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DERLEME / REVIEW

PEST MANAGEMENT FOR-*Apis mellifera*: RISKS AND MITIGATION STRATEGIES

Zirai Mücadele-*Apis mellifera* Etkileşimi: Riskler ve Koruma Stratejileri

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ABSTRACT

Agricultural pesticides play a crucial role in modern crop protection; however, they pose significant risks to honey bees (*Apis mellifera*), which are essential for pollination and ecosystem stability. This review synthesizes current evidence on the physiological, behavioral, and colony-level impacts of agrochemicals, highlighting sustainable alternatives. Insecticides, herbicides, fungicides, and other chemical agents can induce acute and chronic toxicity in bees, impairing their orientation, communication, and foraging behavior. They also weaken immune defenses, disrupt gut microbiota, and increase susceptibility to pathogens. Adverse outcomes extend to queen health, reproductive success, and colony integrity with direct implications for Colony Collapse Disorder (CCD). Risk factors such as hive placement near agricultural fields and improper timing of pesticide application further exacerbate these threats. To mitigate risks, bee-friendly strategies— including organic farming, biological control, integrated pest management (IPM), and responsible pesticide use—are emphasized. Policy analyses from Turkey and global contexts reveal the urgent need for pollinator-focused regulations. In conclusion, protecting bee health is crucial for the sustainability of agriculture and food security. Promoting bee-friendly agricultural practices is essential not only for maintaining ecological balance but also for ensuring the continuity of ecosystem services.

Keywords: *Apis mellifera*, Pesticides, Colony Collapse Disorder, Sustainable Agriculture, Pollinators

ÖZ

Modern tarımda pestisitler, ürün korumada merkezi bir rol oynamakta, ancak ekosistem dengesi ve tozlaşma için vazgeçilmez olan bal arıları (*Apis mellifera*) açısından ciddi riskler oluşturmaktadır. Bu derleme, tarım kimyasallarının bal arıları üzerindeki fizyolojik, davranışsal ve koloni düzeyindeki etkilerine ilişkin güncel kanıtları özetlemekte ve sürdürülebilir alternatiflere dikkat çekmektedir. İnsektisitler, herbisitler, fungisitler ve diğer kimyasal ajanlar, arılarda akut ve kronik toksisiteye yol açarak yön bulma, iletişim ve besin arama davranışlarını bozabilmektedir. Ayrıca bağışıklık savunmalarını zayıflatmakta, bağırsak mikrobiyotasını bozmakta ve patojenlere duyarlılığı artırmaktadır. Olumsuz sonuçlar, kraliçe sağlığı, üreme başarısı ve koloni bütünlüğüne kadar uzanarak Koloni Çöküş Sendromu (KÇS) ile doğrudan ilişkilendirilmektedir. Kovanların tarım alanlarına yakın konumlandırılması ve pestisit uygulamalarının uygunsuz zamanlaması gibi risk faktörleri bu tehditleri daha da ağırlaştırmaktadır. Riskleri azaltmak için organik tarım, biyolojik mücadele, Entegre Zararlı Yönetimi (EZY) ve bilinçli pestisit kullanımı gibi arı dostu stratejiler ön plana çıkmaktadır. Türkiye ve dünya genelindeki politika analizleri, tozlayıcı odaklı düzenlemelerin aciliyetini ortaya koymaktadır. Sonuç olarak, arı sağlığının korunması, sürdürülebilir tarım ve gıda güvenliği için hayati öneme sahiptir. Arı dostu tarım uygulamalarının teşvik edilmesi, yalnızca ekolojik dengenin korunması için değil, aynı zamanda ekosistem hizmetlerinin sürekliliğinin sağlanması açısından da gereklidir.

Anahtar Kelimeler: *Apis mellifera*, Pestisitler, Koloni Çöküş Sendromu, Sürdürülebilir Tarım, Tozlayıcılar

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GENİŞLETİLMİŞ ÖZET

Amaç: Modern tarımda kullanılan pestisitler, verimliliği artırmada ve bitkisel üretimde kayıpları azaltmada önemli bir araç olarak kabul edilmektedir. Ancak bu kimyasallar, ekosistem dengesinde kilit rol üstlenen ve bitkisel üretimin devamlılığı için vazgeçilmez bir tozlayıcı olan bal arıları (*Apis mellifera*) açısından ciddi tehditler barındırmaktadır. Bal arıları yalnızca bal ve diğer arı ürünleri ile ekonomik değer sağlamamakta, aynı zamanda ekosistem hizmetlerinin temel unsurlarından biri olan tozlaşmayı gerçekleştirerek biyolojik çeşitliliğin sürdürülmesinde kritik rol oynamaktadır. Bu derleme çalışmasının amacı, zirai mücadele uygulamalarının bal arıları üzerindeki fizyolojik, davranışsal ve koloni düzeyindeki etkilerini ortaya koymak, risk faktörlerini tanımlamak ve arı dostu sürdürülebilir alternatif tarım stratejilerini değerlendirmektir.

