



PESTICIDE EXPOSURE AND REPRODUCTIVE PERFORMANCE IN WILD BEES AND ITS IMPLICATIONS FOR POLLINATOR POPULATION STABILITY

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ABSTRACT

Wild bees are critical pollinators in both natural and agricultural systems but are now becoming more susceptible to pesticides and other factors that can impact reproductive success. This review discusses the effects of pesticide use on the reproductive output of wild bees and proposes some options for long-term stability of pollinator populations. There are signs that pesticides have the potential to influence female fecundity, queen survival, nest establishment, brood production, male reproductive behaviour, processes involved in fertilization and offspring development. These can occur via neuro physical disruption, oxidative stress, changes in energy metabolism, immune dysfunction, sub-optimal foraging efficiency and interaction with other environmental stressors. Reproductive impairment varies in magnitude among species, influenced by ecological traits, landscape structure, availability of floral resources, climate, exposure duration and mixtures of pesticides. Reproductive effects are especially significant as they can happen at the sublethal level of exposure and can be cumulative over reproductive cycles or generations. A decline in mating success, offspring production and recruitment can ultimately affect population growth, resilience, and persistence. There are important gaps in current evidence, particularly with respect to male reproductive endpoints, solitary bees, long-term field exposure, and multigenerational responses, all across wild bee taxa. Reproductive toxicology studies should be combined with population monitoring, habitat quality, and landscape level exposure assessment in future studies. Assessing pesticide risk for reproductive endpoints will further add to the conservation strategies to ensure resilient wild bee populations and stable pollination services.

Keyword: Bee reproduction; Pesticide exposure; Pollinator conservation; Population stability; Wild bees

1. Introduction

Pollinators are a key element in terrestrial ecosystems as they provide a service for the sexual reproduction of flowering plants and play a significant role in plant biodiversity, ecosystem function and agriculture productivity. Bees are a crucial group of pollinators among insects due to their high requirement for floral resources, and their efficiency of pollen transfer between flowers. Thus, plant–pollinator interactions are a critical ecological interaction with implications for plant reproduction, community structure and the viability of natural and managed ecosystems (Ghosh & Hasan, 2025). Solitary bees, bumblebees, and other wild bees are also important pollinators of agriculture crops and wild plants which play an essential role in food production, biodiversity and ecosystem resilience (Roy et al., 2025).

Pollinator populations are subject to significant stressors in many areas, even though they are of ecological and economic importance. Losses have been related to many interacting factors such as habitat destruction and fragmentation, agricultural intensification, loss of floral resources, climate change, pathogens, invasive species and chemical exposure. The significance of these factors differs between species and landscapes, but pesticide application is a key factor as it can be repeatedly applied during the bee life cycle and may interact with other factors (Brunet & Fragoso, 2024). The nesting biology, foraging range, social organization and reproductive strategies of the various wild bee species differ significantly, and this may affect their vulnerability. Thus, impacts due to pesticides that have been found in managed honeybees do not necessarily directly translate to the wide variety of wild bee species.

The effects of the loss of wild bees go beyond a decrease in the number of species. Reduced bee diversity and abundance can impact plant reproductive success, important ecological interactions, and possibly the stability of pollination services. Wild bee declines may be attributed to a variety of factors, including habitat loss and destruction, intensive farming practices, pesticide exposure, climate change and biological stressors, and understanding the impact of these stressors on individual bee fitness and population persistence is needed (Lima et al., 2022). In this context, reproductive performance is particularly significant because maintenance of a population relies not on the survival of adults alone, but on all aspects of the mating, nest building and incubation, chick rearing and survival, and recruitment into future generations (Parreño et al., 2022).

Traditional pesticide risk assessments often have focused on acute toxicity and adult mortality. But even sub-lethal levels of pesticides can affect reproduction via physiological, behavioural, developmental and nutritional avenues. Sublethal exposure can disrupt reproductive development, foraging success, nesting habits, maternal care, brood care or brood development. These could be hard to see in a short-term toxicology test but can be important when they lead to fewer or less healthy young over multiple generations. In addition, impacts can be different for different sexes, species, life stages, nutritional status, pesticide combinations and landscapes.

There is thus growing interest in connecting individual-level health outcomes with large-scale conservation outcomes. Biodiversity, nutrition, environmental stressors, and species-specific vulnerabilities are just some of the interconnected biological and environmental processes that affect bee health and good wild bee conservation should take them into account, not just death points. It is especially critical to understand pesticide impacts on reproduction as reproduction is the direct link to sublethal effects on recruitment, population growth, and long-term population stability. An analysis targeted specifically at this pathway can serve to elucidate evidence and highlight key knowledge gaps while enriching the ecological relevance of pesticide-risk assessment and pollinator conservation.

Objectives

- To review the major pathways and effects of pesticide exposure on the reproductive performance of wild bees, including female and male reproductive endpoints.
- To examine the biological and environmental mechanisms and modifying factors that influence pesticide-associated reproductive impairment in wild bees.
- To evaluate how pesticide-induced reproductive effects may influence wild bee recruitment, population persistence, and long-term pollinator population stability.

2. Pesticide Exposure in Wild Bees

2.1 Major Pesticide Classes Relevant to Wild Bees

Insecticides, fungicides, herbicides and other crop-protection chemicals can be found in agricultural and urban settings to which wild bees may have access. The insecticides are typically the most important pesticides to consider because they impact the physiology of insects, but other pesticide classes can have sublethal effects or affect flower resources. The toxicity will be dependent on the compound, dose, persistence, formulation, and duration of exposure (Afroz & Khan, 2024). Systemic pesticides are particularly significant as they can be found in pollen and nectar, providing a source of repeated exposure during normal foraging and are moved through plant tissues. They could have different impact on non-Apis bees and wild bees due to the difference in body size, nesting biology and foraging behaviour (Shangpliang et al., 2025).

2.2 Routes and Pathways of Exposure

Exposure may occur when wild bees feed on nectar or pollen contaminated with the pesticide, or from pesticide spray residues or drift, contaminated water, soil, and nesting materials. Residues in soil can be a problem for ground nesting species while other bee species may be exposed through treated vegetation or contaminated floral resources. Pesticides can also carry over into other habitats through runoff, dust and airborne particles from the treated fields (Ige et al., 2025). Particulate matter containing pesticides is also

a route of exposure, with evidence linking it to bee deaths and suggesting that it is not only floral sources that pose a toxicological threat (Green et al., 2023).

2.3 Landscape-Level Variation in Exposure

Landscape composition, farming pressure, crop type, habitat fragmentation and availability of alternative floral resources are all important factors affecting pesticide exposure. Combining pesticide application with known pollinator distributions can allow for mapping where the exposure pressure is highest and make more targeted conservation planning (Douglas et al., 2022). Landscape structure also influences the frequency of bee turn to treated crops for food. Landscapes with higher or lower abundance of natural or semi-natural habitat can lead to greater or less reliance on pesticides used in the landscape, respectively, while more complex habitat can offer alternative forage and even help mitigate exposure (Hisamoto et al., 2024). The major pesticide exposure pathways relevant to wild bees are summarized in Table 1.

