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Feature Review **Open Access**

Threats to Honeybee Populations: Pathogens, Pesticides, and Environmental Changes

Jun Li
Animal Science Research Center, Cuixi Academy of Biotechnology, Zhuji, 311800, Zhejiang, China
Corresponding email: jun.li@cuixi.org

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Abstract Honeybee populations are facing severe threats due to pathogens, pesticides, and environmental changes. These essential pollinators play a critical role in ecosystems and agriculture, contributing significantly to global food security. This study examines the multifaceted challenges to honeybee health, detailing the impacts of viral, bacterial, fungal, and parasitic pathogens. It also explores the detrimental effects of various pesticides, including acute and chronic toxicity, and their sublethal impacts on honeybee behavior and physiology. Environmental changes, such as habitat loss, climate change, pollution, and alterations in floral resources, further exacerbate these threats. The interplay between these stressors often results in compounded negative effects on honeybee populations. Current monitoring and diagnostic techniques are evaluated, alongside mitigation and conservation strategies like Integrated Pest Management (IPM), habitat restoration, breeding for disease resistance, and policy measures. Case studies from different regions illustrate the variability in threats and the success of various mitigation efforts. This review underscores the necessity of integrated approaches to safeguard honeybee populations and highlights recommendations for future research and policy to ensure their survival and the continued health of ecosystems and agriculture.

Keywords Honeybee health; Pathogens; Pesticides; Environmental changes; Conservation strategies

1 Introduction

Honeybees (*Apis mellifera*) are vital pollinators, playing a crucial role in maintaining biodiversity and supporting agricultural productivity. However, honeybee populations have been experiencing significant declines globally, raising concerns about the sustainability of pollination services and the broader implications for ecosystems and food security.

Over the past few decades, honeybee populations have faced numerous challenges that have led to their decline. These challenges include exposure to various pathogens, the widespread use of pesticides, and significant environmental changes (Kom et al., 2019; Morales et al., 2019). The decline in honeybee populations has been documented in many regions, including North America, Europe, and Asia, with some areas experiencing more severe losses than others (Goulson et al., 2015; Lin et al., 2023). The intensification of agriculture, habitat loss, and climate change have further exacerbated these issues, making it increasingly difficult for honeybee colonies to thrive (García-Valcárcel et al., 2019).

Honeybees are among the most important pollinators, contributing to the pollination of approximately 87.5% of flowering plants and a significant portion of food crops (Moorthy et al., 2023). Their role in pollination is essential for the production of fruits, vegetables, nuts, and seeds, which are critical components of human diets and agricultural economies. The decline in honeybee populations poses a direct threat to food security and biodiversity, as many plants rely on bees for reproduction and genetic diversity (Gill and Raine, 2014). Additionally, honeybees support the health of ecosystems by pollinating wild plants, which in turn provide habitat and food for other wildlife (Halvorson et al., 2021).

This study examines the various threats to honeybee populations, focusing on pathogens, pesticides, and environmental changes. By synthesizing current research, this study aims to provide a comprehensive understanding of the factors contributing to honeybee declines and to highlight potential strategies for mitigating these threats. The study will explore the interactions between different stressors and their cumulative impact on honeybee health, as well as discuss practical measures that can be implemented to support honeybee populations and ensure the sustainability of pollination services.

2 Pathogens Affecting Honeybee Populations

2.1 Viral pathogens

Viral pathogens are a significant threat to honeybee populations, with Deformed Wing Virus (DWV) being one of the most prevalent and destructive. The spread of DWV is closely linked to the parasitic mite *Varroa destructor*, which facilitates the transmission of the virus among bees. The mite's role in the global epidemic of DWV has been well-documented, showing that the virus has spread rapidly from European honeybees (*Apis mellifera*) to other regions, driven by trade and movement of bee colonies (Giacobino et al., 2016). The interaction between Varroa mites and DWV has transformed the virus from a relatively benign pathogen into a highly virulent one, leading to significant colony losses (Nazzi et al., 2012). Studies have shown that the presence of Varroa mites increases the prevalence and load of DWV, reducing viral diversity and leading to the dominance of a single, more virulent strain (Martin et al., 2012).

2.2 Bacterial infections

Bacterial infections, while less frequently discussed in the provided data, also pose a threat to honeybee health. One notable bacterial pathogen is *Nosema apis*, a microsporidian that affects the digestive system of bees. In a survey conducted in Kenya, *Nosema apis* was found at several sites, indicating its presence in honeybee populations (Muli et al., 2014). Although the impact of *Nosema apis* on colony size and survival was not as pronounced as that of Varroa mites and viruses, its presence still warrants attention as part of the broader spectrum of pathogens affecting honeybees.