Çalışma, son on beş yıl içerisinde yayımlanmış ulusal ve uluslararası literatürün kapsamlı bir incelemesine dayandırılmıştır. Bal arıları üzerinde pestisitlerin etkilerini değerlendiren deneysel araştırmalar, saha çalışmaları ve epidemiyolojik veriler taranmış; arı sağlığına dair elde edilen bulgular analiz edilmiştir. Ayrıca Dünya Sağlık Örgütü (DSÖ), Gıda ve Tarım Örgütü (FAO), Avrupa Gıda Güvenliği Otoritesi (EFSA) gibi uluslararası kuruluşların raporları ve Türkiye'de yürürlükte olan tarım politikaları incelenerek, küresel ve ulusal ölçekte mevcut uygulamalar karşılaştırmalı olarak değerlendirilmiştir.

Elde edilen veriler, pestisitlerin bal arıları üzerinde çok yönlü olumsuz etkiler meydana getirdiğini göstermektedir. İnsektisitler, herbisitler, fungisitler ve diğer kimyasal ajanların akut ve kronik toksisiteye yol açtığı; yön bulma, dans dili ile iletişim, polen ve nektar toplama gibi hayati davranışlarda bozulmalara sebep olduğu tespit edilmiştir. Ayrıca pestisitler, bağışıklık sistemini baskılayarak arıların viral, bakteriyel ve fungal patojenlere duyarlılığını artırmakta, bağırsak mikrobiyotasını bozmakta ve kolonilerin genel sağlığını zayıflatmaktadır. Kraliçe arı sağlığı ve üreme başarısındaki düşüş, kolonilerin bütünlüğünü doğrudan etkilemekte; bu durum Koloni Çöküş Sendromu (KÇS) ile ilişkilendirilmektedir. Kovanların tarım alanlarına yakın konumlandırılması, pestisit uygulamalarının gündüz saatlerinde yapılması ve uygun olmayan dozlarda kullanımı, riskleri daha da artırmaktadır. Bununla birlikte, organik tarım uygulamaları, biyolojik mücadele yöntemleri, Entegre Zararlı Yönetimi (EZY) ve pestisitlerin bilinçli kullanımı gibi stratejiler arı dostu yaklaşımlar olarak öne çıkmaktadır. Bu yöntemlerin hem Türkiye'de hem de dünya genelinde yaygınlaştırılmasının, arı sağlığını koruma açısından kritik bir adım olduğu ortaya konmuştur.

Sonuç: Bal arılarının sağlığı, yalnızca arıcılık sektörünün sürdürülebilirliği için değil, aynı zamanda gıda güvenliği ve ekosistem hizmetlerinin devamlılığı için stratejik öneme sahiptir. Zirai kimyasalların arılar üzerindeki olumsuz etkileri dikkate alındığında, mevcut tarım politikalarının yeniden gözden geçirilmesi ve tozlayıcı dostu tarım yaklaşımlarının yaygınlaştırılması gerekmektedir. Özellikle pestisitlerin bilinçli ve kontrollü kullanımı, kovanların güvenli bölgelerde konumlandırılması, uygulama zamanlarının çevreyle ilgili takvime göre düzenlenmesi ve EZY yöntemlerinin teşvik edilmesi, arı sağlığının korunması açısından temel önlemler arasında yer almaktadır. Sonuç olarak, arı dostu tarım uygulamalarının benimsenmesi yalnızca çevreyle ilgili dengenin korunmasına değil, aynı zamanda tarımsal üretimin sürdürülebilirliğine ve gıda güvenliğinin sağlanmasına da katkıda bulunacaktır.

INTRODUCTION

The honey bee (*Apis mellifera*) is an indispensable species not only for honey production but also for maintaining ecosystem balance and ensuring the continuity of agricultural production. Its pollination activities in natural and agricultural ecosystems contribute directly to biodiversity conservation and the productivity of numerous crops. Globally, *A. mellifera* is one of the most important pollinator species actively involved in the production of more than 75% of approximately 100 major cultivated crop species (Klein et al. 2007, Tanda 2022). The ecological significance of honey bees extends beyond food production. In forest ecosystems, grasslands, and meadows, the survival of many wild plant species largely depends on bee-mediated pollination. This process is closely linked to various ecological functions, including food webs, wildlife maintenance, soil health, and the carbon cycle (Potts et al. 2010).

