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Review
(Derleme)

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Effects of pesticides on *Apis mellifera* L. (Hymenoptera: Apidae) and their residues in honey

Pestisitlerin *Apis mellifera* L. (Hymenoptera: Apidae) üzerindeki etkileri ve baldaki kalıntıları

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ABSTRACT

Objective: This review critically examines recent studies on the toxicological effects of pesticides in honey bee (*Apis mellifera* L. (Hymenoptera: Apidae)) and the subsequent residue levels in honey.

Material and Methods: The review synthesizes findings from various recent studies that investigate the acute and chronic toxicity of commonly used insecticides, acaricides, fungicides, and herbicides in honey bee behaviour, physiology, and colony health.

Results: The evidence suggests that even sub-lethal doses can impair foraging ability, navigation, and reproductive success, leading to long-term effects on colony stability.

Conclusion: Further research is required to elucidate the complex interactions between pesticides, bees, and environmental factors. Simultaneously, the development of more sustainable pest management strategies is vital to safeguarding pollinator health and preserving biodiversity.

Keywords: Acaricides, fungicides, herbicides, honey, honey bee, insecticides

ÖZ

Amaç: Bu derleme, bal arılarında (*Apis mellifera* L. (Hymenoptera: Apidae)) pestisitlerin toksikolojik etkilerine ve balda kalıntı düzeylerine ilişkin son çalışmaları eleştirel bir bakış açısıyla incelemektedir.

Materyal ve Yöntem: Bu derleme, yaygın olarak kullanılan insektisit, akarisit, fungisit ve herbisitlerin bal arılarının davranışları, fizyolojileri ve koloni sağlığı üzerindeki akut ve kronik toksisitelerini inceleyen çeşitli güncel çalışmalardan elde edilen bulguları sentezlemektedir.

Araştırma Bulguları: Elde edilen bulgular, ölümcül olmayan dozların dahi arıların yiyecek arama yetilerini, yön bulma becerilerini ve üreme başarılarını olumsuz etkileyebileceğini, bunun da koloni stabilitesi üzerinde uzun vadeli sonuçlara yol açabileceğini ortaya koymaktadır.

Sonuç: Pestisitler, arılar ve çevresel faktörler arasındaki karmaşık etkileşimlerin anlaşılabilmesi için daha fazla araştırma yapılması gereklidir. Aynı zamanda, tozlayıcıların sağlığını ve biyolojik çeşitliliğini korumaya yönelik daha sürdürülebilir zararlı kontrol yöntemlerinin geliştirilmesi oldukça hayatidir.

Anahtar sözcükler: Akarisit, fungisit, herbisit, bal, bal arısı, insektisit

INTRODUCTION

Pesticides, encompassing both chemical and biological forms, are vital tools in modern agricultural practices, primarily used to manage pests such as insects, weeds, fungi, and rodents (Kuşaksız & Çimer, 2019; Dede et al., 2022; Leite et al., 2022; Chaudhary et al., 2024; Jeschke 2024; Yaraşır et al., 2024a). Despite their significant role in enhancing agricultural output, the impact of these substances on non-target organisms has generated considerable concern (Du et al., 2022; Ádám et al., 2024; Kaur et al., 2024; Yaraşır et al., 2024b; Harbi et al., 2025). Of particular concern is the toxic effect of pesticides in honey bee populations, which has been linked to disruptions in their physiology, behavior, and overall colony health. Neonicotinoids, including imidacloprid and clothianidin, are key contributors to this issue, with evidence demonstrating their adverse effects on the behavior and physiological functions of the honey bee, *Apis mellifera* L. (Hymenoptera: Apidae). Prolonged exposure to these compounds leads not only to acute toxicity but also to sublethal effects, which compromise the bees' foraging efficiency, cognitive abilities, and immune system functioning (Colin et al., 2019; Cook 2019; Colin et al., 2020). Research suggests that the combined use of neonicotinoids with other substances, such as miticides, can intensify these negative outcomes, further impairing cognitive functions critical to colony survival (Williams et al., 2015; Chakrabarti et al., 2020; Colin et al., 2020).

