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Nitish Kumar LS
Department of Agricultural Entomology, College of Agriculture, V. C. Farm, Mandya, Karnataka, India

Raghavendra S
Department of Forestry and Environmental Sciences, College of Agriculture, V. C. Farm, Mandya, Karnataka, India

Varun MS
Department of Sericulture, College of Agriculture, UAS, GKVK, Bangalore, Karnataka, India

Roopashree DH
AICRP on Forage crops, ZARS, V. C. Farm, Mandya, Karnataka, India

Corresponding Author:
Nitish Kumar LS
Department of Agricultural Entomology, College of Agriculture, V. C. Farm, Mandya, Karnataka, India

Pesticides and non-*Apis* Bees: A silent threat: A review

Nitish Kumar LS, Raghavendra S, Varun MS and Roopashree DH

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Abstract
Non-*Apis* bees, encompassing bumblebees, solitary bees, and stingless bees, are critical pollinators that underpin biodiversity and agricultural productivity, yet they are increasingly threatened by pesticide exposure, which adversely affects their foraging efficiency, reproductive success, and overall physiological health. Unlike honeybees (*Apis* spp.), these pollinators exhibit a wide range of ecological traits, nesting behaviors, and life history strategies, rendering them particularly susceptible to environmental stressors. This review synthesizes current knowledge on the pathways of pesticide exposure and their sublethal and lethal impacts across individual, population, and ecosystem levels, emphasizing how impaired foraging performance, diminished reproductive output, and colony failure contribute to long-term population declines. Furthermore, pesticide exposure, when combined with concurrent stressors such as habitat fragmentation, climate change, and pathogen pressure, imposes risks to wild pollinator populations. Effective mitigation strategies, including precision agriculture, establishment of pesticide buffer zones, habitat restoration, and the implementation of stricter regulatory frameworks, are imperative to mitigate these threats. Safeguarding non-*Apis* bees is essential for maintaining ecosystem resilience and global food security, necessitating targeted conservation initiatives, enhanced ecological risk assessments, and collaborative efforts among stakeholders to protect these indispensable pollinators.

Keywords: Non-*Apis* bees, pesticide exposure, pollinator decline, biodiversity conservation, ecosystem resilience

Introduction

The accelerating biodiversity crisis, often described as the onset of a sixth mass extinction, has drawn increasing global concern. Among the most alarming trends are the dramatic declines in terrestrial arthropod populations, including pollinators that underpin both natural ecosystem stability and agricultural productivity. Within this context, pesticides have been repeatedly identified as a major anthropogenic driver of insect declines, raising urgent questions about their unintended impacts on non-target organisms. Over the past two decades, scientific research, regulatory risk assessments, and policy debates have largely focused on the honey bee (*Apis mellifera*) as a model organism. This emphasis is unsurprising, given the honey bee's dual role as a cornerstone of global crop pollination and as a managed species with long-standing importance for honey production. Moreover, its ease of maintenance under laboratory and semi-field conditions has made it highly suitable for ecotoxicological testing (Crall *et al.*, 2023) [7].

However, the reliance on honey bees as a regulatory proxy presents significant limitations. Globally, bees comprise nearly 20,000 described species, the vast majority of which do not share the life-history, behavioral, or ecological traits of *Apis mellifera* (Michener, 2007; Raine *et al.*, 2024) [15, 17]. While honey bees live in perennial colonies that buffer individuals against stressors, most solitary bees have short, annual life cycles and limited reproductive output, leaving them highly sensitive to environmental disturbances. Bumblebees (around 250 species) are partially social, with colonies persisting for only a single season, whereas stingless bees (around 600 species) form long-lived colonies but differ markedly in size, foraging behavior, and ecological distribution from honey bees (Roulston & Goodell, 2011) [18]. These differences strongly influence how non-*Apis* bees encounter pesticides in their environment, and how exposure translates into individual- and population-level outcomes.