From an economic perspective, *A. mellifera* provides both direct and indirect contributions. Direct contributions include honey, pollen, propolis, royal jelly, and beeswax, collectively representing a multibillion-dollar global market. Indirect contributions are realized through pollination services that enhance the value of agricultural products. According to the Food and Agriculture Organization (FAO), animal pollinators collectively contribute an estimated USD 235-577 billion per year (2015 USD) to global crop production; managed honey bees together with wild pollinators supply most of these services, although non-bee taxa (e.g. flies, butterflies, birds, bats) are regionally important (FAO, 2019). While beekeeping is often considered an accessible livelihood option, modern apiculture typically requires investments in hive and extraction equipment, ongoing disease and pest management (e.g. Varroa control), supplemental feeding, and beekeeper training, which collectively determine economic viability and sustainability (Gallai et al. 2025, Crane 1990, FAO 2021b, FAO 2025b, Fusté-Forné et al. 2025).

Plant protection refers to all preventive, mechanical, biological, and chemical methods applied against harmful organisms (diseases, pests, weeds, etc.) that adversely affect crop production. These practices are crucial for safeguarding plant health and enhancing agricultural productivity (Finger et al. 2025, Tiryaki et al. 2010). Plant protection strategies may be implemented individually or in integrated approaches, with their success being crucial for both environmental health and economic sustainability. Conventional practices have been largely based on chemical control. These chemicals, collectively termed pesticides, are categorized into subgroups such as insecticides, herbicides, fungicides, acaricides, and rodenticides. However, their indiscriminate and extensive use has detrimental effects not only on target organisms but also on soil microorganisms, water resources, pollinating insects, and particularly honey bees (Aktar et al. 2009). Consequently, sustainable strategies such as Integrated Pest Management (IPM) have gained prominence in recent years. IPM emphasizes the use of chemical control only when necessary and in combination with biological, cultural, and physical control measures. This integrated approach minimizes environmental damage while preventing yield losses. The scope of plant protection is not limited to field interventions but also encompasses timing, choice of pesticide type, dosage adjustments, and application techniques, all of which play critical roles in developing environmentally friendly, bee-sensitive practices (Sanchez-Bayo & Goka 2014).

Agricultural practices aimed at combating harmful organisms, particularly through the use of chemical pesticides, seek to ensure high productivity. However, their effects are not restricted to target pests and often extend to pollinators that play an essential role in agricultural production, especially *A. mellifera* (Sanchez-Bayo & Goka, 2014). In ecosystems where agriculture and apiculture coexist, pesticide applications may lead to colony losses, behavioral disorders, and disruptions in food chains. This delicate relationship between crop protection and beekeeping has gained increasing attention in recent years, particularly due to the widespread phenomenon of colony losses globally, referred to as Colony Collapse Disorder (CCD), which has been directly linked to pesticide exposure (Wan et al. 2025; van der Sluijs et al. 2013). Notably, systemic pesticides from the neonicotinoid group have been shown to exert detrimental effects on bees' navigation, learning capacity, and immune system (Ahsan et al. 2025, Woodcock et al. 2017).

In this context, integrating apiculture and crop protection practices is crucial for both bee health and sustainable agricultural production. Environmentally friendly strategies, such as IPM, aim to reduce pesticide use while safeguarding pollinators. Furthermore, effective communication networks between farmers and beekeepers can help schedule pesticide applications at times that minimize risks to bees (Calatayud-Vernich et al. 2018). Today, although chemical pesticides are widely used to increase agricultural productivity, their harmful effects are not limited to target pests but also extend to beneficial organisms. Among these, pollinators, particularly A. mellifera, face significant risks. Bees play a vital role in food security, biodiversity preservation, and the continuity of ecosystem services (Klein et al. 2007, Potts et al. 2010). Growing scientific evidence indicates that pesticides play an increasingly recognized role in colony losses worldwide (Goulson et al. 2015).

The primary aim of this review is to examine the ecological, physiological, and toxicological impacts of pesticides used in agricultural practices on *A. mellifera*, and to evaluate protective approaches to mitigate these adverse effects. The review addresses both the direct and indirect impacts of pesticides on bees (acute toxicity, impaired orientation, immune suppression, colony collapse, etc.) by integrating experimental findings and field observations. In addition, preventive strategies such as IPM, bee-friendly pesticide selection, application timing, and farmer-beekeeper collaboration are discussed to highlight a holistic perspective on the relationship between sustainable agriculture and apiculture. This review aims to emphasize the importance of environmental management strategies for safeguarding pollinator health, thereby providing insights for both scientists and policymakers.

