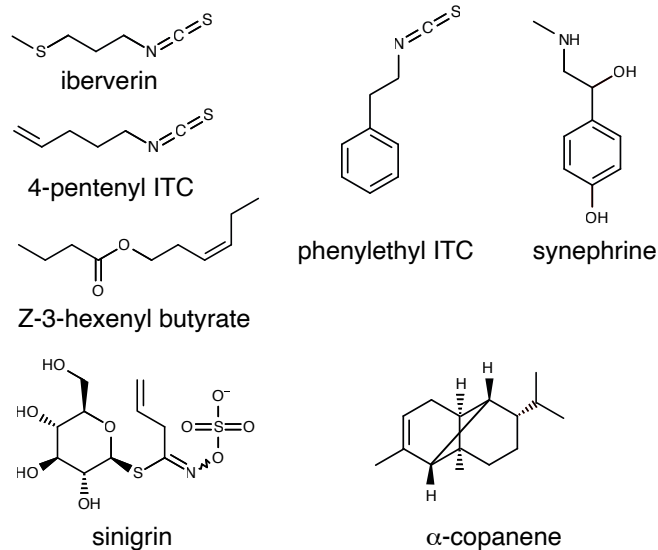
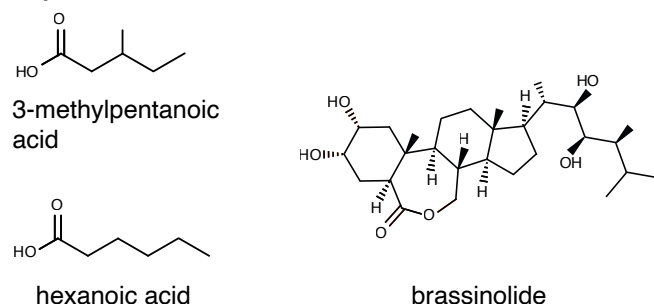
Stimulants**Repellents**

Fig. 1. Oviposition stimulants and repellents with known receptors in female insects.

Remarkably, *Manduca sexta* moth prefers to oviposit on *Datura wrightii* that is already infested by the potato beetle *Lema daturaphila*, to the detriment of larval performance. *M. sexta* detects α -copanene, a terpenoid emitted by beetle-infested plants, via the odorant receptor MsOr35 in antennae (Fig. 1). This unexpected oviposition choice is driven by the avoidance of the parasitoid wasp *Cotesia congregata*, which is not attracted by odors from *M. sexta*-beetle infested plants.^[15] Thus, it appears that *M. sexta* females make a trade-off between larval growth and parasitism.

Collectively, these findings show that different organs and chemoreceptors are involved in finding a suitable host for oviposition. Given the large repertoire of genes coding for gustatory, odorant and ionotropic receptors in insects, and the fact that female insects often rely on multiple oviposition stimulants, much more work will be needed to discover the multitude of ligand–receptor pairs involved in host recognition.^[4,16,17]

2.2 Avoiding a Plant for Oviposition

Plants not only provide chemical information for oviposition, they can also be a source of deterrents that prevent insects from laying eggs. For example, methyl salicylate (MeSA), indole-3-acetonitrile or *E*-2-hexenyl acetate inhibit oviposition, although their respective chemosensory receptors are unknown.^[18–20] In *Arabidopsis*, we found that *Pieris brassicae* butterflies laid fewer eggs on plants pretreated with egg extract, but that this effect was kept in the MeSA biosynthesis mutant *bsmt1-1*, suggesting that other, yet unknown, compounds repel ovipositing females.^[21] However, plants overexpressing *BSMT1* or placed next to a MeSA dispenser were still repellent to butterflies. This effect can be explained by the observation that *BSMT1* expression is induced by

feeding larvae and thus that butterflies may respond to larvae-induced MeSA.^[21]

Recently, the gustatory receptor Pxy1Gr34 from *P. xylostella* was found to detect the steroid plant hormones brassinolide and 24-epibrassinolide. Dual-choice oviposition tests showed that females laid fewer eggs on brassinolide-coated plastic film than on a control film. Since plant hormones are regulating growth but also defense responses, it was hypothesized that brassinolide levels may inform on the defensive status of the host plant and thus may lead to oviposition avoidance (Fig. 1).^[22]

