OnLine Journal of Biological Sciences

Review

The Exposure of Pesticides to Honeybees: A Global Threat to Food Security

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Article history
Received: 29-09-2023
Revised: 26-11-2023
Accepted: 15-12-2023

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Abstract: The pivotal role of honeybees as global pollinators underscores their significance in ecological and agricultural systems. However, the beekeeping industry faces a significant challenge due to the improper utilization of pesticides, resulting in adverse effects on honeybee populations. This comprehensive review endeavors to investigate the toxicity of pesticides to honeybees, examining the various routes of exposure. Furthermore, it aims to delineate the repercussions of pesticide exposure on honeybee foraging behavior and the quality of essential hive products. Additionally, the review explores effective strategies to mitigate pesticide risks to advance contemporary apiculture practices. Pesticides, inherently poisonous, disrupt crucial physiological and behavioral mechanisms in honeybees. Notably, organophosphates and carbamates function as neuroinhibitors by impeding the acetylcholine neurotransmitter action in the insect nervous system. Among the insecticides, imidacloprid, clothianidin, and thiamethoxam, classified as neonicotinoids, demonstrated high toxicity even at minimal exposure doses. Acaricides, while less toxic to bees than their target parasites, pose potential risks when excessive residues accumulate in combs, impacting bee health adversely. Moreover, pesticides contaminate hive products, with beeswax identified as the most heavily contaminated, followed by pollen. The degree of pesticide contamination in pollen samples correlates with the detected pesticide quantities. Analyses of two key hive products, honey, and pollen, reveal that approximately 90% of pesticide residues are found in pollen, while honey contains 50%. The contamination of hive products underscores the pervasive nature of pesticide exposure within the honeybee environment. Encouraging the use of Integrated Pest Management (IPM) strategies among farmers emerges as a crucial recommendation. This approach not only safeguards beneficial insect diversity but also enhances agroecosystem services, ultimately ensuring a secure global food supply in the future.

Keywords: Toxicology, Pesticide Exposure, Beekeeping, Pollination, Sustainability, Food Security

Introduction

The honeybee stands as a pivotal and economically predominant species in global food crop production as the primary pollinator. According to Alemberhe and Gebremeskel (2016), insects contribute to 80-85% of all pollination, with honeybees specifically accounting for a substantial 75-80% of this vital role. Possessing distinctive characteristics such as dense body hair, efficient foraging habits, and the provision of sustenance for themselves and their offspring, bees emerge as highly effective pollinators, especially within agroecosystems.

Their effectiveness is not limited to pollination alone; bees, being the most effective and widely used pollinators in agroecosystems, yield a diverse array of valuable and commercially significant products. These include honey, wax, propolis, royal jelly, pollen, and bee bread, which hold both commercial and medicinal importance.

However, honeybees confront a myriad of challenges in their natural environment, navigating through a dynamic extent of foreign substances stemming from natural and artificial sources. Recent research has illuminated a concerning decline and disappearance of bee populations, attributed to colony collapse disorder is the cause of death in 30-40% of honeybee colonies in the United States, as identified by Lebuhn *et al*. (2013). The precipitous decline in honeybee populations is characterized as a disease syndrome. Over the last few decades, the United Kingdom has witnessed a substantial 54% reduction in honeybee populations. In China, home to six million honeybee hives, beekeepers report perplexing colony losses and a decline in bee numbers. This global decline is not attributable to a singular factor but rather stems from a complex interplay of biotic and abiotic causes, with pesticides emerging as a prominent and pivotal factor among various contributors.

Pesticides, identified as a paramount and substantial factor, present a notable threat to honeybee populations. The Food and Agricultural Organization of the United Nations (FAO) characterizes pesticides as substances, whether chemical or biological, designed to repel, destroy, or control pests or regulate plant growth. Widely employed across diverse industries, including food production, forestry, agriculture, and aquaculture, these chemical agents, encompassing herbicides, fungicides, and notably, insecticides, either individually or in conjunction with other elements such as elevated temperatures and the cultivation of hybrid varieties with reduced pollen and nectar, have inflicted catastrophic repercussions on honeybee populations globally, as outlined by Kumar *et al*. (2020).

While the historical use of insecticides dates back to 1000 BC for pest control in agriculture, their more extensive application gained momentum in the mid-19th century. This intensified usage of insecticides, notably, has proven to be a successful tool for managing pest infestations and preventing substantial crop losses, as emphasized by Oberemok *et al*. (2015). Recent data from (FAO, 2021) indicates an annual global crop yield loss estimated to range between 20 and 40%, providing a partial justification for pesticide use in agricultural fields. This aligns with the broader objective of meeting global food requirements and advancing the Sustainable Development Goal (SDG) of zero hunger.

