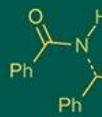


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A review on RNA interference based insect pest management

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Abstract

RNA interference has moved from a laboratory curiosity into one of the more closely watched platforms for insect pest suppression in field crops, yet the distance between mechanistic promise and reliable commercial deployment remains uneven across insect taxa. The current state of that transition, drawing together evidence on the molecular machinery governing double stranded RNA uptake and processing, the competing delivery platforms now under development, and the comparative sensitivity of major pest orders. Coleopteran pests such as the western corn rootworm continue to anchor the only large scale commercial success, while lepidopteran and hemipteran targets have proved far less tractable, a pattern this review argues reflects differences in cellular uptake pathways and dsRNA stability rather than any single unifying biological rule. Field level resistance in rootworm populations exposed to dsRNA traits is treated here not as an isolated case study but as an early signal of the durability problems the wider technology will eventually face.

Keywords: RNA interference, double stranded RNA, insect pest management, host induced gene silencing, spray induced gene silencing, dsRNA resistance, non-target risk assessment

Introduction

The discovery that double stranded RNA could trigger sequence specific gene silencing in *Caenorhabditis elegans* reframed how molecular biologists thought about post transcriptional gene regulation and, within a decade, how crop protection scientists thought about insect control (Fire *et al.*, 1998) [5]. Unlike conventional insecticidal chemistry, which acts on a protein target shared across broad taxonomic groups, RNA interference offered the prospect of suppressing a single gene in a single pest species while leaving related, non-target organisms untouched. That specificity is the feature that continues to attract regulatory and public interest, and it is also the feature that has proved hardest to deliver consistently once research moved from model organisms into economically important field pests.

Two developments in 2007 established RNA interference as a credible pest management tool rather than a molecular biology technique confined to reverse genetics. Baum *et al.* (2007) [2] demonstrated that transgenic maize expressing dsRNA targeting a vacuolar ATPase subunit could suppress feeding damage and larval development in western corn rootworm, while Mao *et al.* (2007) [10] showed that plant mediated silencing of a cytochrome P450 gene in cotton bollworm reduced the insect's tolerance of gossypol, a natural plant defence compound. These two papers, published within months of each other, effectively defined the two poles of the field that this review returns to repeatedly, namely a coleopteran system in which RNA interference works with striking efficiency and a lepidopteran system in which the same basic approach produces a far more modest and inconsistent effect.

The commercial trajectory since those early demonstrations has been narrower than the initial optimism implied. A single dsRNA trait, targeting the *Snf7* gene in western corn rootworm, reached deregulation and stacked commercial deployment as part of SmartStax PRO maize, and it remains, more than a decade after the founding papers, essentially the only large scale example of RNA interference operating as a stand alone or stacked trait in a row crop grown at continental scale (Head *et al.*, 2017) [6]. This review takes that asymmetry, a technology that works exceptionally well in one insect order and considerably less well in most others, as its central organising problem. The sections that follow examine the molecular basis for that asymmetry, the delivery platforms competing to overcome it, the

comparative efficacy data across insect orders, the early evidence of resistance evolution in the one system where the technology has been deployed at scale, and the gaps that continue to separate RNA interference from being a general purpose pest management tool rather than a coleopteran specialty.

Molecular machinery and the source of taxon dependent variability

Much of the confusion in the early RNA interference literature stemmed from treating the phenomenon as a single, transferable mechanism rather than as a set of related but taxonomically divergent processes. The core silencing machinery, involving Dicer-2 processing of long dsRNA into small interfering RNAs and their loading into an Argonaute containing RISC complex, is conserved widely enough across insects that its presence is rarely in doubt (Zhu and Palli, 2020) [16]. What differs sharply between species is everything upstream of that core step, namely how efficiently dsRNA is taken up by cells, how well it survives extracellular and intracellular nucleases, and whether a systemic signal spreads the silencing effect beyond the tissue of initial exposure. Huvenne and Smagghe (2010) [7], reviewing uptake mechanisms across insect orders, distinguished two broad routes, a clathrin mediated endocytic pathway analogous to the SID-1 independent route described in some invertebrates and a channel mediated route resembling the SID-1 transporter first characterised in nematodes; the relative contribution of each route appears to vary by species and by tissue in ways that are still only partially mapped.