Feces from feeding larvae may provide useful information to conspecific females that the host plant is already attacked and that eggs may face competition for food. Indeed, *Manduca sexta* laid fewer eggs on leaves treated with 3-methylpentanoic acid and hexanoic acid, which are compounds emitted from feces of *M. sexta* caterpillars. A mutant in the ionotropic co-receptor IR8a lost responsiveness to 3-methylpentanoic acid and hexanoic acid, indicating that yet unknown IRs detect these oviposition-detering compounds (Fig. 1).^[23]

2.3 Egg-associated Molecular Patterns

Since the discovery of egg-induced plant defenses, the search for egg-derived or egg-associated compounds that trigger these responses has had limited success. Currently, only few egg-associated molecular patterns (EAMPs), named by analogy to pathogen-associated molecular patterns (PAMPs) that are known immunogenic patterns from microbial pathogens,^[24] have been identified (Fig. 2).

Oviposition by cowpea and pea weevils stimulates cell division beneath the egg in pea pods, creating a neoplastic tissue that presumably blocks larval entry. The active compounds, bruchins, were characterized as C22–C24 long chain α,ω -diols esterified at one or both ends with 3-hydroxypropanoic acid.^[25] Oviduct secretions from the pine sawfly *Diprion pini* and the elm leaf beetle *Xanthogaleruca luteola* induce emission of volatile terpenoids that attract egg parasitoids. Recently, the nature of the defense-eliciting activity in *D. pini* was elucidated by fraction-

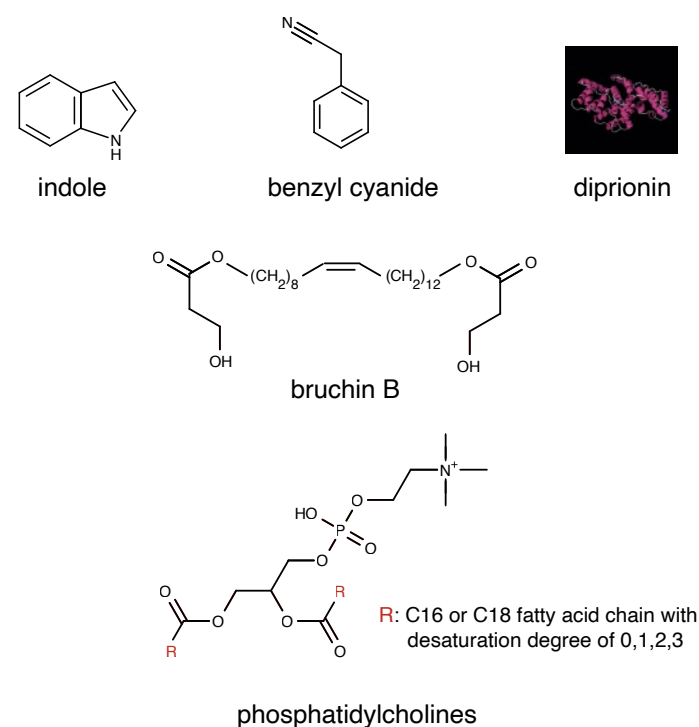


Fig. 2. Egg-associated molecular patterns (EAMPs) that induce plant defenses. Diprionin predicted 3D structure was obtained with the online tool Phyre2.

ating oviduct secretions and testing attraction of the parasitoid *Closterocerus ruforum* to pine twigs treated with different fractions. An annexin-like protein, called diprionin, triggered emission of (*E*)- β -farnesene, attracted *C. ruforum*, and induced expression of terpene synthase genes.^[26] This constitutes the first characterized proteinaceous EAMP eliciting indirect defense against eggs. Whether diprionin is processed *in planta* to generate immunogenic peptides is, however, currently unknown.

When deposited on a leaf, eggs of *Pieris brassicae* are covered by secretions from accessory reproductive glands (ARG). These secretions modify leaf surface chemistry in *Brassica oleracea* and *Arabidopsis*, provoking arrest of the egg parasitoid wasp *Trichogramma brassicae*.^[27,28] Benzyl cyanide and indole, which are male-derived anti-aphrodisiacs found in ARG secretions of *P. brassicae* and *P. rapae*, respectively, activate this indirect defense response.^[27,29]