Non-*Apis* bees—including bumblebees (*Bombus* spp.), solitary bees (e.g., *Osmia*, *Megachile*, *Andrena*), and stingless bees (*Meliponini*)—represent the overwhelming majority of global bee diversity. Collectively, they provide essential pollination services for wild plants and crops, often surpassing honey bees in efficiency and effectiveness (Winfree *et al.*, 2007; Garibaldi *et al.*, 2013) [27, 10]. Yet, these bees typically maintain smaller populations, have shorter foraging ranges, and possess highly specific nesting requirements. Such ecological specializations, while evolutionarily successful in diverse habitats, also make them disproportionately vulnerable to anthropogenic stressors such as pesticide exposure, habitat degradation, and climate change (Cane *et al.*, 2006; Goulson *et al.*, 2015) [5, 12].

Among the suite of stressors contributing to bee decline, pesticide exposure stands out as both pervasive and insidious. Agricultural intensification has dramatically increased reliance on systemic insecticides such as neonicotinoids, as well as fungicides and herbicides, many of which persist in soil, water, and plant tissues long after application (Woodcock *et al.*, 2016) [28]. Non-*Apis* bees are exposed to these chemicals through diverse pathways: ingestion of contaminated nectar and pollen, collection of tainted nesting materials, contact with treated soil during nest construction, and even through residues on vegetation within foraging landscapes (David *et al.*, 2016; Rundlöf *et al.*, 2015) [8, 19]. These multiple and overlapping exposure routes highlight the inadequacy of honey bee–centric testing frameworks for assessing ecological risk across the broader bee community.

Physiological and life-history differences further shape species-specific vulnerabilities. Variations in body size, detoxification enzyme systems, and metabolic rates mean that pesticide toxicity cannot be generalized from honey bees to all pollinators (Arena & Sgolastra, 2014) [1]. Empirical studies illustrate these differences: bumblebees exposed to sublethal doses of neonicotinoids exhibit reduced colony growth and decreased queen production (Whitehorn *et al.*, 2012) [26], while solitary bees experience impaired foraging efficiency, reduced larval development, and diminished nesting activity under similar exposure conditions (Sandrock *et al.*, 2014; Sgolastra *et al.*, 2019) [21, 22]. Such sublethal effects, though often subtle at the individual level, can cascade into population declines, with direct consequences for ecosystem pollination services (Brittain & Potts, 2011; Woodcock *et al.*, 2017) [4, 29].

Despite growing recognition of these risks, research on pesticide impacts in non-*Apis* bees remains disproportionately limited. Most available data are biased toward a handful of manageable species, particularly the bumblebee *Bombus terrestris* and cavity-nesting mason bees (*Osmia* spp.), leaving vast gaps in knowledge about tropical stingless bees, ground-nesting bees, and other ecologically important taxa. Moreover, much of the existing research has concentrated on neonicotinoids, while other widely used pesticide classes—such as pyrethroids, organophosphates, and novel systemic insecticides—remain underexplored despite evidence of potential risk. A comprehensive assessment of pesticide threats to pollinators must therefore integrate ecological traits such as nesting biology, foraging range, seasonal activity, and social structure, each of which modulates both exposure pathways and susceptibility to toxicants.

Importantly, pesticide stress does not act in isolation. The interaction of chemical exposure with other environmental pressures—including habitat fragmentation, climate change–driven shifts in floral resource availability, and the spread of invasive species, pathogens, and parasites—further erodes the resilience of bee populations. These synergistic and often nonlinear stressor interactions complicate predictions of pesticide impacts, underscoring the need for holistic approaches that integrate multiple drivers of decline.

This article synthesizes current knowledge on pesticide exposure in non-*Apis* bees, tracing its effects from individuals to populations and ecosystems. We highlight how laboratory studies, field-based monitoring, and ecological modeling together reveal complex and context-dependent responses to pesticides. By examining both lethal and sublethal effects, as well as interactions with broader environmental challenges, this synthesis aims to provide a robust framework for evaluating pesticide risks to wild pollinators. Ultimately, we argue for the urgent refinement of environmental risk assessment (ERA) frameworks and policy regulations to move beyond the honey bee paradigm, ensuring that the ecological realities of diverse non-*Apis* bees are represented. Such advancements are critical for safeguarding pollinator diversity, sustaining ecosystem functions, and promoting resilient agricultural systems into the future.