Table 1. Major Pesticide Exposure Pathways and Their Relevance to Wild Bees

Pesticide exposure component	Main source/pathway	Potential relevance to wild bees	References
Systemic pesticide exposure	Contaminated pollen, nectar, and plant tissues	Repeated oral exposure during routine foraging and resource collection	(Shangpliang et al., 2025)
Environmental residues	Soil, vegetation, water, and nesting substrates	Exposure may extend beyond directly treated crops and persist in bee habitats	(Ige et al., 2025)
Contaminated particulate matter	Airborne dust and pesticide-containing particles	Provides a non-floral exposure pathway and may contribute to mortality and physiological stress	(Green et al., 2023)
Landscape-level pesticide use	Intensively managed agricultural areas	Determines spatial overlap between pesticide application and pollinator populations	(Douglas et al., 2022)
Landscape structure	Crop composition, habitat arrangement, and alternative forage	Influences the frequency and intensity of pesticide exposure during foraging	(Hisamoto et al., 2024)
Multiple pesticide classes	Insecticides, fungicides, herbicides, and other agrochemicals	Can produce lethal, sublethal, or interactive effects depending on exposure characteristics	(Afroz & Khan, 2024)

2.4 Acute, Chronic, and Repeated Exposure

Pesticide exposure can be acute, chronic or repeated. Acute exposures typically refer to a relatively high exposure over a short time and can result in immediate impairment or death. Chronic exposure refers to lower levels of exposure for extended time periods and may be of particular significance in the reproductive arena as subtle effects can add up and these effects can impact nesting, fecundity, brood development and offspring production. Exposure to more than a single compound can add or interact to further increased risk with repeated exposures. Hence, realistic evaluation of pesticide exposure in wild bees must consider the pesticide, route of exposure, dose, duration, timing and landscape. The principal pathways through which wild bees may encounter pesticides are illustrated in Figure 1.

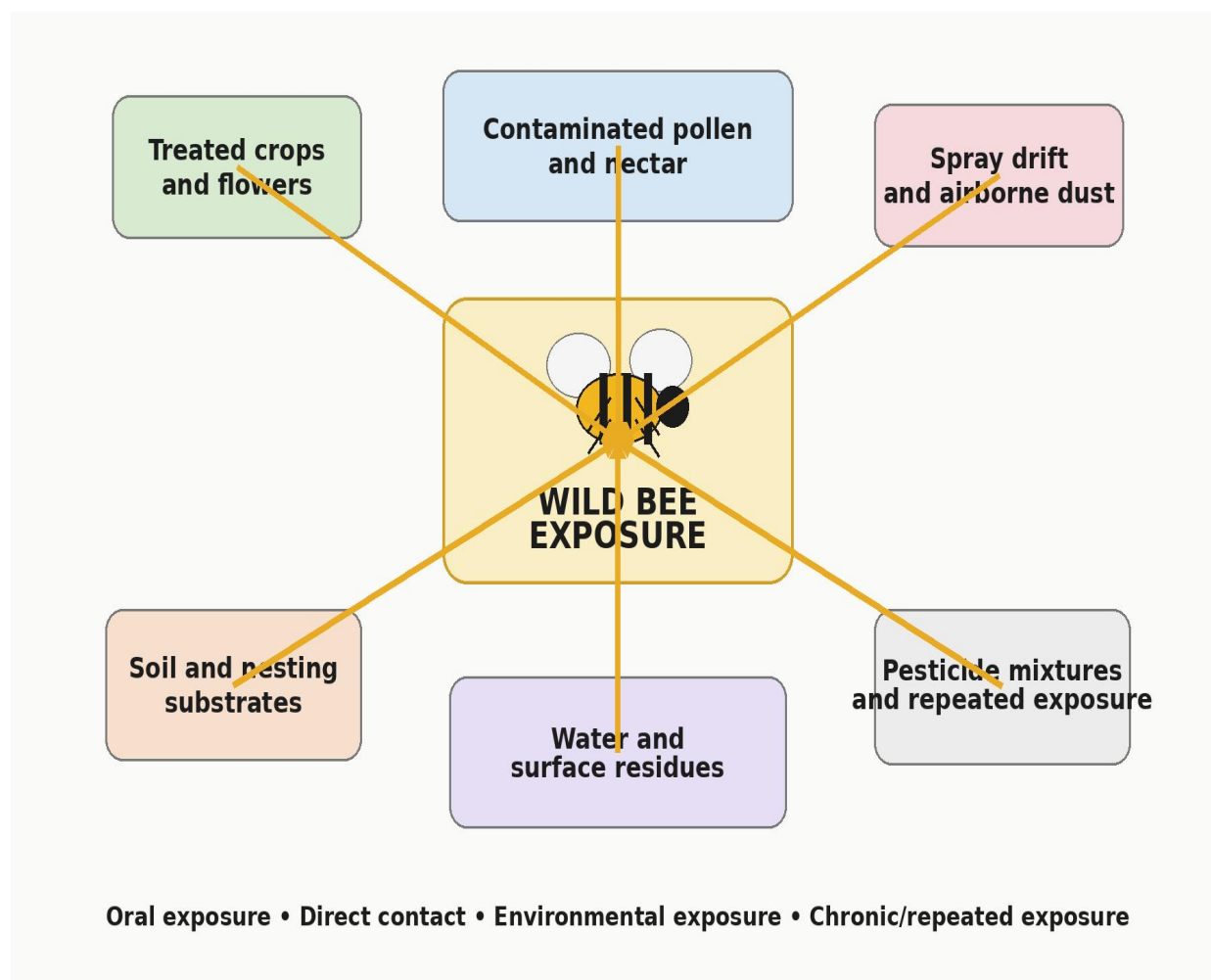


Figure 1. Pathways of Pesticide Exposure in Wild Bees

3. Reproductive Biology and Key Reproductive Endpoints in Wild Bees

3.1 Reproductive Diversity Among Wild Bees

Wild bees exhibit significant differences in reproductive strategy, social organization, nesting behaviour and reliance on floral resources. Solitary species tend to produce independent brood cells, colonies, and queens, while social species, like the bumblebees, need colonies to develop, workers to be produced, and

the establishment of a queen to produce brood. These differences affect the determination of reproductive success and environmental stressors' impact on populations. Plant–pollinator relationships, closely associated with bee foraging, nesting and acquisition of resources, are strongly influenced by the availability and quality of floral resources in the surrounding habitat (Patil, 2024). Bumblebees are important since in their reproductive cycle there is queen emergence, mating, overwintering, nesting, worker production and finally production of new queens and males. They also play a role in pollination, and their reproductive status is crucial for both pollination and crop production (Bie et al., 2025). Pollinator biology can vary significantly among pollinator groups, potentially affecting pollination effectiveness, resource utilization, and environmental sensitivity (Xiu & Green, 2025).

3.2 Female Reproductive Endpoints

Several interrelated reproductive endpoints can be used to measure female reproductive performance, such as ovarian development, mating success, egg production, nest initiation, brood-cell construction, larval provisioning, brood survival, and emergence of offspring. For solitary bees, the number of finished nests and viable young may be a direct measure of reproductive output. In social species, queen survival, colony establishment, worker production and successful production of new reproductive individuals are also important factors determining reproductive success. These endpoints are vulnerable to the effects of the availability, the efficiency of food foraging and the physiological condition. Decreased pollen and nectar availability may restrict the number of available resources which the bees use to produce eggs and provision brood and disturbances that affect foraging behaviour may have indirect effects on reproductive output. In agriculture, the balance between insecticide application, pest management, and the performance of bees and pollinators, as well as crop yields, may thus be affected (Knapp et al., 2022).