Eggs of Pierid species also induce direct defenses, which can either impair egg development by generating reactive oxygen species (ROS) accumulation and a hypersensitive response (HR)-like necrosis beneath the eggs,^[30–33] or inhibit subsequent larval development.^[34,35] Using a PR1::GUS *Arabidopsis* reporter line, we tested the gene induction activity of HPLC-fractionated *P. brassicae* egg extract (EE). NMR spectroscopy and mass spectrometry of active fractions allowed the identification of phosphatidylcholines (PCs) containing C16 to C18-fatty acyl chains with various desaturation levels. Further analysis showed that PCs are freely released from the egg and trigger HR-like, ROS, and defense gene expression when applied onto *Arabidopsis* leaves.^[36] Intriguingly, purification of female extracts from the planthopper *Sogatella furcifera*, whose eggs induce a direct defense response in rice, led to the characterization of active PC(18:2/18:2) and a mix of phosphatidylethanolamines.^[37] Since females insert their ovipositor into rice leaf sheath to deposit eggs, more work will be needed to test whether PCs or PEs originate from the ovipositor, egg-coating secretions, or eggs. Anyhow, these results indicate that plants have evolved to recognize certain exogenous phospholipids as a warning signal for the presence of eggs.

A recent search for HR-like inducing factors from *P. brassicae* eggs on *Brassica nigra* revealed that the activity is present in an egg wash, obtained after incubation in MES buffer, or in the glue produced by ARG.^[38] Similarly, an unknown compound in *P. brassicae* glue initiated the preactivation of defenses against hatching larvae in *Arabidopsis*.^[39] Further research will be needed to identify the nature of glue-derived EAMPs and whether the same compound induces both responses.

In summary, the current knowledge on EAMPs indicates that they can be of diverse chemical nature and that several active molecules can be found in eggs or egg-associated secretions, even in the same insect species.

2.4 Perception of EAMPs

PAMPs from microbial pathogens are recognized by plasma membrane-localized pattern recognition receptors (PRRs), which contain an extracellular binding domain and an intracellular kinase domain that triggers defense signaling.^[40] Whereas a similar perception mechanism is likely to operate for insect- and egg-derived cues,^[41] information on PRRs for EAMPs is scarce. Searching for PRRs involved in *Arabidopsis* responses to oviposition, we identified 41 candidates whose expression was enhanced by *P. brassicae* eggs.^[32] Testing knockout lines for each of the candidates revealed that a lectin receptor kinase, LecRK-I.8, significantly contributed to defense gene expression, ROS accumulation and cell death induction.^[42,43] Furthermore, *lecrk-I.8* mutant displayed reduced defenses after PC treatment, strongly suggesting that this PRR is required for perception of egg-derived PCs.^[36] However, responses were not completely abolished in *lecrk-I.8*, likely because of redundant activity. LecRK-I.8 belongs to a subclade of 11 highly

related members that are clustered on two loci in the *Arabidopsis* genome.^[43,44] Indeed, a genome-wide association study (GWAS) on 295 natural *Arabidopsis* accessions showed that variation in the severity of EE-induced HR-like response was explained in part by the genetic variability associated with *LecRK-I.1*.^[33] Further validation with a *lecrk-I.1* mutant confirmed that this PRR functions in the same signaling pathway as LecRK-I.8.^[33] Future work should aim at testing whether these PRRs directly bind to PCs and investigate the role of other LecRKs from the same subclade. Similarly, a GWAS on *Brassica rapa* identified three loci associated with the HR-like response induced by *P. brassicae* egg wash. Strikingly, these loci contain PRRs, including a *LecRK-I.1* homolog, intracellular receptors and ROS-related genes but additional work will be needed to identify the causal gene(s).^[45]

Another GWAS on 146 maize lines looked at the genetic variability associated with the attraction of the egg parasitoid *Cotesia sesamiae* after oviposition by the stem borer *Chilo partellus*. Interestingly, a locus containing a leucine-rich repeat protein kinase was associated with the response and constitutes an interesting candidate for molecular recognition of *C. partellus* eggs.^[46]

2.5 Signaling

Plant defenses against feeding larvae and necrotrophs are primarily regulated by the jasmonic acid (JA) pathway and its bioactive conjugate JA-Ile, whereas defenses against biotrophic fungal and bacterial pathogens require the salicylic acid (SA) pathway.^[47] Intriguingly, *P. brassicae* oviposition triggered SA accumulation in *Arabidopsis*^[35,48] and PR1 induction by EE treatment was significantly reduced in the SA biosynthesis mutant *sid2-1* and in mutants of *EDSI* and *NPRI*, which are regulators of the SA pathway.^[42] Also, PC treatment induced SA accumulation and oviposition-dependent SA levels were lower in *lecrk-I.8*.^[36,43] In addition, egg-induced priming of defense against hatching larvae was found to depend on the SA pathway, as the reduced performance of *P. brassicae* larvae on oviposited *Arabidopsis* leaves was abolished in *sid2-1*.^[35] Finally, oviposition by *Spodoptera exigua* induced SA accumulation in *Solanum dulcamara*.^[49] These findings clearly demonstrate that eggs from lepidopteran species activate the SA pathway, in contrast to the larvae-induced JA pathway (Fig. 3).