This uptake bottleneck helps explain why coleopteran insects, and western corn rootworm in particular, have become the default proof of concept species for the technology. Bolognesi *et al.* (2012) [3], working through a systematic screen of candidate genes in western corn rootworm, found that dsRNA activity against this species is unusually robust across a wide range of target genes and delivery concentrations, a pattern consistent with efficient cellular uptake and limited extracellular degradation in the coleopteran gut environment. Lepidopteran insects present a

markedly different picture. Terenius *et al.* (2011) [13], surveying a large set of published and unpublished RNAi experiments in Lepidoptera, reported that a substantial proportion of attempts produced no detectable phenotype at all, and that success was strongly dependent on the specific gene targeted, the developmental stage of the insect, and the delivery route used, with injection generally outperforming oral or feeding based delivery. The authors argued, and subsequent work has largely supported the argument, that lepidopteran midgut conditions, including high nuclease activity and rapid dsRNA degradation, constitute a more hostile environment for orally delivered dsRNA than the coleopteran gut.

Hemipteran insects add a further complication that does not fit neatly into either the coleopteran or lepidopteran pattern. Christiaens *et al.* (2014) [4] demonstrated that pea aphid failed to respond consistently to dsRNA delivered by both feeding and injection, and traced the poor response in part to rapid degradation of dsRNA in the aphid gut and haemolymph rather than to any deficiency in the downstream RNAi machinery itself. This finding is important because it shifts the explanatory burden away from a simple presence or absence of core silencing genes and toward the physiological environment the dsRNA molecule must survive before it can ever reach that machinery. Read together, these three lines of evidence, from Coleoptera, Lepidoptera and Hemiptera, support a conclusion that is easy to state but has been slow to gain traction in applied research programmes, namely that RNA interference efficiency is not a property of an insect species in isolation but an outcome of the interaction between dsRNA stability, tissue specific uptake capacity and target gene selection, and any single one of these variables studied alone will give an incomplete picture of why a given experiment succeeded or failed.

Table 1 summarises this comparative pattern across the four insect orders most heavily represented in the applied RNA interference literature, drawing together the delivery routes and outcomes discussed above rather than reproducing any single study's dataset.

Table 1: Comparative RNA interference response across major insect pest orders

Insect order	Representative species	Typical RNAi response	Reported route of delivery	References
Coleoptera	<i>Diabrotica virgifera virgifera</i>	Strong, systemic, dose dependent	Transgenic maize expressing dsRNA; injection	Baum <i>et al.</i> (2007) [2]; Bolognesi <i>et al.</i> (2012) [3]
Lepidoptera	<i>Helicoverpa armigera</i> ; <i>Bombyx mori</i>	Weak to moderate, highly gene and tissue dependent	Plant-mediated feeding; oral dsRNA	Terenius <i>et al.</i> (2011) [13]; Mao <i>et al.</i> (2007) [10]
Hemiptera	<i>Acyrtosiphon pisum</i>	Inconsistent; degradation limited response in some assays	Artificial diet feeding; injection	Christiaens <i>et al.</i> (2014) [4]
Diptera	<i>Drosophila melanogaster</i>	Species and strain dependent, generally robust in laboratory strains	Oral feeding of sequence specific dsRNA	Whyard <i>et al.</i> (2009) [15]

Delivery platforms competing for field relevance

If uptake and stability limit which insects respond to dsRNA at all, delivery platform determines whether a workable laboratory result can ever reach a farmer's field. Host induced gene silencing, in which a crop plant is transformed to constitutively express dsRNA against a target pest gene, was the platform behind both founding demonstrations of field relevant RNA interference and remains the only platform to have achieved regulatory approval and commercial sale (Baum *et al.*, 2007; Mao *et al.*, 2007) [2, 10]. Its principal advantage is continuous exposure; a rootworm

larva feeding on transgenic root tissue encounters dsRNA throughout the growing season without any additional application. That same continuity, however, is also its principal commercial constraint, since each new target pest or gene combination requires a fresh transformation event and a fresh, multi year regulatory dossier, a process too slow to respond to newly emerging or regionally specific pest problems.