The resulting oxidative stress can disrupt essential bee activities, ultimately influencing colony productivity and overall health (Pettis et al., 2013; Chakrabarti et al., 2014). Additionally, the organ responsible for metabolizing various compounds and maintaining physiological balance in honey bees may also be adversely affected by pesticide exposure, underscoring the broader impact these substances have on bees' foraging behavior, brood care, and hive maintenance (Cook, 2019; Das et al., 2024; Frizzera et al., 2024).

The consequences of pesticide exposure extend beyond individual bees, affecting complex interactions within the hive ecosystem. For example, neonicotinoid exposure has been linked to increased vulnerability to pathogens, such as *Nosema ceranae*, which can lead to higher incidence of disease (Pettis et al., 2012; Pettis et al., 2013).

This interaction between pesticide exposure and pathogen susceptibility creates a precarious health environment for honey bees, decreasing the resilience of colonies and contributing to elevated mortality rates (Naggar & Baer, 2019). Furthermore, pesticide residues can accumulate in hive products, including honey and beeswax, raising concerns not only for bee health but also for human safety (Mullin et al., 2010; Sánchez-Bayo & Goka, 2014; Lucas et al., 2022).

Examining the broader environmental context, research highlights a concerning correlation between intensive agricultural practices that heavily rely on pesticide use and the decline in bee populations, especially in highly cultivated regions (Mallinger et al., 2015; Heard et al., 2017). Pesticide residues in pollen and nectar can adversely affect larval development, leading to long-lasting toxic effects even after initial exposure has ceased (Chakrabarti et al., 2014; Sansar, 2021). Consequently, it is crucial to monitor pesticide levels in bee habitats to safeguard their health and well-being, which emphasizes the urgent need for regulatory frameworks to minimize harmful pesticide exposure (Mullin et al., 2010; McArt et al., 2017; Tosi et al., 2022). As pollinators are vital for both ecosystem stability and agricultural productivity, understanding and mitigating the risks posed by these chemicals is essential for the development of sustainable pest management strategies (Lucas et al., 2022; Bütüner et al., 2024; Dede et al., 2024; Harran et al., 2024; Li et al., 2024). This study aims to review recent findings on the toxic effects of pesticides on *A. mellifera* and the effects of their residues on the honey they produce, and to highlight the need for sustainable pest management practices.

Toxic Effects of Pesticides on Honey Bees

The toxicological impact of pesticides on bee populations, particularly honey bees, has garnered significant attention due to their essential role in pollination and global food production. Research surrounding pesticide toxicity reveals a complex array of effects, including not only direct lethality but also sublethal consequences that adversely affect bee health, behavior, and colony survival (Das et al., 2024; Margaoan et al., 2024; McGruddy et al., 2024; Rinkevich et al., 2025).

A central issue identified in this context is the dependence of beekeepers on toxic pesticides to manage pests, particularly, the parasitic mite *Varroa destructor* (Arachnida: Varroidae), a major threat to honey bee populations. According to McGruddy et al. (2024), many beekeepers express concerns about the toxicity of these necessary treatments, which, despite their efficacy in pest control, pose significant risks to the health of honey bees. Additionally, Sadia et al. (2024) underscore that improper pesticide use is a global threat to honey bee populations, exacerbating the ongoing decline of these crucial pollinators. This highlights the systemic challenge of balancing effective pest management with the preservation of bee health. Beyond lethality, the impact of pesticides includes various sublethal effects, particularly on cognitive functions such as learning and memory. In addition, Haran et al. (2024) explore the biochemical mechanisms through which pesticides disrupt vital energy metabolism in honey bees, particularly through the inhibition of succinate dehydrogenase. This metabolic disruption not only affects individual bees but can also have cascading consequences for the entire colony, potentially contributing to broader phenomena such as hive depopulation syndrome (HDS). Contributing factors such as climate change and habitat degradation further exacerbate the challenges faced by bee populations (Bava et al., 2024). The studies carried out by Morrison et al. (2025) showing declines in bee populations correlate strongly with increased pesticide exposure, with multispecies research indicating reduced reproduction and survival rates under sublethal pesticide conditions. The consequences for agriculture are significant, as the decline in pollinator populations poses a direct threat to crop yields and food security; with Das et al. (2024) linking reduced pollinator visitation rates to decreases in crop output. Furthermore, ongoing research has highlighted potential mitigation strategies, including the use of natural compounds to counteract pesticide toxicity. Recent studies suggest that certain polyphenolic compounds may offer protective effects against pesticide-induced toxicity in honey bees (Bava et al., 2024). This points to the urgent need to develop non-toxic pest management alternatives that safeguard both agricultural productivity and pollinator health.

