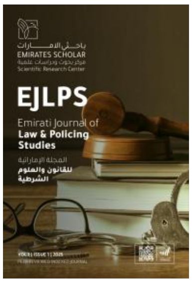

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The Role of Honeybees in Forensic Evidence Detection: Review of Their Application in Environmental and Criminal Investigations

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ABSTRACT

Honeybees (*Apis mellifera*) have emerged as a promising tool in forensic science because of their distinctive biological and behavioral characteristics. This review investigates the role of honeybees in the detection of forensic evidence, emphasizing their use in criminal and environmental investigations. Honeybees have exceptional olfactory abilities that can be utilized to identify a diverse array of substances, such as illegal drugs and explosives, through associative learning and conditioning techniques. Furthermore, their sensitivity to ecological changes makes them effective bioindicators, capable of reflecting the levels of environmental health and contamination. The incorporation of honeybees into forensic entomology offers a unique method of ecological monitoring and crime scene analysis. Nevertheless, to improve their efficacy in forensic applications, it is necessary to address obstacles such as ethical considerations, legal admissibility of evidence, and behavioral variability. This review emphasizes the necessity of standardized methodologies and interdisciplinary collaboration to capitalize on the distinctive characteristics of honeybees in forensic science, thereby facilitating the development of innovative detection strategies and enhanced environmental monitoring.

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1. Introduction

The purpose of forensic pathology (FP) is to facilitate the timely and accurate administration of justice. An efficient and dependable medicolegal system is advantageous to societies in general, not merely the judicial system. To prevent crime by establishing means of detection and punishment and accidents such as substance abuse or road traffic accidents, a properly functioning medicolegal system supports crime detection and investigation and presents certified expert witnesses in court. FP is a medical specialty that is a hybrid of law and medicine (Ketsekioulafis et al., 2024; Madea, 2014).

The study of insects and other arthropods to assist in criminal investigations and legal proceedings is the primary focus of forensic entomology, a specialized branch of forensic science (Byrd & Tomberlin, 2019). Science is predicated on the premise that necrophagous insects, which consume carcasses or carrion, exhibit predictable life cycles and behaviors. These patterns can provide critical information regarding the time of death, the location of the crime site, potential suspect associations, and other significant details. The body commences to decompose immediately following death, which attracts insects that are attracted to the volatile chemicals released from the carrion. These insects are actively involved in the decomposition process (Amendt et al., 2007; Anderson et al., 2000). The objective of forensic entomology is to ascertain the post-mortem interval, which is the duration of time that a corpse has been exposed to the environment (Matuszewski, 2021). The principle that insects invade dead corpses in a predictable sequence is the foundation of forensic entomology. Colonization commences shortly after death and progresses through various stages because of the consumption of the remains by a variety of insect species. Eggs, larvae, pupae, and adults are among the developmental phases that insects undergo. Depending on factors such as temperature, humidity, and geographic location, the duration of each stage can vary significantly (Bhuyan et al., n.d.; Fremdt & Amendt, 2014).

Honeybees (Apis mellifera) are endowed with extraordinary olfactory abilities. They employ these senses to forage for abundant food sources in a quick and efficient manner in their natural environment. Furthermore, it has been learnt that bees are trained to forage for food using a variety of methods. Bees can recognize a recognized food source by utilizing visual stimuli and olfactory or fragrance detection (Giurfa, 2007; Menzel, 2014). Bees can be trained to detect and forage for odors that are introduced to them as a food source through reward-based conditioning, as evidenced by research conducted over the past few decades. Additional research into the ability of bees to search for a diverse array of objects after being trained has been prompted by the success of this conditioning such as bodies, explosives, and drugs, as well as their use in forensics (Couvillon et al., 2015; Filipi et al., 2022; Leitch et al., 2013; Rodacy et al., 2002; Schott et al., 2015). The objective of this review is to investigate the efficacy of honeybees in the context of forensic evidence.

2. Honeybee Biology and Behavior

The Western honeybee, Apis mellifera, is the most extensively studied because of its global distribution and ecological significance. Honeybees (Apis spp.) are eusocial insects. Whitfield et al. (2006) and other genetic research have demonstrated the substantial diversity of species and subspecies, which are influenced by adaptations to local climates and disease resistance, which in turn influence their behavior and survival. For instance, the Eastern honeybee, Apis cerana, demonstrates unique foraging strategies and parasite defenses in comparison to A. mellifera, thereby emphasizing the significance of evolutionary pressures in species differentiation (Ben et al., 2016; Johnson, 2023; Whitfield et al., 2006; Winston, 1991).

A single reproductive queen, sterile female workers, and male drones comprise honeybee colonies, which operate under a highly organized caste system (Mortensen et al., 2015). The waggle dance, which encodes the distance and direction of food sources, and pheromones such as the queen mandibular pheromone for colony cohesion are used to facilitate communication (Bortolotti & Costa, 2014). Seeley (2010) conducted research that illustrated how this system enhances foraging efficiency, allowing colonies to dynamically adjust to resource availability. Particularly in environments that are subject to fluctuations, these mechanisms are indispensable for the preservation of colony health (Seeley, 2010).

Honeybees, which are keystone pollinators, depend on visual and olfactory cues to navigate floral resources, with foraging ranges that extend from 3 to 5 km². Insights into ecosystem health are provided by their behavior: changes in pollen diversity or foraging patterns can indicate habitat degradation or floral changes caused by climate change (Couvillon et al., 2014; Mishra et al., 2023; Ozanne & Hales, 2004). Klein et al. (2007) conducted research that documented the correlation between altered honeybee foraging activity and declines in pollinator-dependent plants, underscoring their function as bioindicators (Burkle et al., 2013; Klein et al., 2007). Furthermore, the capacity of honeybees to accumulate environmental toxins (e.g., pesticides) in hive products further establishes them as valuable tools for the monitoring of ecological contamination (Botías et al., 2015; Chauzat et al., 2011; Zavrtnik et al., 2024).

