Trichome mimics: sprayable plant-based adhesives for crop protection against thrips

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Chapter 7

General Discussion

7.1 Introduction

For several decades, chemical pesticides have been one of the main tools to control pests and diseases in agriculture. However, the use of these chemicals comes with several negative aspects (e.g., hazards for human, animal and environmental health, and loss of effectiveness due to pest resistance) and is therefore not sustainable over the long term (Mahmood et al. 2016; Reitz et al. 2020). In search of greener pest control methods, this thesis aimed to evaluate the potential of plant-based adhesives made from vegetable oils to control one of the most severe global crop pests: western flower thrips (*Frankliniella occidentails*), the effects of spraying such adhesives on plant physiology, and the potential for using these adhesives alongside predatory arthropods.

The main questions addressed in this thesis were:

(1) Can we use plant-oil-based adhesives to physically trap thrips and to reduce their damage and reproduction?
(2) What are the local and systemic effects of plant-oil-based adhesive application on plant growth and metabolomic contents and in what way are such effects altered by thrips infestation?
(3) To what extent does the application of plant-oil-based adhesives affect the ability of predatory arthropods to control thrips populations?

To answer these questions, first, a literature review (chapter 2) was done to get an overview of how stickiness plays a role in plant defense against herbivory, to understand the mechanisms of how sticky plants trap insects, and to summarize to what extent plant-based sticky materials are already applied in agriculture for pest control. Then, several experimental bioassays were done, mainly using *Chrysanthemum* plants as a model system, to investigate the effectiveness of different types of sprayable plant-oil-based adhesives as a method to trap arthropod pests and reduce their performance (chapter 3, 4, 5, and 6), to measure the effects of these adhesives on plant physiology using GC-MS and NMR metabolomics techniques (chapter 4 and 5), and to assess the effects of these adhesives on the predation effectiveness of predatory arthropods, in this case on the predatory bug *Orius laevigatus* and predatory mite *Transeius montdorensis* (chapter 6).

The following paragraphs will now first discuss the findings of the studies in this thesis and their scientific, agricultural, and societal implications in more detail. Then, an outlook is given for future research that is still required for the application of plant-based adhesives in agriculture. At the end, a conclusion is given.

7.2 The potential of sticky plants, predators living on sticky plants, and plant-based adhesives for crop protection

From the review of the literature on sticky plants (chapter 2), it became clear that adhesiveness is a widespread and diverse form of plant defense against biotic and abiotic stressors and that there is a strong yet unrealized potential for utilizing the sticky defenses of plants, the predators that live on sticky plants, and nature-based sticky materials for crop protection. Many plants have evolved diverse surface structures and chemically diverse secretions including glandular trichomes and resinous exudates to deter and immobilize small arthropods, including herbivores such as thrips, aphids, and whiteflies (Narita et al. 2023; Popowski et al. 2024). These sticky traits often function in symbiosis with other organisms such as predatory arthropods that possess anti-stick adaptations (Romero et al. 2008; Wheeler and Krimmel 2015). The ecological relevance of stickiness as a plant trait suggests a strong potential for bioinspired applications in agriculture. By harnessing naturally adhesive materials, it may be possible to replicate the protective function of plant stickiness while reducing reliance on synthetic inputs. To an extent, promising developments are already being made on a small scale, particularly in the use of sticky plants as trap crops (Han et al. 2024), the predators of sticky plants as biocontrol agents (Nelson et al. 2019a, b), and plant-based materials as glues for sticky traps (Hansupalak et al. 2023; Wiroonpochit et al. 2024), as physiochemical pest trapping biopesticides (this thesis), and as carriers of botanicals and pesticides (Iqbal et al. 2022; Fang et al. 2023) However, many aspects of naturel stickiness remain underexplored. In the pursuit of the adaptation of stickiness as an integral aspect of crop protection, the use of plant-based sticky materials as a physiochemical pest control method for thrips was therefore further explored in this thesis.

7.3 Plant-based adhesives can trap thrips, but their effectiveness is still limited

Although the use of plant-based oils and plant-based adhesive coatings for crop protection is not new, this is the first time as far as we know that anyone has attempted to apply plant-oil-based adhesives substances directly on other plants than trees to function as a sticky trap for arthropod pests. Based on the overall results of the experiments in chapter 3, 4, 5 and 6 it can be concluded that plant-oil-based adhesives can be used to physically trap thrips and to reduce thrips damage and reproduction. However, the results also indicate that the ability of plant-oil-based adhesives to do so depends on multiple factors, including the type of oil used, the size of the individual droplets, and the level of coverage achieved.