2.3 Fungal diseases

Fungal diseases, particularly those caused by *Nosema* species, are another concern for honeybee populations. *Nosema apis* and *Nosema ceranae* are microsporidian fungi that infect the gut of honeybees, leading to dysentery and reduced colony productivity. The survey in Kenya identified *Nosema apis* at multiple locations, suggesting that fungal infections are present but not yet causing significant colony declines (Muli et al., 2014). The interaction between fungal pathogens and other stressors, such as environmental changes and parasitic mites, could exacerbate their impact on honeybee health.

2.4 Parasitic infestations

Parasitic infestations, particularly by *Varroa destructor*, are among the most critical threats to honeybee populations. *Varroa* mites not only cause direct damage by feeding on bee hemolymph but also act as vectors for various viral pathogens, including DWV (Wilfert et al., 2016). The mites' ability to spread rapidly and their increasing resistance to chemical treatments have made them a formidable challenge for beekeepers worldwide (Mondet et al., 2020; Traynor et al., 2020). Research has shown that *Varroa* mites destabilize the within-host dynamics of DWV, leading to lethal levels of the virus and contributing to colony collapse (Nazzi et al., 2012). Additionally, *Varroa* infestations have been linked to alterations in bee physiology, such as impaired water regulation, which further compromises bee survival (Annoscia et al., 2012). Efforts to breed *Varroa*-resistant honeybee populations have shown promise, with certain traits like brood removal and reduced mite reproduction being identified as key factors in natural resistance (Figure 1) (Mondet et al., 2020; Grindrod and Martin, 2021).

The research of Grindrod and Martin (2021) presents a detailed framework for understanding the development of Varroa resistance in honeybee colonies. Central to this framework is the increased detection of mites by resistant bees, leading to several defensive behaviors and outcomes. Resistant bees demonstrate a higher rate of recapping infested cells and removing infested brood, which significantly reduces the number of viable mite offspring. This is depicted by the average recapping rates and brood removal percentages, which are higher in resistant bees compared to susceptible ones. Additionally, mite infertility rates are higher in resistant colonies, contributing to a population decrease in mites. Lower viral loads of deformed wing virus (DWV) in resistant bees further enhance colony health and survival. Over time, selective pressures favoring drone over worker cells have resulted in reduced worker brood infestation. This comprehensive approach highlights the interconnectedness of various behaviors and biological responses in achieving and maintaining Varroa resistance.