The expansion of agrochemicals, which aims at enhancing agricultural productivity has unfortunately resulted in a loss of essential pollinators, notably honeybees, which offer invaluable ecological services. Genomic studies on honeybees reveal a notable susceptibility to pesticidal effects due to the absence of genes encoding detoxification enzymes, such as cytochrome P450 monooxygenases (P450s), glutathione-S-transferase and carboxylesterases, setting them apart from other insects (Claudianos *et al*., 2006). Despite this susceptibility, comparative studies on the sensitivity of *Apis mellifera* to insecticides in relation to other insects indicate a general equivalence in sensitivity to insecticides or specific classes thereof (Hardstone and Scott, 2010).

The heightened risk to honeybees is exacerbated by the extended half-lives of pesticides (Bonmatin *et al*., 2015) and their pervasive presence in food (Lu *et al*., 2018) and honey (Mitchell *et al*., 2017). According to Nakasu *et al*. (2014), recent agricultural expansion has resulted in a dramatic decrease in honeybee populations as a consequence of the intensified use of pesticides. Regrettably, the recognition of the pivotal role of honeybees in agriculture remains inadequate among farmers and other stakeholders, leading to the injudicious application of agrochemicals.

This issue is further exacerbated in underdeveloped countries where limited regulatory and protective measures intensify the challenges faced by honeybee populations (Teshome *et al*., 2023). Pesticides used in crops exhibit extreme toxicity to bees, impacting them through direct harm to foraging workers, drifting into adjacent apiaries from agricultural land, rendering entire colonies more susceptible to various pathogens, and impeding their ability to thrive in the natural environment by accumulating in pollen grain within the apiary (Kumar *et al*., 2020). The extensive and continuous use of herbicides is now recognized to contribute to a reduction in the diversity of flowering plants, further affecting bee colonies and their productivity (Sanchez-Bayo and Goka, 2016).

Besides unwitting exposure, intentional exposure occurs through hive management practices employed by beekeepers to combat pests and pathogens using miticides and fungicides (Chmiel *et al*., 2020). Unfortunately, a lack of awareness among consumers regarding the toxicological and chemical characteristics of these compounds forebodes a worsening scenario for insecticides' effects on honeybee productivity.

The inappropriate application of insecticides, leading to the mortality of honeybees, represents a primary challenge confronting the beekeeping sector, resulting not only in decreased crop yields but also in restricted access to honeybee products (Mengistie, 2016). As the global population burgeons and the demand for crop production rises, the critical importance of pollination benefits becomes even more pronounced.

In response to these pressing conditions, a paradigm shift in beekeeping management strategies is imperative. Safeguarding pollinators necessitates a concerted human effort aimed at minimizing the harm caused by chemical poisoning to bees. This review endeavors to explore the toxicity towards honeybees and their routes of exposure, systematically documenting the consequences of pesticide exposure on foraging behavior and major bee products within the apiary. Additionally, it seeks to unveil effective techniques for mitigating pesticide hazards on honeybees to ensure global food security.

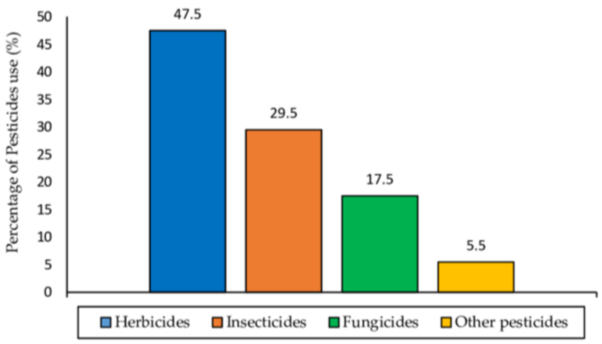

Fig. 1: Global status of pesticide use. Source: (Sharma *et al*., 2019)

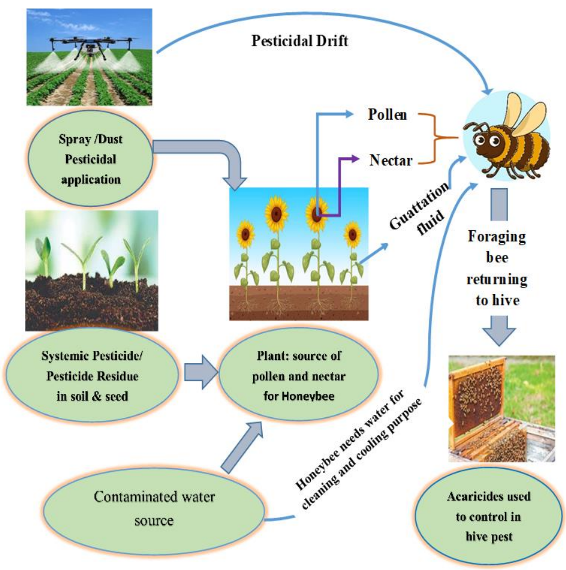

Fig. 2: Simplified diagram showing various routes of pesticide exposure to honeybees

Global Status of Pesticide Use

Since the early 1940s, pesticides have been employed for effective pest management and they have proven to be a useful strategy for preventing major agricultural losses brought on by infestations of insect pests. The world consumed 4.19 million metric tons of pesticides in 2019, with China using 1.76 million metric tons, the most of any nation, followed by the United States (408 thousand tons) Brazil (377 thousand tons), and Argentina (204 thousand tons) (Fernández-López *et al*., 2017). The WHO noted an annual increase in pesticide use in Southeast Asia, with 20% of emerging nations using them. Predictive studies show that herbicides account for 47.5% of pesticide use worldwide, (Fig. 1) followed by insecticides at 29.5%, fungicides at 17.5%, and other pesticides at 5.5% (Sharma *et al*., 2019).