The results from the filter paper and detached-leaf experiments (chapter 3) provide direct evidence that plant-oil-based adhesives can be an effective way to trap small arthropods such as thrips under controlled conditions. During experiments in Petri-dishes, thrips were consistently immobilized by droplets of adhesive, although it was clear that the capture rate depended strongly on the size of the droplets, indicating that a certain minimum size is required for successful thrips capture. In this way, high thrips capture rates of up to 94% were obtained. However, when adhesives were applied on the upper side of leaves of young *Chrysanthemum* plants that were placed in thrips-proof cylinders (chapters 4, 5 and 6), thrips capture rates were significantly lower, being almost at 0% for the more droplet-like adhesive solutions (named RGO and MIX in prior chapters) and at maximum 55 out of 1200 released adult thrips or 4.8% for the more fluid RGO-OLO prototypes. Contact area plays an important role in the trapping success of arthropods of various sizes by sticky plants (Gibson 1991). A part of the reason for the low capture rates by the droplet-like RGO and MIX adhesive solutions could therefore be that the achieved levels of coverage and the size distribution of the droplets were not optimal. Only the upper side of the leaf was coated, the leaf area was often not entirely covered despite repeated spraying, and most droplets were of small size, likely not having enough adhesive contact area on their own to restrain a thrips individual. The more fluid RGO-OLO prototype gave a more homogeneous coverage and this clearly helped to catch more thrips.

Assuming the adhesives stayed sticky enough to trap thrips for at least two days as seen during the Petri-dish experiments (chapter 3), it seems that other factors are limiting the ability of plant-based adhesives to effectively trap thrips.

In combination with the observation that thrips tend to prefer feeding on the bottom of the leaves of sprayed plants (see chapter 4 and 6), the low trapping rates suggests that in a more a complex plant environment where coverage is only partial, thrips avoid contact with the adhesives, possibly by navigating to the underside of the leaves or stems. In the plant assays with *Orius* bugs and predatory mites this was confirmed. Thrips and predators alike were mostly located on the underside of leaves of sprayed plants. From the literature we know that arthropod size and morphology (Voigt and Gorb 2010b) and arthropod behaviors, including foraging behavior, oviposition preferences (Rogge and Meyhöfer 2021; Mouratidis et al. 2024) and preferences for certain colors, odors, and glue types (Gillespie and Veron 1990; Van Tol et al. 2021), all can play a role in the success of adhesive materials to trap arthropods. Especially the strong odors of plant-derived oils frequently act as a deterrent and are often toxic to arthropods (Giuti et al. 2022; Kirk et al. 2021). Several of the oils used to formulate the plant-based adhesives in this thesis have been found to have repellent or other negative effects on arthropods, for example: linseed oil (Rajput et al. 2017), sunflower oil (Lachance and Grange 2014) and rice bran oil (Shaaya et al. 1997). In addition, in chapter 3 it was observed that the application of just the spraying solution, which contains other chemicals such as alginic acid (a gelling agent sourced from algae), F108 (a surfactant) and $CaCl_2$ also by itself reduced thrips damage This suggests that the effectiveness of the plant-based adhesives used in the studies of this thesis may (at least in part) be due to direct avoidance by thrips of the used materials.

Since trapping approaches rely on physical contact between pest and substrate and it is almost impossible to keep plants always fully covered, the results obtained in this thesis highlight a key limitation of pest trapping with adhesive substances as a stand-alone control mechanism and point to the importance of understanding insect behavior in three-dimensional plant environments. Nevertheless, the strong trapping effect observed in the Petri-dish experiments and the reductions in thrips damage and reproduction that were also found on sprayed plants support the potential for targeted applications in strategic locations such as on plant stems, on the outside of buds, to block tight spaces where thrips otherwise like to hide, or in crops where thrips behavior may be more predictable and avoidance is less possible.

7.4 Plant-oil-based adhesives come with side-effects but could be useful elicitors of plant innate chemical defenses.

Interestingly, even in the absence of high catch rates, the treatment of *Chrysanthemum* plants with plant-oil-based adhesives reduced thrips damage and reproduction. This suggests that other factors than adhesiveness alone play a role in the thrips suppression effects of plant-based adhesives. The plant assays and metabolomics profiling done in chapter 4 and 5 using GC-MS and ^{1}H NMR techniques revealed that the application of plant-oil-based adhesives affects the physiology of *Chrysanthemum* in multiple ways. While the total biomass of sprayed plants was not reduced on the short term, phytotoxic damage was observed (especially by the MIX formulation) and plant metabolomic changes were clearly induced in sprayed areas. These findings are to a large extent comparable with those of other studies that have shown that the application of plant oils may cause damage and affect plant chemistry (De Almeida et al. 2010; Abd-ElGawad et al. 2020; Verdeguer et al. 2020).