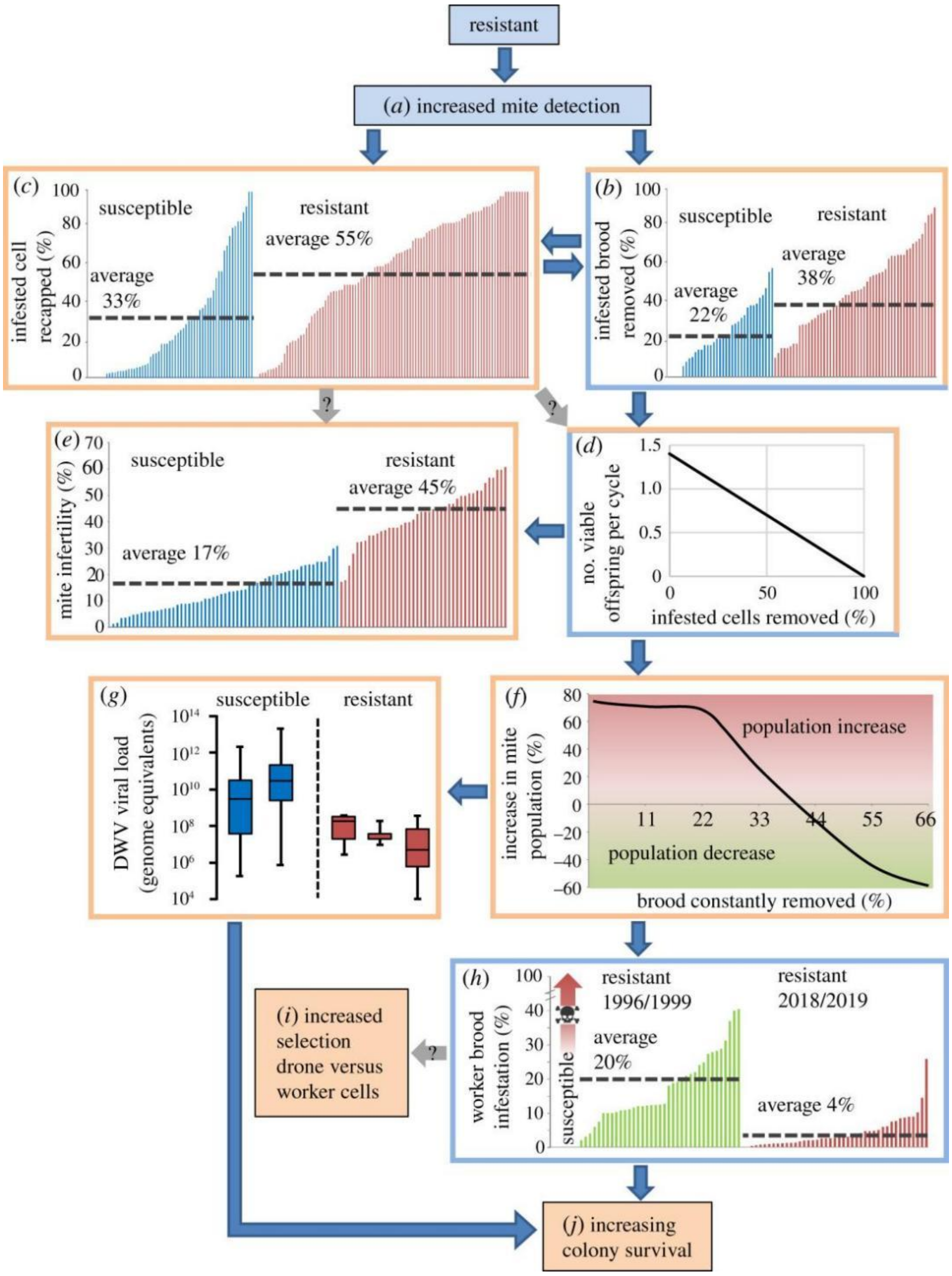

Figure 1 A proposed framework for the development of *Varroa* resistance (Adopted from Grindrod and Martin, 2021)

Image caption: Boxes in blue (a) or with a blue border (b, d, h) are ‘causes’ of the ‘effects’ that are indicated by boxes in orange (i, j) or with orange borders (b-g). All source data for each chart are available in the electronic supplementary material, tables S1-S8 and figure S1. Arrows with a question mark indicate possible links suggested in the literature. In box h, the red arrow indicates that in untreated, susceptible colonies Varroa infestations continuously rise until colony death. Deformed wing virus data in box g are adapted from-and discussed below (Adopted from Grindrod and Martin, 2021)

In summary, honeybee populations are under threat from a range of pathogens, including viral, bacterial, and fungal diseases, as well as parasitic infestations. The interaction between these pathogens and environmental factors complicates the management of honeybee health, necessitating integrated approaches to mitigate their impact.

3 Impact of Pesticides on Honeybees

Pesticides, particularly neonicotinoids, have been identified as a significant threat to honeybee populations. These chemicals can have various detrimental effects on bees, ranging from acute toxicity to more subtle, sublethal impacts on behavior and physiology. Additionally, the interaction of pesticides with other environmental stressors can exacerbate their harmful effects.

3.1 Types of pesticides

Neonicotinoids are the most widely used class of insecticides globally and pose a major threat to bees (Arce et al., 2017). These systemic pesticides, including imidacloprid, thiamethoxam, and clothianidin, are commonly found in nectar and pollen, leading to direct exposure for foraging bees (Chan and Raine, 2021). Other pesticides, such as the novel butenolide insecticide flupyradifurone (FPF), also act as nicotinic acetylcholine receptor (nAChR) agonists and have been shown to have adverse effects on bee health (Cabirol and Haase, 2019; Tosi et al., 2019).

3.2 Acute and chronic toxicity

Both acute and chronic exposures to pesticides can negatively impact honeybees. Acute exposure often involves high doses over a short period, while chronic exposure involves lower doses over extended periods. Studies have shown that field-realistic doses of neonicotinoids can significantly reduce bee survival rates and affect their behavior and physiology (Stanley et al., 2016; Tosi et al., 2017). For instance, imidacloprid exposure has been linked to reduced nest initiation and offspring production in solitary bees (Chan and Raine, 2021).

3.3 Sublethal effects on behavior and physiology

Sublethal doses of pesticides can have profound effects on bee behavior and physiology. These include impairments in learning and memory, reduced foraging efficiency, and altered social behaviors. For example, exposure to imidacloprid has been shown to reduce nursing behavior in bumblebees (Crall et al., 2017). Additionally, sublethal doses of neonicotinoids have been found to affect learning and memory in bees, which can reduce their foraging efficiency and overall colony health (Siviter et al., 2018).

3.4 Synergistic effects with other stressors

The interaction of pesticides with other environmental stressors, such as nutritional deficiencies and pathogens, can amplify their harmful effects. For instance, the combination of poor nutrition and pesticide exposure has been shown to synergistically reduce bee survival and food consumption (Tosi et al., 2017). Similarly, the interaction between neonicotinoids and microbial pathogens like Nosema ceranae can significantly elevate bee mortality rates (Doublet et al., 2015). These synergistic effects highlight the need for comprehensive risk assessments that consider multiple stressors simultaneously (Tosi et al., 2019).