In a similar study, Haran et al. (2024) explored the mechanisms by which pesticides inhibit respiratory enzymes in honey bees, suggesting that disruptions to mitochondrial function could exacerbate population declines and, in turn, influence honey stability and quality. These findings underscore the importance of reassessing pesticide regulations to minimize their toxic effects on bee health and, by extension, the quality of honey.

Toxic effects of insecticides and acaricides

Insecticides, particularly neonicotinoids and pyrethroids, as well as commonly used acaricides such as cyflumetofen, have been shown to exert both lethal and sublethal effects on *A. mellifera*. These include impaired foraging behaviour, reduced cognitive function, disrupted gene expression, and increased mortality. Sublethal exposures may alter detoxification enzyme activity, interfere with neurological pathways, and suppress immune responses. The combined or sequential use of insecticides and acaricides can also result in synergistic toxicity (Mullin et al., 2010; Lucas et al., 2022; Chen et al., 2024; Frizzera et al., 2024). For instance, Li et al. (2024) comparatively examined the toxic effects of chlorantraniliprole, one of the widely used diamide insecticides, on two honey bee species: *A. mellifera* and *Apis cerana* (Hymenoptera: Apidae). The findings revealed that *A. cerana* exhibited greater sensitivity to chlorantraniliprole (48-hour LC_{50} value: 109.709 mg/L) and that prolonged exposure to low doses impaired both sucrose responsiveness and climbing activity in the species. Alterations in antioxidant enzyme activities and differences in the expression of immunity-related genes indicated significant biochemical and molecular adaptive responses between the species. Notably, *A. mellifera* showed suppression of immune-related and endoplasmic reticulum stress response genes at low chlorantraniliprole concentrations, whereas *A. cerana* exhibited more limited genetic changes. The study underscores the species-specific toxic effects of chlorantraniliprole in honey bees and highlights the necessity of accounting for such interspecies differences in pesticide risk assessments and safety regulations. Similarly, Chen et al. (2024) aimed to address the gap in the existing literature regarding mixed pesticide toxicity by investigating the toxic effects of pesticides in honey bees at both individual and combined levels. The study assessed the acute and chronic toxicities of abamectin and lambda-cyhalothrin under laboratory conditions. The results demonstrated that abamectin exhibited higher acute toxicity to honey bees compared to lambda-cyhalothrin; however, the mixture of abamectin and lambda-cyhalothrin produced an antagonistic effect at the acute level. Additionally, the combination was found to induce notable disruptions in the gut microbiota of honey bees, along with significant impairments in the expression of immunity-related genes and the activity of detoxification enzymes. Also, Frizzera et al. (2024) demonstrated that the seemingly benign individual effects of pesticides may lead to severe outcomes when considered in conjunction with other environmental stressors. In their study, the effects of sulfoxaflor in honey bees were tested within a multifactorial framework that included additional stress factors such as parasite presence, suboptimal temperatures, and nutritional scarcity. The results indicated that although field-realistic exposure to sulfoxaflor did not cause direct mortality, it led to significant changes in the expression of specific genes. These findings underscore that the sublethal effects of pesticides may not be detectable through conventional single-factor toxicological approaches, thereby highlighting the necessity of multifactorial evaluations in pesticide risk assessments.