Spray induced gene silencing has attracted growing interest precisely because it promises to decouple RNA interference from the transgenic development and approval cycle. San

Miguel and Scott (2016) ^[12] showed that dsRNA applied topically to plant foliage retained sufficient stability and insecticidal activity to suppress feeding in a lepidopteran pest, evidence that dsRNA need not be produced inside the plant to be effective against at least some targets. Zotti *et al.* (2018) ^[17], reviewing the broader RNA interference technology landscape for crop protection, framed spray applied dsRNA as the platform most likely to extend the technology beyond the narrow set of pests currently addressed by transgenic events, largely because it allows rapid reformulation against new targets without requiring a new deregulated plant variety. The obstacle this platform has not yet overcome at commercial scale is cost; producing dsRNA in the quantities needed for field level spray application, and doing so with sufficient environmental persistence to survive rainfall and ultraviolet exposure between applications, remains substantially more expensive per hectare than either synthetic chemical insecticides or a one time transgenic seed cost.

Nanoparticle and carrier based formulations occupy a middle position between these two platforms, attempting to solve the stability and penetration problems that limit naked dsRNA spray applications without requiring a transgenic host plant. Joga *et al.* (2016) ^[8], reviewing delivery innovations across the RNA interference pest control

literature, catalogued a range of carrier chemistries, including cationic liposomes and layered double hydroxide nanosheets, that had been shown in laboratory assays to protect dsRNA from nuclease degradation and improve uptake efficiency relative to naked dsRNA controls. Vogel *et al.* (2019) ^[14] reached a broadly similar conclusion in their assessment of RNA interference delivery for pest management, noting that carrier formulated dsRNA had produced encouraging results in several proof of concept studies but had rarely been tested under realistic field conditions, where formulation cost, carrier toxicology to non-target organisms, and manufacturing scalability all remain open questions rather than solved problems. The pattern across all three platforms is therefore one of trade offs rather than a clear winner, with host induced silencing offering proven but inflexible commercial performance, spray induced silencing offering flexibility at a cost that has not yet come down enough for broad adoption, and nanoparticle carriers offering a partial technical solution to stability that has yet to be matched by an economically viable production pathway.

Table 2 sets these three delivery platforms side by side, highlighting that no single platform currently dominates on both technical performance and commercial readiness.

Table 2: Comparison of dsRNA delivery platforms for insect pest management

Delivery platform	Principal advantage	Principal limitation	References
Host induced gene silencing (transgenic plant)	Continuous exposure through the growing season, no repeat application	Regulatory burden of a new transgenic event; slow deployment against emerging pests	Baum <i>et al.</i> (2007) ^[2] ; Mao <i>et al.</i> (2007) ^[10]
Spray induced gene silencing (topical dsRNA)	Flexible, non-transgenic, rapid reformulation against new targets	Environmental degradation of naked dsRNA; cost of production at field scale	San Miguel and Scott (2016) ^[12] ; Zotti <i>et al.</i> (2018) ^[17]
Nanoparticle or carrier formulated dsRNA	Improved cuticular or gut penetration and dsRNA stability	Formulation cost, limited field validation, carrier toxicology unresolved	Joga <i>et al.</i> (2016) ^[8] ; Vogel <i>et al.</i> (2019) ^[14]

Note: Adapted from Baum *et al.* (2007) ^[2], Mao *et al.* (2007) ^[10], San Miguel and Scott (2016) ^[12], Zotti *et al.* (2018) ^[17], Joga *et al.* (2016) ^[8], and Vogel *et al.* (2019) ^[14].