3.3 Male Reproductive Endpoints

Male reproductive performance may also be critical for the persistence of populations but has been less studied than female reproductive performance. Endpoints are relevant if they relate to sexual maturation, mating activity, sperm production, sperm viability, mating competitiveness or fertilization success. The function of any of these processes may be impaired, decreasing effective reproduction, even though adult survival may not be affected. Where females mate once or mate a few times, decreased male fertility may disproportionately impact the production of future brood. Mating behaviour or sperm quality may also affect the number and viability of offspring produced, thus directly connecting the reproductive health of males with recruitment of future populations. The principal reproductive endpoints used to evaluate wild bee reproductive performance are presented in Table 2.

Table 2. Key Reproductive Endpoints Relevant to Pesticide Effects in Wild Bees

Reproductive domain	Major endpoints	Biological significance	Population relevance	References
Female reproduction	Ovarian development, egg production, fecundity	Determines reproductive output of individual females	Reduced fecundity can lower recruitment	(Patil, 2024)
Queen performance	Queen survival, nest establishment, worker and reproductive production	Determines successful development of social bee colonies	Queen failure can prevent colony replacement	(Bie et al., 2025)
Male reproduction	Sexual maturation, mating activity, sperm quality, fertilization	Supports successful insemination and offspring production	Reduced male performance can restrict effective reproduction	(Xiu & Green, 2025)
Nesting and brood production	Nest construction, brood-cell provisioning, larval development	Integrates maternal behaviour and resource acquisition	Reduced brood production decreases future population size	(Knapp et al., 2022)

3.4 Reproduction as a Link to Population Stability

Reproductive endpoints are an important linkage between individual level stress and long-term population dynamics. Slower mating success, less eggs, poorer brood development or lower survival of offspring can lead to lower numbers of recruits in subsequent generations. These effects may be particularly significant for species with short nesting seasons, restricted dispersal and/or high nesting and/or foraging site specificity. Therefore, reproductive performance should be considered when assessing threats to wild bees, in addition to adult mortality. Fecundity, brood production, offspring survival and successful production of new reproductive adults may be more ecologically relevant measures of the potential effects of environmental stressors on population persistence over time. The reproductive cycle of wild bees and the major pesticide-sensitive reproductive endpoints are illustrated in Figure 2.

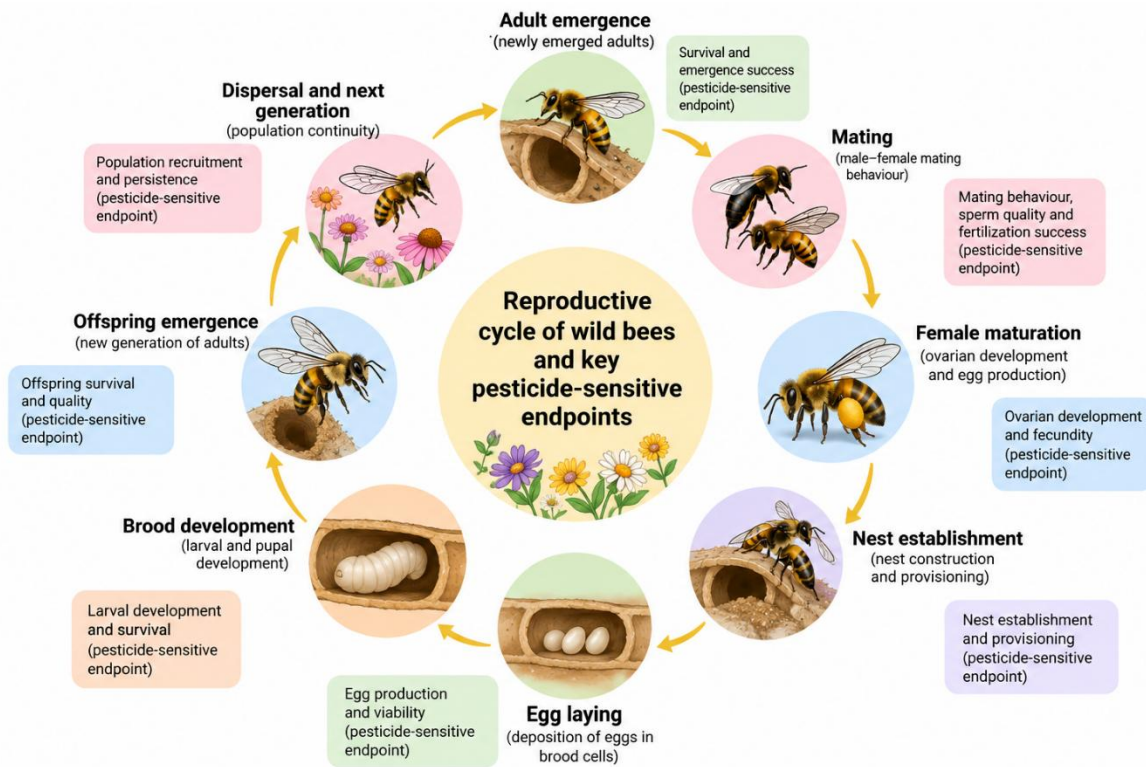


Figure 2. Reproductive Cycle of Wild Bees and Major Pesticide-Sensitive Endpoints

4. Effects of Pesticides on Female Reproductive Performance

4.1 Ovarian Development and Fecundity

Pesticide exposure can impact female reproductive performance, even at low levels of mortality. Sublethal exposure can influence ovarian development and egg maturation, energy allocation, and fecundity (total egg output) with a decrease in egg production. These effects may be particularly significant in social bees if applied during the critical reproductive period for the queen. Some studies, such as on honeybee queens, indicate that exposure to insecticides can also affect reproductive capacity and have negative impacts on colony development after exposure, suggesting that there can be reproductive toxicity effects beyond those on the individual female exposed (Huang et al., 2025).

4.2 Queen Survival and Reproductive Success

Bumblebee queens are especially important since it is essential to their survival, mating, overwintering, initiation of nest, and brood production for colony establishment. The queens may die due to repeated exposure to pesticides or pesticide exposure may affect their reproductive ability and thus may ultimately restrict new colony establishment. Experimental work suggests that repeated exposures to pesticides might affect both lifetime and reproductive success of bumblebee queens, highlighting the need to consider repeated exposures to pesticides, rather than just a single exposure (Morrison et al., 2025).

4.3 Nesting, Brood Production, and Offspring Output

Pesticide-induced effects on female behaviour can also result in decreased nesting activity, decreased

brood provisions and decreased production of offspring. Exposed females may be less efficient at foraging, provide less brood food or fewer viable brood. Importantly, the reproductive effects may be long-lasting and continue beyond the period of direct exposure. The chronic exposure of insects to insecticide (carryover) has been linked to decreased bee reproduction over consecutive years and may affect reproductive output in the coming years as well as in the present ones (Dolezal, 2022).