Agricultural Pest Control Practices

Within crop protection, chemical interventions should be reserved for instances where economic thresholds are exceeded and applied to minimize non-target impacts, particularly the translocation of systemic compounds into pollen and nectar that exposes *A. mellifera* to acute and chronic risks (Aktar et al. 2009, Sánchez-Bayo & Wyckhuys 2019, Woodcock et al. 2017). The use of chemical pesticides has significantly enhanced agricultural productivity, preventing substantial yield losses caused by pests and diseases. For instance, pesticide use has been reported to increase global agricultural production by approximately 30% (Popp et al. 2013, Oerke 2006). However, excessive and uncontrolled pesticide application has negative consequences for soil health, water quality, and non-target organisms, especially pollinators, ultimately threatening ecosystem stability (Sánchez-Bayo & Wyckhuys, 2019). Systemic insecticides, particularly those from the neonicotinoid group, can penetrate plant tissues and be transferred into pollen and nectar, which are consumed by bees, leading to acute and chronic pesticide exposure risks (Woodcock et al. 2017). Pesticide residues have also been detected in bee products and surrounding environments, indicating that these chemicals pose risks beyond target pests and may disrupt ecosystems (Çakar et al. 2019, Calatayud-Vernich et al. 2018).

The growing awareness of the ecological and environmental harms of conventional chemical control has led to the adoption of more sustainable agricultural practices. Biological control and IPM have emerged as environmentally friendly and economically viable alternatives (Parsa et al. 2014). Biological control utilizes natural enemies, including predators, parasitoids, entomopathogenic fungi, bacteria, and viruses, to suppress pest populations without harming non-target organisms and leaving behind pesticide residues (van Lenteren et al. 2018). IPM integrates chemical, biological, cultural, and physical control methods to maintain pest populations below economic thresholds while minimizing environmental impacts. IPM reduces dependency on pesticides by optimizing application timing, techniques, and target selection, thereby preventing harm to pollinators, such as *A. mellifera*. The European Union's Directive 2009/128/EC has made IPM implementation mandatory, aiming to reduce the impact of pesticides on non-target organisms (European Commission 2009).

The timing and methods of pesticide application play a critical role in both efficacy and environmental safety. Correct application ensures maximum pest control while minimizing harmful effects on pollinators and natural enemies. Application schedules are typically based on the biology of pests, climatic conditions, and crop phenology. Applying pesticides during key stages of pest development reduces pesticide use while improving effectiveness. Spraying during early morning or late evening hours, when bees are less active, is safer for pollinator health (Stoner & Eitzer 2012). Application techniques also impact the efficiency of pesticides and the risks of off-target effects. Factors such as sprayer calibration, droplet size, application height, and wind speed influence pesticide drift. Modern spraying technologies optimize droplet size and minimize wind effects, aiming to reduce environmental contamination. Additionally, precision agriculture, including GPS-assisted and drone-based localized spraying, significantly reduces pesticide use and minimizes risks to both the environment and bee health (Ye et al. 2025, Zhang & Kovacs 2012).

Pest control policies worldwide are shaped by national priorities for agricultural security, environmental protection, and public health. The Food and Agriculture Organization and the World Health Organization (WHO) provide frameworks for pesticide use and pest management (FAO 2021a, FAO 2025a). The European Union has integrated IPM into its regulations through Directive 2009/128/EC, which aims to reduce pesticide-related risks to human health and the environment while promoting the use of biological control (European Commission 2009). In Türkiye, pest control policies are managed by the Ministry of Agriculture and Forestry, in collaboration with the Ministries of Environment, Agriculture, and Health. Turkish regulations are increasingly aligned with EU standards, with several initiatives aimed at promoting IPM practices nationwide (T.C. Tarım ve Orman Bakanlığı 2022). Globally and in Turkey, reducing pesticide use and protecting beneficial organisms such as bees remain key policy priorities. Implementing pollinator-risk-mitigation practices in pesticide use, optimizing application timing, and promoting biological control are central to these objectives (Altıkat et al. 2009).

Effects on *Apis mellifera*

Pesticides used in agricultural pest control can cause both acute and chronic toxic effects on *A. mellifera*. Acute toxicity typically results from short-term exposure to high doses, leading to rapid mortality, impaired motor skills, and loss of coordination (Buluş et al. 2025, Mullin et al. 2010). Chronic toxicity, however, arises from long-term exposure to low doses and manifests in weakened immune responses, reduced reproductive capacity, impairments in learning and memory, navigation problems, and overall weakening of the colony (Henry et al. 2012, Woodcock et al. 2017). Collectively, acute and chronic pesticide toxicities contribute to significant declines in bee colony health and, through interactions with other stressors in this multifactorial context, have been associated with CCD (Goulson et al. 2015). Pesticides' synergistic effects, when combined with other stressors such as parasites, poor nutrition, and habitat loss, further exacerbate toxicity (Sánchez-Bayo & Wyckhuys 2019).