Routes of Pesticide Exposure

Honey bees that are foraging can travel up to five miles (8.0-13.2 km) from their hive in any direction in search of food. Therefore, within a radius of 5 miles (8 km) around the hive, an actively feeding colony can cover a territory up to 80 miles (201 km^2) in size. Bees are more likely to come into contact with pesticides and other environmental contaminants in the foraging area during foraging hours and at the sites of interaction (flora, pollen, nectar, water and propolis) (Ellis *et al*., 2014) (Fig. 2). Particularly in humid situations, bees flying over planting fields are instantly exposed to lethal concentrations of pesticides as dust particles adhere to the abdomen in humid environment (Tapparo *et al*., 2012). Before planting the crops, herbicides and fungicides were applied directly to the soil, while most insecticides were sprayed aerially onto the crops. Flying honeybees can be poisoned by pesticide dust and aerial droplets that come into direct contact with them. Furthermore, tiny droplets can harm bees while foraging over a long distance from treated locations to untreated sites. Bees are exposed to pesticides through their food, water, and the guttural fluid that plants exude.

Pesticides have the ability to translocate across the plant body due to their systematic nature. Several investigations have found pesticide residues in seeds, pollen, and nectar. Pesticides applied to seeds have the potential to spread throughout developing plants, contaminating nectars and pollen. According to Bonmatin *et al.* (2015) in Gaucho seed dress sunflowers, imidacloprid residues (3 g/kg) were found in pollen grains.

In apiaries, acaricides are used to control *Varroa* mites and other parasites, which is also a source of pesticide exposure for honeybees. Tau-fluvalinate, pyrethroid, and coumaphos have historically been used to control *Varroa* chemically (Sanchez-Bayo and Goka, 2016). They were both initially effective against the mite; however, numerous *Varroa* populations have developed resistance to them. Sanchez-Bayo and Goka (2016). Today, beekeepers frequently employ the formamidine insecticide amitraz to combat mites. Formic acid, hop beta acid, oxalic acid, and thymol are other active substances used to combat *Varroa* (Sanchez-Bayo and Goka, 2016). The remnants of several of these pesticides have been discovered in different hive components. According to Zhu *et al.* (2014), the high residue levels seen in the waxy cells of the comb come into contact with honey bees, mostly affecting the developing larvae and maybe the adult honey bees and the queen.

Pesticide Toxicology of Honeybee

Pesticide toxicity is generally measured using acute contact toxicity values LD_{50} the exposure level that causes

50% of the population to be exposed to diet. According to Kumar *et al*. (2020), toxicity thresholds are typically set at "Highly toxic (acute LD_{50} <2 μg/bee); moderately toxic (acute LD_{50} 2-10.99 μg/bee); slightly toxic (acute LD_{50}11-100 μg/bee); non-toxic (acute LD_{50} >100 μg/bee)".

Acute and Chronic Toxicity

A single or brief exposure to the chemical can lead to death, which is referred to as acute toxicity. The toxic effects are more intense and unanticipated in acute poisoning. In a dire circumstance, individual honeybees and entire colonies may perish from toxic exposure instantly or in a matter of hours. In modest doses, a pesticide with high acute toxicity can be fatal. By direct exposure (such as pesticide spray), exposure to pesticide residues on foliage or flowers, or absorption of the pesticide through nectar or pollen (subacute or dietary exposure), pesticides can induce acute poisoning in pollinators (Manzoor and Pervez, 2021).

Chronic toxicity is the phrase used to describe the negative consequences resulting from chemical exposure on a regular basis that may have an impact on a particular bee's or a colony's ability to survive, develop, or reproduce.

Sublethal Toxicity

Sublethal bee exposure has a negative impact on bees' capacity to distinguish floral odors and blossoms, as well as their ability to navigate in space and graze. In an investigation, honeybees exposed to sublethal levels of thiamethoxam had impaired memory, brain, and gastrointestinal functioning, ultimately leading to a reduced lifespan (Oliveira *et al*., 2014). Sublethal doses of imidacloprid significantly altered bees' respiratory patterns and caused their hypopharyngeal glands to shrink compared to untreated bees. Similarly, mobility behavior was altered after modest dosages of imidacloprid were administered. Sanchez-Bayo and Goka (2016) found that relatively few queens were produced by honey bee larvae fed pollen contaminated with chlorpyrifos after repeated exposure. In wild bees, sublethal amounts of thiamethoxam and clothianidin lowered reproductive success by 50%, while honeybee queens experienced exceptionally high rates of supersedure (60%) (Sanchez-Bayo and Goka, 2016).