3. Forensic Applications of Honeybees

3.1. Honeybees as Bioindicators

The sensitivity of honeybees to ecological changes has led to their recognition as effective bioindicators of environmental health. Research suggests that the presence and behavior of honeybee populations can serve as a proxy for evaluating the integrity of ecosystems, as they can reflect the levels of pollutants in their environment (Catalano et al., 2024; K. E. Smith et al., 2019). For example, research has shown that honeybees accumulate neonicotinoids and other agrochemicals, which serves as forensic evidence of illegal pesticide use and localized environmental contamination (Ward et al., 2022). Additionally, controlled experiments have investigated their capacity to identify chemical contaminants, explosives, and drugs, underscoring their potential for use in forensic investigations (Ćosović Bajić, 2014).

3.2. Collection Methods for Forensic Analysis

Forensic entomology is increasingly incorporating honeybees into crime scene investigations to evaluate environmental conditions and determine the time of death. Various methods are employed to collect honeybees and related materials for forensic analysis, such as direct observation, trapping, and the use of specialized collection kits. Dahlem, G. A. (2022) described standardized protocols for the collection and analysis of bees in forensic contexts (Rivers & Dahlem, 2022; K. G. V Smith, 1986).

Techniques such as passive air sampling using hives, honey sampling, and pollen analysis on bees have improved the reliability of evidence while minimizing disturbance to bee populations and their habitats (Ilić et al., 2024). In recent years, the identification of contaminants has been enhanced by the use of pollen traps, hive product analysis (including honey, beeswax, and propolis), and non-destructive sampling methods. This finding is particularly significant as it highlights the improved sensitivity in detecting airborne toxins achieved through the application of passive sampling techniques, thereby enhancing the overall effectiveness of environmental monitoring strategies (Murcia-Morales et al., 2023).

3.3. Honeybee Associative Learning and Conditioning

The remarkable capacity of honeybees to be trained for a variety of tasks, such as visual discrimination and Odor detection Fig 1 (B), has been the subject of numerous studies. A single study demonstrated that honeybees can be trained to identify human faces by employing a combination of pre-training on basic discrimination tasks, punishment for errors with bitter solutions, extensive differential conditioning, and consistent stimulus presentation. The bees achieved performance levels that were significantly higher than chance by successfully learning to discriminate between target and distractor faces and recognizing the target face from novel distractors (Dyer et al., 2005). An additional investigation concentrated on the training of honeybees to identify illicit substances such as heroin, cocaine, amphetamines, and cannabis. Researchers evaluated the antennal responses and learning capabilities of bees using automated training chambers and portable electroantennographic (EAG) devices, demonstrating their potential as biosensors for illegal substances (Schott et al., 2015). Furthermore, research has been conducted to train honeybees to identify explosives such as TNT, DNT, and RDX. This research demonstrated that bees can be trained to distinguish between various Odors and selectively target specific explosive-related compounds. The deployment and training process required only a few hours (Rodacy et al., 2002) Fig 2 (A,D). Finally, a hybrid bio-hybrid system was created to detect landmines by utilizing trained honeybees. This system integrated classical conditioning techniques with advanced tracking methods that utilized UAV-mounted cameras and computer vision to identify areas where bees spent more time, thereby indicating the presence of landmines (Filipi et al., 2022). One study demonstrated that honeybees can be trained to associate chemical compounds found in decaying tissues with a high-quality food source by introducing these compounds into a sugar solution. Field trials showed that trained honeybees exhibited increased foraging activity around scented feeders and carrion placed at varying distances from the hive, suggesting their potential use in locating vertebrate remains for forensic investigations (Morice et al., 2020). Another study focused on stingless bees in Brazilian dry forests and found that these species are naturally attracted to animal carcasses, playing a role in decomposition processes. This behavior has implications for forensic entomology, as it provides insights into insect succession patterns on carrion and how these insects contribute to estimating post-mortem intervals in tropical ecosystems (Santos et al., 2014). These studies collectively underscore the cognitive capabilities and adaptability of honeybees in the context of undertaking intricate detection tasks.

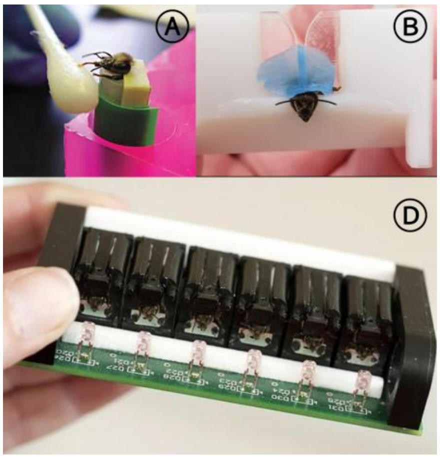

Figure 1 *A- Training honeybees to detect explosives (©Leroy N. Sanchez, Los Alamos National Lab), B- Testing honeybees 'ability to detect different infinitesimal odors (©Saha Lab), D- Training honeybees to detect explosives (©LOUISE MURRAY / REX FEATURES) Image quality: 200 dpi*

3.3.1 The sensitive sniffer bee technology (Police bees)

Honeybees have an exceptional olfactory system that allows them to detect and differentiate a diverse array of odorants with remarkable specificity and sensitivity **Fig 2**. Research has shown that classical conditioning techniques, such as the Proboscis Extension Reflex (PER), can be employed to train bees to recognize target Odors, including explosives, disease biomarkers, and environmental contaminants (Hadagali & Suan, 2017) **Table 1**. This ability is attributed to the highly developed antennal lobe and mushroom body neural structures, which facilitate the formation of robust olfactory memories and the acquisition of olfactory skills (Kerk & Chua, 2016). Additionally, research has demonstrated that honeybees are capable of identifying volatile organic compounds that are linked to lung cancer and other diseases. This demonstrates their potential for use in medical diagnostics through non-invasive scent analysis (Sahoo et al., 2025). Furthermore, the development of bio-inspired gas sensors for environmental monitoring and security applications has been facilitated by research into the neurophysiological basis of bee olfaction, which has provided valuable insights into the processing and integration of Odor information within the bee brain (Bromenshenk et al., 2015).