Pesticide exposure also diminishes the effectiveness of communication within the colony, particularly the waggle dance used to convey foraging information, which weakens knowledge transfer and foraging efficiency (Tison et al. 2017). Additionally, foraging behavior is disrupted, with pesticides altering the duration, preferences, and intensity of nectar and pollen collection, thus reducing nutritional quality and negatively affecting reproduction and colony development (Yang et al. 2008).

Pesticides used in crop protection not only affect worker bees but also impact reproductive individuals, including queens and drones, which are essential for colony survival and genetic integrity. Queen health is crucial for egg-laying, mating success, and pheromone production, and pesticide exposure can impair these functions, particularly under exposure to neonicotinoids. This leads to reduced queen longevity and reproductive capacity (Williams et al. 2015). Colony-level pesticide exposure can lower queen survival and significantly reduce the number of fertilized eggs (Tsvetkov et al. 2017). Drones are particularly vulnerable, as pesticide residues can reduce sperm viability and motility, compromising the queen's ability to store viable sperm for future reproduction (Chaimanee et al. 2016).

The immune system of honey bees plays a critical role in protecting against pathogens and maintaining colony health. However, systemic insecticides and fungicides suppress immune functions and disrupt beneficial gut microbiota. Neonicotinoids and organophosphates, for example, downregulate immune-related genes, increasing susceptibility to viral infections (Di Prisco et al. 2013, Motta et al. 2024). Furthermore, pesticides reduce the abundance and diversity of beneficial gut bacteria, which impairs nutrient absorption, toxin detoxification, and resistance to pathogens (Kakumanu et al. 2016). Disruption of the microbiota fosters opportunistic pathogens like *Nosema spp.*, which accelerates colony collapse (Doublet et al. 2015). These effects highlight that pesticides harm not just individual bees, but also colony-wide immunity and resilience (Pettis et al. 2012).

Colony Collapse Disorder, characterized by sudden and unexplained losses of worker bees, poses a significant threat to global apiculture. While CCD is caused by multiple factors, pesticides are considered a major trigger (Sánchez-Bayo & Goka 2014). Neonicotinoid insecticides, such as imidacloprid, thiamethoxam, and clothianidin, impair bees' navigation and neurological functions, preventing them from returning to their hives, which is a hallmark of CCD (Goulson et al. 2015, Henry et al. 2012). Additionally, pesticides interact with pathogens, such as viruses and *Nosema spp.*, suppressing immunity and making colonies more vulnerable to collapse (Pettis et al. 2012). International bodies such as the FAO and European Food Safety Authority (EFSA) have recognized the risks pesticides pose to pollinators, prompting several countries to restrict the use of certain neonicotinoids (EFSA 2018, EFSA 2023, FAO 2019).

Pesticides affect not only honeybees but also wild pollinators, such as bumblebees, solitary bees, butterflies, and flies. Although honey bees may show relatively higher tolerance, wild pollinators are often more sensitive (Arena & Sgolastra 2014). For example, neonicotinoids harm both *A. mellifera* and *Bombus terrestris*, but bumblebees are generally more susceptible (Woodcock et al. 2017). Solitary bees face even greater risks, as the death of a single individual can lead to reproductive failure, making pesticide effects irreversible (Sgolastra et al. 2018). Although the *A. mellifera* has historically served as the primary surrogate in pesticide risk assessment, the revised EFSA guidance (2023) extends the framework to bumble bees (*Bombus* spp.) and solitary bees, with tiered exposure and effects endpoints-thereby directly addressing concerns that single-species assessments may underestimate risks to other pollinators (EFSA 2023, Stokstad 2013).

Routes of Exposure

Positioning bee colonies near agricultural fields is a common practice in beekeeping, aimed at maximizing pollination services. However, this strategy increases the exposure of bees to pesticides, particularly during spraying events. Agrochemicals, including systemic neonicotinoids, pyrethroids, and fungicides, can affect bees directly through contact with spray clouds and indirectly through contaminated pollen, nectar, and water (van der Sluijs et al. 2013, Mullin et al. 2010). When hives are positioned within 50-300 meters of treated areas, the likelihood of direct exposure increases significantly (Stewart et al. 2014). If spraying coincides with peak foraging periods, usually in the early morning or around sunset, the risk of acute toxicity is further elevated (Decourtye et al. 2004).

The level of exposure depends on various factors, such as the method of pesticide application (aerial, backpack, or irrigation), formulation type, weather conditions, and hive placement. These exposures affect not only the health of individual bees but also colony productivity, navigation abilities, larval development, and queen health (Henry et al. 2012). To reduce exposure, careful hive placement, adjusting application schedules to avoid bee activity, and effective communication between farmers and beekeepers are essential. In the European Union and several other countries, regulations require beekeepers to be notified before pesticide applications (EFSA 2013, European Commission 2019).