Divergent efficacy across insect orders: the coleopteran-lepidopteran contrast reconsidered

It has become something of a shorthand in the applied entomology literature to describe Coleoptera as RNAi responsive and Lepidoptera as RNAi recalcitrant, and the data summarised in the previous sections support that generalisation as a starting point. Treating it as a fixed biological law, however, obscures evidence that the lepidopteran picture is considerably more differentiated than a single order wide efficiency deficit would suggest. Mao *et al.* (2007) ^[10] obtained a clear, biologically meaningful phenotype in cotton bollworm using plant mediated dsRNA delivery, which means the recalcitrance documented by Terenius *et al.* (2011) ^[13] cannot be attributed to Lepidoptera as a taxon being uniformly unresponsive to RNA interference; rather, the outcome appears to depend heavily on which gene is targeted, the tissue in which that gene is expressed, and whether the delivery route bypasses the midgut degradation problem that dominates oral feeding assays. This distinction matters for how the field interprets negative results. A failed lepidopteran RNAi experiment is too often reported, and subsequently cited, as evidence against the feasibility of RNA interference in that order generally, when a more defensible reading of the comparative literature is that the experiment failed to overcome a specific, identifiable barrier, most commonly dsRNA degradation in the gut lumen, that a different target

gene, developmental stage, or delivery method might have avoided.

A parallel argument applies within Coleoptera, where the apparent uniformity of strong RNAi response is itself partly an artefact of which species have been studied most intensively. Bolognesi *et al.* (2012) ^[3] screened dozens of candidate genes in western corn rootworm and found broad, though not universal, susceptibility to knockdown, a result that has understandably encouraged the assumption that coleopteran insects generally share this trait. Far fewer comparably systematic screens exist for other economically important coleopteran pests, which leaves open the possibility that western corn rootworm sits toward the responsive end of a coleopteran distribution rather than representing its typical member. The comparative evidence assembled here therefore points toward a more cautious conclusion than either the optimistic early literature or the more recent, occasionally dismissive commentary on lepidopteran RNAi would suggest, namely that order level generalisations about RNA interference efficacy are useful for setting research priorities but poor substitutes for species and gene specific validation, and that publication patterns favouring successful coleopteran demonstrations over the more heterogeneous lepidopteran and hemipteran results have probably widened the perceived gap between orders beyond what the underlying biology strictly warrants.

Resistance evolution and the durability question

The commercial deployment of Snf7 targeted dsRNA against western corn rootworm has generated the field's first direct test of whether RNA interference traits face the same durability pressures that have eroded the effectiveness of *Bacillus thuringiensis* toxins over the past two decades. Khajuria *et al.* (2018) ^[9] documented the development and characterisation of a laboratory selected western corn rootworm population with substantially reduced sensitivity to dsRNA, tracing the resistance mechanism to reduced dsRNA uptake rather than to a change in the downstream RNAi processing machinery. This finding matters beyond the specific population studied because it identifies the uptake step, the same step highlighted in the earlier discussion of taxon dependent efficiency differences, as a plausible and mechanistically tractable point of resistance evolution, which suggests that resistance to one dsRNA trait targeting a given uptake dependent pathway could in principle confer at least partial cross resistance to other dsRNA traits relying on the same entry route, independent of which gene is being silenced.

Head *et al.* (2017) ^[6], evaluating the field performance of stacked SmartStax and SmartStax PRO maize against both western and northern corn rootworm populations, situated the dsRNA trait within a broader resistance management framework that already had to account for reduced susceptibility to several Bt proteins in some rootworm populations. Their analysis treated the dsRNA trait as one additional mode of action within a pyramided stack rather than as a stand alone solution, an approach that implicitly acknowledges the same durability concerns that motivated Bt pyramiding in the first place. The parallel to Bt resistance evolution is instructive but should not be overstated, since the mechanistic basis for reduced dsRNA uptake documented by Khajuria *et al.* (2018) ^[9] differs from the receptor binding disruption mechanisms typically responsible for Bt resistance, and it remains unclear whether the two resistance types will respond similarly to rotation, pyramiding or refuge based management strategies. What the rootworm case does establish clearly, and what this review treats as a signal relevant to any future dsRNA trait rather than a rootworm specific curiosity, is that RNA interference is not inherently immune to the selection pressure that erodes any single mode of action deployed at scale over multiple growing seasons, and that resistance management planning needs to be built into dsRNA trait deployment from the outset rather than added retrospectively once field failures accumulate.