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Table 1: Conditioning Protocols in Honeybee Training Assays

Type of training	Application	Analysis of results	Ref.
Landmine detection	sample: Carniolan bees (Apis mellifera carnica) Control groups: 66 testing boxes of 10 × 10 m have been set up according to IMAS 09.42. Teste groups: Two boxes with partially visible landmines. Application: Targets were composed of a 20 cm diameter Petri dish with odor of raw military TNT covered with soil from surrounding, on the top of the soil feeder made of 10 cm diameter Petri dish with glass, filled with light sugar solution, was placed.	The training features two detection methods: passive sampling and active searching, both of which use honeybees as biosensors. Use the active search method with honeybee colonies conditioned to search for explosive vapors during foraging flight, UAV-mounted cameras to monitor free-flying honeybees, and video analysis to detect honeybees and build a spatial map of honeybee detections. Short preparation time, low costs, the ability to scan a large area in a short time without direct contact with landmines.	(Filipi et al., 2022)
Locating land mines	Training objective: Bee density was measured over the full mine field, with a scanning lidar system. Control area: The lidar scanned over an 83-m-long mine-free control area to the 44-m × 24-m active test area Application: Use syrup with 2,4-DNT to condition the bees to hunt for land mines. Measurement: Each 10-ns laser pulse was sampled 109 times per second	A lidar map of bee density shows good correlation with maps of chemical plume strength and bee density determined by visual and video counts. Laboratory measurements show that the depolarization ratio of scattered light is near zero for bee wings and up to 30% for bee bodies.	(Shaw et al., 2005)
Detect explosives	Sample: The targets consist of TNT, DNT, and RDX odor. Sample Control: Targets blanks (i.e. contain only sugar water). Training: One colony of honeybees was trained to detect 2,4-DNT.	The bees that were trained to detect the DNT essentially targeted only the feeders containing the DNT odor. The blanks and targets contaminated with TNT and RDX were largely ignored. Probability of Detection of DNT targets by bees at SwRI was 98.7%	(Rodacy et al., 2002)
Detection of Illicit Drugs	Sample: Honeybees (Apis mellifera) Sample Control: Used males (2-5 days old) European grapevine moth (Lobesia botrana), Second-instar larvae Madagascar hissing cockroach (Gromphadorhina portentosa) Drugs used: Heroin, cocaine, amphetamine and cannabis. Scent Detection Tool: A portable electroantennographic (EAG) device was used to measure how the insects' antennae reacted (via electric signals) to drug scents.	Honeybees responded strongly and consistently to pure heroin and cocaine, even at very low concentrations. Cockroaches and moths showed inconsistent or weak responses. Conditioning Success: Trained honeybees learned to avoid the scent of heroin after conditioning.	(Schott et al., 2015)

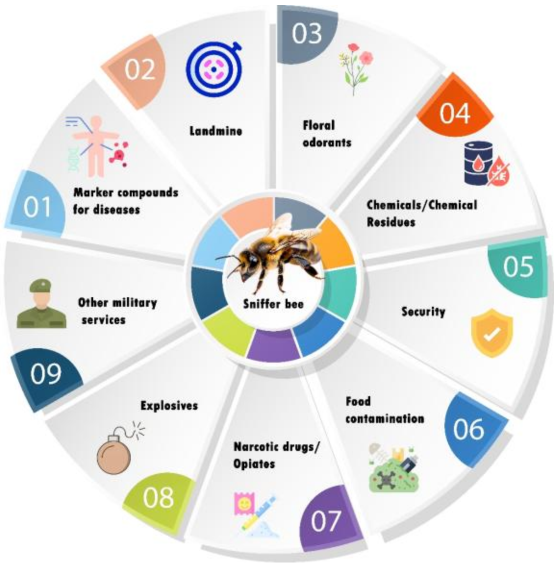

Figure 2 Utilization of sniffer bee technology across multiple domains as a biological sensor (Hadagali & Suan, 2017) *Image quality: 300 dpi*

4. Chemical Analysis

4.1 Pollen Analysis Techniques

Melissopalynology, or pollen analysis, is a critical forensic tool that entails the examination of pollen grains that honeybees collect from their environment. The pollen that honeybees collect is a reflection of the floral diversity in the surrounding area, as they forage over vast areas (up to 3-5 km²) (Huyop et al., 2024). This pollen is then incorporated into hive products, including honey and beeswax. Forensic scientists can reconstruct past environmental conditions, determine the geographical origin of hive products, and identify exposure to specific plants including toxic or illegal crops by analyzing these pollen grains (Wiltshire, 2016). Furthermore, pollen profiles function as environmental fingerprints, revealing seasonal and regional variations in flora (Milne et al., 2004). They can also be used to link suspects, victims, or evidence to specific crime scenes (Alotaibi et al., 2020).