4.4 Influence of Floral Resources on Reproductive Outcomes

Flower can play a crucial role in determining the severity of pesticide effects on reproduction. Nutritional condition can enhance female's capacity to sustain reproduction during environmental stress and diverse and abundant floral resources support better nutritional condition. Studies indicate that flower plantings can contribute to wild bee reproduction and at least mitigate the impacts of pesticide exposure on wild bee reproduction by offering forage and enhancing the quality of the habitat (Rundlöf et al., 2022). Concurrently, pesticide hazard does not affect the reproductive fitness in all bee species in the same way. Ecological characteristics and dependence on crops can change the intensity of the effects of pesticide exposure on reproductive performance. There is evidence that pesticide hazard is interacting with resources and ecological factors to influence bee fitness, and the reproductive effects of pesticide exposure are highly context-dependent (Knauer et al., 2024). The main effects of pesticide exposure on female reproductive performance are summarized in Table 3.

Table 3. Reported Effects of Pesticide Exposure on Female Reproductive Performance

Reproductive response	Pesticide-related effect	Possible consequence	References
Queen reproduction	Impaired reproductive performance and colony development	Reduced colony establishment and reproductive output	(Huang et al., 2025)
Queen survival and reproduction	Repeated exposure may affect queen survival and subsequent reproduction	Lower probability of successful colony initiation	(Morrison et al., 2025)
Reproductive carryover	Effects may persist beyond the initial exposure period	Reduced reproduction across successive reproductive periods	(Dolezal, 2022)
Wild-bee reproduction	Floral resources may partly buffer pesticide-associated reproductive stress	Improved reproductive capacity under better habitat conditions	(Rundlöf et al., 2022)
Overall fitness	Pesticide hazard interacts with resource availability and ecological conditions	Species-specific variation in reproductive consequences	(Knauer et al., 2024)

4.5 Implications for Female-Mediated Population Recruitment

The reproductive impairment of females is directly relevant to population renewal due to the number of offspring to the next generation due to successful reproduction. When adult bees are still in the environment, reduced egg production, poor establishment of nests, impaired brood development, or lower queen survival, can result in lower recruitment numbers. These effects are particularly significant to solitary species in which each female will raise the next generation and social species in which the failure of queens can result in the lack of development of a whole colony. Female reproductive endpoints thus serve as a good indicator of the potential for long term effects of pesticide exposure on populations. The major female and male reproductive effects associated with pesticide exposure are summarized in Figure 3.

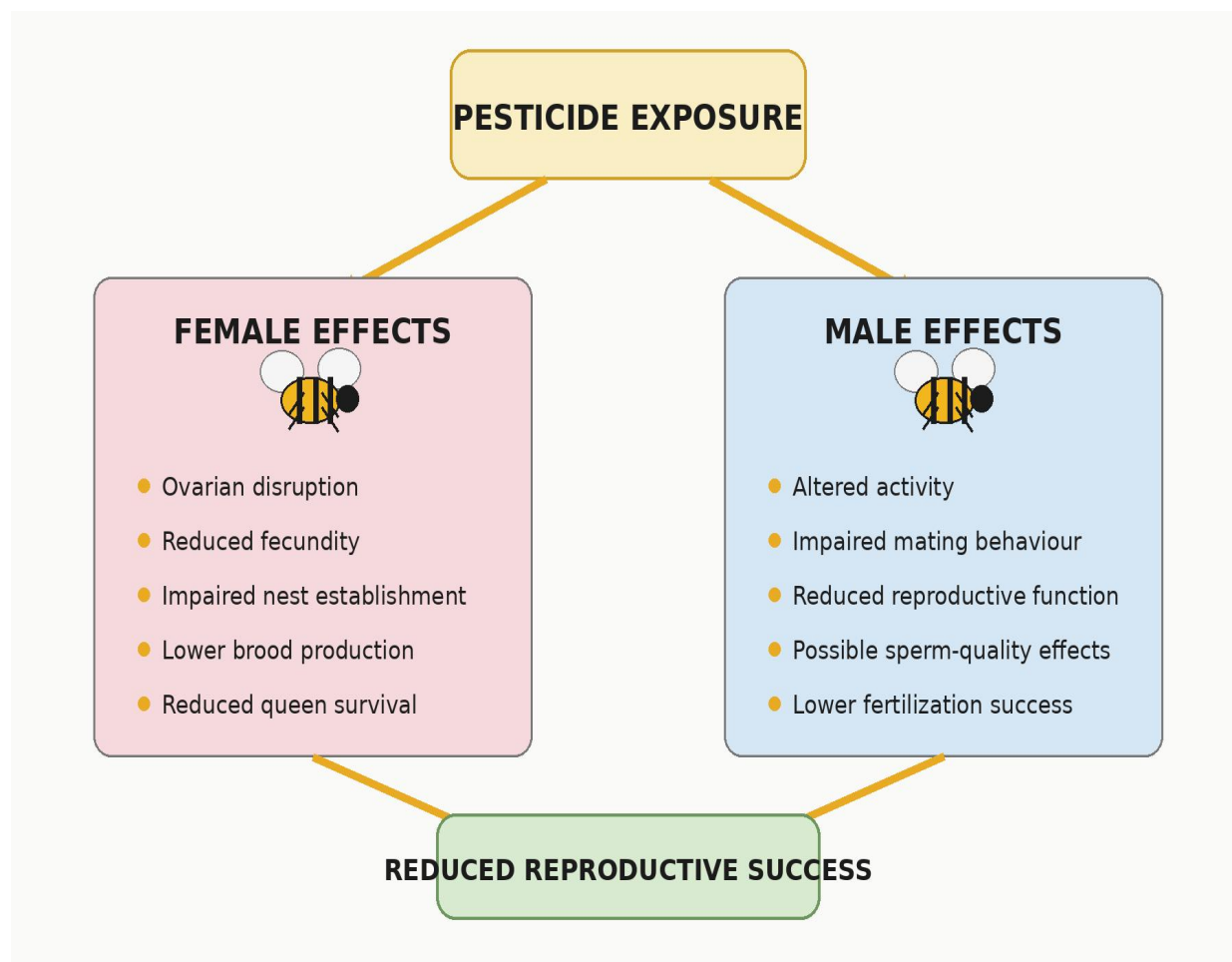


Figure 3. Pesticide Effects on Female and Male Reproductive Performance

5. Effects of Pesticides on Male Reproductive Performance

5.1 Male Reproductive Physiology and Pesticide Sensitivity

Male reproductive performance is considered an important yet under-researched aspect of pesticide risk in wild bees. For successful reproduction, normal sexual maturation, physiological condition, location of

mates, courtship and successful insemination are all necessary. Physiological stress from pesticides can disrupt these processes, even if the pesticide exposure is not fatal. Disruptions of physiological functioning, energy balance, behaviour and interactions with other environmental stressors are mechanisms associated with wild-bee decline, and any of these mechanisms could indirectly affect male reproductive capacity (Gekière et al., 2025).

5.2 Behavioural Changes and Mating Performance

Movement, activity, sensory abilities and the capacity to find and compete with males for females are all important in determining male reproductive success. These behaviours could be changed through sublethal exposure to pesticides through neurological or motor processes. Bumblebees also reveal non-lethal effects of non-neonicotinoid pesticides on activity and pollen-related behaviours (O'Reilly & Stanley, 2023). While this is not necessarily a male reproductive endpoint, similar alterations in locomotion, orientation and activity may disrupt mate searching and the mating opportunity.

