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PESTICIDES, HERBICIDES AND THEIR EFFECTS ON POLLINATORS

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ABSTRACT

Pesticides used in agriculture, urban areas, and gardens are raising concerns about their impact on pollinators. Exposure to pesticides through direct contact, ingestion, and accumulation can harm pollinators. High pesticide concentrations cause immediate harm, while chronic exposure weakens their immune systems, impairs reproduction, and leads to population declines. Neonicotinoids, a type of insecticide, are especially problematic. They are absorbed by plants and spread to nectar and pollen, affecting foraging abilities, navigation, immunity, and reproductive success in pollinators. Integrated pest and pollinator management (IPPM), sustainable agriculture practices, and pesticide-free zones aim to maintain ecological balance and reduce chemical use. We observe lethal, sub lethal impacts on pollinator species including Honeybees (*Apis mellifera*), Bumblebees (*Bombus* spp.), butterflies, and other beneficial insects, and assess ecological consequences. Empirical data from field and laboratory studies are synthesized, and a comparative table summarizes pesticide usage and recorded pollinator mortality rates. Raising awareness about pollinator importance and pesticide impacts is crucial for conservation, and by balancing pest control with pollinator protection, long-term sustainability of agriculture and natural ecosystems dependent on pollination services can be ensured.

No. of Pages: 10	**Table: 1**	**Fig.: 3**	**References: 59**

Keywords: Pollinators, Pesticides, Herbicides, Honeybees, Sub-lethal Effects, Agriculture, IPPM.

INTRODUCTION

Pollinators, including bees, pollen wasps (Masarinae); ants; butterflies, moths, flies, beetles, and birds, (Figure.1) are indispensable agents in the reproduction of over 75% of leading global crops and nearly 90% of wild flowering plants (Klein et al., 2007; Baskar et al., 2017). Unfortunately, multiple pollinator species are currently experiencing contracting ranges and reductions in species richness and abundance (Evans *et al.,* 2018). For instance, domestic honeybee stocks declined by 59% in the USA between 1947 and 2005, and by 25% in Europe between 1985 and 2005. Even though beehives have increased by 45% since 1961, however, the proportion of agricultural crops depending on pollinators is increasing much more rapidly (>300%) so that the demand for pollination services could outstrip the increase in hive numbers (Aizen and Harder, 2019).

Pesticides are any substance or mixture of substances intended for preventing, destroying, repelling, or mitigating any pest including weeds. The term pesticide applies to insecticides, herbicides, fungicides, and various other substances used to control pests. Pesticides also include plant regulators, defoliants, and desiccants (Aoun, 2020; Arya *et al.,* 2021; Prakash and Verma, 2021). The introduction to the market in the early 1990s of Imidacloprid and thiacloprid opened the neonicotinoid era of insect pest control. This class of systemic water-soluble insecticides chemically related to nicotine affects the central nervous system of insects. Acting systemically, this class of neurotoxic insecticides taken by plants, primarily through the roots, and translocate to all parts of the plant through stem transport. This systemic property combined with very high toxicity to insects enabled formulating neonicotinoids for soil treatment and seed coating with typical doses high enough to provide long-lasting protection of the whole plant from

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pest insects (Van der Sluijs *et al.,* 2013). The declines of pollinator populations, excessive anthropogenic activities and pollution have raised alarms over potential cascading effects on biodiversity, ecosystem stability, and agricultural yield (Prakash and Verma, 2022; Verma and Prakash, 2022; Singh *et al.*, 2023). Concurrently, the intensification of agricultural practices has driven the extensive use of synthetic pesticides and herbicides to control pests and weeds. While these chemicals enhance crop output, they often exert unintended adverse effects on non-target organisms, particularly pollinators and field observations. Pollinators play an essential role in the sexual reproduction of most flowering plants while obtaining pollen and nectar rewards from their flowers. Most plant species on earth depends on pollination services from animal pollinators (Kearns *et al.,* 1998; Arya *et al.,* 2024).