The precision of pollen identification is improved using advanced analytical techniques. Molecular methods, including DNA barcoding and metabarcoding, facilitate high-resolution species identification, while light microscopy and scanning electron microscopy (SEM) facilitate detailed morphological examination (Bell et al., 2016, 2023) For example, research has shown that the sequencing of DNA extracted from pollen in honey can accurately identify plant species, making it a potent tool for forensic geolocation (Miller Coyle, 2025) **Table 2**. With these methodologies, pollen analysis becomes a dependable and adaptable method for forensic investigations, providing valuable information regarding environmental contamination, geographical provenance, and evidentiary connections.

4.2 Isotope Analysis in Forensics

Isotopic analysis of honey and beeswax offers valuable insights into the origin and movement of bees by exploiting regional variations in stable isotopes of carbon ($\delta^{13}C$), nitrogen ($\delta^{15}N$), and hydrogen (δ^2H) that are influenced by climate, soil, and water sources (Khatun et al., 2024). For example, $\delta^{13}C$ ratios can differentiate between C3 and C4 plants, whereas δ^2H is indicative of local precipitation patterns (Valappil et al., 2022). This method is particularly advantageous in forensic applications, such as the identification of adulteration in honey and the tracking of illegal trade routes, to ensure its authenticity.

4.3 Contaminants and Residue Identification

Honeybees are highly susceptible to environmental toxins and serve as effective bioindicators for a variety of pollutants, such as neonicotinoids, organophosphates, and pyrethroids (Ruvolo-Takasusuki et al., 2015). As a result of their foraging behavior and close interaction with the environment, they also function as bioaccumulators of contaminants, including pharmaceuticals, heavy metals, persistent organic pollutants (POPs), and illicit substances. These compounds can be retained in hive products such as honey and beeswax, providing long-term chemical records of environmental exposure and having particular value in cases involving environmental crimes, such as illegal dumping or pesticide misuse (Hassona & El-Wahed, 2023).

Various analytical techniques, such as gas chromatography-mass spectrometry (GC-MS), liquid chromatography-tandem mass spectrometry (LC-MS/MS), and enzyme-linked

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immunosorbent assays (ELISAs), are employed to detect and quantify these residues (Almeida et al., 2020). For example, the forensic relevance of hive-derived samples has been increasingly demonstrated by the use of neonicotinoid pesticides in honey as evidence in cases of environmental violations and the association of traces of explosives or narcotics in beeswax with clandestine laboratories or drug storage sites (Ćosović Bajić, 2014; Zafeiraki et al., 2022; Zhang et al., 2024) **Table 2**. Bullock et al. (2020) have also investigated innovative, non-invasive monitoring methods, such as silicone wristbands that are placed inside hives to passively collect contaminant data over time (Bullock et al., 2020). This approach enhances surveillance capabilities without disrupting colony health. Collectively, these methodologies emphasize the indispensable function of honeybees and hive products in forensic investigations, regulatory enforcement, and environmental monitoring.

Table 2 Analytical Techniques with Validation Metrics in Bee-Based Forensic Studies

Analytical method	Detection Limits	Quantification Ranges	Applications in Forensic Contexts	Ref.
DNA barcoding	Pollen DNA Recovery: DNA can be recovered from single pollen grains. Pine (Pinus) pollen DNA remains detectable on cotton clothing for ≥14 days. Pollen Preservation: Pollen grains resist chemical/mechanical degradation and persist for years to millions of years in geological contexts. Survives extreme conditions: Identifiable after 30 min at 400°C (tulip/lily/daffodil pollen).	Traditional Microscopy: Focuses on relative abundance (%) of pollen types in assemblages (e.g., crime scene vs. suspect samples). DNA Metabarcoding (HTS): Enables high-throughput sequencing of pollen mixtures without prior separation.	Crime Scene Linking: Pollen on clothing/shoes ties suspects to locations. Geographic Sourcing: Proves origin of illicit goods. Victim/Scene Identification: Pollen "fingerprints" reconstruct victim movement.	(Alotaibi et al., 2020)
LC-MS/MS and ic-ELISA	IMI (imidacloprid): 0.003 ng/mL in honey. ACE (acetamiprid): 0.40 ng/mL in honey. Sensitivity: IC50 values for neonicotinoids ranged from 0.01 to 7.31 ng/mL, with the highest sensitivity for IMI, IMZ (imidaclothiz), and CLO (clothianidin).	IMI: 0.007 ng/mL. ACE: 0.99 ng/mL.	Residue Tracking: Identified neonicotinoid residues (IMI, ACE, CLO, THI, IMZ) in 59.4% of Chinese commercial honey (95/160 batches), with regional variability (highest in South China). Ecological Forensics: Bee Toxicity Risk: Imidacloprid and clothianidin posed acute risks to bees (Risk Quotient > 1), supporting forensic investigations into colony collapses. Key Forensic Implications: Evidence for Regulatory Violations: Residue levels (e.g., IMI at 0.57 µg/kg) were below EU limits but could inform compliance investigations.	(Zhang et al., 2024)

5. Legal Considerations

The incorporation of honeybee-based forensic evidence into legal frameworks necessitates a strict adherence to ethical integrity, admissibility, and judicial precedents. In order for insect-derived evidence to be admissible in court, it must meet the fundamental legal criteria of scientific validity, reliability, and relevance, as outlined in standards such as the Daubert Rule or Frye Standard (Amendt et al., 2007, 2015). The admissibility of evidence derived from honeybees, such as contamination levels in hive products or behaviorally conditioned responses, remains less established and requires further judicial scrutiny, despite the fact that forensic entomology has gained increasing recognition in legal contexts, particularly in the estimation of post-mortem intervals through the analysis of necrophagous insect development (ROXANA, A.P.; KARLA, C.; CLAUDIU, I.N.; LUCIAN, 2025).