5.3 Neurochemical Stress and Reproductive Function

Another possible link between pesticide exposure and male reproductive performance would be through neurochemical pathways. Biogenic amines are involved in most of the important functions in bees such as cognition, motivation, movement, learning and reaction to the environmental stress. Dysfunctions of these signaling pathways may change the behavioural performance and physiological homeostasis, which may include courtship and mating-related activities. Reproductive effects can thus occur indirectly because of environmental stressors affecting neurochemical regulation, without any overt toxicity (Raza & Li, 2025).

5.4 Sperm Quality and Fertilization Success

Reproductive toxicity in males also can include abnormalities in sperm production, viability, or fertility. These effects are important from an ecological point of view since if the insemination is successful females will be able to produce viable offspring during the next reproductive periods. But evidence of effect on sperm endpoints is far more limited than evidence with respect to survival or foraging behaviour for wild bees. This is an important area of research, since apparently normal males could have substantially diminished reproductive potential if their sperm production is poor or their mating ability is affected.

5.5 Implications for Population Reproduction

Male reproductive output can have an impact on population stability without a corresponding decrease in female abundance. The reduced successful mating rate, mating behaviour or fertilization ability can result in reduced effective reproduction and a reduced recruitment into the next generation. These effects can be more significant in small and/or fragmented populations where the number of available mates is already limited. Enhanced use of male-specific reproductive endpoints for pesticides in pesticide risk assessment studies is therefore needed to better understand the potential impacts of sublethal exposure on the

persistence of wild-bee populations.

6. Mechanisms Underlying Pesticide-Induced Reproductive Impairment

6.1 Neurophysiological and Behavioural Disruption

Pesticides can affect reproduction by interfering with neurological pathways that affect movement, learning, orientation, feeding and reproduction behaviour. Sublethal exposures can thus have an impact on bees' ability to find floral resources, find their way back to nests, find mates, or engage in behaviours that are essential for successful reproduction. Such impacts can happen even with low levels of mortality, highlighting behavioural disruption as a critical pathway by which pesticide residues can impact pollinator health and ecological functioning (Ambhure, 2023).

6.2 Oxidative Stress and Metabolic Disturbance

Oxidative stress and disruption of normal energy metabolism is another important mechanism. The metabolic costs of pesticide detoxification can also be used for reproduction, growth, immune defence, or brood provisioning. Excessive exposure can lead to an increase in physiological stress and decreases in energy available for ovarian development, egg production, mating activity and care of offspring. Pesticides can also interact with pathogens or other environmental stressors, resulting in synergistic impacts on bee health beyond the impacts of any individual stressor (Li, 2024).

6.3 Immune Dysfunction and Multiple Stressor Interactions

Pesticide exposure may also have an indirect effect on reproductive performance by reducing the ability to withstand other biological stressors or by compromising immune function. Bees in agricultural landscapes are not only directly affected by pesticides, but can also suffer from nutritional stress, habitat disruption, diseases, parasites and climate stress. This combination of interacting pressures can impact individual and colonies and may exacerbate declines in survival, activity, and reproductive performance (Straub et al., 2023). This points towards the need to assess pesticide effects under realistic ecological conditions. The major biological mechanisms and environmental factors modifying pesticide-related reproductive impairment are outlined in Table 4.

Table 4. Mechanisms and Modifying Factors Linking Pesticide Exposure with Reproductive Impairment

Mechanism/modifying factor	Potential effect on bees	Reproductive implication	References
Physiological and immune stress	Reduced health and resilience under pesticide and pathogen pressure	Less energy available for reproduction and brood production	(Li, 2024)
Multiple environmental	Combined effects of	Greater reduction in	(Straub et al.,

stressors	habitat, nutritional, and chemical pressures	individual and colony reproductive performance	2023)
Agricultural and pesticide stress	Altered resources and physiological functioning	Reduced reproductive capacity and offspring production	(Swathi et al., 2025)
Systems-level disruption	Interactions among pesticides, plants, climate, and pollinator biology	Indirect reproductive effects extending beyond direct toxicity	(Sprayberry et al., 2025)
Species traits and landscape context	Differences in exposure according to ecology and foraging behaviour	Variable reproductive sensitivity among species	(Knapp et al., 2023)
Climate-related stress	Altered flowering, metabolism, and reproductive timing	May increase sensitivity to pesticide exposure	(Sinha et al., 2025)

6.4 Impairment of Foraging and Resource Acquisition

Pollinators require plenty of pollen and nectar to be successful in their reproduction. Pesticide-induced impacts on mobility, navigation, feeding or foraging efficiency may lead to a decrease in the quantity and quality of resources available to nests. This can then lead to a decrease in the acquisition of resources which impacts on egg production, larval provisioning, brood development and offspring survival. Intensification and pesticide use in agriculture can thus impact reproductive success both directly (via pesticide toxicity) and indirectly (via alteration of pollinator resource quality and availability).

6.5 Systems-Level Pathways from Exposure to Reproductive Effects

Finally, reproductive impairment from pesticides needs to be placed in the context of a larger ecological system. Floral resources, habitat structure, interactions of plants and pollinators, pathogens, climate and pesticide exposure all influence bee reproduction. Disturbance at one level may impact on other components of the system and cause indirect impacts that are not apparent in short-term toxicity tests. A systems-based approach is thus useful to understand how anthropogenic pressures are interacting to influence pollinator behaviour, reproductive success, and persistence (Sprayberry et al., 2025). This is also an approach that highlights the reproductive toxicity is often caused by multiple pathways and is a product of physiological, behavioural and environmental mechanisms in interacting pathways.

7. Factors Modifying Reproductive Responses to Pesticides

7.1 Species Traits and Ecological Sensitivity

Pesticide effects on reproduction vary greatly among wild bee species, as they differ in body size, nesting behaviour, diet breadth and foraging range, phenology, and social organization. Species with limited foraging ranges or with high dependence on specific crops may be at higher risk of exposure than those species able to utilize more crops or a broader range of habitat and floral resources. The ecological characteristics also influence pesticide related risk, as not all pesticides are equally toxic and can be considered risky (Knapp et al., 2023).

7.2 Landscape Context and Agricultural Intensity

The surrounding landscape can have a significant effect on how pesticides affect reproduction. Repeated exposure may occur for bees in intensively managed agricultural systems due to the frequent application of pesticides, the decreased diversity of habitats and lack of access to uncontaminated forage. Landscape scale evidence suggests pesticide use can impact bumblebee populations on a larger spatial scale, such that reproductive consequences may be a result of a series of pesticide events occurring at the field level, but not necessarily a single event (Nicholson et al., 2024).

7.3 Adaptation to Anthropized Environments

Some bee species might exhibit behavioural and/or ecological adaptations that enable them to persist in highly disturbed habitats, while others might be less tolerant to rapid environmental change. Responses to urbanization, agriculture and habitat alteration may impact resource use, nesting opportunities and exposure patterns. This adaptive variation could be partly responsible for the differential response of some pollinator species to anthropized landscapes, which are relatively stable, and others, which are declining more strongly (López-Uribe et al., 2025). These opposing responses are significant when attempting to interpret the reproductive effects of pesticides relating to species.

7.4 Climate and Other Environmental Stressors

Climate conditions such as temperature, drought and rainfall may affect pesticide toxicity. Stress from climate change may change when bees flower, which would affect the availability of food, as well as bee physiology and reproductive maturity and thus sensitivity to chemicals. Pesticide exposure combined with heat stress and/or nutritional deficiency can cause greater stress to reproduction and population recovery than either alone. Climate change is thus now seen as one of the factors contributing to the decline of pollinators and the reproductive vulnerability of them (Sinha et al., 2025).