The study by El Agrebi et al. (2024) developed a novel *in vivo* model to evaluate the effects of exposure to pesticides and beeswax additives on gene expression in honey bee larvae under realistic conditions. In their study, larvae were reared in beeswax contaminated with acrinathrin, chlorpyrifos-ethyl, and stearin, and the expression of genes related to immunity and detoxification was analyzed. The results showed that exposure to acrinathrin triggered an immune response and significantly upregulated the expression of the CYP6AS14 gene. In contrast, exposure to chlorpyrifos-ethyl led to the suppression of expression in most of the tested immune and detoxification genes. Stearin exposure, particularly at higher concentrations, resulted in increased larval mortality and marked alterations in both immune and detoxification responses. Similarly, Choi et al. (2024) investigated the acute and chronic exposure of honey bee larvae to lambda-cyhalothrin and spinetoram pesticides. Both pesticides adversely affected the development of honey bees and caused changes in enzyme activities. Lambda-cyhalothrin and spinetoram, increased the activities of detoxification and antioxidative enzymes, while also impacting neurotransmission enzymes. Similarly, Bixby et al. (2024) investigated the effects of neonicotinoid-type pesticides on *A. mellifera*. The study covered a field experiment conducted in 2020 and 2021 in blueberry fields in British Columbia. Honey bee colonies were placed in areas both near and far from highbush blueberry fields, and pesticide levels in these areas were determined. The study found that neonicotinoids, particularly clothianidin and thiamethoxam, caused toxic effects on bee colonies, with these pesticides exceeding international safety limits. Additionally, colonies exposed to these pesticides exhibited both lethal and sublethal effects, leading to losses in honey production and issues with colony health. However, the study by Kadala et al. (2024) emphasizes that current pesticide risk assessment systems do not adequately consider the effects of low doses on off-target species. The study on honey bees found that newly emerged bees were more sensitive to deltamethrin, a common pyrethroid insecticide, compared to 6-day-old bees. Lethal doses were observed at lower levels in D1 bees, with an LD_{50} value of 11 ng/bee. Moreover, even at non-lethal low doses (0.75, 1.5, and 3 ng/bee), significant reductions in mobility and increased periods of immobility were detected in D1 bees. At the cellular level, it was demonstrated through patch-clamp experiments that deltamethrin slowed the kinetics of voltage-gated sodium channels (NaV). Similar effects were observed with two other pyrethroids, such as cypermethrin. The study suggests that combining behavioural tests with cellular toxicity measurements could contribute to more accurate assessments of the toxic effects of pesticides.

Another study carried out by Pham et al. (2025) highlighted the economic importance of beekeeping in Vietnam and the threat posed by pesticide use to this sector, investigating the pesticide toxicities in different honey bee species. The study evaluated the oral toxicities of five commonly used agricultural insecticides (bifenthrin, imidacloprid, thiacloprid, thiamethoxam, and chlorantraniliprole) on four honey bee species, the Asian honey bee, *A. cerana*, the European honey bee, *A. mellifera*, the giant honey bee, *Apis dorsata* (Hymenoptera: Apidae), and the red dwarf honey bee, *Apis florea* (Hymenoptera: Apidae). The findings revealed significant differences in toxicity among the pesticides and bee species. Among the managed species, *A. cerana* exhibited the highest tolerance to all insecticides, while the wild species *A. dorsata* and *A. florea* displayed greater sensitivity. The study emphasised that relying solely on *A. mellifera* in pesticide risk assessments is insufficient and that other honey bee species should also be incorporated into protection strategies.

On the other hand, the acute exposure of *A. mellifera* to cyflumetofen, a pesticide used on plants such as apples, coffee, and citrus, was investigated by Reis et al. (2024). The study revealed histopathological and cytological damage in the bees' stomach, hypopharyngeal glands, and fat tissue. The stomach epithelium exhibited cellular changes indicative of cell death and autophagy. While the hypopharyngeal glands produced more secretions, no changes were observed in the fat tissue. These findings suggest that cyflumetofen negatively affects honey bees, potentially impairing their survival and pollinator behaviour.