In practice, courts frequently depend on expert testimony to interpret intricate entomological data. For instance, Proteins analyses in bee honey may substantiate allegations of environmental contamination (Bilandžić et al., 2011; John Hollis, 2022); however, this is contingent upon the presentation of findings by qualified experts, the quantification of error rates, and the peer-review of methodologies. Consequently, the scientific basis of this evidence must be defensible and robust in a courtroom setting.

The application of forensic entomology is also significantly influenced by ethical considerations. Despite the fact that honeybees are not protected under vertebrate animal welfare laws, their ecological importance requires responsible handling during forensic sampling (Tomberlin et al., 2011). Non-invasive or minimally disruptive collection techniques should be prioritized in order to reduce the impact on colony health and biodiversity(Shaw et al., 2010). Additionally, it is imperative that researchers and practitioners refrain from exaggerating the conclusions that can be drawn from entomological observations, particularly when making direct connections between human activities and bee behavior or hive contamination (Amendt et al., 2011). It is imperative to preserve scientific credibility and establish judicial trust by ensuring transparency through the clear documentation of experimental design, calibration of detection systems, and replication of results (Amendt et al., 2007).

The judiciary's willingness to accept well-supported insect-related data is demonstrated by historical precedents, despite the fact that there is limited direct case law involving honeybee-derived evidence. For example, Benecke 1998 mention six cases forensic entomology played a critical role in challenging the timeline of death by utilizing maggot developmental stages (Benecke, 1998). Similarly, beekeepers have successfully pursued legal action against agrochemical companies in environmental litigation, citing pesticide residues detected in hive materials as key evidence in losses attributed to neonicotinoid exposure (Loewen, 2018). Advocate General Kokott's Opinion in Case C-514/19 Union des industries de la protection des plantes v. Premier ministre and Others, delivered on 4 June 2020, addressed the compatibility of emergency national measures restricting neonicotinoids with EU law, specifically Regulation (EU) No 1107/2009 on the placing of plant protection products on the market. The case examined the legality of these measures in relation to the protection of bees, the obligation of sincere cooperation among Member States, and the notification requirements pursuant to Directive (EU) 2015/1535 regarding technical regulations and information society services. The European Commission's protective measures were also taken into account by the Advocate General (Leone, 2022)(Lawfulness of an Emergency Measure - Neonicotinoids - Protection of Bees - Notification of Concerns, 2020). As the field of forensic entomology continues to develop, legal systems must also adapt to accommodate these developments within the confines of ethical responsibility and evidentiary rules.

6. Challenges and Limitations

In forensic investigations, the use of honeybees presents several limits and challenges. The variability in honeybee behavior and environmental conditions is a substantial obstacle that can affect their detection capabilities. Olfactory sensitivity and foraging patterns can be influenced by factors such as temperature, humidity, and local flora, which may result in inconsistent results in various contexts (Gebremedhn et al., 2014; Soares et al., 2021).

In addition, the training protocols for honeybees, although promising, necessitate standardized methodologies to guarantee reliability and replicability in a variety of forensic applications. In real-world scenarios, the deployment of bees may be complicated by the time-sensitive nature of the conditioning process to detect specific Odors, which can be influenced by the bees' prior experiences.

The challenges are also posed by ethical considerations. Honeybees are not protected under vertebrate welfare laws; however, their function as critical pollinators requires responsible handling during forensic sampling to reduce ecological damage. In addition, the legal admissibility of honeybee-derived evidence in court is not yet fully established, necessitating the rigorous validation of scientific methodologies to satisfy judicial standards.

Finally, the integration of honeybees into forensic science requires interdisciplinary collaboration among entomologists, forensic scientists, and legal experts to manage the intricacies of evidence interpretation, thereby guaranteeing that the results are effectively communicated within legal frameworks.

7. Conclusion

Honeybees are a novel and valuable resource in the field of forensic science, with a wide range of applications, including the detection of explosives and drugs and the monitoring of environmental contamination. They are versatile in both criminal and ecological investigations due to their capacity to function as bioindicators, biosensors, and environmental samplers. Honeybees can be trained and employed to identify volatile organic compounds that are linked to illegal substances, landmines, and decomposing remains by employing advanced analytical methodologies and associative learning. Additionally, traditional forensic methods are supplemented by forensic palynology and isotopic analysis of hive products, which offer dependable geolocation and chronological insights. Nevertheless, there are substantial obstacles to the integration of honeybee-based forensic tools into mainstream practice. In order to achieve widespread acceptance, it is imperative to address methodological inconsistencies, validate results under legal standards, and ensure ecological sustainability. Future research should prioritize the development of standardized protocols, the enhancement of detection specificity, and the promotion of interdisciplinary collaboration. Honeybees exhibit significant potential as an environmentally friendly and scientifically robust element of contemporary forensic investigation, if they are subject to rigorous regulation and ongoing innovation.

References

Almeida, M. O., Oloris, S. C. S., Faria, V. H. F., Ribeiro, M. C. M., Cantini, D. M., & Soto-Blanco, B. (2020). Optimization of method for pesticide detection in honey by using liquid and gas chromatography coupled with mass spectrometric detection. *Foods*, *9*(10), 1368.

Alotaibi, S. S., Sayed, S. M., Alosaimi, M., Alharthi, R., Banjar, A., Abdulqader, N., & Alhamed, R. (2020). Pollen molecular biology: Applications in the forensic palynology and future prospects: A review. *Saudi Journal of Biological Sciences*, *27*(5), 1185-1190.

Amendt, J., Anderson, G., Campobasso, C., Dadour, I., Gaudry, E., Hall, M., Moretti, T., Sukontason, K., & Villet, M. (2015). *Standard Practices* (pp. 381-398). https://doi.org/10.1201/b18156-33

Amendt, J., Campobasso, C. P., Gaudry, E., Reiter, C., LeBlanc, H. N., & JR Hall, M. (2007). Best practice in forensic entomology—standards and guidelines. *International Journal of Legal Medicine*, *121*, 90-104.