Pesticides also harm bees through environmental contamination. Bees ingest pesticide residues when they consume contaminated pollen, nectar, and water, which can lead to chronic toxicity, immune suppression, behavioral changes, and even colony collapse. Systemic pesticides, such as neonicotinoids, are absorbed by plants and spread throughout their tissues, including pollen and nectar. As a result, even untreated plants grown from treated seeds or plants exposed to systemic chemicals may contain pesticide residues (Carroll et al. 2024, Mullin et al. 2010, Tsvetkov et al. 2017).

Moreover, pesticide residues can spread through surface runoff, volatilization, and spray drift, contaminating water sources that bees use. Water is essential for both individual consumption and hive temperature regulation, so such contamination can distribute pesticides throughout the colony (Hladik et al. 2016, Samson-Robert et al. 2014). The EFSA now recommends that pesticide risk assessments encompass multiple bee taxa (honey bees, bumble bees, solitary bees) and incorporate dynamic exposure simulations (ApisRAM) and realistic environmental scenarios, thereby moving beyond single-species/static approaches to better capture both direct applications and secondary contamination pathways across the pollinator life cycle (EFSA 2023).

Pesticides applied through aerial spraying or dusting can disperse into the environment, affecting ecosystems far beyond the target areas. Wind can carry airborne pesticide particles to hives, flowering plants, water sources, and natural habitats. This phenomenon, known as "drift," contributes to both direct and indirect pesticide exposure in bees (EFSA 2013). Airborne pesticides can cause acute toxicity at high doses and neurotoxic or behavioral impairments at lower, sublethal levels. Spraying during early morning, when bees are active and foraging, often leads to high mortality due to direct exposure to pesticide clouds (Long & Krupke 2016). Furthermore, pesticide residues deposited on wildflowers contribute to prolonged exposure (David et al. 2016).

Systemic seed treatments, especially those using neonicotinoids, also represent significant routes of airborne exposure. Dust from treated seeds can be released during planting and carried by machinery. Krupke et al. (2012) found neonicotinoid residues in air samples and nearby flowering plants during periods of peak bee mortality, indicating that pesticide particles can travel kilometers beyond target fields.

Bee exposure to pesticides is influenced not only by the type of chemical or application method, but also by climate and seasonal factors. Temperature and timing are particularly important in determining exposure intensity. High temperatures coincide with peak foraging activity, increasing the likelihood of direct contact with pesticides. Heat also accelerates volatilization, prolonging pesticide persistence in the air and thereby increasing inhalation and contact risks (EFSA 2013, David et al. 2016).

Pesticides are often applied during flowering periods, which coincide with the peak of bee activity (Tsvetkov et al. 2017). Applications during spring and summer pose greater risks to colony health, as systemic pesticides directly contaminate pollen and nectar. Wind and rainfall further influence pesticide exposure. Wind increases pesticide drift to non-target areas, while rainfall after application enhances pesticide runoff into soil and water, creating additional exposure pathways (Hladik et al. 2016).

Global climate change is also altering crop phenology and pest populations, increasing the frequency of pesticide spraying and extending periods of bee vulnerability. Rising temperatures affect bee metabolism and pesticide toxicokinetics, potentially intensifying the toxic effects on bees (Goulson et al. 2015).

Protective Measures and Proposed Solutions

Integrated Pest Management (IPM) Approaches: Modern agricultural practices often rely on pesticide use for pest control; however, these chemicals pose significant risks not only to target pests but also to overall biodiversity, particularly beneficial pollinators like bees. Despite their critical role in agriculture and ecosystem health, bees are frequently overlooked in conventional pest control strategies (Goulson et al. 2015). Integrated Pest Management offers an environmentally friendly solution by reducing pesticide use and employing preventive, biological, and cultural control methods (Kogan, 1998). IPM prioritizes pesticide application as a last resort, recommending treatments during periods when bees are least active. It also incorporates strategies to minimize off-target effects, such as using selective pesticides, optimizing application timing, spot treatment, and establishing buffer zones (Van der Sluijs et al. 2013).

Bee-Safeguarding Methods Within IPM: One of the key components of IPM is adjusting application timing. Pesticides should be applied when bees are least active, such as after sunset, to minimize direct exposure (EFSA 2013). Preference should be given to biological and mechanical control methods that utilize natural pest predators and cultural practices, such as crop rotation and weed management. These techniques reduce the need for chemical interventions (Kremen & Miles 2012). Careful pesticide selection is also essential-choosing products that are less harmful to bees. For instance, systemic neonicotinoids can be replaced with less persistent, contact-active products (Siviter et al. 2021). Additionally, pesticide use should be avoided during flowering periods, when foraging activity is highest and the risk of exposure is greatest (Tsvetkov et al. 2017). Buffer zones around agricultural fields and clear communication with beekeepers about spraying schedules can further reduce pesticide exposure (Nicholls & Altieri 2013). Regular IPM training for farmers, combined with regulatory oversight, ensures responsible pesticide use (OECD, 2006).