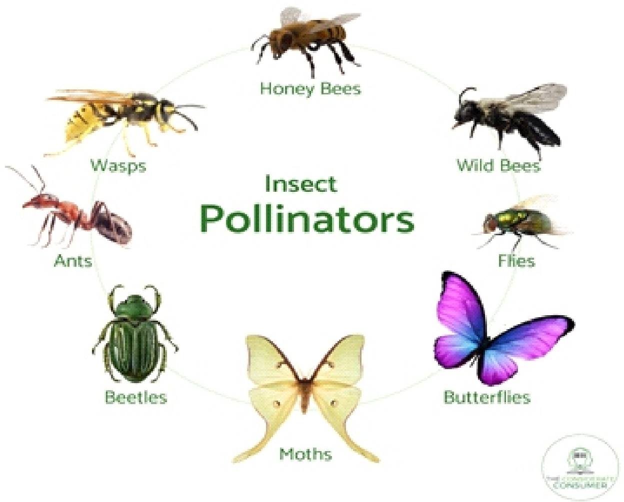


Fig. 1: (16-22 June, 2025- Pollinator Week).

This mutualism is not only crucial for the maintenance of biodiversity but also provides important services, with an estimated 35% of global food production relying on insect pollination (Klein *et al.,* 2007). Other pesticides that can be harmful to pollinators include organophosphates such as diazinon, chlorpyrifos, disulfoton, azinphosmethyl, and fonofos. This class of organophosphorus compounds has been used widely in agriculture and in household applications as pesticides (Verma and Prakash, 2018; Prakash and Verma, 2020). Pyrethroids, a class of synthetic insecticides similar to natural pyrethrins, have neurotoxic effects on insects as well. These were introduces into widespread use for the control of insect pests and disease vectors more than three decades ago (Aoun, 2020). Pollinators can be bare to pesticides not only in agricultural areas but in urban areas as well. Surface water residue data suggest that the intensity of pesticide use in urban areas may sometimes exceed that of agricultural areas, and for some pesticides, labeled application rate can be much higher for non-agricultural than for agricultural use. This is the case of pesticides used for mosquito abatement and in aerial application in response to fears of insect-borne virus. These were found to be a major contaminant of pollen collected by honeybees (Long and Krupke, 2016; Guarino, 2016).

1. Pesticides, Herbicides vs Pollinators:

Types of Pesticides and Herbicides:

1. **Neonicotinoids:** Systemic insecticides (e.g., Imidacloprid, Clothianidin) that bind to nicotinic acetylcholine receptors in insects.
2. **Organophosphates:** Acetylcholinesterase inhibitors (e.g., Chlorpyrifos) reducing neural function.
3. **Pyrethroids:** Synthetic analogues of pyrethrins (e.g., cypermethrin) affecting sodium channel gating.
4. **Glyphosate:** Broad-spectrum herbicide inhibiting the shikimate pathway enzyme EPSP synthase.
5. **Atrazine:** Triazine herbicide that disrupts photosynthesis by inhibiting photosystem II.

Key Pollinator Species: (Figure. 2)

1. Honeybees (*Apis mellifera*): Economically dominant, managed colonies.
2. Bumblebees (*Bombus* spp.): Wild and managed, critical in cooler climates.
3. Butterflies and Moths (Order Lepidoptera): Indicators of environmental health.
4. Hoverflies (Family Syrphidae): Dual-role pollinators and aphid predators.

Fig 2: Honeybee, Humming bird, butterfly and beetle.

Insect pollinators in particular bees (Hymenoptera: Anthophila) are uniquely specialized for pollen transport and account for the bulk of pollination services. European honeybees (*Apis mellifera*) often considered as the most valuable agricultural pollinator. However, wild pollinators, such as wild bumblebees (*Bombus* spp.), solitary bees, flies, wasps, and Lepidoptera pollinate certain and prevalent crops such as oilseed rape and orchard fruit species and contribute approximately the same value toward crop production as managed bees do (Kleijn *et al.,* 2015). Pollinator loss impact two broad groups of pollinator-dependent flowering plants: wild flowers and cultivated crops. In wild plant species, almost 80% are directly dependent on insect pollination for fruit and seed set, although this may vary markedly between sites and seasons (Potts *et al.,* 2010).

One of the most frequent proximate causes of reproductive impairment of wild plant populations in fragmented habitats is careful pollination limitation. In cultivated crops, until now, most growers have either matched their pollinator needs by renting honeybees or utilized the "free" services of wild bee species foraging in farm fields, a component of pollination services that has mostly overlooked in economic calculations. It has been likely that without bees, some 60 species of crop plants would fail to produce fruit (Heard, 1999); the economic consequences of this impact are obvious. The global annual economic value of insect pollination was estimated to be approximately153 billion during 2005 (i.e., 9.5% of the total economic value of world agricultural output considering only crops that are used directly for human food. Complete pollinator loss would translate into a production deficit over current consumption levels of 12% for fruits and 6% for vegetables (Halm *et al.,* 2006).