Amendt, J., Richards, C. S., Campobasso, C. Pietro, Zehner, R., & Hall, M. J. R. (2011). Forensic entomology: applications and limitations. *Forensic Science, Medicine, and Pathology*, *7*, 379-392.

Anderson, G. S., Byrd, J. H., & Castner, J. L. (2000). *Insect succession on carrion and its relationship to determining time of death*. Byrd and Castner (Eds.). Forensic Entomology: The Utility of Arthropods in ….

Bell, K. L., Burgess, K. S., Okamoto, K. C., Aranda, R., & Brosi, B. J. (2016). Review and future prospects for DNA barcoding methods in forensic palynology. *Forensic Science International: Genetics*, *21*, 110-116.

Bell, K. L., Turo, K. J., Lowe, A., Nota, K., Keller, A., Encinas-Viso, F., Parducci, L., Richardson, R. T., Leggett, R. M., & Brosi, B. J. (2023). Plants, pollinators and their interactions under global ecological change: The role of pollen DNA metabarcoding. *Molecular Ecology*, *32*(23), 6345-6362.

Ben, G., Hill, K., & Walter, T. (2016). *The Role of Honey Bees as Pollinators in Natural Areas*.

Benecke, M. (1998). Six forensic entomology cases: description and commentary. *Journal of Forensic Sciences*, *43*(4), 797-805.

Bhuyan, P. R., Borah, B. K., Rajkumari, P., Borah, N., Bora, B., & Chaya, S. (n.d.). *Forensic entomology: Unraveling the secrets of insect evidence*.

Bilandžić, N., Đokić, M., Sedak, M., Kolanović, B. S., Varenina, I., Končurat, A., & Rudan, N. (2011). Determination of trace elements in Croatian floral honey originating from different regions. *Food Chemistry*, *128*(4), 1160-1164.

Bortolotti, L., & Costa, C. (2014). Chemical communication in the honey bee society. *Neurobiology of Chemical Communication*.

Botías, C., David, A., Horwood, J., Abdul-Sada, A., Nicholls, E., Hill, E., & Goulson, D. (2015). Neonicotinoid residues in wildflowers, a potential route of chronic exposure for bees. *Environmental Science & Technology*, *49*(21), 12731-12740.

Bromenshenk, J. J., Henderson, C. B., Seccomb, R. A., Welch, P. M., Debnam, S. E., & Firth, D. R. (2015). Bees as biosensors: chemosensory ability, honey bee monitoring systems, and emergent sensor technologies derived from the pollinator syndrome. *Biosensors*, *5*(4), 678-711.

Bullock, E. J., Schafsnitz, A. M., Wang, C. H., Broadrup, R. L., Macherone, A., Mayack, C., & White, H. K. (2020). Silicone wristbands as passive samplers in honey bee hives. *Veterinary Sciences*, *7*(3), 86.

Burkle, L. A., Marlin, J. C., & Knight, T. M. (2013). Plant-pollinator interactions over 120 years: loss of species, co-occurrence, and function. *Science*, *339*(6127), 1611-1615.

Byrd, J. H., & Tomberlin, J. K. (2019). *Forensic entomology: the utility of arthropods in legal investigations*. CRC press.

Catalano, P., Della Sala, F., Cavaliere, M., Caputo, C., Pecoraro, D., Crispino, G., Lettera, S., Caioni, G., Esposito, M., & Verre, A. (2024). Use of honey bees and hive products as bioindicators to assess environmental contamination in targeted areas of the campania region (Italy). *Animals*, *14*(10), 1446.

Chauzat, M., Martel, A., Cougoule, N., Porta, P., Lachaize, J., Zeggane, S., Aubert, M., Carpentier, P., & Faucon, J. (2011). An assessment of honeybee colony matrices, Apis mellifera (Hymenoptera: Apidae) to monitor pesticide presence in continental France. *Environmental Toxicology and Chemistry*, *30*(1), 103-111.

Ćosović Bajić, S. (2014). Analysis of the possibility of utalization of honey bees in explosive detection. *Polytechnic and Design*, *2*(1), 58-63.

Couvillon, M. J., Al Toufailia, H., Butterfield, T. M., Schrell, F., Ratnieks, F. L. W., & Schürch, R. (2015). Caffeinated Forage Tricks Honeybees into Increasing Foraging and Recruitment Behaviors. *Current Biology*, *25*(21), 2815-2818. https://doi.org/https://doi.org/10.1016/j.cub.2015.08.052

Couvillon, M. J., Schürch, R., & Ratnieks, F. L. W. (2014). Waggle dance distances as integrative indicators of seasonal foraging challenges. *PloS One*, *9*(4), e93495.

Dyer, A. G., Neumeyer, C., & Chittka, L. (2005). Honeybee (Apis mellifera) vision can discriminate between and recognise images of human faces. *Journal of Experimental Biology*, *208*(24), 4709-4714.

Filipi, J., Stojnić, V., Muštra, M., Gillanders, R. N., Jovanović, V., Gajić, S., Turnbull, G. A., Babić, Z., Kezić, N., & Risojević, V. (2022). Honeybee-based biohybrid system for landmine detection. *Science of the Total Environment*, *803*, 150041.

Fremdt, H., & Amendt, J. (2014). Species composition of forensically important blow flies (Diptera: Calliphoridae) and flesh flies (Diptera: Sarcophagidae) through space and time. *Forensic Science International*, *236*, 1-9.