Toxicity of Agrochemicals

Insecticidal Toxicity

Honey bees are vulnerable to several pesticides and the various detrimental effects of these insecticides are thought to be the primary cause of the global honey bee population drop. The individual honey bee as well as its colony are subject to varying risks from various chemical insecticide classes. Among various insecticides, four classes (organophosphate, carbamates, neonicotinoids, and pyrethroids) are the most widely used (Table 1). Neonicotinoids such as systemic insecticides are more toxic and persistent, in contrast to greater parts of organophosphates, carbamates, and pyrethroids (Sanchez-Bayo and Goka, 2016). The two widely used groups of insecticides, organophosphates, and carbamates, act on insects in a similar way as acetylcholinesterase (AChE) inhibitors, which, under normal conditions, inhibit the activity of the neurotransmitter acetylcholine in the insect nervous system (Hardstone and Scott, 2010). These two classes of insecticides exhibit varying levels of topical toxicity to bees, with LD50 ranging from 0.018 and 31.2 μg/bee. Neonicotinoids, which are synthetic analogs of nicotine insecticides, have a higher affinity for nAChR in the neural systems of insects, including bees. Nitroguanidine neonicotinoids such as imidacloprid, clothianidin, and thiamethoxam have been shown to be extremely toxic to bees, with toxicity values ranging from 0.004-0.075 μg/bee (Bortolotti *et al*., 2009). Some neonicotinoid metabolites are also neurotoxins and are involved in honeybee mortality. Pyrethroids can create effects such as excitation, exhaustion, and subsequent paralysis and death of insects and mites by disturbing the conduction of nerve impulses by prolonging the opening of sodium channels in the nerve impulses (Murawska *et al*., 2021).

Residual toxicity can vary depending on the formulation and application rate:

- RT-Residual Toxicity: This represents the length of time that residues of the products remain toxic to bees' application
- ERT-Extended Residual Toxicity: Residues are expected to cause at least 25% mortality for more than 8 h after application

The data shown in the above table are for the adult honeybee, both contact LD_{50} (μg/bee) and Oral LD_{50} (μg/bee) can vary depending on the different casts of the honeybee and various developmental stages of the bee.

Fungicidal Effects on Honeybee

Most of the fungicides are considered non-toxic to bees; hence, it is mostly applied during the flowering of the plant with maximum bee activity. Kumar *et al.* (2020) reported that the toxicity levels for different fungicides are in the range of LD50 >200 to as low as 0.2 μg/bee. Although fungicides are considered more or less safe for use, (Schuhmann *et al*., 2022) reported that depending on the specific group of fungicides, mixtures of fungicides and insecticides and their combination can be lethal for the pollinators. Adult honey bees have been demonstrated to become hypothermic when exposed to fungicides. Based on the discovery of deformed, usually wingless pupae and recently emerging adult bees, the fungicide had deleterious effects on the honey bee brood (Sanchez-Bayo and Goka, 2016).

Table 1: List of insecticides toxic to honeybees

Insecticidal group	Active ingredient	Contact LD_{50} (µg/bee)	Oral LD_{50} (µg/bee)	Residual toxicity	Risk Rankin
Organophosphate	Acephate	1.200000	1.370000	>3 days ERT	High
	Bifenthrin	0.015000	0.100000	<1 day RT >1 day ERT	High
	Chlorpyrifos	0.059000	0.250000	2 h RT 4-6 days ERT	High
	Coumpahos	22.150000	26.000000	-	High
	Diazinon	0.370000	0.200000	RT? 2 days ERT 2-6 h	High
	Malathion	0.270000	0.380000	RT 2-5 days ERT	High
	Methidathion	0.236000	-	1-3 days ERT	High
Carbamates	Aldicarb	2.360000	-	-	Moderate
	Aminocarb	0.616500	-	<2 h RT	High
	Bendiocarb	2.640000	-	<2 h RT	Moderate
	Carbaryl	1.100000	0.125000	<1 day RT 2-4 day ERT	High
	Carbofuran	0.160000	-	7-14 days	High
	Methomyl	1.290000	0.230000	2 h RT 1.5 days ERT	High
	Oxamyl	10.130000	0.094000	3 h RT 3-4 days ERT	High
Pyrethroid	Beta-cyfluthrin	0.012000	0.050000	1 day RT >1 day ERT	High
	Bifenthrin	0.015000	0.100000	<1 day RT >1 day ERT	High
	Cyfluthrin	0.037000	-	>1 day ERT	High
	Deltamethrin	0.037825	0.464500	<4 h RT	High
	Esfenvalerate	0.017200	-	<1 day RT 1 day ERT	High
	Lamda-cyhalothrin	0.050000	0.900000	>1 day ERT >7 days ERT(encapsulated)	High
	Permethrin	0.028000	0.280000	0.5-2 days ERT or >5 days ERT	High
Neonicotinoids	Acetamiprid	17.045000	11.815000	2 days ERT	Moderate
	Clothianidin	0.030000	0.003440	RT? >5 days ERT	High
	Dinotefuran	0.038700	0.015300	RT? 39 h ERT	High
	Imidaclorpid	0.046450	0.049000	8 h RT >1 day ERT	High
	Thiaclorpid	38.820000	19.955000	Less toxic to bees. 1-2 days ERT for bumble bees	Low
	Thiamethoxam	0.040000	0.004358	7-14 days ERT	High