4 Environmental Changes and Their Effects

4.1 Habitat loss and fragmentation

Environmental changes have profound impacts on honeybee populations, influencing their health, behavior, and survival. Habitat loss and fragmentation are significant drivers of honeybee population declines. The reduction of semi-natural habitats has led to a scarcity of floral resources and nesting sites, which are crucial for bee survival. Agricultural intensification and urbanization have further exacerbated this issue by converting diverse landscapes into monocultures and urban areas, thereby limiting the availability of diverse pollen and nectar sources (Goulson et al., 2015). The loss of habitat not only reduces the quantity of food available to bees but also affects the quality and diversity of their diet, which is essential for their health and resilience against other stressors (Requier et al., 2015; Jones et al., 2021).

4.2 Climate change

Climate change poses a multifaceted threat to honeybee populations. Alterations in temperature and precipitation patterns can disrupt the synchrony between bee emergence and flower blooming, leading to mismatches in the availability of floral resources when bees need them the most (Belsky and Joshi, 2019). Additionally, climate change can exacerbate the spread of pests and pathogens, further stressing bee populations. For instance, warmer temperatures may facilitate the spread of invasive species and parasites that negatively impact bee health (Pirk et al., 2016). The combined effects of these changes can lead to reduced foraging efficiency and increased mortality rates among honeybees.

4.3 Pollution and contaminants

Pollution and environmental contaminants, including pesticides and other agrochemicals, have been widely documented to affect honeybee health adversely. Bees are exposed to a variety of chemicals through their foraging activities, which can impair their immune systems and make them more susceptible to diseases and parasites (O'Neal et al., 2018; García-Valcárcel et al., 2019). The interaction between pesticides and pathogens is particularly concerning, as exposure to certain chemicals can increase the toxicity of others and reduce bees' resistance to infections (Centrella et al., 2019). Moreover, pollutants can accumulate in bee habitats, leading to chronic exposure and long-term health effects (Lin et al., 2023).

4.4 Changes in floral resources

Changes in floral resources, driven by both natural and anthropogenic factors, significantly impact honeybee populations. The decline in the abundance and diversity of flowers due to habitat loss, agricultural practices, and invasive species reduces the availability of essential nutrients for bees (Jones et al., 2021). Seasonal variations in floral resource availability can create periods of food scarcity, particularly during critical times of the year when bee populations are at their peak (Requier et al., 2015). Enhancing floral diversity and availability through agri-environmental schemes and sustainable farming practices can help mitigate these effects and support bee health and productivity (Samuelson et al., 2020).

In conclusion, environmental changes, including habitat loss, climate change, pollution, and alterations in floral resources, play a critical role in the decline of honeybee populations. Addressing these challenges requires a multifaceted approach that includes habitat restoration, sustainable agricultural practices, and effective management of pollutants and pests. By understanding and mitigating these environmental stressors, we can help ensure the survival and health of honeybee populations, which are vital for ecosystem services and agricultural productivity.

5 Combined Effects of Multiple Stressors

5.1 Interactions between pathogens and pesticides

The interaction between pathogens and pesticides has been shown to significantly impact honeybee health. For instance, studies have demonstrated that the combination of the microsporidian parasite Nosema and neonicotinoid pesticides like Thiamethoxam and Imidacloprid can lead to increased mortality and reduced immunocompetence in honeybees (Grassl et al., 2018; Alaux et al., 2020). These synergistic effects are particularly concerning as they can exacerbate the decline in bee populations. Additionally, the combination of Nosema ceranae and the insecticide fipronil has been found to have a synergistic effect on honeybee survival, especially when stressors are applied at the emergence of honeybees (Aufauvre et al., 2012). This highlights the importance of considering the sequence and timing of exposure to multiple stressors.

5.2 Combined impact of environmental changes and pathogens

Environmental changes, such as habitat loss and climate change, combined with pathogen exposure, can further stress honeybee populations. The Bumble-BEEHAVE model, which simulates the impact of multiple stressors on bumblebee populations, has shown that environmental changes can interact with pathogens to affect bee numbers and population dynamics (Becher et al., 2018). This model underscores the complexity of these interactions and the need for a holistic approach to understanding and mitigating the impacts of environmental changes on bee health. Furthermore, the absence of certain pathogens, such as Varroa destructor, in specific regions like Australia, provides unique insights into how environmental factors alone can influence viral landscapes and colony losses (Roberts et al., 2017).