In addition, declining pollinator supply has the potential of increasing costs of food production. Increased yields are usually the result of increasing farm inputs such as fertilizers, labor, and water. For some crops, this increasingly intensive management may have overcome any losses in pollination services, but it also increases production costs. There is also evidence that one response to lower yield growth for highly pollinator-dependent crops is a growing demand for land in a time when farmland is contracting as development replaces agriculture (Aizen and Harder, 2009). Of particular importance is the collapse of honeybee (*Apis mellifera*) colonies in America and other developed countries, because they provide honey and wax commodities to our society. One of the main fronts advanced for their decline along with other pollinators is the use of pesticides, including not only insecticides and acaricides but also fungicides and herbicides (Sanchez-Bayo and Goka, 2014; Siviter *et al.,* 2018).

Instances of "bee kills" associated with use of pesticides have documented since the late 19thcentury. But the discovery in the mid-2000s of parallel declines in wild pollinators and plants depending on pollinators. Along with widespread losses of managed honey bees raisedthe possibility that the effects of pesticides on pollinators might be more than merely episodic (Sponsler *et al.,* 2019).Pesticides and herbicides target specific physiological pathways in pests and weeds but can cross-react with similar pathways in pollinators. Systemic uptake leads to residues in pollen and nectar, exposing foraging insects. Global pesticide usage exceeded 3.5 million tons in 2020, with neonicotinoids accounting for 25% of insecticide market share (Wanner *et al.,* 2022). Herbicide application rates have risen by 30% over the past two decades, primarily driven by glyphosate-resistant crop cultivation. Pollination services are valued at an estimated USD 235–577 billion annually (Gallai et al., 2009). Loss of pollinators jeopardizes fruit set, seed quality, and nutritional diversity. The diversity and abundance of pollinators is crucial in maintaining biodiversity on land and food production demands by the agricultural industry. Unfortunately, multiple pollinator species are currently experiencing contracting ranges and reductions in species richness and abundance (Evans *et al.,* 2018).

3. Effects of Pesticides and Herbicides on Pollinators:
In agricultural areas, an adverse relationship was found between pesticide use on agriculture sites and pollinator abundance, group richness, and diversity. Pollinators in agriculture areas can be visible to plant protection products in two ways (Arya and Dubey, 2013; Sanchez-Bayo and Goka, 2014):

1. By direct exposure to either drift droplets, which are scattered during the foliar spraying of crops, dust from seed drilling at planting, or inhalation of volatile pesticides during or after application to the crops.
2. By exposure to residues present in pollen, wax, nectar, honey, and guttation drops, which may result either from direct spray contamination of flowers, translocation through the treated plants or soil, or direct contamination during treatment of the combs (for honey bees only). In fact, the most frequently detected pesticides for honey bees and the two that occur in the highest quantity are those used by beekeepers to control Varroa mites (coumaphos and fluvalinate) (Mullin *et al.,* 2010).

Bees also drink water and were observed drinking from paddy field waters contaminated with pesticides. Although herbicides target plants, surfactants and adjuvants can be toxic to insects. Glyphosate formulations cause mortality in bee larvae at high application rates (Balbuena et al., 2015). Herbicide-driven reduction of flowering weeds diminishes forage diversity and floral resources. Atrazine use in field margins reduced wildflower richness by 60%, affecting bumblebee foraging ranges (Rundlof *et al.*, 2015). Pesticides encompass a diverse range of chemicals used in agriculture, forestry, and public health to manage pests. In the agricultural sector alone, pesticides play a pivotal role in ensuring food security by protecting crops from insects, weeds, and diseases. They can have short-term toxic effects on directly exposed organisms, and long-term effects can result from changes to habitats and the food chain. Excess use of pesticides may lead to the destruction of biodiversity (Prakash and Verma, 2014; Masih, 2021; Arya *et al.*, 2023).