7.5 Habitat Quality and Floral Resource Availability

A variety and abundance of floral resources can affect bee's ability to cope with pesticide exposure. Good habitat quality can help to sustain reproductive condition and resilience in the form of enhanced nutrition, alternative forage and reduced reliance on treated crops. Habitat-management practices like agroforestry can be used to enhance habitat and pollinator resources, which may help to mitigate pollinator

vulnerability by expanding pollinator access to resources within the agricultural landscape (Paudel et al., 2025). Thus, the impacts of pesticides on reproduction should be viewed in the context of the quality of the habitat, nutritional conditions, and landscape management practices.

7.6 Combined Influence on Reproductive Outcomes

Reproductive effects of pesticides are thus influenced by several interacting factors, not just exposure. The severity of reproductive impairment may change due to species biology, habitat structure, climatic conditions, food availability and level of agricultural intensification. It is important to acknowledge these modifying factors, to account for the inter-study variation and to create realistic estimates of pesticide risk to wild bee populations.

8. Implications for Wild Bee Population Stability

8.1 Reduced Recruitment and Population Growth

Pesticide exposure can impact reproductive ability, which could affect population stability if the viable offspring produced are lower in number to go into the next generation. Teasing out reducing recruitment and diminishing population replacement can be a slow process through lower fecundity, impaired brood development, lower queen success or poor male reproductive performance. More broadly, pesticide use has been linked to shifts in distribution of wild bees, suggesting that exposure to pesticides could be a factor in trends of population contraction at locations where exposure is chronic or extensive (Guzman et al., 2024).

8.2 Changes in Population Dynamics and Persistence

Changes at the population level will not only be a result of death but of the interaction of reproduction, survival and recruitment over time. Environmental stress caused by pesticides can affect colony and population dynamics through impacts on reproductive output, adult persistence and/or the ratio of adult losses to replacement. The impacts of pesticide-related stress on bee populations are further illustrated by modelling the population dynamics of bees under such stress, which shows that chronic stress can alter population dynamics and lead to reduced long-term stability when reproductive recovery is not sufficiently rapid (Martínez-Álvarez et al., 2025).

8.3 Ecological Consequences of Pollinator Decline

The loss of bees can have an impact on more than just the bees themselves. The decline in pollinator abundance and diversity could lead to a decline in plant reproduction, ecological interactions and ecosystem stability. Thus, pollinator decline can affect the wildlife, as well as the plant communities directly or indirectly rely on pollination services, thereby highlighting the potential for reproductive impairment of bees to have broader ecological impacts (Maqbool et al., 2025).

8.4 Biodiversity Conservation and Population Resilience

Stable populations of pollinators will require management strategies that help support their reproduction, habitat quality, and population recovery. Population resilience can be enhanced through conservation

actions which protect, conserve and enhance nesting sites, increase the availability of flowers and reduce any unnecessary pesticide exposure. Pollinator management is thus intimately intertwined with biodiversity conservation as stable and diverse bee communities play a key role in supporting ecologic functions across agricultural and natural systems (Faisal et al., 2025). The progression from reproductive impairment to broader population-level consequences is summarized in Table 5.

Table 5. From Reproductive Impairment to Wild Bee Population Instability

Level of effect	Pesticide-associated change	Potential population consequence	Conservation implication	References
Individual	Reduced fecundity and reproductive success	Fewer offspring produced	Reproductive endpoints should be included in risk assessment	(Guzman et al., 2024)
Colony/population	Altered survival, reproduction, and recruitment under environmental stress	Declining population growth and persistence	Long-term demographic monitoring is required	(Martínez-Álvarez et al., 2025)
Community	Decline in pollinator abundance and diversity	Reduced ecological stability and pollination function	Protection of diverse pollinator communities is required	(Maqbool et al., 2025)
Conservation management	Improvement of habitat and pollinator-support measures	Greater resilience and recovery potential	Integrate biodiversity conservation with pollinator management	(Faisal et al., 2025)
Landscape	Combined pesticide, habitat, and environmental pressures	Increased risk of persistent pollinator decline	Apply integrated habitat restoration and threat-reduction strategies	(Sadafale et al., 2025)

8.5 Mitigation and Long-Term Population Stability

Pesticide exposure, habitat loss, climate stress, resource limitation and other environmental stresses play a role in population stability. But integrated strategies are needed to ensure effective mitigation, instead of relying on a single intervention. Minimizing pesticide use in sensitive reproductive periods, creating a

more connected landscape, providing a diversity of floral resources, and better landscape management practices can encourage recovery and lessen the chance of further population declines. More comprehensive studies of pollinator decline also highlight the need to integrate pollinator threat reduction with habitat restoration and conservation planning to maximize long-term pollinator persistence (Sadafale et al., 2025). The pathway linking pesticide exposure with reproductive impairment and long-term pollinator population instability is illustrated in Figure 4.

