REVIEW ARTICLE

Advances in insect biomonitoring for agriculture and forestry

The smell of infection: Disease surveillance in insects using volatile organic compounds

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Abstract

1. Insects play crucial roles in nearly every ecosystem and provide a wide array of ecosystem services. However, both managed and wild insect populations face threats from parasites and pathogens, which require surveillance to mitigate.

2. Current infectious disease surveillance methods for insects often involve invasive, time-consuming and occasionally destructive techniques, such as manual inspections and molecular detection.

3. Volatile organic compound (VOC) surveillance provides a real-time, accurate and non-invasive alternative for disease detection and has been well-established in humans and livestock.

4. Recent advances in sensor technology now allow for the development of in-field VOC surveillance devices. This review explores the need for disease surveillance in insects and highlights recent advances of using VOCs for this purpose, focusing on honey bees as an example.

5. We outline potential applications, challenges and future prospects of using VOCs for insect disease surveillance, providing examples of how this technology could be globally applied to mitigate the impacts of disease in a range of insect systems.

KEYWORDS
biomonitoring, chemical ecology, disease surveillance, insect disease, volatile organic compounds

INTRODUCTION

Outnumbering any other taxa in terms of species diversity, insects provide crucial ecosystem services as pollinators, decomposers, soil aerators and nutrient cyclers (Schowalter, 2013). They are critical food sources for various taxa including humans, and also include numerous pest species that cause significant global economic losses (Losey & Vaughan, 2006; Schowalter, 2013). Insects face threats from a diverse range of parasites and pathogens, further exacerbated by the intensive farming of insects for pollination and protein, putting key ecosystem services and global food security at risk (Manley et al., 2015; Mennerat et al., 2010). Yet, despite their importance, disease surveillance is mostly focused on insects that vector diseases (Kading

et al., 2018; Kalluri et al., 2007) and key pathogens in agricultural species (Lee et al., 2015). In particular, infections threaten apiculture (Forsgren, 2010; Genersch, 2010; Noël et al., 2020; Pasho et al., 2021), sericulture (Chopade et al., 2021) and insects cultured for food and feed (Eilenberg et al., 2015; Maciel-Vergara & Ros, 2017) used to meet a growing demand for protein (Specht et al., 2019).

Detection and analysis of volatile organic compounds (VOCs) offers a promising avenue for surveillance of insect diseases, providing an opportunity to develop an innovative approach to non-invasive surveillance. VOCs serve as the chemical language of communication and thus are commonly emitted by insects (Ali & Morgan, 1990). Advances in analytical techniques have resulted in rapid detection and high sensitivity (as low as 1 part per trillion) sufficient to detect

changes in the VOC signatures of individuals (Liu et al., 2012; Misra, 2021).

This review explores the need for disease surveillance, current knowledge and suitable approaches for VOC disease surveillance in insects. Throughout, we use the western honey bee (*Apis mellifera*) as an example, which, with respect to VOC disease surveillance, is the most widely researched of all insect species, to date. This review seeks to explore the potential applications, challenges and future prospects of utilizing VOCs as a diagnostic tool for infectious disease surveillance in insects, enabling effective management strategies.

WHY MONITOR INFECTION IN INSECTS?

Around 35% of all global food production benefits from insect pollination, with an estimated value of €153 billion (Gallai et al., 2009; Klein et al., 2007; McGregor, 1976). Managed insects, such as honey (*Apis* spp.) and mason bees (*Osmia* spp.), play a crucial role in pollination, especially in monocultures with lower native bee diversity (Vides-Borrell et al., 2019).

Honey bees, integral to pollination, host a diverse array of parasites and pathogens that directly and indirectly lead to colony collapse (Pasho et al., 2021). Six of these are 'listed diseases' by the World Organization for Animal Health (WOAH), defined as those that could cause serious impact on global health and/or adversely affect wildlife conservation (WOAH, 2023), including Acarapisosis (*Acarapis woodi*), American foulbrood (*Paenibacillus larvae*, AFB), European foulbrood (*Melissococcus plutonius*, EFB), Varroosis (*Varroa destructor*), Small hive beetle (*Aethina tumida*) and Tropilaelaps mite (*Tropilaelaps* spp.). Migratory beekeeping, that is, seasonally transporting hives between different crops, is a major contributor to global parasite dispersal that has sparked debates over the potential ban of this practice to curb the spread of emerging parasites (Martínez-López et al., 2022; Schäfer et al., 2019). Similarly, the importation and international trade of pollinators, such as bumble bees, often introduces parasites and pathogens that threaten native bees (Figueroa et al., 2023; Graystock et al., 2013).