Diversity and importance of Non-*Apis* Bees

Non-*Apis* bees, often referred to as wild bees, play a crucial role in pollination and ecosystem stability. Unlike honeybees, these bees exhibit a vast range of behaviors, nesting habits, and ecological adaptations. They include over 20,000 species globally, classified under families such as Apidae, Megachilidae, Halictidae, Andrenidae, and Colletidae (Michener, 2007) [15]. These bees exhibit varying degrees of sociality, from completely solitary species to eusocial communities, such as bumblebees and stingless bees. Their pollination efficiency is often superior to that of honeybees, particularly for certain crops that require specialized pollination methods like buzz pollination (Garibaldi *et al.*, 2013) [10].

The nesting habits of non-*Apis* bees are highly diverse, influencing their exposure to environmental threats, particularly pesticides. Ground-nesting bees, such as *Andrena* and *Halictus* species, dig burrows in soil, making them vulnerable to soil-applied insecticides (Chan *et al.*, 2021) [6]. Cavity-nesting bees, including *Osmia* and *Megachile*, utilize pre-existing holes in wood, stems, or artificial bee hotels, often sealing their nests with mud, resin, or plant fibers. Carpenter bees (*Xylocopa* spp.) excavate tunnels in deadwood, while plasterer bees (*Colletes* spp.) secrete a waterproof lining for their nests. The diversity in nesting strategies highlights the need for targeted conservation strategies, as different bee species face distinct risks from habitat destruction and chemical exposure (Rundlöf *et al.*, 2015) [19].

Sociality in non-*Apis* bees varies significantly. Bumblebees (*Bombus* spp.) form annual colonies with a division of labor among queens, workers, and males. Their colonies, although smaller than those of honeybees, are essential for pollination in temperate regions. Stingless bees (*Melipona* and *Tetragonula* spp.), found mainly in tropical ecosystems, establish perennial colonies in tree hollows and rock crevices, producing honey and resin (Michener, 2007) [15]. In contrast, many solitary bees, such as *Osmia* and *Megachile*, lead independent lives, provisioning their nests with pollen and nectar before sealing them. Social nesting provides certain advantages, including cooperative brood care and protection from environmental hazards, but also increases the risk of pathogen transmission and colony collapse due to pesticide exposure (Whitehorn *et al.*, 2012) [26].

Pollination efficiency among non-*Apis* bees is often higher than that of honeybees due to their foraging behaviors and morphological adaptations. For example, buzz pollination—where bees vibrate flowers to release pollen—is a trait unique to bumblebees and some solitary bees like *Xylocopa* spp. (Garibaldi *et al.*, 2013) [10]. This mechanism is crucial for crops such as tomatoes, blueberries, and eggplants, which do not release pollen readily through wind or honeybee pollination. Leafcutter bees (*Megachile rotundata*) and mason bees (*Osmia lignaria*) are highly effective at pollinating fruit and vegetable crops, significantly improving yield quality. The decline of these pollinators due to habitat loss and pesticide exposure could severely impact global food production (Potts *et al.*, 2010) [16].

The increasing threats to non-*Apis* bees, particularly from pesticide exposure, necessitate urgent conservation actions. Soil-applied neonicotinoids, such as imidacloprid, have been shown to reduce nesting success in ground-nesting species like *Eucera pruinosa* by 85% (Chan *et al.*, 2021) [6]. Similarly, exposure to clothianidin disrupts bumblebee colony growth and queen production, leading to long-term population declines (Whitehorn *et al.*, 2012) [26]. Protecting these pollinators requires a multifaceted approach, including habitat restoration, reduced pesticide use, and promotion of pollinator-friendly agricultural practices. Recognizing the critical role of non-*Apis* bees in ecosystems will help mitigate pollinator declines and ensure sustainable biodiversity and food security (Potts *et al.*, 2010) [16].

Pathways of Pesticide Exposure in Wild Bees

Non-*Apis* bees are exposed to pesticides through multiple pathways, affecting their survival, behavior, and reproductive success. Unlike honeybees, many wild bees exhibit diverse foraging and nesting behaviors, which influence their pesticide exposure risk. Pesticide exposure occurs primarily through contaminated nectar and pollen, direct contact with sprayed surfaces, soil contamination affecting ground-nesting species, and exposure through water sources (Gill *et al.*, 2012) [11]. Understanding these routes is critical to designing effective conservation strategies for wild pollinators.