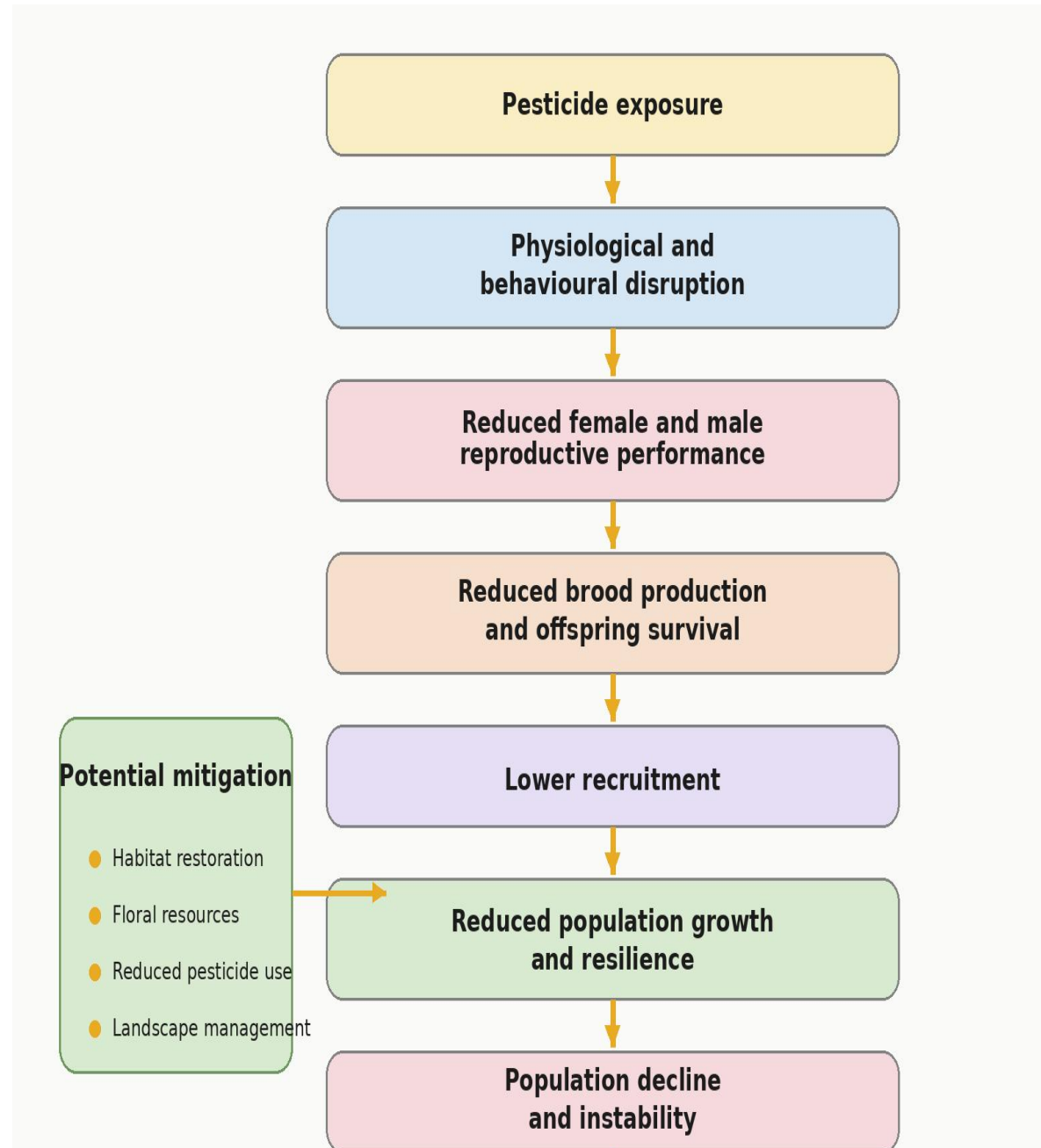


Figure 4. From Pesticide Exposure to Pollinator Population Instability

8.6 From Reproductive Effects to Population-Level Risk

Perhaps the greatest consequence of pesticide-induced reproductive dysfunction is the potential for

sublethal effects to be passed on from generation to Generation. Loss of mating success, fecundity, brood production, or offspring survival can be repeated over years and despite relatively low adult mortality will result in a gradual decline in population size and recovery potential. Reproductive endpoints should be included in population-level risk assessment, therefore, in addition to mortality and exposure measures. Correlating individual reproductive effects with demographic consequences allows for a more realistic understanding of the potential long-term impacts on wild bee populations when exposed to pesticides.

9. Knowledge Gaps and Future Research Directions

While there is increasing evidence of the effects of pesticides on bee health and reproduction, there are still significant knowledge gaps. Most of the literature focuses on managed bees and a few bumblebee species; many wild bees, for which there is no model species, are poorly known, particularly solitary bees. More focus is required on male reproductive endpoints, long-term and multigenerational effects, pesticide mixtures and exposure conditions that are more representative of field conditions. The relationship between the reproductive impairment of individual animals and measurable population level responses (recruitment, population growth, persistence, and recovery) should also be improved upon in future studies. Common reproductive endpoints would facilitate the comparison of data between species and studies, and long-term monitoring would help to better understand whether apparently sublethal effects are correlated with long-term demographic changes.

The study of interaction among habitat quality, climate, nutrition, pathogens and pesticide exposure in the future should also be considered. Conservation-oriented research is particularly notable, as creating or restoring habitat can quickly help support a diversity of pollinator species and may help to sustain them in the long-term, and conservation efforts should focus on restoring floral and nesting resources as well as minimizing chemical stress (Ulrich & Sargent, 2025). Therefore, an integrated management approach should be used, which includes pesticide-risk reduction, habitat enhancement, landscape connectivity and adaptation to environmental change. Adaptive management strategies for bees buffeted by climate change also highlight the need for context-specific and flexible responses to changing ecological conditions (Richardson & Thompson, 2025). Generally, future studies need to expand beyond individual toxicity studies and incorporate ecological approaches that will link pesticide exposure, reproductive success, habitat, and population dynamics. This will give a better foundation for safeguarding populations of wild bees and for a stable supply of pollination services in the face of growing environmental pressures.

10. Conclusion

Pesticide exposure is a key and multifaceted risk factor for wild bees' reproductive success and hence pollinator population persistence. There is evidence available that pesticides can impact on a variety of reproductive processes, such as female fecundity, queen survival, nest establishment, brood production, male reproductive behaviour and development of the young. These impacts can manifest as a direct physiological toxicity or as a behavioural disruption; as an effect on energy balance; and as an impact on

immune function, foraging efficiency, and in interaction with other environmental stressors. The level of reproductive damage varies among bee species. Reproductive responses can be modified by ecological traits, landscape structure, and availability of floral resources, as well as by climate conditions and exposure intensity and duration to pesticides. This volatility is an indicator that pesticides should be assessed for risk in realistic ecological context not just based on short-term mortality. Reproductive effects are especially significant due to the potential to impact recruitment, population growth, and persistence through generations via sublethal exposure. Even small decreases in reproductive success can be large if exposure occurs repeatedly, and/or in the context of habitat loss, nutritional stress, and climate change. Reproductive endpoints, long term monitoring of populations, habitat restoration, and landscape level management should therefore be considered in future pesticide-risk assessment and conservation strategies. To preserve wild bee diversity and resilient pollinator populations, a more integrated approach that connects toxicological, reproductive and demographic evidence is crucial.

References

1. Afroz, A., & Khan, H. R. (2024). THE IMPACT OF PESTICIDES ON POLLINATOR HEALTH. *COMPREHENSIVE INSIGHTS INTO ENVIRONMENTAL SCIENCE*, 364.
2. Ambhure, K. (2023). Impacts of Pesticide Residues on Pollinator Diversity and Ecosystem Services. Available at SSRN 6383798.
3. Bie, M., Song, K., Dong, H., Zhao, W., Lin, H., Shi, D., & Liu, D. (2025). Advancing sustainable agriculture through bumblebee pollination: bibliometric insights and future directions. *Sustainability*, 17(5), 2177.
4. Brunet, J., & Fragoso, F. P. (2024). What are the main reasons for the worldwide decline in pollinator populations?. *CABI Reviews*, (2024).
5. Dolezal, A. G. (2022). Carryover insecticide exposure reduces bee reproduction across years. *Proceedings of the National Academy of Sciences*, 119(1), e2120128118.
6. Douglas, M. R., Baisley, P., Soba, S., Kammerer, M., Lonsdorf, E. V., & Grozinger, C. M. (2022). Putting pesticides on the map for pollinator research and conservation. *Scientific Data*, 9(1), 571.
7. Faisal, M., Saritha, K., Srikanth, T., & Soujanya, A. (2025). POLLINATOR MANAGEMENT AND BIODIVERSITY CONSERVATION. *INNOVATIONS IN MODERN HORTICULTURE*, 254.
8. Gekière, A., Gérard, M., Potts, S. G., Michez, D., & Ghisbain, G. (2025). Underlying mechanisms shaping wild bee decline. *Biological Journal of the Linnean Society*, 145(4), blaf043.
9. Ghosh, S., & Hasan, M. N. (2025). Plant-Pollinator Interaction. In *Pollinators: Life, Biology and Threats* (pp. 63-73). Singapore: Springer Nature Singapore.
10. Green, F. B., Peterson, E. M., Emert, A. D., Subbiah, S., & Smith, P. N. (2023). Bee pollinator mortality due to pesticide-laden particulate matter from beef cattle feedyards. *Environmental Science & Technology*, 57(40), 14839-14848.
11. Guzman, L. M., Elle, E., Morandin, L. A., Cobb, N. S., Chesshire, P. R., McCabe, L. M., ... & M'Gonigle, L. K. (2024). Impact of pesticide use on wild bee distributions across the United States. *Nature Sustainability*, 7(10), 1324-1334.
12. Hisamoto, S., Ikegami, M., Goka, K., & Sakamoto, Y. (2024). The impact of landscape structure on pesticide exposure to honey bees. *Nature Communications*, 15(1), 8999.
13. Huang, Y., Gao, Q., He, Q., Liu, Q., Liu, Y., Shi, Y., ... & Cao, H. (2025). Diamide insecticides impair honey bee queen reproduction and colony development. *Science Bulletin*, 71(4), 697-700.
14. Ige, O. E., Aliu, F. P., Omole, A. E., & Alabi, O. O. (2025). Ecotoxicological impacts of pesticide. In *The interplay of pesticides and climate change: Environmental dynamics and challenges* (pp. 231-252). Cham: Springer Nature Switzerland.
15. Knapp, J. L., Bates, A., Jonsson, O., Klatt, B., Krausl, T., Sahlin, U., ... & Rundlöf, M. (2022). Pollinators, pests and yield—Multiple trade-offs from insecticide use in a mass-flowering crop.