Beyond pollination services, insects can be farmed for the products that they produce, such as domestic silk moths (*Bombyx mori*) for sericulture, which benefits economies worldwide by generating income for farmers through silk and mulberry plant (*Morus* spp.) production (Ssemugenze et al., 2021; Van Huis, 2020). Insect farming also includes the practice of raising insects as a protein source, and is expanding in attempts to improve future food security (Van Huis, 2020). The international trade of insects for food and feed has seen substantial growth, with major producers like Thailand, France, South Africa, China, Canada and the United States contributing to a projected market value of $16.39 billion USD by 2032 (Rowe, 2020). Major insect taxa already used in mass edible insect farming include Coleoptera (*Tenebrio molitor*, mealworm), Orthoptera (*Acheta domesticus*, house cricket), Lepidoptera (domestic silk moth), *Galleria mellonella* (greater wax moth) and Diptera (*Hermetia illucens*, black soldier fly) (Van Huis et al., 2013). However, intensive insect farming,

whether for food sources or farmed products, faces a myriad of parasites and pathogens impacting their survival, reproduction and behaviour, which could have cascading effects in ecosystems and threaten food security.

Insect farming comprises dense collections of beehives or large insect colonies, which come with the risk of disease outbreaks (see Eilenberg et al., 2015, for review, Mennerat et al., 2010). For example, densoviruses are associated with high mortalities in commercial *T. molitor* farms (Armién et al., 2023). The same pathogen caused such severe mortality in cricket farming that suppliers went into bankruptcy (Szelei et al., 2011; Weissman et al., 2012). Fungal and viral pathogens, causing diseases such as grasserie (Baculoviridae), muscardine (*Beauveria* spp.) and Pebrine (*Nosema bombycis*), increase mortality and decrease silk production in sericulture (Chopade et al., 2021). Many pathogens/parasites infect multiple orders of insect, and could impact both native and managed insect populations through spillover events into other arthropods (Manley et al., 2015; Nanetti et al., 2021). Therefore, effective disease surveillance in insects is not just vital for agriculture and insect farming, but for conserving arthropods in general. Furthermore, many insects themselves vector devastating diseases, causing agricultural losses by transmitting diseases to plants (Butter, 2018), livestock (Narladkar, 2018) and humans (Asenso-Okyere et al., 2011). Detecting the pathogens they harbour as early as possible is vital to reducing the damage caused by vector-borne diseases (Dórea et al., 2016; Parnell et al., 2017).

TRADITIONAL DISEASE SURVEILLANCE IN INSECTS

Traditionally, disease surveillance involves visually inspecting insects for symptoms of disease and/or mortality (Chopade et al., 2021; FAO, 2021). For example, detecting pebrine disease in domestic silk moths relies on manual inspections of moths, larvae and eggs (Chopade et al., 2021). However, manual inspections are labour-intensive, impractical for large-scale applications and are challenging to perform reliably due to the need for specific expertise in identifying infections due to the similarities in symptoms between diseases (Chopade et al., 2021). Moreover, relying on visual inspection alone has limitations, as by the time clinical symptoms become apparent, it is often too late to treat, meaning infected colonies must be destroyed, as observed in American foulbrood infection in honey bees (Locke et al., 2019). Therefore, early detection of sub-clinical symptoms is crucial for minimizing losses during outbreaks (Locke et al., 2019).

Molecular techniques, such as PCR, offer a potential solution for early detection, but their effectiveness for surveillance can come at a cost if the pathogen requires destructive sampling for detection, which could impact yield (Evans et al., 2013; Maciel-Vergara & Ros, 2017). Non-destructive molecular screening can be achieved using faecal sampling by placing individuals in containers until defecation occurs before returning them to the colony (Evans et al., 2013). However, this non-destructive approach will only detect those pathogens that are faecal–oral transmitted, and only if they are being shed

in the faeces at the time of sampling. It should be noted that non-destructive does not equal non-invasive, as faecal sampling can involve the disturbance of a colony. Disturbance during winter, particularly in apiculture, is potentially harmful due to the risk of cold stress (FAO, 2021). While non-invasive and non-destructive molecular screening of dead individuals is possible, the reliability of detection depends on the samples being fresh; RNA, for example, degrades rapidly after death, which can lead to false-negative results in the case of some viruses (Evans et al., 2013). Therefore, there is a pressing need to develop non-invasive methods that are effective for large-scale in-field disease surveillance of insects.