Gaps in the evidence base and unresolved regulatory questions

Non-target risk assessment for RNA interference traits has generally proceeded on the premise that sequence specificity

provides an inherent safety advantage over broad spectrum insecticidal chemistry, and the underlying molecular logic for that premise is sound; a dsRNA molecule designed against a target specific gene sequence should not silence the same gene in an organism whose sequence diverges sufficiently at the relevant region. Bachman *et al.* (2013) ^[11], characterising the spectrum of activity of the Snf7 dsRNA trait against a panel of non-target arthropods, reported no adverse effects across the species tested, a result consistent with the sequence specificity argument. The evidentiary base supporting broader ecological safety claims remains considerably thinner than the base supporting Bt non-target studies, which have accumulated across several decades and a much wider range of taxa and exposure routes. Reviews of the delivery literature, including Vogel *et al.* (2019) ^[14], have noted that non-target assessment work has concentrated disproportionately on close taxonomic relatives of the intended target and on short term laboratory exposure, leaving comparatively little published evidence on chronic, low dose environmental exposure or on soil and aquatic organisms that might encounter dsRNA residues from root exudates or spray drift.

A second gap concerns the scalability of spray induced gene silencing once it moves beyond controlled greenhouse trials. The stability improvements reported by San Miguel and Scott (2016) ^[12] and the carrier based formulations reviewed by Joga *et al.* (2016) ^[8] both address dsRNA degradation under relatively controlled experimental conditions, but neither literature has yet produced the kind of multi season, multi location field efficacy data that would be needed to support a commercial spray product, and production cost figures reported across the literature vary widely depending on the fermentation or *in vitro* transcription method assumed, making it difficult to draw a confident conclusion about when, if ever, spray applied dsRNA will reach cost parity with conventional insecticides. A third and related gap concerns target gene selection itself; much of the applied literature reviewed here selected candidate genes based on their known role in core physiological processes such as membrane trafficking or detoxification, but comparatively few studies have systematically compared candidate genes within a single pest species under standardised delivery conditions, which limits the field's ability to predict, in advance, which genes will translate into field relevant mortality rather than a modest laboratory phenotype. Addressing these three gaps, namely non-target exposure breadth, field scale delivery economics, and systematic target gene comparison, would do more to move RNA interference toward broad commercial relevance than further mechanistic characterisation of the core silencing pathway, which is already reasonably well understood relative to these applied uncertainties.

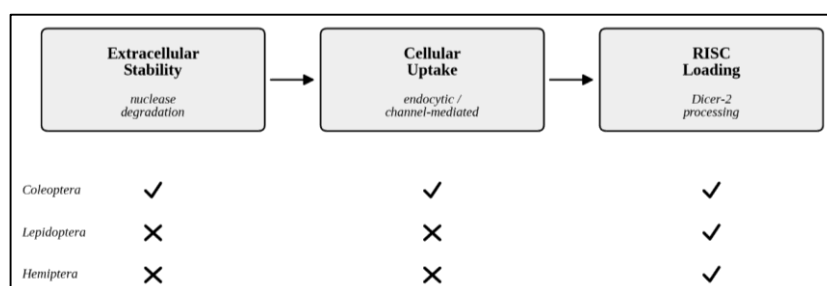


Fig 1: Proposed points of divergence in dsRNA processing across insect orders

Future perspectives and research priorities

The research priorities implied by the gaps identified above are not primarily about discovering new molecular mechanisms but about closing the distance between laboratory demonstration and field deployment for pests outside the coleopteran group where the technology has already succeeded. Systematic, standardised comparison of candidate target genes within economically important lepidopteran and hemipteran pests, conducted under consistent delivery and dosage conditions rather than compiled after the fact from disparate published studies, would allow the field to distinguish genuinely recalcitrant species from species that have simply not yet been tested with an effective gene and delivery combination, a distinction the current literature, following Terenius *et al.* (2011)^[13], has only begun to make systematically.