Gebremedhn, H., Tadesse, A., & Belay, T. (2014). Relating climatic factors to foraging behavior of honeybees (Apis mellifera) during blooming period of Guizotia abyssinica (LF). *Livestock Research for Rural Development*, *26*(4), 2-7.

Giurfa, M. (2007). Behavioral and neural analysis of associative learning in the honeybee: a taste from the magic well. *Journal of Comparative Physiology A*, *193*(8), 801-824.

Hadagali, M. D., & Suan, C. L. (2017). Advancement of sensitive sniffer bee technology. *TrAC Trends in Analytical Chemistry*, *97*, 153-158.

Hassona, N. M., & El-Wahed, A. A. A. (2023). Heavy metal concentrations of beeswax (Apis mellifera L.) at different ages. *Bulletin of Environmental Contamination and Toxicology*, *111*(3), 26.

Huyop, F., Wahab, R. A., Sujana, I. G. A., Antara, N. S., & Gunam, I. B. W. (2024). Using pollen DNA metabarcoding to trace the geographical and botanical origin of honey from Karangasem, Indonesia. *Heliyon*, *10*(12).

Ilić, D., Brkić, B., & Sekulić, M. T. (2024). Biomonitoring: Developing a beehive air volatiles profile as an indicator of environmental contamination using a sustainable in-field technique. *Sustainability*, *16*(5), 1713.

John Hollis. (2022). *Honey bees and their honey could be a big help in solving police cases*. https://www.gmu.edu/news/2022-01/honey-bees-and-their-honey-could-be-big-help-solving-police-cases

Johnson, B. R. (2023). *Honey bee biology*.

Kerk, W. C., & Chua, L. S. (2016). Sniffer bees as a good alternative for the current sniffing technology. *Biointerface Research in Applied Chemistry*, *6*(4).

Ketsekioulafis, I., Filandrianos, G., Katsos, K., Thomas, K., Spiliopoulou, C., Stamou, G., & Sakelliadis, E. I. (2024). *Artificial Intelligence in Forensic Sciences: A Systematic Review of Past and Current Applications and Future Perspectives. Cureus, 16 (9), e70363*.

Khatun, M. A., Yoshimura, J., Yoshida, M., Suzuki, Y., Huque, R., Kelly, S. D., & Munshi, M. K. (2024). Isotopic characteristics (δ13C, δ15N, and δ18O) of honey from Bangladesh retail markets: Investigating sugar manipulation, botanical and geographical authentication. *Food Chemistry*, *435*, 137612.

Klein, A.-M., Vaissière, B. E., Cane, J. H., Steffan-Dewenter, I., Cunningham, S. A., Kremen, C., & Tscharntke, T. (2007). Importance of pollinators in changing landscapes for world crops. *Proceedings of the Royal Society B: Biological Sciences*, *274*(1608), 303-313.

Lawfulness of an Emergency Measure - Neonicotinoids - Protection of Bees - Notification of Concerns, Pub. L. No. 1107/2009 (2020).

Leitch, O., Anderson, A., Kirkbride, K. P., & Lennard, C. (2013). Biological organisms as volatile compound detectors: A review. *Forensic Science International*, *232*(1-3), 92-103.

Leone, L. (2022). Pesticides in Court: Ruling on the use of neonicotinoids in EU Member States. *BioLaw Journal*, *2022*(4), 321-354.

Loewen, C. (2018, February 26). Beekeeper's $20K class-action suit goes ahead as evidence mounts of neonicotinoids' effects. *Cbc*. https://www.cbc.ca/news

Madea, B. (2014). *Handbook of forensic medicine*. John Wiley & Sons.

Matuszewski, S. (2021). Post-mortem interval estimation based on insect evidence: current challenges. *Insects*, *12*(4), 314.

Menzel, R. (2014). Learning, memory, and "cognition" in honey bees. In *Neurobiology of comparative cognition* (pp. 237-292). Psychology Press.

Miller Coyle, H. (2025). DNA Barcoding for Plant Genetics: A Role in Palynology. In *Advances in Forensic Biology and Genetics* (pp. 443-458). Springer.

Milne, L. A., Bryant, V. M., & Mildenhall, D. C. (2004). Forensic palynology. In *Forensic botany* (pp. 112-146). CRC Press.

Mishra, M., Bhunia, P., Sen, R., Bhunia, R., Gulia, J., Mondal, T., Zidane, Z., Saha, T., Chacko, A., & Raj, R. (2023). The Impact of Weather Change on Honey Bee Populations and Disease. *Journal of Advanced Zoology*, *44*.

Morice, B. D., Lord, W. D., Barthell, J. F., Jourdan, T. H., & Morris, T. L. (2020). Necrophagy in honey bees (Apis mellifera L.); a forensic application of scent foraging behavior. *Journal of the Kansas Entomological Society*, *92*(2), 423-431.

Mortensen, A. N., Smith, B., & Ellis, J. D. (2015). The Social Organization of Honey Bees: ENY-166/IN1102, 11/2015. *EDIS*, *2015*(9), 3. https://doi.org/10.32473/edis-in1102-2015

Murcia-Morales, M., Vejsnæs, F., Brodschneider, R., Hatjina, F., Van der Steen, J. J. M., Oller-Serrano, J. L., & Fernández-Alba, A. R. (2023). Enhancing the environmental monitoring of pesticide residues through Apis mellifera colonies: Honey bees versus passive sampling. *Science of The Total Environment*, *884*, 163847.

Ozanne, S. E., & Hales, C. N. (2004). Olfaction: scent-triggered navigation in honeybees. *Nature*, *427*(6973), 411.

Rivers, D. B., & Dahlem, G. A. (2022). *The science of forensic entomology*. John Wiley & Sons.