Sources: (Chmiel *et al*., 2020; Hooven *et al*., 2013); Toxicity of pesticides to pollinators and beneficial, center for agriculture, food and environment, university of Massachusetts Amherst; pesticides and bee toxicity, Minnesota Department of Agriculture

Herbicides and Honeybee

Herbicides are used to control undesired weed growth in the field and therefore, are not formulated to kill insect populations. The toxicity level of herbicides is known to be much lower for most insects. Herbicides are not toxic to bees, but disturb the foraging environment of honeybees. According to Schmitz *et al*. (2014), the diversity of plants is reduced across the area where herbicides are applied regularly.

Toxicity of Pesticides Used in Apiculture

Honeybee pests are common issues for hives throughout the world. The *Varroa* mite, a worldwide hazard to the health of honey bees, is treated with acaricides in honey bee colonies. Traditionally, *Varroa* has been chemically controlled with tau-fluvalinate and coumaphos. As a pyrethroid, tau-fluvalinate kills mites by blocking the voltage-gated sodium and calcium channels (Davies *et al*., 2007). Tau-fluvalinate-treated queens were noticed smaller than untreated queens. Drones exposed to tau-fluvalinate had a lower chance of living to sexual maturity than drones that were not exposed to the substance and they also had reduced weight and produced fewer sperm. However, exposure to coumaphos can have deleterious consequences on honey bees; exposed queens were smaller, suffered higher mortality, and were more likely to be rejected when introduced to a colony (Johnson *et al*., 2010). Burley *et al*. (2008) found the viability of drone sperm was also reduced in preserved sperm taken from drones treated with coumaphos. Two organic pesticides, formic acid and oxalic acid, were introduced for the better management of the *Varroa* destructor. Both formic acid and oxalic acid are effective in controlling *Varroa* mites, but few researches have been done to determine their detrimental effect on honey bees. Honey bees may exhibit a variety of harmful effects from formic acid, including decreased worker bee longevity and decreased brood survival rates (Kumar *et al*., 2020). Kumar *et al*. (2020) also reported in colonies treated with oxalic acid, there have been reports of high queen mortality and fewer sealed broods. It has been documented that worker bees given oxalic acid during their early life stages exhibit an aberrant age-related pattern issue.

Impact of Pesticide Exposure on Honeybee Reproduction

Pesticide exposure can decrease the reproductive cycle of queens, reducing body weight and decreasing the likelihood of queen success (Gajger *et al*., 2017). It has been observed that queens exposed to field-realistic concentrations of neonicotinoids carry fewer viable sperm and lay fewer fertilized eggs (Chmiel *et al*., 2020) (Fig. 3) that would normally develop into diploid (female) workers. Forfert *et al*. (2017) found that neonicotinoids at sublethal concentration can decrease the mating ability of affected queens compared to untreated queens. Sublethal concentrations of neonicotinoids and phenylpyrazoles can reduce sperm viability (Kairo *et al*., 2017), which can hamper the fertilization of queens and the production of diploid workers. Together, reduced sperm transfer and fertilization may limit the production of a genetically diverse workforce, which can compromise the division of labor and response to disease. Exposure to even a single insecticide application can have long-lasting impacts which can slow population expansion. According to Stuligross and William (2021), almost 30% fewer progeny were produced by bees exposed to pesticides as larvae in the previous year than by control bees that were never exposed to it.

Effect of Pesticide Exposure on Honeybee Foraging

In order to keep the honeybee colony's food supply stable and to predict its chances of survival and reproduction, foraging behavior is crucial. Pesticides designed to repel or deter bees from feeding typically alter their foraging patterns. Nevertheless, extended exposure to such pesticides may lead to colony starvation and nutritional deficiency. Manzoor and Pervez (2021). Pesticides including carbamate and organophosphates disrupt the cholinesterase enzyme, also known as acetylcholinesterase, a crucial enzyme that regulates the transmission of nerve impulses. Organophosphate fenitrothion significantly decreased the number of forager bees during flowering. The harmful effects of organophosphate are more pronounced when bees come into direct contact with it (Guez *et al*., 2005**)**. Neonicotinoid insecticides, including imidacloprid, exhibit a moderate level of toxicity (Colin *et al*., 2004). Imidacloprid toxicity includes a reduction in the frequency of hunting trips, a decline in the presence of active bees at foraging locations, an elongation of duration between successive visits, inconsistencies in communication or waggle dance, and interference with visual cognition and navigation.