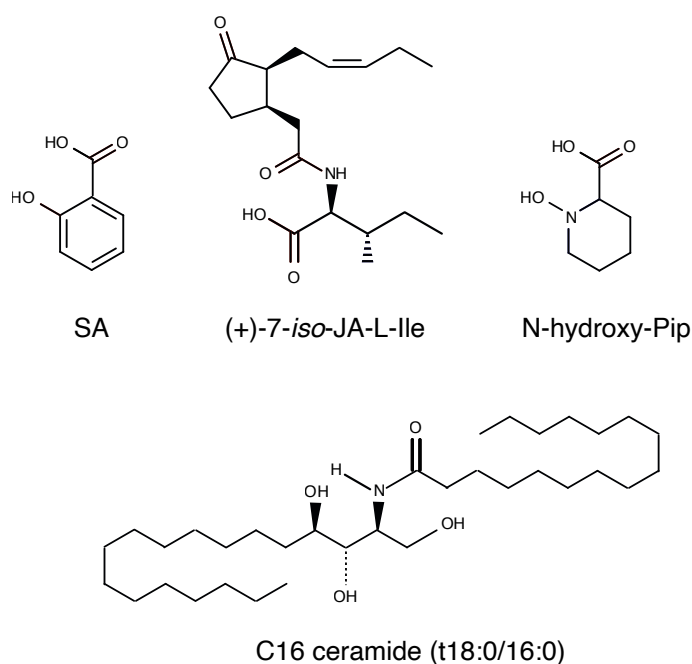


Fig. 3. Signaling molecules involved in egg-induced plant responses. SA; salicylic acid. JA; jasmonic acid. Pip; piperolic acid.

However, oviposition by the spider mite *Tetranychus urticae* activates the JA pathway (Fig. 3). Indeed, a transcriptome of *Arabidopsis* treated with *T. urticae* egg extract showed an enrichment of genes of the JA pathway^[50] and a tomato mutant defective in JA signaling displayed enhanced egg hatching, suggesting that JA-dependent defenses directly target egg development.^[51] In the case of oviposition by *D. pini* on pine needles or by the elm leaf beetle *Xanthogaleruca luteola* on *Ulmus minor*, females wound the leaf tissue before inserting their eggs. In both cases, JA treatment was able to mimic the emission of volatiles that attract egg parasitoids.^[52,53] If activation of the JA pathway was due to EAMP perception or to the mechanical wounding associated with oviposition is unknown but a recent study in elm found no increase in JA and JA-Ile levels after egg deposition by beetles.^[54]

Thus, two distinct signaling pathways are involved in response to oviposition, depending on the insect species considered. More work will be needed to understand the reason for such discrepancy and if it relates to the nature of EAMPs or to the type of oviposition. How EAMP perception is connected to the activation of SA/JA pathways and which downstream transcription factors are necessary for the regulation of egg-induced genes are poorly understood and will require further investigation. Only one study identified a role for NaMYB8 transcription factor in egg-dependent enhancement of defenses against *S. exigua* larvae in *Nicotiana attenuata*.^[55]

In some conditions, egg-induced SA signaling could also affect the outcome of larvae-induced JA signaling. Indeed, both pathways are known to act antagonistically on each other.^[47] We found that *Arabidopsis* pretreatment with *Spodoptera littoralis* or *P. brassicae* EE inhibited the induction of JA-responsive genes by feeding larvae. This suppression was accompanied by enhanced larval development of the generalist *S. littoralis* but not the adapted *P. brassicae*. Since the suppression was abolished in *sid2-1*, it was concluded that EE-induced SA accumulation was responsible for inhibiting the JA pathway, for the benefit of hatching larvae of a generalist herbivore.^[48] The observation that prior oviposition can either enhance^[34,55] or inhibit^[48] defenses against larvae is currently difficult to explain and may need deeper analysis of SA- and JA-pathway activation during oviposition and further feeding. Intriguingly, pre-exposure of *Arabidopsis* with *T. urticae* EE led to reduced female fertility at early time points but increased plant susceptibility after longer exposure.^[50] Thus, timing of hatching^[56] or other physiological and environmental factors may contribute to the outcome of larval performance following oviposition.