Rodacy, P. J., Bender, S. F. A., Bromenshenk, J. J., Henderson, C. B., & Bender, G. L. (2002). Training and deployment of honeybees to detect explosives and other agents of harm. *SPIE Defense + Commercial Sensing*. https://api.semanticscholar.org/CorpusID:110184499

ROXANA, A.P.; KARLA, C.; CLAUDIU, I.N.; LUCIAN, C. (2025). BUGS TELL NO LIES: ENHANCING THE ROLE OF INSECTS IN FORENSIC SCIENCE. *In Proceedings of the 2nd International Electronic Conference on Entomology, 19-21 May 2025, MDPI: Basel, Switzerland*. sciforum.net

Ruvolo-Takasusuki, M. C. C., Ronqui, L., Barateiro-Stuchi, A. L. P., Araujo, M. C., Fermino, F., Santos, P. R., & de Toledo, V. de A. (2015). *Biomonitoring the environmental quality by bees*. IntechOpen London, UK.

Sahoo, B. K., Pathak, M., Boruah, S., Sarmah, K., Ningthoujam, K., Sehgal, M., & Ikram, M. (2025). Integrating Sniffer Bees into Security and Defenses: Advancements in the Detection of Explosives and Illicit Substances. *Biotica Publications*, 155-172. https://doi.org/10.54083/978-81-986377-3-4_11

Santos, W. E., Carneiro, L. T., Alves, A. C. F., Creão-Duarte, A. J., & Martins, C. F. (2014). Stingless bees (Hymenoptera: Apidae: Meliponini) attracted to animal carcasses in the Brazilian dry forest and implications for forensic entomology. *Sociobiology*, *61*(4), 490-493.

Schott, M., Klein, B., & Vilcinskas, A. (2015). Detection of Illicit Drugs by Trained Honeybees (Apis mellifera). *PLOS ONE*, *10*(6), e0128528. https://doi.org/10.1371/journal.pone.0128528

Seeley, T. D. (2010). *The Five Habits of Highly Effective Honeybees (and What We Can Learn from Them): From Honeybee Democracy* (Vol. 5). Princeton University Press.

Shaw, J. A., Nugent, P. W., Johnson, J., Bromenshenk, J. J., Henderson, C. B., & Debnam, S. (2010). Long-wave infrared imaging for non-invasive beehive population assessment. *Optics Express*, *19*(1), 399-408.

Shaw, J. A., Seldomridge, N. L., Dunkle, D. L., Nugent, P. W., Spangler, L. H., Bromenshenk, J. J., Henderson, C. B., Churnside, J. H., & Wilson, J. J. (2005). Polarization lidar measurements of honey bees in flight for locating land mines. *Optics Express*, *13*(15), 5853-5863. https://doi.org/10.1364/OPEX.13.005853

Smith, K. E., Weis, D., Amini, M., Shiel, A. E., Lai, V. W.-M., & Gordon, K. (2019). Honey as a biomonitor for a changing world. *Nature Sustainability*, *2*(3), 223-232.

Smith, K. G. V. (1986). *A manual of forensic entomology.*

Soares, K. O., Lima, M. V, Evangelista-Rodrigues, A., Silva, A. A. F., Silva, F. J. de A., Lima, A. I. B. L. C., &

Da Costa, C. R. G. (2021). Factors influencing the foraging behavior of Trigona spinipes (Apidae, Meliponinae). *Biological Rhythm Research*, *52*(7), 1109-1119.

Tomberlin, J. K., Mohr, R., Benbow, M. E., Tarone, A. M., & Vanlaerhoven, S. (2011). A roadmap for bridging basic and applied research in forensic entomology. *Annual Review of Entomology*, *56*(1), 401-421.

Valappil, N. K. M., Viswanathan, P. M., Hamza, V., & Sabarathinam, C. (2022). Isoscapes to address the regional precipitation trends in the equatorial region of Southeast Asia. *Physics and Chemistry of the Earth, Parts A/B/C*, *127*, 103159.

Ward, L. T., Hladik, M. L., Guzman, A., Winsemius, S., Bautista, A., Kremen, C., & Mills, N. J. (2022). Pesticide exposure of wild bees and honey bees foraging from field border flowers in intensively managed agriculture areas. *Science of the Total Environment*, *831*, 154697.

Whitfield, C. W., Ben-Shahar, Y., Brillet, C., Leoncini, I., Crauser, D., LeConte, Y., Rodriguez-Zas, S., & Robinson, G. E. (2006). Genomic dissection of behavioral maturation in the honey bee. *Proceedings of the National Academy of Sciences*, *103*(44), 16068-16075.

Wiltshire, P. E. J. (2016). Protocols for forensic palynology. *Palynology*, *40*(1), 4-24.

Winston, M. L. (1991). *The biology of the honey bee*. harvard university press.

Zafeiraki, E., Sabo, R., Kasiotis, K. M., Machera, K., Sabová, L., & Majchrák, T. (2022). Adult honeybees and beeswax as indicators of trace elements pollution in a vulnerable environment: distribution among different apicultural compartments. *Molecules*, *27*(19), 6629.

Zavrtnik, S., Loborec, J., Kapelj, S., & Grčić, I. (2024). Environmental Biomonitoring of Heavy and Toxic Metals Using Honeybees and Their Products—An Overview of Previous Research. *Sustainability*, *16*(19), 8526.

Zhang, J., Wang, Y., Wurjihu, S., Ruan, H., Huang, Y., Guo, M., Kong, D., Luo, J., & Yang, M. (2024). Comprehensive analysis of neonicotinoids in Chinese commercial honey and pollen: A corresponding health risk assessment for non-targeted organisms. *Science of The Total Environment*, *919*, 170937.