Five insecticides, methyldemeton, acetamiprid, imidacloprid, dimethoate, and thiamethoxam, were sprayed in the mustard field (Table 2) during full bloom to check the repellency effect on bee foraging. The number of mean bee visitors was counted 24 h before and 24 h after the spray. The result shows a drastic reduction in mean bee visitors immediately after spray. The highest decrease (79.4%) was observed for methyl-demeton followed by acetamiprid (75.5%), imidacloprid (73.7%), dimethoate (70.3%), and thiamethoxam (66.1%). Overall, there was an average 75% reduction in bee visitors.

Table 2: Effect of insecticidal application on honey bees

Treatment	Mean bee visitors: 24 h before the spray	24 h after the spray
Imidacloprid 17.8 SL	28.5	7.5
Thiamethoxam 25 WG	30.3	10.3
Acetamiprid 20SP	27.5	6.8
Diamethoate 30 EC	29.5	8.8
Methyldemeton 35 EC	26.8	5.5

Bajiya *et al*. (2020); *SL- Soluble Liquid; *WG/WDG- Water-Dispersible Granules; *SP-Soluble Powder; *EC- Emulsifiable Concentrate

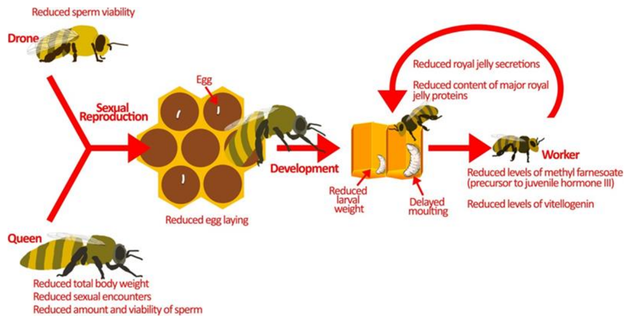

Fig. 3: Effect of pesticides on the reproduction of honeybees. (Source: Chmiel *et al*., 2020)

Pesticide Residues on Honeybee and Bee Products

Residues of pesticides in hive products may result from bees searching for nectar and pollen in crops treated with various agrochemicals for various purposes (Bogdanov *et al*., 2007). Different scientific studies have demonstrated the presence of pesticide remnants in honeybees and their hive components around the world. The residues may vary from country to country because this depends upon the amount of pesticides applied in the agricultural practices of that particular country. Determining pesticide residues from various regions of the world supports this fact. The sample collected from different agroecological zones in various African countries shows that about 98% of the pesticide residues determined are well within the acceptable limits of 70-120%. Seventeen pesticides were detected in the commercial honey sample that was 10 times below the established Maximum Residue Limit (MRL) values, excluding malathion, which exceeded its set MRL by a factor of 2. Therefore, it can be concluded that honey collected in this region is safe for human consumption (Irungu *et al*., 2016). When 887 samples (honey, bee, and hive components) from the United States and Canada were analyzed, 121 different pesticides (parent pyrethroids, organophosphate, carbamates, neonicotinoids, insect growth regulators, chlorinated cyclodienes, organochlorines, formamidine, miscellaneous miticides/insecticides, synergists, fungicides, and herbicides) were detected. Pyrethroids and organophosphate were detected dominantly in the wax and bee as fungicides were detected dominantly in pollen. More than 40 of the detected pesticides were systemic pesticides. Beeswax was found to have a higher concentration of varroacides whereas pollen has a higher concentration of externally derived pesticides. Among the 887 samples examined, only one wax, three pollen, and twelve bee samples showed no detectable pesticides (Johnson *et al*., 2010). In a four-year study conducted in China, the biggest honey producer in the world, it was found that 93.6% of pollen, 81.5% of nectar, 96.6% of beebread, and 49.3% of honey containing at least one target pesticide were spotted at or surpassing the Method Detection Limits (MDL). This study encompassed a total of 1783 samples (pollen, nectar, beebread, and honey) collected from various regions across China. The study revealed the presence of up to 19 pesticides per sample, with 40 different active compounds identified corresponding to twenty-three insecticides (61.5%), 10 fungicides (51.5%), four acaricides (32.8%), and three herbicides (4.2%). The result also shows that the frequency of occurrence of varied residue samples (58.4%) surpasses the individual pesticides (20.8%). Carbendazim was the most frequently detected pesticide with a detection rate of 45.0% followed by the tau-fluvalinate and acaricides tau-fluvalinate at 36.8%. Subsequently, the insecticides bifenthrin (19.7%), chlorobenxuron (16.0%), chlorpyrifos (15.8%), lambda-cyhalothrin (11.7%), and fenpropathrin (11.6%) were also detected. Approximately 23.6% of the contaminated samples surpassed the MRL set by the EU pesticide database (2.2) (Xiao *et al*., 2022). When samples (beeswax, freshly stored pollen, and in-hive worker bees) were gathered from 45 apiaries across 39 different sites in Spain, the findings show that miticides (coumaphos, fluvalinate, flumethrin, and amitraz) that beekeepers use to control *Varroa* mites served as the primary source of contamination. The honeybee sample was found to be contaminated with seven different pesticides. Acaricides were detected more frequently in the bees as they are in greater contact with the acaricides used in the hive. These acaricides are found in honeybees around Europe. Organophosphate and agricultural pesticides were also detected with a higher frequency in honeybees, but honeybees are the least contaminated matrix with each sample having a consistent occurrence of one pesticide and 20 samples were devoid of pesticides, whereas pollens were the most contaminated products in the hive. Neonicotinoids like imidacloprid, clothianidin, and thiamethoxam were absent in the sample as they are banded for use in Europe. The samples were contaminated mainly with miticides employed in beekeeping with comparatively lower levels of contamination attributed to insecticides and fungicides from nearby agricultural fields. The study also shows that beeswax exhibits the highest pesticide detection among hive products, whereas pollen samples predominantly display contamination in terms of the number of pesticides spotted. Agrochemicals were detected in more amounts from the sample collected from grassland areas (Calatayud-Vernich *et al*., 2018. Various research carried out in the representative countries (France, Italy, Spain, Belgium, and Slovenia) of the EU show somewhat similar patterns of taint in the honey bee and hive matrices. The major contaminants were acaricide (coumpahos, amitraz, fluvalinate), fungicides (carbendazim) and insecticides (chlorpyrifos). Lambert *et al.* (2013); Tosi *et al.* (2018); Ravoet *et al*. (2015); Premrov Bajuk *et al*. (2017). Residues of pesticides in pollen and honey are anticipated to contribute significantly to the exposure of honeybees to chemical contaminants. This aspect may encompass a major portion of associated risks, considering that honey bees depend on honey and pollen to fulfill the majority of their nutritional needs.