We recently discovered that egg-induced HR-like response is modulated by sphingolipids (Fig. 3). Treatment with *P. brassicae* EE induced the expression of sphingolipid metabolism genes and the accumulation of C16:0 ceramides in *Arabidopsis* and *Brassica nigra*. In addition, ceramide synthase mutants displayed a reduced HR-like response.^[57] Sphingolipids are known regulators of various cellular processes in animals and plants, including programmed cell death.^[58] They thus appear to be important for plant responses to eggs but their role as signaling components needs to be further investigated.

2.6 Direct Defenses

Although plants clearly react to oviposition, information on compounds or proteins that directly impact egg survival or development is relatively scarce. The only known ovicidal substance was found in some *japonica* rice varieties. After oviposition by *S. furcifera*, rice plants develop watery lesions. Benzyl benzoate was identified in the lesions and egg development was completely inhibited when exposed to solutions containing this compound (Fig. 4).^[59]

The severe HR-like response that develops underneath the eggs has been correlated with death,^[60] poor survival^[30,61,62] or

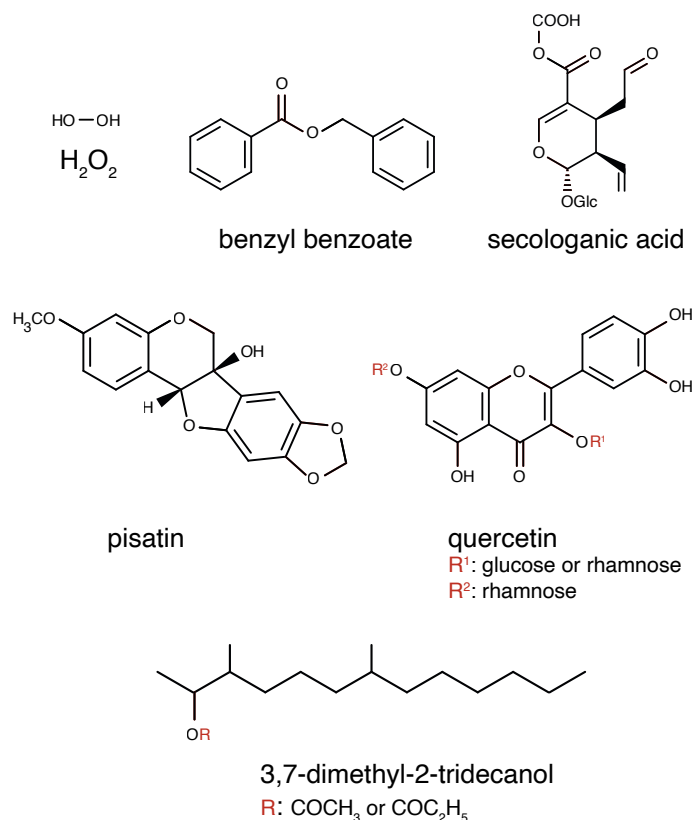


Fig. 4. Compounds that have a demonstrated or putative role in impairing egg survival.

dropping from the leaf.^[63] But whether the effect is solely due to desiccation of the plant tissue or is accompanied by the additional action of toxic molecules is unknown. Oviposition-induced HR-like is often accompanied by ROS production^[42,49,64] and in *Solanum dulcamara* the HR-like associated production of H₂O₂ inhibited egg hatching.^[49] Similarly, bruchins stimulated neoplasm formation on pea pods that physically impede larval entry.^[25] In addition, oviposition by bruchids on the black gram pod triggered HR-like and accumulation of ROS but whether this impacted egg development was not tested.^[65] Also, treatment of pea pods with bruchin B led to the accumulation of pisatin, a known antimicrobial isoflavone, although the role of such defense compound against eggs was not evaluated (Fig. 4).^[66]

Strikingly, survival of *D. pini* eggs was significantly lower on pine trees that were exposed to *D. pini* sex pheromone (acetate and propionate esters of (2*S*,3*R*,7*R*)-3,7-dimethyl-2-tridecanol) than on untreated controls. Pheromone exposure enhanced H₂O₂ production and expression of defense-related genes, suggesting that early detection of cues indicating imminent oviposition may be beneficial for the plant (Fig. 4).^[67]

Iridoids are cyclopentanoid terpenes that are known to deter feeding from generalist insect herbivores. In contrast, they act as oviposition stimulants for adapted species that sequester glycosylated forms for their own defense against predators.^[68] Oviposition by the specialist *Euphydryas aurinia* induced a localized and substantial increase of secologanic acid in leaves of *Lonicera implexa*.^[69] This high foliar concentration may provide hatching larvae a competitive advantage against generalists or protection against predators but it could also have a toxic effect against the eggs. Similarly, levels of two quercetin glycosides (Q3G7R and Q3R7R) were enhanced in *Arabidopsis* leaves after *P. brassicae* oviposition.^[35] Flavonoids are known to impair larval performance^[70] but, again, whether they can affect egg survival is unknown (Fig. 4).