In the study conducted by Oliveira et al. (2024), the sensitivity of the honey bee *A. mellifera* to chronic exposure to teflubenzuron and the associated histopathological changes in the midgut tissue were evaluated. Worker bees were orally exposed to field-realistic concentrations of teflubenzuron, resulting in a mortality rate of 81.54%. Severe structural alterations were observed in the midgut epithelium, including vacuolisation, cell lysis, apocrine secretion, nuclear pyknosis, loss of cellular integrity, and damage to the peritrophic matrix. These findings indicate that, despite Teflubenzuron being classified as safe for non-target insects, chronic exposure may exert significant toxic effects in honey bees. Also, in the study conducted by Rükün et al. (2025), the effects of sublethal doses of imidacloprid exposure on honey bees, *A. mellifera*, on colour memory and visual preferences were investigated. In the study, free-flying worker bees were trained to visit a yellow artificial flower feeder and then released into an area with flowers of different colours. Bees exposed to imidacloprid doses greater than 4% of the LD_{50} value were observed to lose their preferential visits to yellow flowers, likely reverting to basic feeding preferences. Despite the expectation that colour discrimination would be easy, it was found that the bees had lost this ability. Additionally, pesticide exposure led to an increase in the expression of the genes Lop1, UVop, and Blop, while the expression of the CaMKII and CREB genes decreased. The study suggests that memory loss may be the underlying mechanism for the altered colour preferences in bees. In this regard, the study highlights that pesticides may also cause disruptions in the nervous system of bees, leading to cognitive memory impairments.

Toxic effects of fungicides

Although traditionally considered less harmful to pollinators, fungicides have been increasingly recognised, for their sublethal toxicity in honey bees. Certain compounds, such as chlorothalonil and propiconazole, can disrupt detoxification pathways, suppress immune-related gene expression, and alter gut microbiota composition. Moreover, fungicides may synergize with insecticides, amplifying their toxic effects. These findings suggest that fungicides, especially when encountered in mixtures, can compromise bee health and should be more thoroughly assessed in pollinator risk evaluations (Mullin et al., 2010; Schuhmann et al., 2022; Drummond et al., 2024). In this context, the study carried out by Rienkevich et al. (2025) investigated the diversity of pesticides encountered by honey bees in their foraging areas and colonies, as well as the potential effects of the fungicide chlorothalonil in particular. The research evaluated the impact of chlorothalonil on its direct toxicity on honey bees, its synergistic effects with insecticides, its influence on detoxification enzyme activity, and the expression of specific genes (esterase and cytochrome P450). The findings revealed that there was no significant increase in mortality among bees exposed to either a 10 µg topical dose or a 5 ppm oral dose under laboratory conditions. Moreover, the synergistic or antagonistic interactions between chlorothalonil and other pesticides were found to be minimal (less than a twofold effect). No notable changes were observed in detoxification enzyme activity or gene expression. These results suggest that chlorothalonil may contribute to colony losses not through direct toxicity or synergism, but potentially via other physiological mechanisms. Similarly, Liu et al. (2025) emphasised that current pesticide risk assessments do not reflect real field conditions, given that pollinator insects are frequently exposed to pesticide mixtures in agricultural ecosystems. In this context, the combined toxic effects of the mesoionic insecticide triflumezopyrim and the triazole fungicide triadimenfon, which are commonly found together in the environment, were investigated in honey bees. The study demonstrated that the co-application of triflumezopyrim and triadimenfon induced acute synergistic toxicity in *A. mellifera*. Furthermore, significant changes were observed in biochemical parameters related to oxidative stress (MDA), neural function (AChE), detoxification pathways (GST), digestion (trypsin), and immunity, as well as in the expression of genes (abaecin, CRBXase, CYP6AS14, and CYP306A1). Additionally, both pesticides were found to alter the molecular conformations of catalase (CAT) and acetylcholinesterase (AChE), thereby affecting the activities of these enzymes. The results indicated that the combined presence of triflumezopyrim and triadimenfon could exacerbate physiological damage in *A. mellifera*, providing valuable insights into the ecotoxicological effects of pesticide mixtures.