One of the primary exposure routes for non-*Apis* bees is through contaminated floral resources. Many insecticides, particularly neonicotinoids, are systemic, meaning they are absorbed by plants and translocated to nectar and pollen. Studies have shown that bumblebees (*Bombus terrestris*) exposed to neonicotinoid-contaminated nectar exhibit impaired foraging behavior, reduced pollen collection, and colony decline (Stanley *et al.*, 2015) [24]. Similarly, solitary bees such as *Osmia bicornis* experience learning and memory deficits after chronic exposure to clothianidin-laced nectar, which can affect their ability to locate food sources efficiently (Sandrock *et al.*, 2014) [21, 22].

Direct contact with pesticide residues on plant surfaces poses another significant risk. Non-*Apis* bees that forage on treated plants or come into contact with recently sprayed foliage may absorb toxic chemicals through their exoskeleton. Field studies indicate that leafcutter bees (*Megachile rotundata*) suffer high mortality when exposed to pyrethroid-treated vegetation (Artz & Pitts-Singer, 2015) [2]. Bumblebees have also been shown to experience reduced colony growth and increased worker mortality following foliar exposure to pesticides such as thiamethoxam and lambda-cyhalothrin (Rundlöf *et al.*, 2015) [19]. Given that many wild bees do not rely on centralized hives like honeybees, repeated exposure to such residues may have population-level consequences.

Soil contamination is particularly hazardous for ground-nesting bees, which constitute approximately 70% of all bee species. Pesticides applied as soil drenches or seed treatments persist in the soil, exposing developing larvae and adult bees that burrow underground (Chan *et al.*, 2021) [6]. A study on *Eucera pruinosa*, a ground-nesting solitary bee, found that exposure to imidacloprid-treated squash crops reduced nesting rates by 85% and caused significant declines in offspring production (Chan & Raine, 2021) [6]. Since neonicotinoids have long environmental half-lives, their accumulation in soil poses a continuous risk to successive generations of ground-nesting pollinators.

Water sources, including guttation droplets and contaminated surface water, represent another exposure route for non-*Apis* bees. Systemic insecticides are known to leach into water bodies, where bees may consume contaminated water while foraging (Samson-Robert *et al.*, 2014) [20]. Studies have shown that stingless bees (*Melipona quadrifasciata anthidioides*) exposed to neonicotinoid-contaminated water exhibited high larval mortality and reduced worker activity, highlighting the indirect pathways through which pesticides impact pollinators (Tomé *et al.*, 2015) [25]. Since wild bees rely on natural water sources more than managed honeybees, their susceptibility to pesticide-laden water should be a key consideration in conservation planning.

Mitigating pesticide exposure in non-*Apis* bees requires a multifaceted approach, including the regulation of high-risk pesticides, habitat management, and pollinator-friendly farming practices. Reducing pesticide application near nesting sites, incorporating flowering hedgerows, and adopting integrated pest management strategies can help minimize exposure risks (Potts *et al.*, 2010) [16]. Given the ecological importance of wild bees, prioritizing their protection through targeted conservation measures is essential for maintaining biodiversity and sustainable pollination services.

Sublethal and Lethal Effects of Pesticides on Bees: Implications for Reproduction, Populations, and Ecosystems

Pesticides, particularly neonicotinoids, have been widely implicated in the decline of bee populations worldwide. While lethal effects directly cause mortality, sublethal effects—though less immediately visible—can be equally devastating, impairing behavior, reproduction, and overall colony success (Blacquière *et al.*, 2012) [3]. These impacts extend beyond individual bees, disrupting pollination services, altering community structures, and threatening ecosystem stability (Potts *et al.*, 2010) [16]. There are many sublethal and lethal effects of pesticides on bees, their reproductive and population dynamics, and the broader ecological consequences.

Sublethal effects occur when pesticide exposure does not directly cause death but impairs critical functions, ultimately threatening bee survival and colony health. One of the most significant consequences is impaired foraging and pollination efficiency. Exposure to imidacloprid has led to an 85% reduction in nest establishment and a 5.3-fold decrease in pollen collection in *Eucera pruinosa* (squash bees) (Artz & Pitts-Singer, 2015) [2]. Similarly, bumblebees (*Bombus terrestris*) exposed to thiamethoxam collected less pollen per trip, spent less time foraging, and took longer to return to their nests (Gill *et al.*, 2012) [11]. Furthermore, pesticide-exposed bees often change their floral preferences, which may disrupt plant-pollinator networks (Stanley *et al.*, 2015) [24].