Resistance management deserves comparable early investment rather than the retrospective treatment it received in the early years of Bt deployment. Given that Khajuria *et al.* (2018)^[9] traced dsRNA resistance in western corn rootworm to an uptake level mechanism, research examining whether uptake based resistance is likely to be shared across dsRNA traits targeting different genes through

the same entry pathway would directly inform whether pyramiding multiple dsRNA modes of action offers genuine redundancy or merely a false sense of redundancy against a shared resistance mechanism. Parallel investment in non-target risk assessment methodology, extending beyond the acute, closely related species testing that has dominated the literature to date, would strengthen the regulatory case for both host induced and spray induced platforms and would help distinguish cases where sequence specificity genuinely limits non-target exposure from cases where broader ecological pathways of exposure have simply not yet been examined. Finally, closing the cost gap for spray induced gene silencing will likely depend less on further formulation chemistry, an area already reasonably well populated by the work reviewed here, and more on production economics, including whether *in vitro* transcription or microbial fermentation platforms can be scaled to the volumes field application would require at a cost competitive with existing insecticide chemistries; without that economic case, spray induced gene silencing risks remaining a technically validated but commercially marginal platform regardless of further biological refinement.

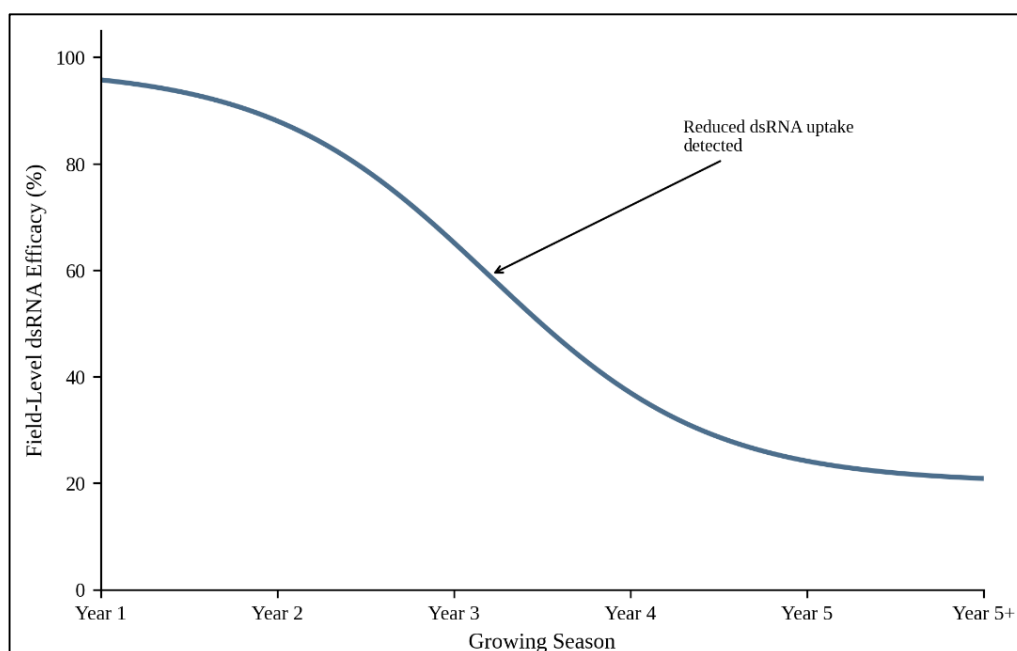


Fig 2: Conceptual trajectory of dsRNA efficacy in western corn rootworm populations over successive growing seasons under continuous selection pressure

Conclusion

RNA interference has earned its place in the insect pest management toolbox, but the evidence reviewed here does not support treating it as a broadly transferable technology in its current state. Its one substantial commercial success rests on a coleopteran pest whose biology happens to favour efficient dsRNA uptake and stability, and extending that success to lepidopteran, hemipteran and other economically damaging pest groups will require solving delivery and stability problems that are qualitatively different from, not simply smaller versions of, the problem already solved in corn rootworm. The early appearance of dsRNA resistance in rootworm populations should temper any assumption that RNA interference traits are inherently more durable than the chemical and *Bacillus thuringiensis* based tools they are meant to complement, and it argues for building resistance

management into future dsRNA trait deployment from the start rather than treating durability as a secondary concern. What the field most needs now is not a further demonstration that RNA interference can work under favourable conditions, a point already well established, but disciplined, comparative work that identifies where and why it fails under less favourable ones, and a realistic accounting of the production economics that will determine whether spray based and nanoparticle formulated platforms can ever compete on cost with the tools already in growers' hands. Progress on those fronts, more than any further elaboration of the core silencing pathway, will determine whether RNA interference becomes a genuinely general purpose pest management technology or remains, a decade and a half after its first field demonstrations, a solution tailored to a narrow set of coleopteran pests.