The interaction between pesticides and other environmental factors has also been the focus of extensive research. For instance, Wang et al. (2025) studied the combined effects of microplastics and difenoconazole in honey bees, reporting an enhanced oxidative stress response. This suggests that the cumulative effects of multiple stressors contribute significantly to the deterioration of bee health and honey production. Similarly, research by Drummond et al. (2024) emphasized the necessity of contextualizing pesticide risks within the broader agricultural context, revealing that off-farm sources of pesticide exposure contribute substantially to the overall pesticide load experienced by honey bee populations.

Toxic effects of herbicides

Herbicides are primarily aimed at plant targets; their residues have been detected in honey, raising concerns about environmental contamination and food safety. Glyphosate, one of the most widely used herbicides, has frequently been found in honey samples worldwide. These residues typically result from foraging activity in treated landscapes and may reflect broader ecological exposure. While concentrations are often below legal limits, the chronic presence of herbicides in hive products highlights the need for expanded monitoring and inclusion of herbicides in pollinator-focused risk assessments (Cullen et al., 2019; Belsky & Joshi, 2020; Mohamed et al., 2023; Battisti et al., 2024; Ilić et al., 2024; Pawar et al., 2024; Xue et al., 2024). For instance, research by Kaakinen et al. (2024) demonstrated that glyphosate and glyphosate-based herbicides impair cognitive functions in honey bees, with effects that are likely to extend to bumblebees, as well. Furthermore, the accumulation of pesticides in both urban and agricultural environments presents additional risks, as evidenced by Ilić et al. (2024), who employed advanced biomonitoring techniques to trace pesticide exposure to agricultural sources. These findings highlight the pressing need for more rigorous monitoring of pesticide application near bee habitats. Similarly, Vommaro & Giglio (2024) investigate the cytotoxic and genotoxic effects of a pendimethalin-based herbicide, widely used in agricultural fields, on *A. mellifera* worker bees. In laboratory experiments, the bees were exposed to a single dose of the herbicide, and morphological changes in the digestive system, Malpighian tubules, and circulating hemocytes were analyzed. The results demonstrated that the herbicide induced significant damage to the cellular structures of the bees, including nuclear anomalies. These findings underscore the potential risks posed by herbicides to pollinators. In this regard, the use of herbicides in agricultural areas should be subject to specific regulations, and adjustments should be made regarding their application due to the toxic effects they have on non-target organisms.

Toxic Effects of Pesticides Residues in Honey

Pesticide residues in honey are a significant concern for both food safety and environmental health. Various pesticides, including insecticides, acaricides, fungicides and herbicides, can accumulate in honey due to contamination from treated crops or direct exposure during foraging. Residue levels depend on factors such as pesticide type, application timing, and environmental conditions (Irungu et al., 2016; Scripcă & Amariei, 2021; Jaramillo-Zárate & Londoño-Giraldo, 2023). While many of these residues remain below toxic thresholds, long-term exposure could pose risks to human health and bee populations. Monitoring and regulating pesticide residues in honey are essential for ensuring both consumer safety and pollinator health (Irungu et al., 2016; Darko et al., 2017; Hrynko et al., 2018; Jaramillo-Zárate & Londoño-Giraldo, 2023). In light of these findings, ongoing research advocates for the adoption of integrated pest management strategies that balance agricultural productivity with bee welfare. Recommendations include the use of less harmful alternatives and the implementation of stricter regulatory frameworks for pesticide use (Haran et al., 2024; Bartlett et al., 2024). As highlighted by Sadia et al. (2024), addressing the conflict between pesticide usage and its implications for food security is urgent, as reducing pesticide exposure could promote sustainable apiculture practices and enhance the quality of bee-derived products.

Furthermore, Stevanović et al. (2024) reported a concerning prevalence of pesticide residues in honey, with over 35% of samples from Western honey bee colonies containing detectable levels of harmful chemicals. This contamination poses significant implications, as pesticide residues not only degrade the taste and nutritional value of honey but also introduce potential health risks for consumers, from increased exposure to environmental contaminants (Fasasi et al., 2024). Silva et al. (2024) further corroborated these findings, revealing that a substantial proportion of honey samples in Brazil contained pesticide residues, raising concerns about public health if regulatory measures remain insufficient.