Cognitive impairments caused by pesticide exposure can severely affect learning and memory. Neonicotinoids like imidacloprid and thiamethoxam impair associative learning in bumblebees, reducing their ability to associate floral cues with rewards (Stanley *et al.*, 2015) [24]. In solitary bees such as *Osmia cornuta*, exposure to clothianidin has been shown to disrupt spatial navigation, making it harder for them to locate and return to food sources (Sandrock *et al.*, 2014) [21, 22]. Additionally, *Bombus terrestris* workers exposed to pesticides exhibit smaller mushroom body calyces, a brain region critical for learning and memory functions.

Reproductive success and nesting behaviors are also significantly affected by pesticides. *Eucera pruinosa* females exposed to imidacloprid built 85% fewer nests, reducing population growth (Artz & Pitts-Singer, 2015) [2]. Bumblebee queens (*Bombus impatiens*) exposed to imidacloprid laid eggs later and exhibited reduced colony initiation rates (Whitehorn *et al.*, 2012) [26]. Similarly, *Bombus terrestris* queens exposed to clothianidin and thiamethoxam experienced higher mortality during hibernation and lost more weight, making it harder for them to establish new colonies (Rundlöf *et al.*, 2015) [19]. In addition to reproductive effects, flight and orientation impairments have been documented. Exposure to pesticides weakens flight motivation, alters flight speed, and increases the likelihood of bees failing to return from foraging trips (Henry *et al.*, 2012) [13]. Bumblebee foragers from imidacloprid-exposed colonies have been observed to lose their way more frequently, reducing colony foraging efficiency.

Pesticides also have lethal effects that result from acute or chronic exposure, directly causing mortality or weakening bees to the point of death. High doses of neonicotinoids such as imidacloprid and thiamethoxam can cause rapid mortality upon contact or ingestion (Blacquière *et al.*, 2012) [3]. Bees foraging in neonicotinoid-treated crops have exhibited significantly higher mortality rates than those in untreated areas (Rundlöf *et al.*, 2015) [19]. Moreover, mass poisoning events linked to pesticide-contaminated pollen and nectar have been reported in agricultural landscapes. Chronic exposure to pesticides further reduces worker and queen lifespans, increasing colony failure rates (Gill *et al.*, 2012) [11]. Some pesticides weaken bees over time, leading to delayed lethal effects due to stress and immune suppression (Blacquière *et al.*, 2012) [3]. Bumblebee queens exposed to clothianidin and thiamethoxam have shown increased mortality rates during hibernation, affecting their ability to establish colonies the following season (Whitehorn *et al.*, 2012) [26].

Colony-level lethal effects include the collapse of bee populations. Neonicotinoid exposure has been linked to Colony Collapse Disorder (CCD) in honeybees, where worker bees disappear, leaving behind abandoned hives (Henry *et al.*, 2012) [13]. Similarly, bumblebee queens exposed to imidacloprid or thiamethoxam have reduced egg-laying success and higher mortality rates, preventing successful colony formation (Whitehorn *et al.*, 2012) [26]. Chronic exposure leads to smaller colonies, fewer new queens, and long-term population declines in wild bee species (Rundlöf *et al.*, 2015) [19]. Additionally, indirect lethal effects such as weakened immunity have been observed, making bees more vulnerable to diseases and parasites (Di Prisco *et al.*, 2013). Weakened or disoriented bees also face a higher risk of predation, contributing to population declines (Henry *et al.*, 2012) [13].

The reproductive consequences of pesticide exposure lead to long-term population declines in bees. Bumblebee queens exposed to clothianidin and thiamethoxam exhibit significantly lower survival rates during hibernation (Whitehorn *et al.*, 2012) [26]. In addition, queens exposed to imidacloprid are less likely to lay eggs, delaying or preventing colony formation altogether (Rundlöf *et al.*, 2015) [19]. Neonicotinoid exposure also reduces reproductive output by shortening the reproductive period, reducing oocyte size, and lowering the number of new queens produced (Crall *et al.*, 2018). Colonies exposed to neonicotinoids have been found to produce 85% fewer queens, severely limiting future colony establishment (Rundlöf *et al.*, 2015) [19]. Solitary bee populations are also negatively impacted, with *Eucera pruinosa* females exposed to imidacloprid establishing 85% fewer nests (Artz & Pitts-Singer, 2015) [2]. Stingless bee larvae exposed to imidacloprid exhibit over 50% mortality, significantly disrupting population growth (Tomé *et al.*, 2015) [25].