NON-INVASIVE DISEASE SURVEILLANCE

Non-invasive surveillance of disease has received much attention in apiculture with the advent of precision beekeeping and smart monitoring of hives. Various metrics, such as temperature, video, weight, humidity and sound, have been employed to assess the state of the colony, including forager activity, nectar flow and swarming (Meikle & Holst, 2015; Zacepins et al., 2015). While these metrics offer insights into colony health, they have limitations as an indirect marker for disease. For instance, honey bee infections influence colony temperature through the social fever response, which is detectable using temperature loggers (Goblirsch et al., 2020). However, these changes could also indicate responses to general stress, immune stimulation or hypermetabolism, resulting from artificial feeding with sucrose (Goblirsch et al., 2020; Nieh et al., 2006). VOC surveillance is advantageous in this regard, as VOC emissions are directly linked to changes in metabolism (Calcagnile et al., 2019; Gaude et al., 2019), which may act as more accurate measures of infection, either through signalling changes in the hosts metabolism in response to the infection or by detecting metabolites produced by the microbe itself. Consequently, VOC surveillance provides a promising avenue for disease surveillance.

WHAT ARE VOCs AND HOW ARE THEY MONITORED?

VOCs are defined as carbon-based chemicals abundant in the air above a sample (i.e. insects), known as the headspace, due to their high vapour pressure at room temperature (Cicolella, 2008; Turner, 2016). Both parasites/pathogens and host naturally produce VOCs as metabolic by-products or signalling molecules that may serve as biomarkers of infection (Shirasu & Touhara, 2011). In the case of insects, capturing the headspace of an entire colony could allow for real-time, accurate and non-invasive detection of infection, a capability not achievable with traditional surveillance techniques.

Actively sampling headspace VOCs involves pumping gas over an adsorbent, while passive sampling relies on diffusion (Kumar & Víden, 2007). Following collection of headspace VOCs, a gas chromatograph (GC) coupled with a detector, such as a mass spectrometer (MS), is employed to separate, identify and quantify the VOCs in the sample – specific VOCs can then, in theory, be identified as bio-markers of disease (Figure 1a). For in-field applications, highly selective semiconductor sensors, such as metal oxide semiconductor (MOS) sensors, could be utilized to detect target VOCs (Schütze et al., 2017) (Figure 1b). As gases interact with the metal oxides present, the conductivity of the sensor increases and an electrical circuit can convert that change in conductivity into a signal that indicates the gas concentration (Bąk et al., 2023). These sensors are cost-effective and portable that can be highly sensitive to specific VOCs, making them particularly well suited to in-field mass applications (Schütze et al., 2017). If key VOCs are associated with a given disease, linking sensor technology with smartphone technology could provide a real-time and non-invasive disease detection tool (Figure 1b).

DISEASE SURVEILLANCE USING VOCs

In humans, VOC surveillance is an established field for detecting respiratory, urinary tract and gastrointestinal infections (Sethi et al., 2013), and was utilized for SARS CoV-2 surveillance during the 2021 pandemic (Sharma et al., 2023). VOC surveillance has been extensively studied for detecting the insects themselves, especially those assessed to be pests, for example, wood borer beetles (*Semanotus bifasciatus* and *Phloeosinus auebi*) (Wang et al., 2020), stink bugs (*Chinavia hilaris* and *Nezara viridula*) (Henderson et al., 2010), flour and grain beetles (*Tribolium castaneum* and *Cryptolestes ferrugineus*, respectively) (Senthilkumar et al., 2012) and bark beetles (Scolytinae spp.) (Amin et al., 2013; Berg et al., 2013; Paczkowski et al., 2021). To the best of our knowledge, the only insect system that VOC disease surveillance has been applied to is apiculture. This proof of concept in honey bees, however, provides valuable insight for expanding disease surveillance to other insect species.

