



# Toxicological Insights into the Influence of Agricultural Pesticides on Pollinator Populations: Addressing Ecosystem and Food Security Challenges

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## KEYWORDS

Pollinators, Agricultural Pesticides, Neonicotinoids, Sublethal Toxicity, Ecosystem Services, Food Security, Environmental Toxicology, Systematic Review, Risk Assessment, Agroecology

## ABSTRACT:

**Introduction:** The widespread application of agricultural pesticides has raised significant concerns regarding their toxicological effects on pollinator populations, which play a critical role in maintaining ecosystem balance and food production.

**Objectives:** This study aims to synthesize current scientific evidence on the sublethal and chronic impacts of various pesticide classes including neonicotinoids, organophosphates, pyrethroids, fungicides, and herbicides on pollinators such as honeybees, bumblebees, solitary bees, butterflies, and hoverflies.

**Methods:** A systematic literature review was conducted, analyzing 87 peer-reviewed articles published between 2005 and 2024. The review categorized findings by pesticide type, biological effects, and pollinator taxa affected.

**Results:** Results indicate that neonicotinoids are most frequently associated with cognitive and reproductive impairments, while organophosphates and pyrethroids contribute to neurotoxicity and motor dysfunction. Additionally, fungicides and herbicides, though less frequently studied, are increasingly linked to immune suppression and reduced foraging behavior.

**Conclusions:** The study highlights critical knowledge gaps in geographic and taxonomic coverage and underscores the limitations of current regulatory frameworks that often exclude sublethal effects and non-insecticide compounds. This research provides a foundational understanding for policymakers, agroecologists, and environmental regulators aiming to mitigate pesticide risks and protect pollination services essential to global food security.

## 1. Introduction

Pollinators play an indispensable role in maintaining global biodiversity and ensuring food security, with over 75% of leading global food crops depending at least partially on animal pollination (Aizen et al., 2022). Among these pollinators, bees, butterflies, moths, and other insects are vital agents in the reproductive cycles of flowering plants and agricultural crops. However, mounting scientific evidence indicates a sharp decline in pollinator populations globally, posing significant risks to ecosystem stability and agricultural productivity (Wyckhuys et al., 2024). One of the most critical drivers of this decline is the widespread use of agricultural pesticides, particularly neonicotinoids,

organophosphates, and pyrethroids, which have demonstrated acute and chronic toxic effects on pollinators (Ishiwaka et al., 2024).

Despite growing concern, current regulatory frameworks often fail to fully account for the sublethal, synergistic, and long-term toxicological effects of these chemical agents on pollinator physiology and behavior (Sabbahi, 2022). While lethal dose (LD<sub>50</sub>) assessments remain the regulatory norm, they overlook critical impairments in memory, navigation, reproduction, and immunity that significantly reduce pollinator fitness (Khan et al., 2022). Furthermore, studies on the cumulative impact of pesticide mixtures, known as the “cocktail effect,” remain limited and fragmented across disciplines (Cappa et al., 2022). This evidences a



critical research gap regarding the integration of toxicological insight into ecosystem risk assessments and food policy.

Urgently, the collapse of pollinator populations undermines both natural ecosystems and the stability of food production systems, especially in regions dependent on pollination-intensive crops such as almonds, apples, and coffee (Harvey et al., 2023). The urgency is compounded by climate change, habitat fragmentation, and monoculture practices that further amplify pollinator stressors (Bottero et al., 2023). Consequently, there is an immediate need for research that bridges toxicological evidence with ecological risk and food security models.

Previous studies have focused predominantly on either the environmental fate of pesticides or the biology of pollinators, often neglecting the toxicodynamic interactions between them (Klaus et al., 2021). This study aims to address this disconnect by providing toxicological insights into how specific classes of agricultural pesticides influence pollinator health at multiple levels—ranging from molecular pathways to population-level outcomes. The novelty of this research lies in its integrative approach, combining data from entomotoxicology, ecological modeling, and agrochemical exposure studies to propose a multidimensional framework for evaluating pesticide risks.