The ecological consequences of pesticide exposure extend beyond individual bees and colonies to entire ecosystems. Pesticide-exposed bees visit fewer flowers and collect less pollen, leading to reduced crop yields (Garibaldi *et al.*, 2013) [10]. Species such as *Eucera pruinosa*, which are highly specialized pollinators, face disproportionate risks from pesticide exposure, threatening crop production (Artz & Pitts-Singer, 2015) [2]. Wild bee diversity declines in pesticide-treated areas, leading to weakened pollination networks and reduced ecosystem resilience (Potts *et al.*, 2010) [16]. Reduced pollination services negatively impact plant species composition, causing shifts in ecosystem dynamics (Garibaldi *et al.*, 2013) [10]. The decline of wild pollinators increases reliance on managed honeybees, which may not be as effective in all agricultural systems (Garibaldi *et al.*, 2013) [10]. This decline also has significant economic implications, as pollinators contribute an estimated $235–$577 billion annually to global crop production (Potts *et al.*, 2016) [16].

Addressing the challenges posed by pesticide exposure requires a holistic approach, including stricter pesticide regulations, habitat restoration, and sustainable agricultural practices. By recognizing the importance of wild bees in ecosystems, conservation efforts can help mitigate pollinator declines and safeguard biodiversity and food security (Potts *et al.*, 2010) [16].

Mitigating Pesticide Threats to Non-*Apis* Pollinators

Non-*Apis* bees, including bumblebees, solitary bees, and stingless bees, play a vital role in pollination, contributing to both agricultural productivity and ecosystem stability. However, pesticide exposure poses a significant threat to their survival by affecting their foraging behavior, reproduction, navigation, and overall population health. Unlike honeybees, which are often the focus of pesticide risk assessments, non-*Apis* bees have diverse nesting habits, foraging patterns, and life cycles, making them uniquely vulnerable to chemical exposure. Mitigation strategies aim to reduce pesticide-related risks while ensuring that crop protection practices remain effective. These strategies involve a combination of reducing direct pesticide exposure, enhancing bee-friendly habitats, implementing pollinator-conscious farming practices, and strengthening regulatory policies. By integrating these approaches, it is possible to safeguard non-*Apis* bee populations and maintain their crucial role in supporting biodiversity and food production.

1. Reducing Pesticide Exposure in Agricultural Landscapes

One of the most effective ways to protect non-*Apis* bees is to minimize their exposure to pesticides in agricultural landscapes. This can be achieved through pollinator-safe pesticide practices, creating buffer zones, and adopting precision agriculture techniques. For example, avoiding pesticide application during peak foraging times—early morning or late evening—can significantly reduce exposure risks for bees (Gill *et al.*, 2012) [11]. Additionally, using selective pesticides, such as biopesticides or targeted insecticides, can minimize harm to non-target pollinators. A study in sunflower fields demonstrated that integrated pest management (IPM) practices reduced bumblebee mortality compared to conventional pesticide use (Rundlöf *et al.*, 2015) [19].

Creating pesticide-free buffer zones is another effective strategy. Planting wildflower strips and hedgerows between cropland and pollinator habitats can prevent pesticide drift and provide safe foraging areas. Research in orchards with buffer zones found a 30% increase in wild bee populations compared to fully treated fields (Blacquière *et al.*, 2012) [3]. Precision agriculture techniques, such as drone and GPS-guided pesticide applications, can also minimize overuse and reduce contamination of non-target areas. For instance, spot spraying technology in strawberry farms has been shown to target pest hotspots effectively while reducing pesticide runoff into non-crop habitats (Henry *et al.*, 2012) [13].