Clearly, more work will be needed to identify plant secondary metabolites that accumulate in response to oviposition and to investigate their specific effect on insect eggs. Large-scale transcriptomic analyses in response to oviposition by different insects in different plant species have revealed an upregulation of genes belonging to a variety of biosynthetic pathways, including phenylpropanoids, terpenoids, alkaloids, ROS, indolics, glucosinolates and lipid metabolism, thus providing a rich source of information to address this question.^[27,32,50,65,71–74]

2.7 Indirect Defenses

The release of oviposition-induced plant volatiles (OIPVs) is known to attract parasitic wasps that kill the eggs but OIPVs can also recruit predators of larvae or constitute a warning signal of future herbivory (Fig. 5).^[5] An early study in elm reported the emission of parasitoid-attractive terpenoids, including (*E,E*)- α -farnesene, β -caryophyllene and (*E*)-4,8-dimethyl-1,3,7-nonatriene (DMNT), after oviposition by *X. luteola*.^[75] Similarly, *D. pini* eggs triggered (*E*)- β -farnesene emission in pine.^[76] Intriguingly, in the same system, predatory birds (great tit and blue tit) were also attracted by egg-induced pine branches, suggesting that they also use olfactory cues to locate insect eggs.^[77]

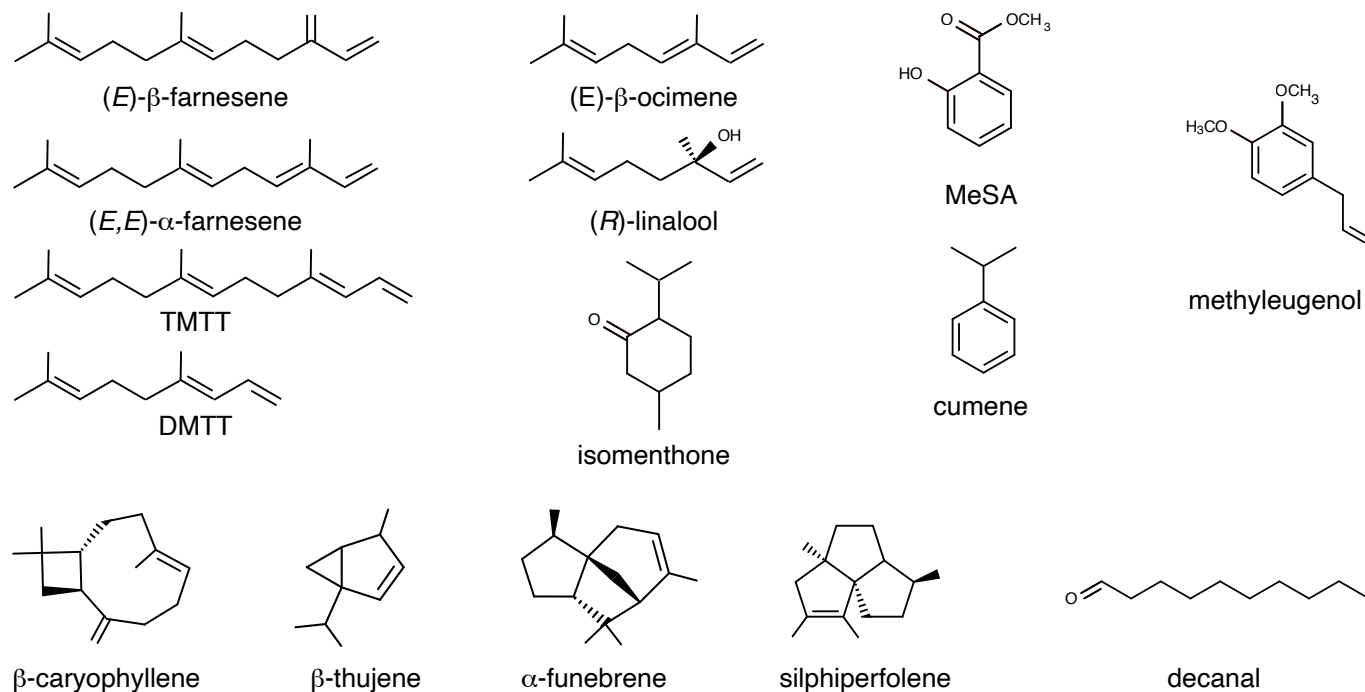
In *B. nigra*, *P. brassicae* oviposition induced the release of the terpenoids (*E*)- β -ocimene, silphiperfolene, α -funebrene, and isomenthone. OIPVs attracted egg and larval parasitoids, but also repelled gravid female butterflies, illustrating the multiple role of such compounds.^[78] The specific effect of each volatile on the respective biological response was, however, not investigated. *B.*