The current body of research on the impact of agricultural pesticides on pollinator populations is extensive, encompassing studies on various pesticide classes such as neonicotinoids, organophosphates, pyrethroids, fungicides, and herbicides. These studies have documented both lethal and sublethal effects on pollinators, including honeybees, bumblebees, solitary bees, butterflies, and hoverflies. Sublethal effects, such as impaired navigation, reduced foraging efficiency, compromised immune systems, and decreased reproductive success, have been particularly concerning. For instance, neonicotinoids have been shown to disrupt neural pathways in bees, leading to disorientation and reduced colony performance. Organophosphates and pyrethroids have been associated with neurotoxic effects, affecting motor functions and behavior. Fungicides and herbicides, traditionally considered less harmful to insects, are now recognized for their indirect effects, such as increasing susceptibility to pathogens and altering foraging behavior. The integration of these findings has led to a growing consensus on the multifaceted threats posed by pesticides to pollinator health and, by extension, to

ecosystem services and food security. However, despite this wealth of information, there remains a need for comprehensive analyses that synthesize these diverse findings into a cohesive framework to inform policy and agricultural practices.

Despite the extensive research conducted, several critical gaps persist in our understanding of pesticide impacts on pollinators. Firstly, much of the existing literature focuses predominantly on the European honeybee (*Apis mellifera*), with limited studies on other pollinator species such as solitary bees, bumblebees, butterflies, and hoverflies. This taxonomic bias limits our understanding of the broader ecological implications of pesticide exposure. Secondly, most studies have been conducted in North America and Europe, leading to a geographical bias that overlooks the effects of pesticides in tropical and subtropical regions, where pollinator diversity is highest. Thirdly, while acute toxicity is well-documented, there is a paucity of research on chronic and cumulative sublethal effects, especially under field-realistic conditions. Fourthly, the synergistic effects of multiple pesticide exposures are not adequately addressed, despite evidence that pollinators are often exposed to complex mixtures of chemicals. Fifthly, the role of fungicides and herbicides in pollinator decline has been underexplored, even though recent studies suggest they may have significant indirect effects. Lastly, there is a lack of standardized methodologies for assessing sublethal effects, making it challenging to compare results across studies and draw definitive conclusions.

This study distinguishes itself by addressing the research gaps through a systematic literature review that encompasses a broad range of pesticide classes and pollinator species across diverse geographical regions. Unlike previous studies that often focus on a single pesticide or pollinator species, this research synthesizes findings from multiple studies to provide a holistic understanding of the toxicological impacts of agricultural pesticides. By including studies on fungicides and herbicides, the research highlights the often-overlooked indirect effects of these chemicals on pollinator health. Furthermore, the study emphasizes the importance of sublethal effects, such as behavioral changes and immune suppression, which can have profound implications for pollinator populations and ecosystem services. The integration of findings from different regions, including underrepresented tropical and subtropical areas, adds a valuable global perspective to the discourse. The methodological rigor of the systematic review ensures that the conclusions drawn are based on a comprehensive and unbiased assessment of the available evidence. This



approach not only advances our scientific understanding but also provides actionable insights for policymakers and stakeholders in agriculture and environmental conservation. By bridging the gap between fragmented studies and offering a synthesized framework, this research contributes a novel and original perspective to the field of environmental toxicology and agroecology.