5.3 Case studies of multifactorial stress

Several case studies have highlighted the detrimental effects of multifactorial stress on bee populations. For example, a study on bumblebees exposed to a combination of the gut parasite *Nosema ceranae* and multiple pesticides found that these stressors reduced food collection, colony growth, and queen production, ultimately impacting colony health and performance (Figure 2) (Botías et al., 2020). Another study demonstrated that the combined effects of pesticides and electromagnetic fields led to higher mortality, disease appearance, and behavioral alterations in honeybee colonies, with only one colony surviving out of four after one year of exposure (Lupi et al., 2021). These case studies illustrate the severe consequences of multifactorial stress and the need for comprehensive risk assessments and management strategies to protect bee populations (Siviter et al., 2021).

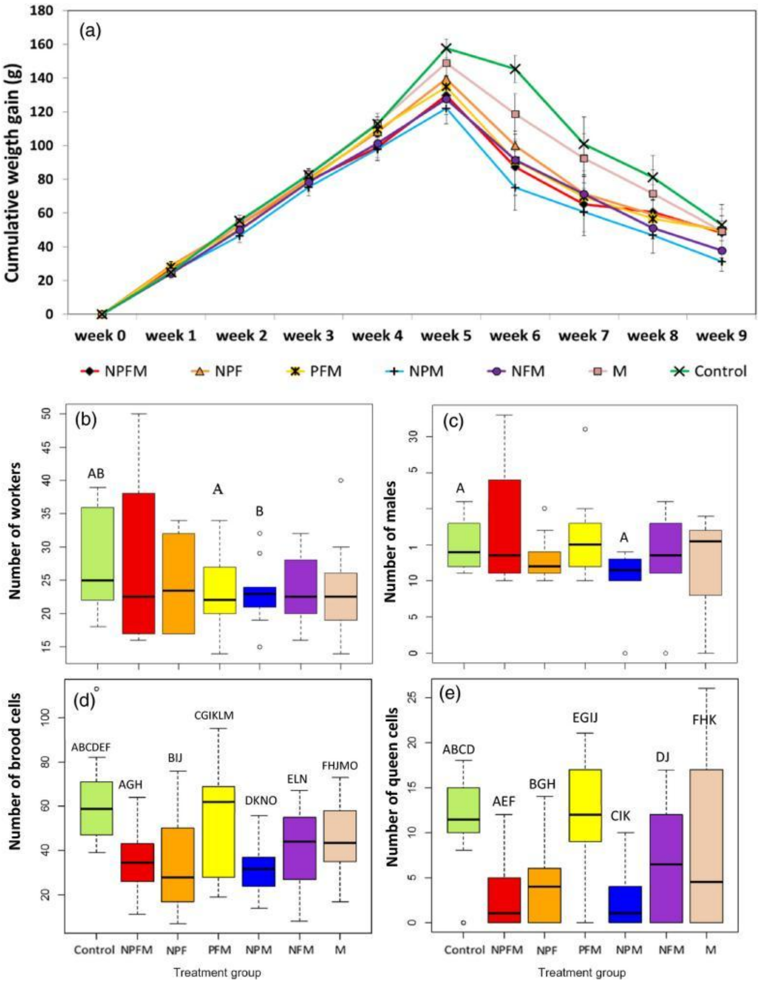

Figure 2 Fitness parameters measured in the *Bombus terrestris* colonies (Adopted from Botías et al., 2020)

Image caption: (a) Mean colony weight observed for the control and treatment groups at weekly intervals. The change in weight over time was significantly smaller (p=0.009) in the colonies that received the four stressors (NPFM) compared to control colonies. (b) Boxplots of the number of workers in each treatment group. (c) Boxplots of the number of males in each treatment group. (d) Boxplots of the number of brood (workers and males) cells produced in each treatment group. (e) Boxplots of the number of queen cells produced in each treatment group. Boxplots with similar letters are significantly different (p<0.05; GLMs with Poisson error distribution followed by Tukey´s post-hoc tests). NPFM=TMX+CYPER+TEB+*N. ceranae*; NPF=TMX+CYPER+TEB; PFM=TEB+CYPER+*N. ceranae*; NPM=TMX+CYPER+*N. ceranae*; NFM=TMX+TEB+*N. ceranae*; M=*N. ceranae*; Control=Untreated (Adopted from Botías et al., 2020)

The research of Botías et al. (2020) depicts the fitness parameters of Bombus terrestris colonies under different treatment conditions. Panel (a) shows the cumulative weight gain over nine weeks, indicating that colonies exposed to multiple stressors (NPFM) exhibited significantly smaller weight gains compared to control colonies. Panels (b) and (c) illustrate the number of workers and males produced, respectively, with noticeable variations among treatment groups. Colonies exposed to the NPFM treatment had fewer workers and males, suggesting a detrimental effect of combined stressors. Panel (d) highlights the number of brood cells, with the control group having higher brood production compared to most treated groups, again emphasizing the negative impact of stressors on colony health. Lastly, panel (e) shows the number of queen cells produced, with significant differences observed across groups, indicating that stress exposure can affect reproductive output. Overall, the data suggest that exposure to multiple stressors severely impacts the health and reproductive success of bumblebee colonies.