While changes in plant chemistry may have positive or negative effects on herbivores and on ultimate plant yield, visual damage is usually a negative aspect, especially when ornamental crops are involved. In *Chrysanthemum*, the older part of the plant is cut off during harvest (Van Iperen B.V., personal communications). Since the oily adhesive droplets are hard to remove from the leaf surface by rinsing with water (chapter 3), the application of such adhesives for thrips management in *Chrysanthemum* is likely limited to the early growth phase. Nevertheless, strong suppression of thrips populations during the early growth phase could be sufficient to ensure low pest pressure during the later growth stage when predatory arthropods and other IPM tools can be used for further control (Mouden et al. 2017). Since different plant species generally show different sensitivity to the application of different plant-based oils (Bainard et al. 2006), the potential range of crops that could benefit from plant-oil-based adhesives may therefore depend on the oil types used. Different formulations may be useful for different crops.

Unlike what was expected, systemic effects on the metabolome of newly grown plant parts were not found to be significant, which was also evident by unsprayed plant areas seemingly developing without further negative side effects. The application of natural materials to younger plant tissues generally leads to a stronger response than when old tissues are treated (van Dam et al. 2001; Köhler et al. 2015; Chen et al. 2018). Moreover, plant responses can be induced within minutes and tend to generally decline after several hours or a few days (Joo et al. 2017; Shulaev et al. 2008; Magalhães et al. 2018). The lack of systemic effects of the plant-based adhesives in our data were therefore likely due to measurements being done at later timepoints after a single application. To induce and maintain metabolomic changes throughout the plant, repeated applications may be needed throughout a growing season (Gatehouse 2002).

Furthermore, the observed metabolomic responses seemed to be independent of and showed overlap with those observed in thrips infested plants, suggesting that the presence of the adhesives and thrips infestation may induce similar metabolomic responses. While the exact mechanisms triggered by the application of plant-oil-based adhesives remain to be identified, some of the observed metabolite shifts such as increased levels of certain lipids and phenolic compounds suggest the activation of pathways involved in general plant defense against biotic and abiotic stress, likely through jasmonic acid (JA) or ethylene (ET) signaling, which are commonly activated by the application of natural materials to plants and by insect infestation (Atkinson and Urwin 2012; Khater 2012; Mithöfer et al. 2012; Qian et al. 2018). The induction of such plant defense pathways through the application of plant-based adhesives could be a useful tool in crop protection to improve crop resilience against pests and diseases. Considering that during experiments only a single application to the adaxial leaf side was done and that the commercial *Chrysanthemum* cultivar used in this study (Baltica) is highly susceptible to thrips and does not possess strong innate anti-herbivore chemical defenses (Leiss et al. 2009b), the studies in this thesis have likely not yet shown the full potential of using plant-based materials to induce plant innate defense responses. Metabolomics studies where multiple applications are done on crops with stronger innate defenses may provide further insights.

7.5 Integrating adhesive-based pest management with biocontrol

An important aspect surrounding the application of plant-based adhesives in crop protection is their combined effectiveness and compatibility with other IPM practices, including the use of biological control agents such as predatory arthropods. In chapter 6, the effects of the adhesive were tested on two important natural enemies of thrips: the minute pirate bug *Orius laevigatus* and predatory mite *Transeius montdorensis*. In our study, some predator deaths and seemingly repellent effects occurred on adhesive sprayed plants. The RGO-OLO adhesive trapped two out of 50 *O. laevigatus* individuals and the number of predatory mites roaming on sprayed plants was reduced by half. However, the results showed that both predators remained effective at reducing thrips populations in the presence of the adhesives. Moreover, the combination of predators and adhesives reduced thrips damage more for the RGO-OLO plant assay over using either method alone, indicating a potential for synergistic or additive effects. These findings support the use of adhesives alongside predatory arthropods as part of integrated pest management (IPM) strategies. However, it must be noted that this study is just a first step towards the assessment of the effect of plant-based adhesives on predatory arthropods. Our experimental design was quite simple and did not incorporate detailed behavioral studies or standardized tests for non-target effects such as repellence, toxicity, and reproduction. Predatory arthropods frequently fall victim to the adhesive substances of sticky plants (Romeis et al. 1999; Riddick and Simmons 2014) and biopesticides commonly show negative non-lethal effects on predators, also when overall effectiveness of combining methods does lead to reduced pest pressure (Guedes et al. 2024; Costa et al. 2025; Lisi et al. 2024; 2025).