Pesticide Management Techniques to Reduce Bee Losses to Ensure Modern Apiculture

The process of making decisions leading to the use of pesticides is complicated and pollinator protection is no different undertaking. In general, pesticide applications that are carried out without proper knowledge or without taking pollinator safety into account result in the death of pollinators. Applying pesticides should occur following a thorough assessment of crop fields to determine the presence of weeds, pest populations, or disease incidence at levels meeting predefined thresholds. This approach is crucial for safeguarding insect pollinators and beneficial insect populations. The time of pesticide application should be avoided during the blooming season. Priority should be given to compounds that pose lower toxicity to the bees instead of highly toxic chemicals. Pesticide labels are required to communicate potential hazards to honey bees (Desneux *et al*., 2007). Insecticide formulations can significantly alter the toxicity of compounds to bees. There are quite a few low-risk formulations. Emulsifiable concentrates pose a lower risk compared to wettable powders. Granular formulations are considered safer for bees since these chemicals are directed to the lower portion of the plant canopy. Dust is more dangerous than liquid formulations. This is because these chemicals can drift with air currents and reach and penetrate bee colonies (Ellis *et al*., 2014).

Pesticide application should be avoided during the hours of 8 a.m. and 5 p.m. when bees are most active. This will especially assist forager bees in avoiding direct contact with the chemical. The majority of applications can be carried out in the early evening. Beekeepers should receive prior notification of the pesticide application to enable them to relocate colonies away from the treated area. It is important to avoid contamination of surrounding water sources as bees utilize these sources of water to cool down their body temperature, especially in the summer (Kumar *et al*., 2020). Utilization of Integrated Pest Management (IPM) techniques rather than chemical products on crops is advisable according to various findings (Manzoor and Pervez, 2021). Collaboration among applicators, growers, beekeepers, extension workers, and government officials is essential to address challenging agricultural pests and safeguard pollinators from exposure to chemicals. To that end, we encourage research into ecological and organic farming approaches that reduce dependency on chemical pest management.

Honeybee Decline and Threat to Food Security

Globally, 87 of the major food crops (vegetables, fruits, nuts, edible oil, and proteinaceous crops) depend on honeybees and other pollinators (Klein *et al*., 2007), constituting 35% of the global food production volume. These pollination-dependent crops are crucial for producing vital micronutrients in the human diet. Micronutrient deficiency, also referred to as "hidden hunger," can cause irreversible human health effects. Lack of pollinators could further exacerbate the deficiency of these micronutrients. Approximately 2 billion people around the world are suffering from hidden hunger, including affluent individuals as well as those with obesity (Gillespie *et al*., 2016). Honeybees and other pollinators play a critical role in sustaining both the human food chain and the ecosystem (van der Sluijs and Vaage, 2016). Their role is vital not only in food crop production but also in producing valuable cash crops like fiber crops, timber, and phytopharmaceuticals. Moreover, it contributes to the subsistence agricultural production that feeds a large global population.