nigra and *B. oleracea* also released the monoterpene β -thujene and the alkylbenzene cumene, respectively, after oviposition by *P. brassicae*. Interestingly, these emitted compounds primed defenses in neighboring plants, which exhibited enhanced resistance to *P. brassicae* larvae.^[79]

A more diverse blend of OIVPs was detected in maize leaves containing eggs of *C. partellus*. Interestingly, terpenoids ((*E*)- β -ocimene, (*R*)-linalool, (*E*)- β -caryophyllene, (*E*)- β -farnesene, DMNT, (*E*)-4,8,12-trimethyltrideca-1,3,7,11-tetraene (TMTT)), the phenylpropanoid methyleugenol, the phenolic MeSA, and the aldehyde decanal were emitted in landrace varieties and attracted egg parasitoids (*Trichogramma bournieri*), but also larval parasitoids (*C. sesamiae*).^[80] These OIVPs were not found in commercial hybrid varieties, suggesting that this defense trait was lost during breeding. This example is similar to the root-emitted (*E*)- β -caryophyllene that attracts entomopathogenic nematodes, which infest the maize pest *Diabrotica virgifera*. Most American maize varieties do not express a terpene synthase (TPS23) that produces (*E*)- β -caryophyllene.^[81] Strikingly, reintroducing this gene in a nonemitting maize line restored (*E*)- β -caryophyllene emission and attractiveness of nematodes, and reduced root damage, illustrating the usefulness of manipulating volatile emissions as a strategy for crop protection.^[82]

A chemical analysis of leaf surface changes that arrest the parasitoid *T. brassicae* on oviposited Arabidopsis revealed a decrease of the saturated fatty acid tetracosanoic acid (C24) and an increase of tetratriacontanoic acid (C34) in epicuticular waxes of egg-laden leaves. But whether this quantitative change in wax

OIPVs



Epicuticular wax

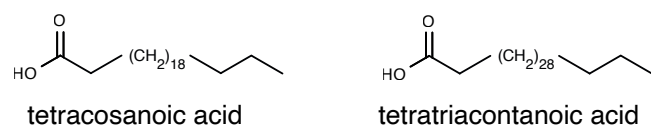


Fig. 5. Oviposition-induced volatiles (OIPVs) that are emitted by different plant species and leaf epicuticular wax components whose abundance changes after oviposition.

composition is responsible for the change in parasitoid behavior was not shown (Fig. 5).^[28]

Thus, studies so far have revealed that plants emit a blend of OIVPs that is largely dominated by diverse terpenoids. Although it has been demonstrated that different terpenoid compounds are attractive to the same parasitoid species,^[83] the reason for the complexity of emitted volatiles is not yet resolved and will need further research. Moreover, identification of receptors for OIVPs in parasitoids will help to better understand how these predators selectively identify their targets. For instance, the aphid parasitoid *Eupeodes corollae* uses the odorant receptor EcorOR3 and the odorant binding protein EcorOPB15 to recognize plant-emitted (*E*)- β -farnesene.^[84]