The combined effects of multiple stressors, including pathogens, pesticides, and environmental changes, pose a significant threat to honeybee populations. Understanding these interactions and their impacts at individual, colony, and population levels is crucial for developing effective conservation and management practices to ensure the sustainability of pollination services.

6 Monitoring and Diagnostic Techniques

6.1 Surveillance methods for pathogens

Surveillance of pathogens in honeybee populations is crucial for understanding and mitigating the threats posed by diseases. Various methods have been developed to monitor the presence of pathogens such as Varroa mites and Nosema microsporidia. For instance, a study in Greece utilized LC-ESI-QqQ-MS and GC-EI-QqQ-MS methods to detect multiple active substances and metabolites in honeybee samples, which also included assessments for Varroa and Nosema infections. This comprehensive approach provided an integrated picture of the stressors impacting bee survival (Kasiotis et al., 2021). Such methodologies are essential for early detection and management of pathogen-related threats to honeybee colonies.

6.2 Detection of pesticide residues

The detection of pesticide residues in honeybee environments is a critical aspect of monitoring their exposure to harmful chemicals. Several advanced analytical techniques have been developed for this purpose. For example, a study in Spain developed an ultrasound-assisted extraction procedure followed by dispersive solid-phase extraction (d-SPE) and LC-MS/MS to evaluate pesticide residue levels in honeybees and corbicular pollen (García-Valcárcel et al., 2019). Another study in Denmark employed APIStrip-based passive sampling, which uses Tenax sorbent to monitor pesticide residues in honeybee colonies without harming the bees. This method allowed for long-term monitoring and provided comprehensive data on pesticide contamination (Murcia-Morales et al., 2020; Murcia-Morales et al., 2021). Additionally, a multi-residue analysis using modified QuEChERS methods combined with GC-ToF and LC-MS/MS (Daniele et al., 2018) was developed to quantify 80 environmental contaminants in honeys, honeybees, and pollens, demonstrating high sensitivity and accuracy (Wiest et al., 2011; Xiao et al., 2021).

6.3 Environmental monitoring tools

Environmental monitoring tools are essential for assessing the broader impact of environmental changes on honeybee populations (Căuia et al., 2020). Honeybee colonies themselves serve as effective bioindicators due to their extensive foraging activities. For instance, a study in Italy used bee-collected pollen to monitor pesticide contamination over three years, revealing widespread contamination by agricultural pesticides (Tosi et al., 2018). Similarly, a study in Brazil demonstrated the use of bee pollen as a bioindicator of environmental contamination by developing a GC-MS/MS analytical method for multiresidue determination of pesticides in pollen (Oliveira et al., 2016). These tools not only help in detecting contaminants but also in understanding the extent and impact of environmental changes on honeybee health.

In summary, the integration of advanced analytical techniques and the use of honeybee colonies as bioindicators provide robust methods for monitoring pathogens, pesticide residues, and environmental changes. These tools are vital for the early detection and management of threats to honeybee populations, ensuring their health and sustainability.

7 Mitigation and Conservation Strategies

7.1 Integrated pest management (IPM)

The decline in honeybee populations due to various stressors such as pathogens, pesticides, and environmental changes necessitates the implementation of effective mitigation and conservation strategies. Integrated Pest Management (IPM) is a holistic approach that combines multiple strategies to manage pest populations while minimizing the use of harmful chemicals. IPM in honeybee management involves the use of biological controls, cultural practices, and selective chemical treatments to control pests like the Varroa mite and small hive beetle. For instance, IPM strategies in citrus orchards have been shown to reduce pesticide residues in honeybees and pollen, thereby mitigating the negative impacts of pesticides on bee health (García-Valcárcel et al., 2019). Additionally, IPM approaches that include hive manipulation, traps, and organic treatments have been effective in controlling various pests and diseases (Kushwaha et al., 2023).

7.2 Habitat restoration and conservation

Habitat restoration and conservation are crucial for providing honeybees with the necessary floral resources and nesting sites. The decline in floral diversity and abundance due to habitat loss has been a significant driver of bee population declines (Goulson et al., 2015). Efforts to restore habitats by incorporating flower-rich areas into farmland and encouraging the growth of bee-friendly plants can alleviate dietary stress and improve bee health (Belsky and Joshi, 2019). Moreover, maintaining semi-natural habitats within agricultural landscapes can enhance the availability of nesting sites and support diverse pollinator communities (O’Neal et al., 2018).