Pollination is a vital process for agriculture and it has huge economic value worldwide, estimated at as much as $577 billion annually, representing 10% of the worldwide crop market. Without natural pollination, crop production could suffer, resulting in higher prices and a potential annual loss of $2 billion. If pollination declines, hand pollination or the use of innovative technology cost may escalate to $90 billion annually in the United States alone. This rise in food production costs could lead to higher food prices, creating food elitism and exacerbating the issue of affordable food and barriers to nutrition and sufficient diets for those in poverty (Marshman *et al*., 2019). Urban agriculture has become increasingly popular, with over 800 million people worldwide engaging in this practice. Most urban farmers grow crops that rely on pollination, making honeybees, as managed pollinators living in proximity to humans, vital for urban agriculture. The yield of these crops is directly linked to the presence of pollinators and their abundance supports higher crop production, addressing food security concerns. Among managed pollinators, the western honeybee *(Apis mellifera)* is the most widely distributed, with around 81 million hives and an annual honey production of approximately 1.6 million tons, as reported by the assessment report on pollinators, pollination and food production (IPBES, 2016). *Apis mellifera* has come to symbolize pollinators in general to a significant extent. Plants relying on honeybees and other pollinators not only provide food for humans and animals but also have cultural and aesthetic value. The practice of wild honey hunting, an ancient human activity, continues among indigenous groups in various regions like Africa, Asia, Australia, and South America. These communities, such as the Gurung tribes in west-central Nepal, the Mawals in Bangladesh, and the Petalangan people in Indonesia, have depended on honey hunting for their livelihoods for millennia. They sell bee products in local markets, fulfilling their needs and providing essential nutrition for their families. The decline in bee populations in these areas threatens both their cultural heritage and food security.

Honeybees offer a wide range of benefits beyond crop pollination, including contributions to medicine, nutritional value through products like honey, royal jelly, and pollen, as well as industrial and construction materials such as beeswax. Beekeeping provides employment, and income through honey sales and supports biodiversity conservation. Bee products are rich in natural nutrients and biologically active compounds. They are consumed directly or used as functional ingredients to enhance the nutritional value of other foods. Honey, a commonly consumed and traded bee product, is a natural sweetener packed with nutrients like carbohydrates, amino acids, and vitamins. Bee pollen is often labeled as "the most ideal food on the planet" due to its essential amino acids, phenolic compounds, proteins, and vitamins, along with potent antioxidant properties. Royal jelly is gaining popularity as a healthy functional food due to its high content of water, crude protein, carbohydrates, lipids, minerals, vitamins, and pharmacological properties.

More than three-quarters of major world food crops rely to varying degrees on animal pollination for both yield and quality. Bee pollination contributes significantly to the billion-dollar food market and plays a crucial role in ensuring nutritional security. The current pollinator crises pose a severe threat to food security and can exacerbate the issue of hidden hunger. Moreover, the decline in pollinators can have far-reaching ecological consequences, leading to shifts in the diversity and abundance of wild plants. This, in turn, affects animals, birds, mammals, and insects that rely on these plants for essential resources such as food, shelter, and opportunities for reproduction.

Conclusion

This article underscores the scientific evidence detailing the adverse effects of pesticides on honeybees and highlights its significant role in the decline of bee populations. Widely employed chemical pesticides, including carbamates, neonicotinoids, organophosphates, organochlorines, pyrethrins, and others, are commonly utilized in agricultural practices. Systemic insecticides such as imidacloprid, clothianidin, and thiamethoxam have demonstrated high toxicity to bees, showing toxicity levels ranging from 0.004-0.075 µg/bee.

The overuse of these insecticides stands as a primary driver behind the global decline in honeybee populations, posing a substantial threat to global food security. Pesticide application directly and adversely impacts bees, leading to significant fatalities and colony losses in beekeeping operations. Additionally, these chemicals indirectly harm honeybees by diminishing their foraging capabilities and contaminating hive products. To ensure the sustainability of the apiculture sector and mitigate the risk of food shortages globally, it is crucial to implement effective management strategies to protect this vital pollinator.

A recommended approach involves establishing agreements between agricultural producers and beekeepers to regulate insecticide use. This may entail practices such as covering beehives during pesticide application or relocating hives to areas free from pesticide application. Furthermore, the promotion of Integrated Pest Management (IPM) adoption among farmers is imperative for effective pest control while simultaneously preserving beneficial insect biodiversity and enhancing agroecosystem services. This concerted effort ultimately contributes to securing the future of the world's food supply.

Acknowledgment

The authors acknowledge the Research Management Wing (RMW) of Bangabandhu Sheikh Mujibur Rahman Agricultural University, Bangladesh for providing the support for writing this manuscript.

Funding Information

The authors have not received any financial support or funding to report.

Author’s Contributions

Halima Sadia: Participated in coordinating the data, analyzed the data, and contributed to the writing of the manuscript.

Pratik Raj Karki: Coordinated the mouse work.

Mansura Afroz: Verified the results and contributed to written the discussion.

Haider Iqbal Khan: Discussed the results and contributed to the final manuscript.

Md. Motaher Hossain: Interpretation of results, written the manuscript.

Md. Mamunur Rahman: Conceived, designed, and implemented the research, the analysis of the results, and the writing of the manuscript.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

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