1.1 Acute Toxicity and Mortality

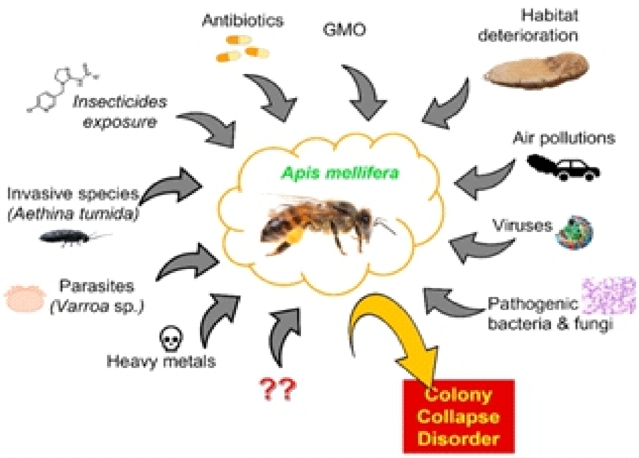
The toxicity of hydrophobic pesticides is mostly by contact exposure, whereas the toxicity of hydrophilic pesticides is mainly by oral ingestion of residues in pollen and honey. It should be noted that pyrethroids, which are highly hydrophobic compounds, are on average three times more toxic to bees by contact than by oral exposure. By contrast, 60% of the systemic (hydrophilic) pesticides have oral toxicities higher than their contact toxicities, up to13 times higher for some products (Sanchez-Bayo and Goka, 2014). Trials report median lethal dose (LD_{50}) values for imidacloprid at 3.7 ng/bee (Decourtye et al., 2003). Field exposures often exceed sublethal thresholds, causing acute colony losses during peak application periods. Neonicotinoids pose the highest direct threat to bees due to their acute toxicity, while herbicides like glyphosate and atrazine cause significant indirect effect by altering bee habitats and food sources. Understanding both direct and indirect pathways is crucial in evaluating the overall impact of agro-chemicals on pollinator populations.

3.2 Sublethal Effects on Behavior and Physiology of Pollinators:

Exposure to pesticides can be lethal or sub lethal with chronic detrimental effect on the individual pollinator and the colony. Sub lethal neonicotinoid concentrations impair navigation, foraging efficiency, brood development, and immune function (Henry et al., 2012).Chronic exposure leads to reduced colony growth, reproductive success and increased disease susceptibility. Chronic toxicity by constant dietary exposure to residues found in pollen and honey affects the mortality of individual bees and the growth and reproduction of their colonies. Such effects include not only sub lethal impairments but also delayed mortality (Tennekes and Sanchez-Bayo, 2011). Pesticide use, fate dynamics, and environmental conditions determine the spatiotemporal patterns of pesticide contamination in the environment (Prakash and Verma, 2020). Connecting patterns of contamination to patterns of pollinator exposure, however, requires an understanding of the behavioral and life history traits that govern the interactions between pollinators and their environment, and hence the spatiotemporal intersection between pollinators and environmental contaminants (Sponsler and Johnson, 2017; Kopit and Pitts-Singer, 2018).

3.3 Colony Collapse Disorder (CCD):

Foraging bees are exposed to multiple pesticides sprayed directly on to crops found on plant tissues including flowers. Thus, foraging bees can suffer combinatorial effect of multiple pesticides. High exposures to pesticides can cause acute mortality of foraging bees, while, at low levels, pesticide exposure has been associated with changes in individual bee behavior such as reduced foraging efficiency and decreases in colony queen production (Kuan *et al.*, 2018).



(Figure 3 - Factors of CCD (Colony Collapse Disorder) Source: Leska et al.2021)

There are many putative factors of CCD, (Figure.3) such as air pollution, GMO, viruses, or predators (such as wasps and hornets). However, it believed that pesticides and microorganisms play a huge role in the mass extinction of bee colonies. Insecticides are chemicals that are dangerous to both humans and the environment. They can cause enormous damage to bees' nervous system and permanently weaken their immune system, making them vulnerable to other factors. Some of the insecticides that negatively affect bees are, for example, neonicotinoids, coumaphos, and chlorpyrifos. Microorganisms can cause various diseases in bees, weakening the health of the colony and often resulting in its extinction. Infection with microorganisms may result in the need to dispose of the entire hive to prevent the spread of pathogens to other hives. Many aspects of the impact of pesticides and microorganisms on bees are still unclear. The need to deepen knowledge in this matter is crucial, bearing in mind how important these animals are for human life. (Leska *et al.,* 2021) Managing plant pests at the time of flowering period is very crucial to achieve maximum yield in agriculture. However, often this step displays undesirable effects on the foraging bees, which are very active at flowering, thus making their foraging trip into a hazardous trip. Due to common behavior of licking and grooming of bees, the pesticides can contaminate to other bees and thereby affecting the entire colony. The affected colony shows decline in its pollen and nectar collection and honey production ultimately resulting in the colony collapse. Honeybees already stressed by a poor diet have been found to be more sensitive to several pesticides (Challa *et al.,* 2019).