7.3 Breeding for disease resistance

Breeding programs aimed at enhancing disease resistance in honeybees offer a sustainable solution to combat the threats posed by pathogens and parasites. Selective breeding for traits such as Varroa resistance has shown promise in developing honeybee populations that can survive without chemical treatments (Mondet et al., 2020). Traits like recapping, brood removal, and reduced mite reproduction have been identified as key factors in naturally resistant bee populations across different regions (Grindrod and Martin, 2021). By focusing on these traits, breeding programs can help create resilient honeybee colonies capable of withstanding parasitic pressures.

7.4 Policy and regulatory measures

Effective policy and regulatory measures are essential to support the conservation of honeybee populations. Policies that promote sustainable agricultural practices, such as the reduction of pesticide use and the adoption of IPM, can significantly benefit bee health (Goulson et al., 2015). Additionally, enforcing quarantine measures to prevent the spread of bee parasites and pathogens is vital for protecting both managed and wild bee populations. Increased monitoring and data collection on pollinator populations can inform policy decisions and ensure timely interventions to prevent further declines (Halvorson et al., 2021).

A multifaceted approach that includes IPM, habitat restoration, breeding for disease resistance, and supportive policy measures is necessary to mitigate the threats to honeybee populations. By integrating these strategies, we can enhance the resilience of honeybee colonies and ensure their vital role in pollination and global food security.

8 Case Studies and Regional Analysis

8.1 Regional differences in threats and impacts

Honeybee populations face a variety of threats that differ significantly across regions. In Spain, for instance, the use of Integrated Pest Management (IPM) in citrus orchards has been studied to understand pesticide residue levels in honeybees and corbicular pollen. This method aims to reduce pest populations while minimizing environmental damage by using chemicals only when necessary (García-Valcárcel et al., 2019). In contrast, the northern hemisphere has seen elevated colony losses due to emergent microbial pathogens, which interact with pesticides to exacerbate their impacts on honeybee health (Doublet et al., 2015). Additionally, global warming has been shown to promote the biological invasion of pests like the small hive beetle, which poses a significant threat to honeybee colonies, particularly in temperate regions of the Northern Hemisphere(Figure 3) (Cornelissen et al., 2019).

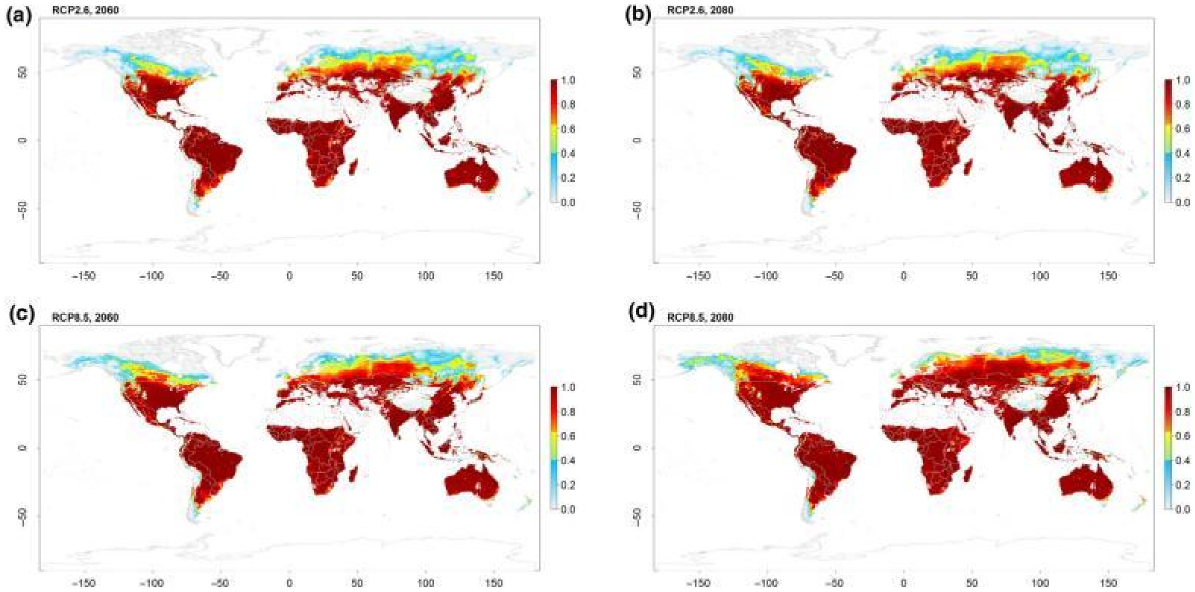

Figure 3 Pupal performance of small hive beetle projected to the representative concentration pathways (RCPs) 2.6 (a,b) and 8.5 (c,d) for the years 2060 (a,c) and 2080 (b,d) (Adopted from Cornelissen et al., 2019)