Previous empirical evidence suggests disease-indicating VOC profiles can either contain compounds specific to the etiological agent or be represented by changes in compounds commonly emitted by honey bees due to the presence of a pathogen/parasite, or potentially a combination of both scenarios. American foulbrood (AFB) infection in vivo, for example, is characterized by unique emissions of propionic acid, valeric acid, 2,5-dimethyl pyrazine, acetamide, isobutyramide, methyl 3-methyl-2-oxopentanoate and 2-nonanone (Bikaun et al., 2022; Lee et al., 2020), alongside a range of volatile sulphides and acids (Gochnauer & Margetts, 1981; Gochnauer & Shearer, 1981). These biomarkers of AFB infection are recognized as metabolites released by the bacteria genus *Paenibacillus*, during feeding, amino acid metabolism and as compounds produced to suppress the growth of competing microbes (Bikaun et al., 2022; Rybakova et al., 2016; Verginer et al., 2010). Similarly, chalkbrood (*Ascosphaera apis*) infection (a fungal brood parasite) emits over 10 VOCs only found during infection, consisting of several lactones, phenethyl alcohol and its derivatives (Finstrom et al., 2023; Swanson et al., 2009). These are metabolites known to be commonly produced by other fungal species (Finstrom et al., 2023; Romero-Guido et al., 2011). By contrast, some
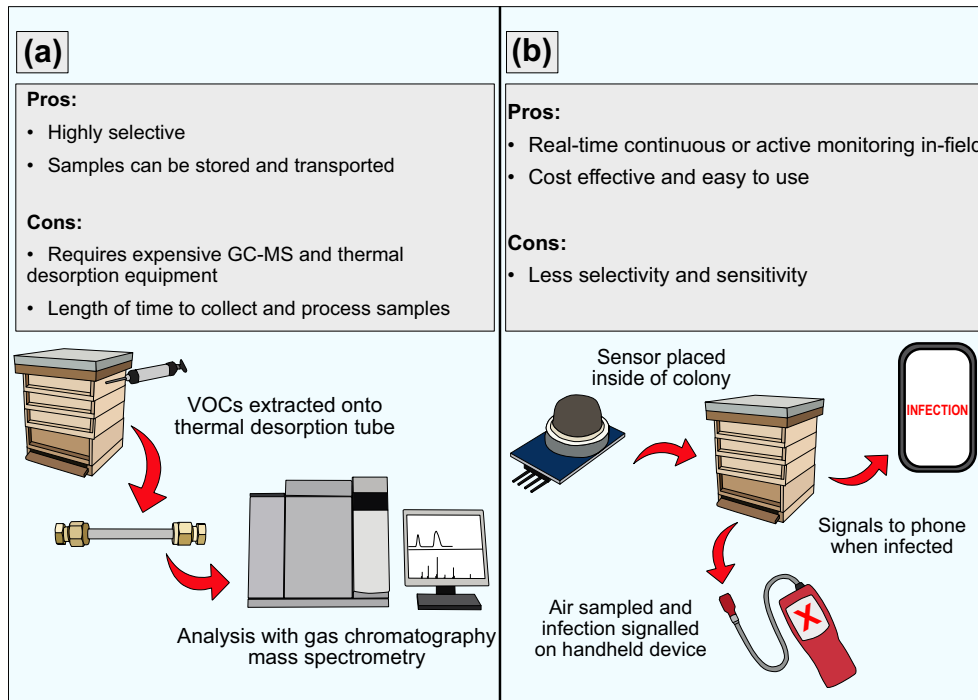
(a)

Pros:
- Highly selective
- Samples can be stored and transported

Cons:
- Requires expensive GC-MS and thermal desorption equipment
- Length of time to collect and process samples

VOCs extracted onto thermal desorption tube

Analysis with gas chromatography mass spectrometry

(b)

Pros:
- Real-time continuous or active monitoring in-field
- Cost effective and easy to use

Cons:
- Less selectivity and sensitivity

Sensor placed inside of colony

INFECTION

Signals to phone when infected

Air sampled and infection signalled on handheld device

FIGURE 1 (a) Current methods for analysing VOCs using gas chromatography and thermal desorption tubes and mass spectrometry. (b) Potential future applications for detecting disease with VOCs. Handheld devices could be used to identify disease in-field. Gas sensors could signal alerts to phones, allowing for real-time remote surveillance.