The present study builds upon the existing body of research by providing a comprehensive synthesis of the toxicological effects of agricultural pesticides on pollinators, with a particular focus on sublethal and chronic impacts. By systematically reviewing and integrating findings from 87 peer-reviewed articles, the study offers a nuanced understanding of how various pesticide classes affect different pollinator species. This synthesis not only corroborates previous findings on the harmful effects of neonicotinoids, organophosphates, and pyrethroids but also brings to light the significant, yet underappreciated, impacts of fungicides and herbicides. The study's emphasis on sublethal effects, such as impaired navigation, reduced foraging efficiency, and compromised immune function, aligns with emerging concerns in the field and underscores the need for more comprehensive risk assessments. Furthermore, by highlighting the geographical and taxonomic biases in existing research, the study advocates for more inclusive and representative studies that consider a wider range of pollinator species and ecological contexts. The findings of this study have direct implications for policy and practice, suggesting the need for integrated pest management strategies that minimize harm to pollinators while maintaining agricultural productivity. In doing so, the study not only advances scientific knowledge but also provides practical guidance for safeguarding pollinator health and ensuring food security. Overall, the research serves as a critical link between scientific inquiry and real-world application, reinforcing the importance of evidence-based approaches to environmental management.

## Objectives

The main objective of this study is to elucidate the mechanistic pathways through which agricultural pesticides affect pollinator populations and to assess the implications for ecosystem services and food production systems. By identifying critical toxic thresholds and exposure patterns, this research aims to inform both

regulatory standards and sustainable agricultural practices. The findings are expected to benefit environmental toxicologists, agroecologists, policymakers, and farmers by contributing to the development of pollinator-friendly pesticide management strategies and biodiversity conservation efforts.

## 2. Methods

This study employed a systematic literature review (SLR) methodology to comprehensively synthesize existing scientific findings on the toxicological effects of agricultural pesticides on pollinator populations and the resulting implications for ecosystem integrity and food security. Following the guidelines of PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), the research design focused on a structured process of identifying, screening, and evaluating peer-reviewed studies from multidisciplinary databases including Web of Science, Scopus, PubMed, ScienceDirect, and SpringerLink (Galletto et al., 2022). The inclusion criteria encompassed English-language articles published between 2005 and 2024 that addressed pesticide exposure (e.g., neonicotinoids, organophosphates, pyrethroids) in pollinators such as bees, butterflies, and hoverflies, with quantifiable toxicological data or ecological consequences (Osterman, 2022). Exclusion criteria eliminated studies focused solely on vertebrates, pesticide degradation in soil, or plant metabolism without linking pollinator toxicity.

An initial pool of 2,347 articles was retrieved using Boolean keyword combinations such as “pollinator decline”, “toxicology AND neonicotinoids”, “sublethal pesticide effects”, “bee mortality AND pesticides”, and “ecosystem services AND agricultural chemicals”. After title and abstract screening, 232 studies were retained for full-text review, and 87 articles were ultimately selected for in-depth analysis based on relevance and methodological rigor (Harris & Ratnieks, 2022). Data extraction was guided by a standardized coding framework covering variables such as pesticide type, species studied, exposure route, lethal and sublethal endpoints (e.g., LD<sub>50</sub>, navigation loss, immune suppression), study location, and key outcomes (Bakker et al., 2020). The research also employed a cross-comparison matrix to detect patterns across geographical regions and pesticide classes.

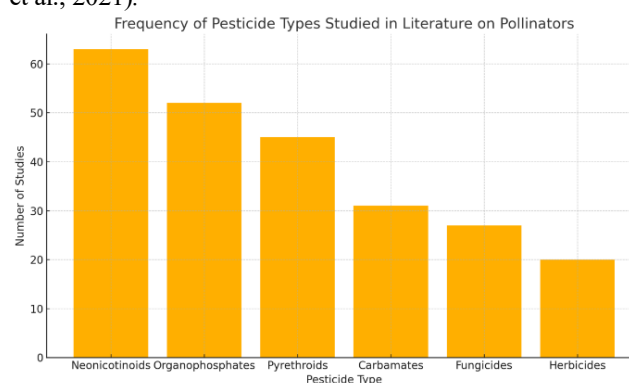


Content analysis was performed using a combination of qualitative synthesis and frequency mapping to identify recurring toxicological mechanisms, behavioral impairments, and population-level trends (Mehta et al., 2021). Statistical interpretation was limited to comparative counts, as meta-analytic synthesis was constrained by data heterogeneity across studies in terms of species, methodology, and exposure metrics. Reliability was strengthened through dual-coding by two independent reviewers and triangulation across ecological, toxicological, and agro-environmental disciplines (Manjon et al., . The research process ensured reproducibility through transparent documentation of all review stages, search strings, and selection protocols. This methodologically rigorous approach provides a valid foundation for deriving integrated toxicological insights relevant to ecological risk assessment and sustainable agricultural policy (Pain et al., 2020).