Image caption: Pupal performance is based on a composite index combing pupal survival rate and development time (Equation 3.1) and ranges between zero (no performance) and one (maximum performance). According to thresholds obtained from model validation (see Figure 2), continuous pupal performance values were classified into conditions of high climatic suitability (values higher than 0.64; red to orange colours), marginally suitable (values between 0.4 and 0.64; yellow to green) and unsuitable climatic conditions (values below 0.4; blue to grey colours). Non-vegetated areas are masked in white (Adopted from Cornelissen et al., 2019)

The research of Cornelissen et al. (2019) illustrates projected pupal performance of the small hive beetle under two representative concentration pathways (RCPs) for 2060 and 2080. Panels (a) and (b) display projections for RCP 2.6, indicating lower greenhouse gas emissions and resultant climatic conditions. Panels (c) and (d) present projections for RCP 8.5, which assume higher emissions and more severe climate change impacts. Across both time frames and scenarios, areas of high climatic suitability (red to orange) for the small hive beetle's pupal stage are widespread, particularly in tropical and subtropical regions. However, the extent of suitable habitat increases under RCP 8.5 compared to RCP 2.6, suggesting that higher emissions will exacerbate the beetle's proliferation. Marginally suitable areas (yellow to green) and unsuitable areas (blue to grey) also shift accordingly, highlighting how future climate conditions could significantly alter the distribution and impact of this pest on beekeeping and ecosystems globally.

8.2 Successful mitigation efforts

Several regions have implemented successful mitigation efforts to combat these threats. In Spain, the development of a simple analytical method to evaluate pesticide residue levels in honeybees has been a significant step forward. This method, which involves ultrasound-assisted extraction and LC-MS/MS pesticide determination, has been validated and applied in citrus orchards over a two-year study period (García-Valcárcel et al., 2019). Globally, breeding programs have been initiated to enhance heritable traits of resistance or tolerance to the Varroa destructor mite, a major pathological threat to honeybees. These programs focus on selectively breeding or naturally selecting honeybee populations that can survive mite parasitism (Mondet et al., 2020). Furthermore, a global survey revealed that many countries have stable or increasing honeybee populations due to routine data collection and conservation efforts, although other pollinators receive less attention (Halvorson et al., 2021).

8.3 Lessons learned from various regions

From these regional analyses, several lessons can be drawn. First, the importance of integrated pest management and the development of precise analytical methods cannot be overstated. These approaches not only help in monitoring pesticide residues but also in reducing their application, thereby minimizing environmental damage (García-Valcárcel et al., 2019). Second, breeding programs that focus on enhancing resistance to specific pathogens like the Varroa destructor mite have shown promise and should be expanded (Mondet et al., 2020). Third, the global survey underscores the need for comprehensive monitoring and conservation programs that include all pollinators, not just honeybees, to ensure ecosystem stability (Halvorson et al., 2021). Lastly, the impact of climate change on the distribution and severity of invasive species like the small hive beetle highlights the need for adaptive management strategies to mitigate these emerging threats (Cornelissen et al., 2019).

By understanding and addressing the regional differences in threats and impacts, and by learning from successful mitigation efforts, we can develop more effective strategies to protect honeybee populations globally.

9 Concluding Remarks

The decline in honeybee populations is a multifaceted issue driven by a combination of pathogens, pesticides, and environmental changes. Research has shown that pesticide exposure, particularly neonicotinoids, significantly impacts bee health by reducing survival rates and impairing immune responses. Pathogens such as Nosema spp. and various viruses also play a critical role in weakening bee colonies, often interacting synergistically with pesticides to exacerbate their effects. Environmental changes, including habitat loss and climate change, further compound these stressors, leading to a decline in floral resources and nesting sites, which are essential for bee survival.

Addressing the decline in honeybee populations requires an integrated approach that considers the complex interactions between various stressors. Integrated Pest Management (IPM) strategies, which minimize pesticide use and focus on sustainable agricultural practices, have shown promise in reducing the negative impacts on bees. Additionally, improving habitat quality by increasing floral diversity and availability can help mitigate some of the dietary stresses bees face. Effective quarantine measures and better management practices are also crucial in preventing the spread of pathogens and parasites.

Future research should focus on understanding the synergistic effects of multiple stressors on bee health under field-realistic conditions. Studies should investigate the long-term impacts of low-dose pesticide exposure combined with pathogen infections on colony survival and reproductive success. There is also a need for more research on non-Apis bee species to fill existing knowledge gaps. Policymakers should consider revising pesticide regulations to account for the interactions between different agrochemicals and their cumulative effects on pollinators. Promoting sustainable farming practices and enhancing habitat quality through conservation efforts can provide long-term benefits for bee populations and the ecosystem services they support. Effective monitoring systems are essential to track pollinator health and inform adaptive management strategies.

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Conflict of Interest Disclosure

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