VOCs associated with infection are compounds whose concentrations may vary in response to infection but are also released by healthy colonies, meaning they are not specific to infection. For example, levels of β-ocimene, a commonly emitted brood pheromone used in social regulation (Maisonnasse et al., 2010), are elevated in dead and Varroa infested bees (McAfee et al., 2017; Mondet et al., 2016), whereas reduced concentrations are linked with AFB infection (Bikaun et al., 2022, Lee et al., 2020). Additionally, brood parasitized by *V. destructor* emit pentadecene, which is believed to trigger the removal of infested brood from the hive (Nazzi et al., 2004). While this compound may signal infection, it is also released by unhealthy brood not necessarily infected, which are signalling for removal (Wagoner et al., 2020).

Developing sensors specific to VOCs that are associated directly with an etiological agent could clearly offer effective surveillance. VOCs that are non-specific, however, present challenges. Concentrations of VOCs may vary with the natural fluctuations in colony populations over the year (Seeley, 2014). Changes in the number of individuals would therefore make it necessary to design sensors that can consistently adapt to varying population densities. Furthermore, infection and mortality can alter VOC production in conflicting ways, further complicating the surveillance of non-specific VOC biomarkers. For example, β-ocimene concentrations are lower in live bees infected with AFB but also increase when brood die from any cause (Lee et al., 2020; McAfee et al., 2017). As AFB infection progresses and leads to an increased number of dead bees in a colony, the reduced β-ocimene concentration associated with AFB infection in live bees may be masked by higher emissions in dead bees from both AFB-induced death, and uninfected dead bees that have died from other

causes. An approach to monitoring VOC disease biomarkers could be to examine entire VOC profiles before and after infection. This method aims to identify shifts in VOC profiles, rather than single compounds, and focus on subsets of those VOCs that remain diagnostic of the disease. Sensor arrays sensitive to both host- and pathogen-derived VOCs could be used to monitor for diagnostic patterns of VOCs that could be distinguished from natural fluctuations.

Therefore, VOC disease surveillance can be achieved by (1) detecting unique VOC biomarkers associated with an infection, or (2) detecting infection-induced changes in concentrations host-derived VOCs, such as brood pheromones. Monitoring VOCs associated directly with the etiological agent is advantageous as they are not only simpler to detect in-field, but biomarkers linked to pathogen metabolism are particularly interesting as disease surveillance targets as they could act as indicators of infection across multiple host species. However, currently, the research focusing on pathogens with broad host ranges is lacking; AFB and other bee diseases (Varroa and chalkbrood) only infect one host species, limiting cross-species inference. Only one study has investigated the VOCs associated with a multi-host pathogen, namely Sacbrood virus (SBV), which infects both social and solitary bees, as well as Lepidoptera (*Galleria mellonela*), Coleoptera (*Aethina tumida*) and wasps (*Vespula vulgaris* and *Polistes metricus*) (Bikaun et al., 2022; Gisder & Genersch, 2017; Manley et al., 2015). Sacbrood virus itself, however, has not been associated with unique VOC biomarkers, rather emissions are associated with compounds released by honey bees during decomposition (Bikaun et al., 2022), meaning disease-induced mortality cannot be easily discerned from other drivers.

There are multiple honey bee viruses that pose threats as emerging diseases to wild pollinators (Manley et al., 2015); however, in the main, the VOCs associated with these infections have not been studied. Furthermore, VOCs of many common infections of honey bees, such as nosemosis (*Vairimorpha* spp.) and European foulbrood (*M. plutonius*), as well as infections of other insect systems have not, to date, been identified. It is unknown whether, in the face of disease, these etiological agents and/or the host emit VOC biomarkers. If unique VOC biomarkers of an etiological agent are not present, detecting changes in host VOCs from pre-post infection could provide biomarkers. However, these would have to be identified on individual host-pathogen cases, as they would likely consist of pheromones or other species-specific VOCs. These biomarkers may prove more challenging to define and adapt to detection with sensors due to their susceptibility to alteration by confounding factors, such as natural colony fluctuations.