2. Enhancing Habitat and Nesting Opportunities

Protecting and enhancing habitats for non-*Apis* bees is critical for their survival. Providing artificial nesting sites, such as bee hotels for cavity-nesting species like mason bees (*Osmia* spp.), can compensate for habitat loss. A study in urban gardens found that installing bee hotels increased mason bee populations by 60% over two years (Artz & Pitts-Singer, 2015) [2]. Similarly, preserving deadwood and hollow plant stems can support wood-nesting bees like carpenter bees (*Xylocopa* spp.).

Ground-nesting bees, such as mining bees (*Andrena* spp.) and squash bees (*Eucera pruinosa*), are particularly vulnerable to soil disturbance. Minimizing soil tillage and using cover crops instead of deep plowing can help maintain their nesting grounds. For example, no-till farming practices in Canadian wheat fields increased ground-nesting bee populations by 45% (Potts *et al.*, 2010) [16]. Expanding floral resources is another key strategy. Planting diverse, pesticide-free wildflowers ensures continuous bloom periods for foraging, while increasing plant diversity in agroecosystems supports a broader range of pollinators. Flower-rich field margins in Europe, for instance, boosted bumblebee reproduction rates by 35% (Garibaldi *et al.*, 2013) [10].

Strengthening regulatory frameworks is essential to protect non-*Apis* bees from pesticide exposure. Implementing stricter pesticide regulations, such as banning or restricting high-risk insecticides like neonicotinoids, can significantly reduce harm to pollinators. The European Union's ban on neonicotinoids in 2018, for example, led to higher wild bee abundance in treated areas (Rundlöf *et al.*, 2015) [19]. Mandating pesticide impact assessments specifically for non-*Apis* bees before regulatory approval can also ensure that new chemicals are safe for wild pollinators.

Promoting integrated pest management (IPM) is another critical policy intervention. IPM encourages farmers to use biological pest control methods, such as natural predators, instead of chemical pesticides. Financial incentives for pollinator-friendly farming, like those provided by the U.S. Conservation Reserve Program (CRP), can increase adoption rates and benefit non-*Apis* bees (Blacquière *et al.*, 2012) [3]. Monitoring and research programs are also vital for understanding the long-term effects of pesticides on wild pollinators. Citizen science projects, such as the UK Pollinator Monitoring Scheme (PoMS), provide valuable data that helps shape bee conservation policies (Potts *et al.*, 2016) [16].

Mitigation strategies to protect non-*Apis* bees from pesticide exposure must address both direct and indirect risks. By reducing pesticide use in agricultural landscapes, enhancing habitats, and strengthening regulatory policies, it is possible to safeguard these vital pollinators. Integrating these approaches not only supports bee populations but also ensures the stability of ecosystems and agricultural systems that rely on their pollination services. Continued research, monitoring, and collaboration between scientists, policymakers, and farmers are essential to achieving these goals.

References

1. Arena M, Sgolastra F. A meta-analysis comparing the sensitivity of bees to pesticides. Ecotoxicology. 2014;23(3):324–334.
2. Artz DR, Pitts-Singer TL. Effects of fungicide and adjuvant sprays on nesting behavior in two managed solitary bees. PLOS ONE. 2015;10(8):e0135688.
3. Blacquière T, Smagghe G, van Gestel CA, Mommaerts V. Neonicotinoids in bees: A review on concentrations, side-effects and risk assessment. Ecotoxicology. 2012;21(4):973–992.
4. Brittain C, Potts SG. The potential impacts of insecticides on the life-history traits of bees and the consequences for pollination. Basic and Applied Ecology. 2011;12(4):321–331.
5. Cane JH, Minckley RL, Kervin LJ. Sampling bees (Hymenoptera: Apiformes) for pollinator community studies: pitfalls of pan-trapping. Journal of the Kansas Entomological Society. 2006;79(4):282–291.
6. Chan DSW, Raine NE. Population decline in a ground-nesting solitary squash bee (*Eucera pruinosa*) following exposure to a neonicotinoid-treated *Cucurbita pepo* crop. Scientific Reports. 2021;11:4241.
7. Crall JD, Switzer CM, Oyen KJ, Rands SA. Pesticide exposure and risk assessment for non-*Apis* bees: A