4. Experiential Data and Comparative Analysis

Data were compiled from peer-reviewed studies (2010–2023) and national pesticide usage databases in table 1. Pollinator impact metrics include LD_{50}, colony loss percentages, and visitation rate changes.

Table 1: Comparative Table of Pesticide Usage and Pollinator Impact.

S. No	Pesticides	Active Ingredient	Annual Use (tons)	LD_{50} (ng/bee)	Observed Colony Loss (%)
1.	Neonicotinoids	Imidacloprid	110,000	3.7	20–35
2.	Organophosphates	Chlorpyrifos	80,000	30	10–15
3.	Pyrethroids	Cypermethrin	70,000	35	8–12
3.	Glyphosate	Glyphosate	820,000	N/A	Indirect (15–25)
5.	Triazines	Atrazine	60,000	N/A	Indirect (10–20)

5. Mitigation Strategies and Best Practices

1. Integrated Pest and Pollinator Management (IPPM):

Integrated Pest Management (IPM) is a program of prevention, monitoring, and control which offers the opportunity to eliminate or drastically reduce the use of pesticides, and to minimize the toxicity of and exposure to any products, which are used. IPM does this by utilizing a variety of methods and techniques, including cultural, biological and structural strategies to control a multitude of pest problems. IPM is a term that is used loosely with many different definitions and methods of implementation. IPM can mean virtually anything the practitioner wants it to mean. Beware of chemical dependent programs masquerading as IPM. Those who argue that IPM requires the ability to spray pesticides immediately after identifying a pest problem are not describing IPM. Conventional pest control tends to ignore the causes of pest infestations and instead rely on routine, scheduled pesticide applications. Pesticides are often temporary fixes, ineffective over the long term (Arya and Dubey, 2013). Integrated Pest and Pollinator Management IPPM emphasizes for the integration of various pest management strategies, such as cultural practices, monitoring, biological controls, and judicious chemical use to minimize pollinator exposure (Chreil and Maggi, 2023).

2. Alternative Agrochemicals and Bio pesticides:

Bio pesticides (e.g., *Bacillus thuringiensis*, neem oil) offer lower non-target toxicity (Verma, 2017). Crop varieties with pest-resistant traits reduce chemical reliance. Neem oil form a coating on the insect body, which block the breathing process and suffocating the insect. Neem oil also work as a repellent on certain insect pests and mites also. The various parts of this tree live neem oil, neem seed cake, neem leaves, neem extracts, neem bark and roots are used in insect-pests management. Azadirectin can act as a feeding differentiates against a number of insect pests including beetles. It reduces the level of the insect hormone 'Ecdysone' by disrupting the insect's molting process so that the immature larvae cannot develop in to adult (Arya and Dubey, 2017). Nanobiopesticides have higher pesticide activity, targeted or controlled release with top-notch biocompatibility and biodegradability. Due to the drawbacks of synthetic pesticides, an alternative means of pest control is being encouraged, which is the use of bio pesticides. The effectiveness of bio pesticides in pest management comes from various modes of action, which include actions that regulate gut disruption, pest growth, and pest metabolism. Bio pesticides work by denaturing protein, causing metabolic disorder and paralysis, activating target-poisoning mechanisms, exhibiting multisite inhibitory actions, and releasing neuromuscular toxins and bioactive compounds. (Ayilara *et al.,* 2023).

3. Pollinator-friendly farming practices and Habitat restoration:

Understanding pesticide-induced changes to plants, microbes, and pollinator attraction is a particularly relevant question. Question given widespread initiatives to plant pollinator-friendly wildflowers in urban, suburban, and agricultural settings, which may inadvertently expose pollinators to pesticides (Williams *et al.,* 2015).Conserving and restoring pollinator habitat, such as native wildflower meadows and hedgerows, plays a crucial role in mitigating the impacts of pesticides. By providing alternative forage sources and nesting sites, pollinators can access pesticide-free areas, reducing their exposure and promoting their overall well-being. (Fountain, 2022). Pollinator-friendly farming enhances biodiversity and crop productivity by supporting bees, butterflies, and other pollinators. Key practices include planting diverse native flowering plants, maintaining wildflower strips and hedgerows, reducing pesticide use, and adopting integrated pest management. Providing nesting habitats, using organic or low-till methods, and preserving natural areas also help sustain pollinator populations. These approaches not only improve pollination and crop yields but also contribute to long-term ecological balance and farm sustainability (Rundlof *et al.*, 2022).