Bee-Friendly Pesticide Selection and Application Scheduling: Pesticides can harm bees not only through acute toxicity but also by causing indirect behavioral and physiological effects (Sánchez-Bayo & Goka 2014). Therefore, selecting bee-friendly pesticides and ensuring proper application timing is crucial for both maintaining agricultural productivity and protecting bee health. When pesticide use is unavoidable, products should be selected for low acute oral/contact toxicity to bees, minimal residual persistence, and reduced exposure potential (e.g. non-dusty formulations), acknowledging that these features reduce-but do not eliminate-risk, especially if applications coincide with bloom or peak foraging. Pesticide risk assessments should consider not only acute toxicity but also sublethal effects and behavioral impacts on bees (EFSA 2013). Neonicotinoids, such as imidacloprid and clothianidin, are particularly harmful to bee navigation and foraging abilities (Henry et al. 2012). Therefore, when chemical control is unavoidable, more selective insecticides with lower acute bee-hazard profiles, such as flonicamid (aphicide) or chlorantraniliprole (anthranilic diamide), may be preferred, applied outside bloom/peak foraging times, and in strict compliance with label pollinator-protection statements. Systemic options, such as flupyradifurone, should be used with caution, as context and exposure level can determine sublethal effects on behavior and colony function (Hesselbach et al. 2018, Meikle et al. 2022, Siviter et al. 2021). Pesticide application should occur during periods when bees are not foraging, typically in the early morning or late evening, to reduce exposure risks. Additionally, pesticide use during flowering should be avoided or limited to crops that bees do not visit, thereby preventing the transfer of residues via pollen and nectar (Tsvetkov et al. 2017).

Farmer-Beekeeper Collaboration and Communication Strategies: The increased scientific and public awareness of pesticide risks to pollinators, especially honeybees, underscores the importance of effective communication and collaboration between farmers and beekeepers to mitigate exposure (Park et al. 2015). A major challenge in reducing exposure is the lack of communication about pesticide application schedules in areas where hives are present. By informing beekeepers in advance, they can take preventive actions such as relocating hives or restricting flight paths (Klein et al. 2007). Many countries have established local coordination committees to align agricultural practices with pollinator safety. In Turkey, the Ministry of Agriculture and Forestry supports such initiatives through "Beekeeping Development Projects" (T.C. Tarım ve Orman Bakanlığı 2022).

Training and awareness-raising are critical components for reducing pesticide risks. Strategies should focus on educating farmers and beekeepers on topics such as identifying hazardous pesticides, the importance of applying treatments after sunset, avoiding pesticide use during flowering, and promoting bee-friendly biological and integrated pest management methods. International organizations such as FAO and Organisation for Economic Co-operation and Development (OECD) have developed joint training modules and guidelines (FAO 2025b, OECD 2023). Additionally, digital tools and SMS-based early warning systems have proven effective in providing timely notifications to beekeepers.

Policy-Level Recommendations: Policies should mandate pre-spray notifications to beekeepers and integrate hive location data into agricultural systems to protect sensitive areas. Pesticide registration should include bee-specific risk assessments, including considerations for wild pollinators, not just honey bees (EFSA 2013, Vanbergen et al. 2013).

Hive Protection and Alternative Placement Strategies: Pesticide exposure, especially to systemic compounds, can significantly harm non-target pollinators. Therefore, protecting and strategically placing hives is essential for reducing exposure to *Apis mellifera* (Sánchez-Bayo & Goka 2014, EFSA 2013).

Hive Protection: Physical measures such as temporarily closing hive entrances before pesticide applications can be effective, especially when treatments occur outside bee flight hours (van der Steen et al. 2012). Placing hives in shaded areas and protecting them from wind reduces exposure to pesticide drift. Relocating hives 3-5 km away from treated areas, particularly during flowering or when systemic pesticides are used, helps further protect colonies (Tsvetkov et al. 2017).

Alternative Placement Strategies: Precision agriculture techniques, such as mapping pesticide intensity, can guide hive placement in low-risk areas (Henry et al. 2012).

Legal Regulations and Legislative Proposals: Pesticide-related risks to pollinators, particularly honey bees, represent a significant environmental challenge at the intersection of sustainable agriculture and apiculture (EFSA 2013).

Existing Regulations:

European Union: The EU has developed a risk assessment system guided by EFSA’s framework, which addresses acute, chronic, and developmental effects on bees. In 2018, the EU banned the open-field use of three neonicotinoids (imidacloprid, clothianidin, thiamethoxam) (EFSA 2018).

US EPA: The EPA's 2019 Pollinator Protection Initiative strengthens pesticide labeling and encourages state-level Managed Pollinator Protection Plans (MP3s) (EPA 2022).