In our experiments, overall predator survival was very low in all treatments, including in the control. Likely this was because no additional food source was provided. Since in greenhouse environments food sources are often used to increase predator survival (Messelink et al. 2009), the survival measurements taken during the plant assays may therefore not be representative of all field situations. In any case, the low survival due to food shortage as a strong factor makes it difficult to conclude whether the presence of the adhesives had non-lethal effects on predator survival. It would therefore be better to assess effects on predator survival sooner (say after 2-3 days) while providing a food source should this experiment be repeated.

In summary, based on the obtained data and the current literature, the use of plant-based adhesives alongside predatory arthropods may be a more viable option over the use of chemical pesticides but likely will still come with risks for said arthropods and potentially other non-target organisms. Before plant-based adhesives and predatory arthropods are implemented in practice, the potential other non-lethal effects on these beneficial insects should therefore be researched further.

7.6 Overall strengths and limitations of the research in this thesis

The research in this thesis combines both bioassay and metabolomic approaches to provide a comprehensive view of how adhesives affect plant-insect interactions. The use of detached-leaf and whole-plant assays allowed for a detailed understanding of how scale and context influence the effectiveness of plant-based adhesives. The incorporation of metabolomics tools in the plant assays provided novel insight into plant responses in reaction to simultaneous stress from to natural materials and herbivores that would otherwise have remained undetected. However, there are also limitations to acknowledge. The adhesives were tested under laboratory and semi-controlled conditions, which may not fully reflect the environmental complexity of field systems. Thrips populations and predator populations were artificially introduced at rather high initial densities, and the duration of the assays was relatively short. Under field conditions, abiotic factors such as watering from above, UV exposure, and plant growth dynamics may also potentially alter adhesive performance and lead to different outcomes. Furthermore, only three different types of adhesive formulation were tested in one crop and on one pest insect. Results from trials with other crops and pests may differ from those achieved with *Chrysanthemum* and *Frankliniella* *occidentalis*. Future work should address these limitations through field trials and by testing a range of adhesive formulations in a diversity of crop systems against multiple arthropod pests.

7.7 Broader implications of the use of plant-based adhesives and natural stickiness in agriculture

Plant-oil-based adhesives represent a promising and innovative approach to crop protection, offering several environmental, agronomic, and ecological advantages. One of the primary benefits is their presumable reduced toxicity. The plant oils used to create the plant-based adhesives are typically biodegradable and derived from renewable sources, making them a more nature friendly choice over synthetic pesticides (Lengai et al. 2020). Their use aligns with current efforts to reduce chemical inputs in agriculture and meets increasing consumer demand for safer, residue-free food. Because these adhesives act through physical entrapment, by stimulating plant innate defensive pathways, and likely via direct repellent and toxic effects, the risk of pest resistance development should also be smaller. This is an important advantage given the rapid evolution of resistance in thrips and other pests to conventional insecticides (Gao et al. 2012; Reitz et al. 2020). Additionally, the reduced non-target effects and potential compatibility of the adhesives with beneficial predatory arthropods such as *O. laevigatus* and predatory mites is a major strength. Other advantages include the ease of formulation and customizability of plant-based adhesives. The procedures to create the adhesives are not complex and the adhesives can likely be adapted to specific crop types, pests, or environmental conditions. Combinations with other control agents (e.g., botanicals, attractant pheromones) may also be possible for even more multi-functionality.

Despite these advantages, several limitations must be considered when assessing the practical application of plant-based adhesives in crop systems. Achieving consistent and effective coverage on complex plant surfaces, clogging during spraying, and degradation under field conditions could limit application and field efficacy. Optimization for different crops and environmental conditions, specialized spray equipment and specific application strategies will likely be needed. To maintain the induced effects of plant induced defensive pathways, likely multiple applications may be needed during a growing season. Furthermore, thrips and other pests may learn to avoid sticky surfaces or adapt their movement to minimize contact, reducing long-term efficacy. Under high pest pressures the adhesives may also not be sufficient unless combined with other control methods. In addition, while the induction of plant stress responses can have protective effects, the over-application or poor formulation of the adhesives may risk phytotoxicity or interfere with growth, photosynthesis and transpiration, particularly if adhesives block stomata or alter the leaf surface microclimate which the application of some horticultural oils is known to do (Baker 1970; Baudoin et al. 2006). Likely there are limitations as to which crops and agricultural systems are suitable. There is also a need to evaluate non-target effects more broadly. Although few adverse effects were observed in this thesis, plant-oil-based adhesives may inadvertently affect predatory arthropods and non-pest organisms such as pollinators and perhaps also affect soil microbial communities or pollute the environment, especially if applied indiscriminately. Finally, economic factors such as labor and production costs, scarcity of materials, shelf-life, consumer acceptance, marketability, and regulatory approval could pose hurdles to commercialization, especially if plant-based adhesives are to be scaled for use in large or open-field systems, which are common challenges for the adoption of biopesticides (Damalas and Koutroubas 2020; Isman 2020; Ngegba et al. 2022). While plant-based adhesives are full of potential, these challenges still need to be overcome before their large-scale application is feasible.