References

- Bachman PM, Bolognesi R, Moar WJ, Mueller GM, Paradise MS, Ramaseshadri P, *et al.* Characterization of the spectrum of insecticidal activity of a double-stranded RNA with targeted activity against *Diabrotica virgifera virgifera* LeConte. *Transgenic Research*. 2013;22(6):1207-1222.
- Baum JA, Bogaert T, Clinton W, Heck GR, Feldmann P, Ilagan O, *et al.* Control of coleopteran insect pests through RNA interference. *Nature Biotechnology*. 2007;25(11):1322-1326.
- Bolognesi R, Ramaseshadri P, Anderson J, Bachman P, Clinton W, Flannagan R, *et al.* Characterizing the mechanism of action of double-stranded RNA activity against *Diabrotica virgifera virgifera* LeConte. *PLOS ONE*. 2012;7(10):e47534.
- Christiaens O, Swevers L, Smagghe G. dsRNA degradation in the pea aphid (*Acyrtosiphon pisum*) associated with lack of response in RNAi feeding and injection assay. *Peptides*. 2014;53:307-314.
- Fire A, Xu S, Montgomery MK, Kostas SA, Driver SE, Mello CC. Potent and specific genetic interference by double-stranded RNA in *Caenorhabditis elegans*. *Nature*. 1998;391(6669):806-811.
- Head GP, Carroll MW, Evans SP, Rule DM, Willse AR, Clark TL, *et al.* Evaluation of SmartStax and SmartStax PRO maize against western corn rootworm and northern corn rootworm: Efficacy and resistance management. *Pest Management Science*. 2017;73(9):1883-1899.
- Huvenne H, Smagghe G. Mechanisms of dsRNA uptake in insects and potential of RNAi for pest control: A review. *Journal of Insect Physiology*. 2010;56(3):227-235.
- Joga MR, Zotti MJ, Smagghe G, Christiaens O. RNAi efficiency, systemic properties, and novel delivery methods for pest insect control: What we know so far. *Frontiers in Physiology*. 2016;7:553.
- Khajuria C, Ivashuta S, Wiggins E, Flagel L, Moar W, Pleau M, *et al.* Development and characterization of the first dsRNA-resistant insect population of *Diabrotica virgifera virgifera* LeConte. *PLOS ONE*. 2018;13(5):e0197059.
- Mao YB, Cai WJ, Wang JW, Hong GJ, Tao XY, Wang LJ, *et al.* Silencing a cotton bollworm P450 monooxygenase gene by plant-mediated RNAi impairs larval tolerance of gossypol. *Nature Biotechnology*. 2007;25(11):1307-1313.
- Price DRG, Gatehouse JA. RNAi-mediated crop protection against insects. *Trends in Biotechnology*. 2008;26(7):393-400.
- San Miguel K, Scott JG. The next generation of insecticides: dsRNA is stable as a foliar-applied insecticide. *Pest Management Science*. 2016;72(4):801-809.
- Terenius O, Papanicolaou A, Garbutt JS, Eleftherianos I, Huvenne H, Kanginakudru S, *et al.* RNA interference in Lepidoptera: An overview of successful and unsuccessful studies and implications for experimental design. *Journal of Insect Physiology*. 2011;57(2):231-245.
- Vogel E, Santos D, Mingels L, Verdonck TW, Vanden Broeck J. RNA interference in insects: Protecting beneficials while enhancing agricultural pest management. *Frontiers in Physiology*. 2019;9:1912.
- Whyard S, Singh AD, Wong S. Ingested double-stranded RNAs can act as species-specific insecticides. *Insect Biochemistry and Molecular Biology*. 2009;39(11):824-832.
- Zhu KY, Palli SR. Mechanisms, applications, and challenges of insect RNA interference. *Annual Review of Entomology*. 2020;65:293-311.
- Zotti M, dos Santos EA, Cagliari D, Christiaens O, Taning CNT, Smagghe G. RNA interference technology in crop protection against arthropod pests, pathogens and nematodes. *Pest Management Science*. 2018;74(6):1239-1250.