- Journal of Applied Ecology, 59(9), 2419-2429.
16. Knapp, J. L., Nicholson, C. C., Jonsson, O., De Miranda, J. R., & Rundlöf, M. (2023). Ecological traits interact with landscape context to determine bees' pesticide risk. *Nature ecology & evolution*, 7(4), 547-556.
 17. Knauer, A., Naef, C., & Albrecht, M. (2024). Pesticide hazard, floral resource availability and natural enemies interactively drive the fitness of bee species depending on their crop fidelity. *Science of the Total Environment*, 922, 171058.
 18. Li, J. (2024). Threats to honeybee populations: pathogens, pesticides, and environmental changes. *Molecular Pathogens*, 15.
 19. Lima, M. A. P., Cutler, G. C., Mazzeo, G., & Hrnčir, M. (2022). The decline of wild bees: Causes and consequences. *Frontiers in Ecology and Evolution*, 10, 1027169.
 20. López-Urbe, M. M., Almeida, E. A., & Alves, D. A. (2025). Adapting to change: bee pollinator signatures in anthropized environments. *Current Opinion in Insect Science*, 68, 101297.
 21. Maqbool, F., Ali, M., Salman, M., Ghani, M. U., Hassan, A., Achakzai, W. M., ... & Humayun, M. (2025). Decline of honeybee populations and its consequences for wildlife and ecosystem stability. *Planta Animalia*, 4(5), 505-515.
 22. Martínez-Álvarez, P. E., Toro-Zapata, H. D., & Salcedo-Echeverry, G. E. (2025). Population dynamics of a honeybee colony *Apis mellifera* under pesticide-induced environmental stress. *Theoretical Ecology*, 18(1), 27.
 23. Morrison, M. A., Linguadoca, A., Šima, P., & Brown, M. J. (2025). Examining the effects of repeated pesticide exposure on bumblebee queen survival and reproduction. *Ecological Solutions and Evidence*, 6(1), e70011.
 24. Nicholson, C. C., Knapp, J., Kiljanek, T., Albrecht, M., Chauzat, M. P., Costa, C., ... & Rundlöf, M. (2024). Pesticide use negatively affects bumble bees across European landscapes. *Nature*, 628(8007), 355-358.
 25. O'Reilly, A. D., & Stanley, D. A. (2023). Non-neonicotinoid pesticides impact bumblebee activity and pollen provisioning. *Journal of Applied Ecology*, 60(8), 1673-1683.
 26. Parreño, M. A., Alaux, C., Brunet, J. L., Buydens, L., Filipiak, M., Henry, M., ... & Leonhardt, S. D. (2022). Critical links between biodiversity and health in wild bee conservation. *Trends in Ecology & Evolution*, 37(4), 309-321.
 27. Patil, P. (2024). Pollination ecology: Understanding plant-pollinator relationships. *International Journal of Research in Agronomy*.
 28. Paudel, S., Bhandari, S., & Upadhaya, S. (2025). Agroforestry for pollinator support and food security: a review. *Frontiers in Sustainable Food Systems*, 9, 1703823.
 29. Raza, M. F., & Li, W. (2025). Biogenic amines in honey bee cognition: Neurochemical pathways and stress impacts. *Current opinion in insect science*, 70, 101376.
 30. Richardson, E., & Thompson, D. (2025). Adaptive beekeeping strategies to mitigate climate impacts on honey bees in Australia. *GRJESTM*, 1(1), 19-27.
 31. Roy, T., Sorahia, D., Chatterjee, S., Pathak, M., Rajesh, T., Ningthoujam, K., & Patidar, R. K. (2025). Importance of hymenopteran pollinators in agriculture ecosystem: a review.
 32. Rundlöf, M., Stuligross, C., Lindh, A., Malfi, R. L., Burns, K., Mola, J. M., ... & Williams, N. M. (2022). Flower plantings support wild bee reproduction and may also mitigate pesticide exposure effects. *Journal of Applied Ecology*, 59(8), 2117-2127.
 33. Sadafale, G. V. R., Vishnupandi, M., Sami, A., Sudalaiyandi, Y., Subal, B. K., Ashish Kamal, P., & Shukla, A. (2025). Global decline of pollinators: Drivers, consequences and mitigation strategies. *Journal of Biology and Nature*, 17(2), 356-379.
 34. Shangpliang, P. W., Lyngkhai, E., Rangad, D., Ranee, G. B., & Kumari, A. (2025). Impact of Systemic Pesticides on Non-Apis and Wild Bee Populations: A Review. *Journal of Advances in Biology & Biotechnology*, 28(10), 1675-1689.
 35. Sinha, A., Das, R., Pramanik, K., & Layek, A. (2025). The Impact of Climate Change on Pollinator Populations: Trends, Challenges, and Conservation Strategies. *Recent Advances in Agricultural Research: A Compendium*, 100.
 36. Sprayberry, J. D., Ashman, T. L., Crall, J., Hranitz, J., Jankauski, M., Lihoreau, M., ... & Westerman, E. L. (2025). Plant-pollinator interactions in the Anthropocene: why we need a systems approach. *Integrative and Comparative Biology*, 65(4), 991-1006.

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37. Straub, F., Birkenbach, M., Leonhardt, S. D., Ruedenauer, F. A., Kuppler, J., Wilfert, L., & Ayasse, M. (2023). Land-use-associated stressors interact to reduce bumblebee health at the individual and colony level. *Proceedings of the Royal Society B: Biological Sciences*, 290(2008), 20231322.
 38. Swathi, P., Nagarjuna, R. K., Gouthami, D., & Chandana, M. S. (2025). Threats to pollinators and agricultural systems. In *Integrated Pest Management* (pp. 107-117). CRC Press.
 39. Ulrich, J., & Sargent, R. D. (2025). Habitat restorations in an urban landscape rapidly assemble diverse pollinator communities that persist. *Ecology Letters*, 28(1), e70037.
 40. Xiu, L., & Green, R. (2025, June). Comparative Study of Pollination Efficiency in Native vs. Invasive Insects. In *PHYTON-ANNALES REI BOTANICAE* (Vol. 65, No. 1).

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