Other detectable changes in insect chemical profiles

While there is a current lack of data focusing on VOC markers for disease in any insects other than honey bees, research has shown that other chemical profiles, specifically cuticular hydrocarbons (CHCs) shift in response to infection. CHCs are non-volatile compounds comprising long-chain alkanes and alkenes, serving essential functions in insect physiology, particularly in moisture retention and nest-mate recognition (Drijfhout et al., 2009). Detectable alterations in CHC profiles have been observed in multiple ant species, for example, *Megaponera analis* infected by soil pathogens (*Burkholderia* sp. and *Pseudomonas aeruginosa*; Frank et al., 2023), *Leptothorax nylanderi* parasitized by tapeworms (*Anomotaenia brevis*; Trabalon et al., 2000) and *Lasius neglectus* pupae infected by fungi (Metarhizium brunneum; Pull et al., 2018). Entomopathogenic fungi, such as *Beuvaria bassiana*, target and breakdown the CHCs of multiple insect orders, which can directly change the CHC profiles during infection (Pedrini et al., 2007; Pedrini et al., 2013). Similarly, distinct CHC profiles have also been observed in paper wasps (*Polistes ferreri*) parasitized by *Xenos* sp. (Torres et al., 2016).

CHCs tend not to be volatile, and thus are not ideal for passive field monitoring of infection, but their modulation in response to infection suggests a potential parallel shift in VOCs could occur. This supposition is supported in studies of honey bees where various infections that induce changes in CHC profiles were also associated with alterations in VOCs (Lee et al., 2020; Wagoner et al., 2019; Wagoner et al., 2020; Wagoner et al., 2021). Therefore, it is likely that VOCs also shift in response to infection in insects other than honey bees, warranting further investigation.

The future of insect disease surveillance

Currently, insect VOC disease surveillance requires access to expensive GC–MS equipment capable of processing VOC samples, followed by specialist knowledge to interpret the outputs produced (Figure 1a). However, once the VOC biomarkers associated with a given disease is known, it can lead to in-field sensors that form multi-sensor arrays or 'E-noses' that react to the identified VOCs (Bąk et al., 2023). Ongoing trials in apiculture have been exploring the in-field application of insect VOC disease surveillance using MOS sensors. Laboratory and field trials have successfully identified *V. destructor* infestations and promising results have also been seen in efforts to detect AFB infection (Bąk et al., 2020; Bąk et al., 2022; König, 2021; Szczurek et al., 2019). While sensors focused on the most important known and prevalent diseases offer valuable in-field surveillance, novel and emerging diseases will be missed by this approach. E-noses, however, also offer some promise for surveillance here, as they could be capable of detecting an unhealthy colony. DL-pantolactone, for example, is associated with decomposing honey bee larvae (Bikaun et al., 2022) and could serve as a biomarker of poor health. Although not a pathogen/parasite-specific VOC, sensors detecting high DL-pantolactone concentrations could indicate elevated larval mortality, serving as a warning system for novel emerging infectious diseases.

The food industry has already developed wireless, portable sensors capable of signalling food spoilage using VOCs (Ma et al., 2018; Xing et al., 2023), and similar devices could be developed for insect disease surveillance. These could offer cost-effective, continuous, non-invasive surveillance of diseases in insect systems. As sensor technology advances, integrating VOC disease surveillance into insect farming seems plausible, enabling sensors to relay colony health directly to an app or database (Figure 1b). This approach would eliminate the need for manual inspections, ensuring early detection and reducing losses (Zacepins et al., 2015; Figure 1b). Furthermore, VOC disease surveillance could extend to handheld sensors (Figure 1b), actively sampling in the field to screen for insect diseases during transportation and importation. With the rise in international insect trade, this screening could facilitate safe trade by detecting insect diseases at borders.

Sensors also have potential for widespread application to disease surveillance in agriculture. Insect pollination is vital for agriculture and agroforestry, with the majority of global crops susceptible to production losses if pollinators are limited (Klein et al., 2007). Both wild and managed pollinators play crucial roles in pollinating a wide range of crops globally (Klein et al., 2007). For certain crops, wild pollinators can be just as, and often more effective for pollination than honey bees (Esquivel et al., 2020; Garibaldi et al., 2013). Furthermore, the presence of wild pollinators on crops, such as sunflowers (*Helianthus annuus*), enhances honey bee pollination efficiency up to fivefold (Greenleaf & Kremen, 2006), and has also been seen to increase honey bee movements between crops, enhancing pollination effectiveness (Brittain et al., 2013). However, the emergence of pollinator pathogens in managed pollinator populations, such as the honey bee viruses capable of infecting multiple orders of insect pollinators (Manley et al., 2015) and *Crithidia bombi* spillover in bumble bees, poses potential dangers to wild pollinator populations and is thought to be a contributing factor for wild pollinator declines (Otterstatter & Thomson, 2008).