Regarding the agricultural potential of natural plant stickiness: breeding for increased stickiness in crops may be a feasible method to achieve increased plant resilience to pests (Tingey 1991; Nelson et al. 2019a) However, stickiness is a complex form of plant defense which in many crops is thought to be regulated by a range of different genes. While simple modifications can be made and re-introduction of sticky defenses may be feasible for crops with adhesively defended wild ancestor, insertion or severe alterations of such defenses in crops that innately do not have them is complicated (Glas et al. 2012). To fully harness the potential of the sticky defenses of plants, our understanding of the genetic architecture of sticky plants and our breeding technologies first will need to advance. The use of predators living on sticky plants and sticky plants as trap crops, while potentially very beneficial since these predators are commonly less affected by sticky plant surfaces (Krimmel and Pearse 2013), is also not straightforward. Especially how to attract and maintain sticky plant and predatory arthropod populations in our cropping systems or how to economically mass produce predatory arthropods for repeated releases are general challenges in biocontrol. Even if we succeed in mass production, stakeholders first need to learn how to effectively use these new biocontrol organisms, especially since plant stickiness may come with negative effects on beneficial and non-target arthropods, such as pollinators. Furthermore, since environmental factors seem to play a key role in determining the arthropod trapping success of sticky plants and nature-based materials alike, the greenhouse environment where the environment can be controlled to an extent may be the most favorable for application. The success of implementing natural stickiness and nature-based sticky materials as a form of crop protection outdoors will likely be determined by local climatic conditions and may be limited when these are highly variable.

7.8 Future research directions

Before plant-based adhesives can be applied in practice, more research is needed in several areas. First, the effectiveness of the current prototypes should be further assessed in greenhouse trials. This may initially be done over short periods before long term effects on yield are assessed. Adhesives made from different types of oils could be investigated in different doses and the effects of abiotic factors on the effectiveness over time could be further explored. Pairing these trials with different levels of coverage and more detailed behavioral investigations may be useful to better understand to what extent arthropods are able to avoid the adhesives. The use of different types of materials (e.g. polysaccharides) to create different types of adhesives may also be worthy of investigation. Furthermore, the long-term effects of repeated applications with adhesives on the plant metabolome, defensive pathways, photosynthesis and respiration could be further investigated with and without herbivores to gain an even deeper understanding of the effect of abiotic and biotic stress on plant physiology. Aside from testing on more pest species, predatory arthropods, an evaluation of the non-target effects on pollinators, non-target plants, other plant diseases such as fungi, and studies on the biodegradability of the plant-based adhesives and their effects on non-target microbial communities on plant surfaces and in the soil would contribute to gaining more information about their ecological safety. Preferably such trials should be done over a sufficiently long period and may include studies on non-lethal effects such as the behavior, fertility, longevity, and other aspects surrounding the arthropods, plants, and microbes in question.

7.9. Conclusion

Together, the findings presented in this thesis demonstrate that plant stickiness and plant-oil-based adhesives hold considerable potential as a tool for pest control. Initially inspired by the natural defense mechanisms of sticky plants, the adhesives were shown to physically entrap thrips under simplified conditions and to reduce damage and reproduction on whole plants even in the absence of high capture rates. Furthermore, the application of the adhesives induced chemical changes in the plant metabolome thought to be related to the plants anti-stress responses against herbivores, suggesting a mode of action that is both physical, and chemical in nature. These results contribute to our understanding of how physical traits and chemical signals interact in plant defense, providing a model for future investigations of the effects of simultaneous natural product application and herbivore infestation on crop physiology. The adhesives were furthermore found to be somewhat compatible with predatory arthropods, not having a negative impact on their thrips predation efficacy. This highlights the value of plant-based adhesives not only as standalone tools but as complementary components in integrated pest management systems. The findings of this thesis have important implications for the development of more sustainable pest control strategies. By bridging concepts from chemical ecology, plant physiology, and sustainable agriculture, this work contributes to a growing body of evidence supporting the use of ecologically informed, low-toxicity alternatives to chemical pesticides. Plant-based adhesives, especially when refined and field-tested, could offer a scalable and environmentally responsible solution for managing pest outbreaks in a changing agricultural landscape