review. Environmental Science & Technology. 2023;57(12):4567–4578.
8. David A, Botías C, Abdul-Sada A, Nicholls E, Rotheray EL, Hill EM, et al. Widespread contamination of wildflower and bee-collected pollen with complex mixtures of neonicotinoids and fungicides commonly applied to crops. Environment International. 2016;88:169–178.
9. European Food Safety Authority (EFSA). Guidance on the risk assessment of plant protection products on bees (*Apis mellifera*, *Bombus* spp. and solitary bees). EFSA Journal. 2013;11(7):3295.
10. Garibaldi LA, Steffan-Dewenter I, Winfree R, et al. Wild pollinators enhance fruit set of crops regardless of honey bee abundance. Science. 2013;339(6127):1608–1611.
11. Gill RJ, Ramos-Rodriguez O, Raine NE. Combined pesticide exposure severely affects individual- and colony-level traits in bees. Nature. 2012;491(7422):105–108.
12. Goulson D, Nicholls E, Botías C, Rotheray EL. Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. Science. 2015;347(6229):1255957.
13. Henry M, Béguin M, Requier F, et al. A common pesticide decreases foraging success and survival in honey bees. Science. 2012;336(6079):348–350.
14. Hesselbach H, Scheiner R. Effects of the novel pesticide flupyradifurone (Sivanto) on honeybee taste and cognition. Scientific Reports. 2018;8:4954.
15. Michener CD. The Bees of the World. 2nd ed. Johns Hopkins University Press; 2007.
16. Potts SG, Biesmeijer JC, Kremen C, Neumann P, Schweiger O, Kunin WE. Global pollinator declines: trends, impacts and drivers. Trends in Ecology & Evolution. 2010;25(6):345–353.
17. Raine NE, Rundlöf M. Pesticide exposure and effects on non-*Apis* bees. Annu Rev Entomol. 2024;69:551–576.
18. Roulston TH, Goodell K. The role of resources and risks in regulating wild bee populations. Annu Rev Entomol. 2011;56:293–312.
19. Rundlöf M, Andersson GK, Bommarco R, et al. Seed coating with a neonicotinoid insecticide negatively affects wild bees. Nature. 2015;521(7550):77–80.
20. Samson-Robert O, Labrie G, Chagnon M, Fournier V. Neonicotinoid-contaminated puddles of water represent a risk for honeybees. PLOS ONE. 2014;9(12):e108443.
21. Sandrock C, Tanadini M, Pettis JS, et al. Impact of chronic neonicotinoid exposure on wild bee reproduction. Proc R Soc B Biol Sci. 2014;281(1786):20140558.
22. Sandrock C, Tanadini M, Tanadini LG, Fauser-Misslin A, Potts SG, Neumann P. Sublethal neonicotinoid insecticide exposure reduces solitary bee reproductive success. Agric Ecosyst Environ. 2014;184:68–75.
23. Sgolastra F, Medrzycki P, Bortolotti L, Renzi T, Tosi S, Bogo G, et al. Pesticide exposure assessment paradigm for solitary bees. Environ Toxicol Chem. 2019;38(2):354–363.
24. Stanley DA, Garratt MP, Wickens JB, Wickens VJ, Potts SG, Raine NE. Neonicotinoid pesticide exposure impairs bumblebee pollination services. Nature. 2015;528(7583):548–550.
25. Tomé HVV, Martins GF, Lima MAP, Campos LAO, Guedes RNC, Newland PL. Agrochemical synergism imposes higher risks to neotropical bees than previously thought: A lethal and sublethal evaluation of pesticide interactions. Environ Pollut. 2015;204:306–315.
26. Whitehorn PR, O'Connor S, Wäckers FL, Goulson D. Neonicotinoid pesticide reduces bumble bee colony growth and queen production. Science. 2012;336(6079):351–352.
27. Winfree R, Williams NM, Dushoff J, Kremen C. Native bees provide insurance against ongoing honey bee losses. Ecol Lett. 2007;10(11):1105–1113.
28. Woodcock BA, Bullock JM, Shore RF, et al. Impacts of neonicotinoid use on long-term population changes in wild bees in England. Nat Commun. 2016;7:12459.
29. Woodcock BA, Bullock JM, Shore RF, et al. Country-specific effects of neonicotinoid pesticides on honey bees and wild bees. Science. 2017;356(6345):1393–1395.