2.8 Systemic Acquired Resistance Against Pathogens

Oviposition triggers plant responses that impact other biotic interactions. Having observed that oviposition triggered the SA pathway, which is also engaged in innate immunity against foliar pathogens,^[85] we speculated that eggs could affect the plant resistance status. Indeed, oviposition or treatment with *P. brassicae* EE significantly reduced Arabidopsis infection by different strains of *Pseudomonas syringae*. Moreover, this enhanced resistance was not only activated in the locally treated leaf but also in distal, untreated, leaves.^[86] This phenomenon is called a systemic acquired resistance (SAR), which is normally observed when a primary infection of a leaf is followed by a secondary infection of distal leaves by compatible pathogens.^[87] Regulation of SAR requires SA and the long-distance signal N-hydroxy-pipecolic acid (NHP) (Fig. 3).^[88,89] Using Arabidopsis mutants impaired in SA signaling or NHP biosynthesis, we showed that EE-induced SAR depended on these metabolites and thus clearly resembled bacteria-induced SAR.^[86] Interestingly, EE-induced SAR was also efficient against the fungal pathogen *Botrytis cinerea* and the oomycete *Hyaloperonospora arabidopsidis*, in an NHP-dependent manner, illustrating a conserved and potentially wide-spectrum protective effect of oviposition against further infection.^[90] The SAR response could be triggered by the application of PCs and was abolished in *lecrk-1.8*, demonstrating that the signaling pathway that controls direct defenses against eggs is also involved in enhanced protection against pathogens.^[90]

Strikingly, we also discovered that egg-induced SAR extends to neighboring plants, as untreated Arabidopsis plants growing next to egg- or EE-treated plants displayed a reduced infection by *P. syringae* and *B. cinerea*.^[90,91] This interplant SAR was abolished when roots were separated by a solid barrier but not when using an 11 μ m nylon mesh, suggesting that roots from treated plants secrete a yet unknown small metabolite that induces the response in neighbors. Again, this effect depended on a functional NHP pathway in the sender plant.^[91]

Collectively, these findings question the role of induced SAR in the context of oviposition. Is it advantageous for the insect, for the plant or both? *P. brassicae* larvae performance was significantly lower on plants infected by *P. syringae* or *B. cinerea* than on uninfected plants.^[86,90] Thus, hatching larvae would benefit from feeding on local and neighboring plants that are more resistant to pathogens. In contrast, larval feeding creates open wounds that may facilitate the entry of opportunistic pathogens, and thus plants may have evolved a strategy to anticipate such threat by responding to oviposition cues and inducing a SAR. Further research should be placed in testing which of the two hypotheses is valid, and whether this intriguing phenomenon is efficient in a more natural environment where multiple biotic stresses dominate.

3. Conclusions and Future Directions

In recent years, studies on what appeared to be inert structures deposited onto leaves have revealed an amazing complexity of

chemical and molecular signals that regulate all steps of plant–insect egg interactions, from the initial choice of the host plant by a butterfly to subsequent perception of EAMPs and triggering of direct and indirect defenses. Such knowledge has been acquired through the development of sensitive instruments for metabolomic analyses, the power of genetics and molecular techniques associated with the use of plant model species, and the quantitative measurements of insect behavior and performance on wild-type and CRISPR/Cas9 mutant lines.

Given the chemical complexity and number of plant species that are hosts for a diverse range of ovipositing insects and arthropods, there is potentially an immense variety of leaf chemicals that await discovery of the corresponding receptors in female tarsi or antennae. Thanks to bioinformatic analyses on available genomes and the feasibility of knocking-out insect genes, significant progress can be foreseen in this area.

In response to oviposition cues, plants not only try to impair egg development but they also preactivate defenses against hatching larvae or opportunistic leaf pathogens. This raises the question whether it is more efficient to directly get rid of eggs or to anticipate subsequent threats that may inevitably occur. Future studies on additional plant–egg interactions may reveal if such trade-off is generic or associated with certain oviposition types or larval feeding styles.

Contrary to the field of plant pathogens and PAMP-triggered innate immunity where many pairs of ligand–receptor (and co-receptor) are known, only a few EAMPs have been identified and there is currently no validated corresponding receptor. Clearly, efforts should be placed in filling this knowledge gap, as well as in unveiling the precise molecular steps that connect egg perception to the expression of defense genes.

Curiously, only two ovidical substances have been discovered and validated. With the help of transcriptomic studies and characterization of biosynthetic pathways, the role of egg-induced secondary metabolites should be investigated. Such research may lead to the finding of new potent ovidical substances that may turn useful for pest control in agriculture.

Finally, the diversity and complexity of OIVPs is remarkable and underlies an exchange of infochemicals that we only start to understand. The specific role of each volatile in attracting parasitoids is rarely known nor validated, and whether the composition of the blend constitutes an additional layer of specificity or information needs further research. Hopefully, future years will provide exciting answers to all these questions and, certainly, unveil striking discoveries as the world of plants and insects conceals an unlimited number of biological innovations.

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