Flower sharing is a major avenue of disease transmission among both managed and unmanaged pollinators (Graystock et al., 2015; Manley et al., 2015). As infected pollinators drink from the same nectar source, rub against and defecate on flowers, they deposit pathogens that can survive and transmit orally to the next pollinator that visits the flower (Graystock et al., 2015). Bumblebees have demonstrated the ability to avoid flowers heavily contaminated with a pathogen, suggesting there must be a detectable signal associated with pathogen contamination (Fouks & Lattorff, 2011). Therefore, it seems likely that VOC biomarkers of pathogens could be detectable on flowers. Recent studies have shown that nectar microbes can influence the VOC profile of flowers, attracting pollinators to enhance their own dispersal (Crowley-Gall et al., 2021; Sobhy & Berry, 2024). Should this phenomenon extend to pollinator pathogens, VOC surveillance could be used to pinpoint hotspots of pollinator pathogens. A similar technique is already developing in agricultural and forestry settings for detecting crop diseases, where E-nose technologies have been used to diagnose diseases caused by phytopathogenic microbes (Wilson, 2013). Similar methods could be applied to monitor for pollinator pathogens harboured on flowers by collecting headspace samples from flowers in agricultural settings. Beekeepers could use these data to avoid transporting managed colonies to contaminated areas, thereby reducing the distribution of pathogens between cropland caused by migratory beekeeping (Martínez-López et al., 2022). Additionally, as wild pollinator diversity is evidently beneficial to crop yields (Brittain et al., 2013; Esquivel et al., 2020; Garibaldi et al., 2013; Greenleaf & Kremen, 2006), farmers could be encouraged to survey crops for pollinator pathogens with handheld gas sensors (Figure 1b) by sampling flower heads for VOCs. Control measures could then be applied, such as the timed application of fungicides or introducing microbial antagonists of the detected pathogen (Heydari & Pessarakli, 2010). This kind of VOC disease surveillance and control could reduce the impact of pathogen spillover on wild pollinator diversity in croplands, thereby enhancing pollination effectiveness and crop yields.

Another interesting potential application for insect VOC disease surveillance in agriculture is to track the effectiveness of entomopathogenic biocontrol. The use of entomopathogens to control pest insects has long been established (Lacey et al., 2015). Entomopathogenic fungi, such as *Beauveria bassiana*, are widely applied to control for a range of pests including various wasp, ant and bark beetle pest species (Singh et al., 2017). One setback with the commercialization and development of entomopathogens is assessing their effectiveness in-field, as their persistence and efficacy vary among insect species (Singh et al., 2017). VOC disease surveillance could be employed in these systems to quantify the efficacy of entomopathogens applied to large pest infestations. Pest species are often characterized by phases of extremely high population densities, as seen in the epidemic phase of bark beetle outbreaks (Hlásny et al., 2021). During these phases, the volume of VOCs emitted by the pests could be detected by gas sensors placed in the field (Figure 1b). Host-specific VOC biomarkers would allow for the identification of how effectively the biocontrol is impacting the target species.

CONCLUSIONS

Insects, vital for ecosystem services and global food security, face threats from infections impacting agriculture and insect farming. VOCs are an exciting, novel method for non-invasive surveillance of infectious diseases in insects. Integrating VOC surveillance into insect farming and international trade could revolutionize disease surveillance by facilitating swift treatment and minimizing losses, with potential applications extending broadly to agriculture and agroforestry. In the future, handheld sensors could be used to monitor for pathogens in the field, allowing for rapid measures to be implemented to control pollinator pathogen levels in agricultural settings. This would enhance both managed and wild pollinator populations. Additionally, VOC disease surveillance may have applications in monitoring the efficacy of entomopathogenic biocontrols. However, while the future looks promising for honey bee disease surveillance, it is important to acknowledge that many pathogens remain understudied. Specifically, there is a critical knowledge gap concerning which VOCs are associated with infection in other insect systems. Addressing this gap is crucial before sensor development can progress effectively in these systems. By deciphering the volatile signatures emitted during infection, we are poised to unlock a new era in the surveillance and management of insect diseases.

AUTHOR CONTRIBUTIONS

Ayman Asiri: Conceptualization; funding acquisition; writing – original draft. **Sarah E. Perkins:** Conceptualization; funding acquisition; supervision; writing – review and editing. **Carsten T. Müller:** Conceptualization; funding acquisition; supervision; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The author declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

No data were used or generated for this manuscript.

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