4. Public Awareness and citizen science:

Increasing awareness and providing education and training to farmers, beekeepers, pesticide applicators, and the public are essential for promoting responsible pesticide use and minimizing harm to pollinators. By understanding the importance of pollinators and the potential impacts of pesticides, individuals can make informed decisions and adopt practices that prioritize pollinator health. The Global Action on Pollination Services for Sustainable Agriculture provides guidance to member countries and relevant tools to use and conserve pollination services that sustain agroecosystem functions and to formulate policies that will ensure sustainability of these ecosystem services. At a legal level, some environmental organizations and several beekeeping organizations and concerned citizens filed lawsuits in federal courts in the USA against registration or use of neonicotinoid insecticides linked with destruction of bee colonies and other beneficial insects. At societal level, accumulative role of Non-Governmental organizations (NGOs) that advise native managers around pollinator health (Sponsler *et al.,* 2019).

5. Policy and Regulatory Frameworks

The first major restriction of pesticide use prompted by concern for pollinator safety occurred in 1999, when France Suspended the insecticide fipronil and the neonicotinoid insecticide imidacloprid applied as seed treatment to pollinator-attractive sunflower crops (Suryanarayanan and Kleinman, 2014). This was followed by a more extensive European Union-wide moratorium in 2013 on three neonicotinoid insecticides (imidacloprid, clothianidin, and thiamethoxam)applied as seed treatments to pollinator-attractive crops (European Commission 2013). Recently, the European Union has issued a ban on all outdoor use of neonicotinoid insecticides (The European Commission, 2018), citing a European Food Safety Authority report concluding that the compounds pose an unacceptable risk to bees (European Food Safety Authority, 2018). In North America, United States Environmental Protection Agency (USEPA), working in collaboration with Health Canada Pest Management Regulatory Agency (PMRA) developed beginning in 2012 a conceptual framework for quantifying risks to bees, is resulting in the 2014 harmonized Guidance for Assessing the Risk of Pesticides to Bees (US Environmental Protection Agency, 2014). Therefore, in 2013, USEPA ordered the revision of thousands of pesticide labels to reduce acute exposure of bees to neonicotinoid insecticides at bloom on crops requiring contracted pollination services. Regulatory measures, such as the EU's neonicotinoid restrictions (2013), demonstrate efficacy in reducing pollinator mortality. National guidelines should incorporate buffer zones and application timing restrictions.

In January 2017, USEPA released its policy to mitigate the acute risk to bees from pesticide products, which affects a broader range of pesticide classes (Fishel *et al.,* 2017), focusing on pesticide use by agricultural applicators when beekeepers are under contract to provide pollination services. When evaluating the safety of pesticides. There is a need to consider several parameters including the risk of exposure to multiple pesticides, or of the same pesticide being applied to different (adjacent) crops, and the need for longer-term toxicity testing on both adult bees and larvae. New protocols to detect cumulative toxicity effects and separate risk assessment schemes for different pollinator species are needed (Gill *et al.,* 2012). These will have clear implications for the conservation of insect pollinators in areas of agricultural intensification, particularly social bees with their complex social organization and dependence on a critical threshold of workers performing efficiently to ensure colony success. It is worthy to note here that the science of exposure to pesticides is still crude for honeybees, nascent at best for wild bees, and practically nonexistent for non-bee pollinators (Sponsler *et al.,* 2019).

Not only synthetic pesticides need to be assessed for safety on pollinators but also botanical pesticides. Few studies showed that field applications of botanical pesticides might represent a risk as the applications of synthetic compounds, indicating that these alternative products should also be submitted to risk assessments comparable to those required for synthetic products (Challa *et al.,* 2019; Tschoeke *et al.,* 2019). It is critical to recognize that the legitimate need to manage harmful pests underlies the phenomenon of pesticide use. Particularly in agriculture accordingly; efforts to protect pollinators from pesticide impacts should reconcile pest control needs with the conservation of pollinators, incorporating pollinator conservation into integrated pest management (IPM) frameworks rather than seeing pesticide use per se as an antagonist of conservation (Biddinger and Rajotte, 2015).

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