Türkiye: In Türkiye, regulations are governed by the “Regulation on the Registration of Plant Protection Products” and the “Communiqué on Good Agricultural Practices.” However, challenges in enforcement hinder effective exposure prevention (Yılmaz et al. 2024).

Legislative Proposals and Policy Needs: Time-of-Day Restrictions: It is crucial to prohibit spraying during peak bee flight periods and require evening applications to minimize exposure (Sponsler & Johnson 2017).

Mandatory Farmer-Beekeeper Communication: Digital notification systems should be implemented to ensure beekeepers are informed of pesticide applications ahead of time (FAO 2021b).

Expanded Risk Tests: Risk assessments should consider not just honey bees but also wild pollinators (e.g., Bombus spp., Osmia spp.) in pesticide registration processes (EFSA 2013).

Stronger Enforcement and Training: Pesticide applicators should be required to undergo training, and inspection mechanisms should be strengthened (T.C. Tarım ve Orman Bakanlığı 2022).

International Agreements and Alignment: The Convention on Biological Diversity (CBD) and Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) reports emphasize the link between pollinator protection and food security, advocating for national action plans to safeguard pollinators (IPBES 2017). Integrating pesticide regulations into national apiculture strategies will benefit both environmental and economic sustainability.

Organic Agriculture and Compatibility with Beekeeping: A highly effective strategy to reduce pesticide exposure is to integrate agricultural production with organic farming and harmonize beekeeping practices accordingly. Organic farming minimizes synthetic inputs, offering an environmentally sustainable and pollinator-conscious approach that aligns with natural cycles (IFOAM 2024).

Contributions of Organic Farming to Bee Health: In organic farming, the use of synthetic pesticides, herbicides, and fungicides is prohibited or strictly limited, thus reducing both direct and indirect exposure of pollinators like *Apis mellifera*. Studies show that colonies near organic fields exhibit stronger immunity, lower pesticide burdens, and better overall stability than those near conventional farming (Mullin et al. 2016, Tsvetkov et al. 2017).

Alternative Methods in Organic Farming: Organic pest management employs biological, mechanical, and cultural techniques that do not harm bees. For example:

Biological Control: Beneficial insects (parasitoids and predators) can naturally control pests, reducing reliance on chemicals (FAO 2019).

Botanical Pesticides: Natural products such as neem oil (*Azadirachta indica* A. Juss., Meliaceae) and pyrethrins are less toxic to bees compared to synthetic chemicals (Isman 2006).

By combining IPM with organic farming, bee-friendly production systems can be developed (Benbrook 2021).

Alignment with Organic Beekeeping: Organic beekeeping, aligned with organic farming practices, offers environmental benefits and enhances product safety. In Turkey, the “Regulation on the Principles and Implementation of Organic Farming” mandates that organic beekeepers place hives within certified organic zones, reducing exposure to crop protection chemicals (T.C. Tarım ve Orman Bakanlığı 2022).

Adoption and Scaling Recommendations: Spatial Planning of Farmland and Apiaries: Place hives near organic farming areas to strategically reduce pesticide exposure.

Farmer-Beekeeper Collaboration: Enhanced coordination between farmers and beekeepers can promote pollinator-friendly agricultural landscapes.

Public Incentives: Government support for organic farming and beekeeping will provide long-term benefits for food security and biodiversity (IFOAM 2024).

Conclusion

While crop protection practices are indispensable to modern agriculture, they exert substantial ecological and biological impacts on *A. mellifera,* a foundational component of ecosystems. In particular, the uncontrolled use of chemical pesticides-or their application without regard to bee health-can lead to acute and chronic toxicity, behavioral disturbances, immune suppression, reproductive impairment, dysbiosis of the gut microbiota, and, most critically, CCD, all of which are difficult to reverse. These outcomes threaten not only bee populations but also the sustainability of pollination-dependent agricultural production and biodiversity at large.

The evidence synthesized in this review underscores the need to develop and scale up bee-friendly agricultural practices. In this context, strategies such as biological and integrated pest management approaches, organic production systems, judicious pesticide selection, application schedules that consider bee activity, safe hive placement at appropriate distances from croplands, and robust farmer–beekeeper collaboration can safeguard both agricultural productivity and bee health. Moreover, revising crop protection policies in Türkiye and globally to align with pollinator-friendly principles, updating legislation, and strengthening enforcement mechanisms are of critical importance. By adopting a balanced approach at the interface of apiculture and agriculture, both food security and ecosystem services can be maintained sustainably.

In sum, protecting *Apis mellifera* is a shared responsibility not only of beekeepers but of all stakeholders in the agricultural sector. Through policies informed by scientific evidence and the adoption of environmentally sound practices, the future of both bees and agriculture can be secured.

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