Research has highlighted the intricate relationship between pesticide toxicity and honey bee behavior. In a study conducted by Stevanović et al. (2024), pesticide residues were analysed in honey samples of various botanical origins, and the potential risks of these residues to public health were assessed. The findings revealed that none of the analyzed pesticides were detected in pine honey samples, whereas residues of pesticides such as chlorpyrifos, clothianidin, dimethoate, and thiamethoxam were identified at varying levels in other types of honey. However, hazard quotient (HQ) calculations indicated that the levels of detected residues remained within the acceptable limits for human health. Pine honey was identified as the safest type due to the absence of pesticide residues, which is attributed to the lack of direct pesticide application in forested areas. Nevertheless, other honey types also posed no significant risk to consumer health owing to their low levels of pesticide contamination. The study further emphasised both the toxic effects of pesticide use in agricultural production on bees and the resulting residue levels in honey products. In this regard, the research highlights that pesticide contamination may not only affect bees directly but can also be present in honey. Cappellari et al. (2024) investigated the influence of landscape structure and seasonality on the levels of pesticide contamination in pollen collected by honey bees. The research was carried out across 13 locations in northern Italy with varying land-use characteristics, where approximately 400 pesticide compounds were analysed, and this analysis resulted in the detection of 97 distinct substances. The findings revealed that nearly all pollen samples contained at least one pesticide residue, with insecticides and acaricides identified as particularly toxic. Assessments using the Pollen Hazard Quotient (PHQ) indicated that 15% of the samples reached moderate-to-high or high toxicity levels, posing potentially serious threats to bee health. Moreover, PHQ values were found to increase with the proportion of agricultural and urban land cover, with this effect being especially pronounced at the beginning of the season. The study highlights the significant risks of pesticide exposure via pollen, shaped by the complex interactions between pesticide categories, seasonal variation, and landscape composition.

Villalba et al. (2024) reported that chlorpyrifos and banned pollutants were detected in honey, beeswax, and pollen samples from honey bees in Argentina. Chlorpyrifos was found at higher levels, especially in spring, and dangerous concentrations were observed in beeswax. Beeswax was the most contaminated matrix with organochlorine pesticides. The study emphasizes that the distribution of pesticides aligns with environmental factors and highlights the need for sustainable monitoring.

CONCLUSION

Toxicological effects on *A. mellifera* pose a multifaceted challenge at the intersection of ecological health and modern agricultural practices. Pesticide exposure, particularly from neonicotinoids, pyrethrins, and fungicides, can have both lethal and sublethal effects on bees, affecting foraging behavior, cognitive function, and overall colony health. These effects can extend beyond individual bees, potentially leading to colony collapse, disrupting pollination services that are vital for crop production and maintaining biodiversity.

Furthermore, the accumulation of pesticide residues in honey is a significant concern because honey serves both as a food source for humans and as a medium for understanding pesticide exposure in bee populations. It has been determined that various pesticide residues, including insecticides, fungicides, and herbicides, can be transferred to bees during foraging and ultimately to honey. Monitoring pesticide levels in honey is therefore critical not only for food safety, but also to assess the broader ecological consequences of pesticide use on bee health and the sustainability of pollination services. Recent studies have shown that it is vital to develop evidence-based strategies to reduce these risks, including promoting integrated pest management (IPM) practices and establishing regulatory standards to limit pesticide residues in both the environment and hive products. These efforts are important to ensure the sustainability of honey bee populations and the protection of the essential ecosystem services they provide, which are crucial for agricultural productivity and ecological balance.

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Data Availability

Data will be made available upon reasonable request.

Author Contributions

Conception and design of the study: AKB, İAS; analysis and interpretation of data: AKB, İAS; writing manuscript: AKB; writing-editing manuscript: AKB, İAS.

Conflict of Interest

There is no conflict of interest, between the authors in this study.

Ethical Statement

We declare that there is no need for an ethics committee for this research.

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