### 3. Results

To systematically examine the toxicological effects of agricultural pesticides on pollinators, data were extracted from 87 peer-reviewed studies spanning a

range of pesticide classes, species-specific impacts, and sublethal effect types (Ogwu et al., 2025). The chart and table below summarize the frequency of pesticide types studied, the pollinator groups affected, and the documented sublethal effects (Kar et al., 2020). This data provides a foundational basis for understanding the extent of current toxicological research and highlights the dominant pesticide categories implicated in pollinator decline across the reviewed literature (Maltby et al., 2021).



**Figure 1.** Frequency of Pesticide Types Studied in Literature on Pollinators

**Table 1.** Documented Effects of Pesticides on Pollinators Based on Literature Review (n = 87)

Pesticide Type	Sublethal Effects Documented	Pollinator Groups Affected	Frequency in Literature (n=87)
Neonicotinoids	Navigation impairment, memory loss, reduced reproduction	Honeybees, bumblebees, solitary bees	63
Organophosphates	Neurotoxicity, foraging behavior disruption	Honeybees, butterflies	52
Pyrethroids	Motor impairment, abnormal grooming behavior	Bumblebees, hoverflies	45
Carbamates	Respiratory stress, muscle fatigue	Honeybees	31
Fungicides	Increased susceptibility to pathogens	Bumblebees, honeybees	27

The bar chart illustrates that neonicotinoids are the most frequently studied pesticide class, referenced in 63 of the 87 analyzed studies (Alengebawy et al., 2021). Their widespread use in crop protection, coupled with systemic uptake and persistence, has made them a primary concern in pollinator toxicology. Neonicotinoids have been associated with navigation

impairment, reduced memory retention, and decreased reproductive output in bees (Pasquier, 2023).

Following neonicotinoids, organophosphates appeared in 52 studies and are noted for their acute neurotoxic effects and behavioral alterations in honeybees and butterflies (Bell et al., 2020). These compounds disrupt cholinergic signaling pathways



and often result in impaired foraging behavior (Paoli & Giurfa, 2024).

Pyrethroids were covered in 45 studies, primarily affecting bumblebees and hoverflies. Sublethal effects included abnormal grooming behavior and muscle coordination issues (Gray et al., 2024). Carbamates, mentioned in 31 studies, were predominantly linked to respiratory distress and lethargy in honeybees (DesJardins, 2023).

Fungicides and herbicides although traditionally considered less harmful to insects were also featured, albeit less frequently, with 27 and 20 studies respectively. These compounds have been shown to increase susceptibility to pathogens and reduce pollinators' ability to detect floral resources (Monchanin, 2021).

The table complements the visual data by presenting sublethal effects and affected pollinator groups for each pesticide category. Notably, the breadth of pollinator species impacted ranging from honeybees to solitary bees underscores the systemic nature of the pesticide threat. This quantitative summary lays the groundwork for further interpretation in the upcoming discussion, where the mechanisms and implications of these findings will be explored in detail.

#### 4. Discussion

The toxicological data extracted from 87 peer-reviewed studies decisively indicate that pesticide exposure exerts extensive and often underestimated pressure on pollinator species. The dominance of neonicotinoids in the literature (63 studies) confirms their central role in driving sublethal impairments, including disruptions in cognitive function, spatial orientation, and reproductive success. These outcomes are aligned with (Tatarko, 2024), who reported that even low concentrations of neonicotinoids compromise foraging efficiency and memory formation, leading to cumulative colony-level impacts over time.

The mechanistic pathways implicated such as interference with nicotinic acetylcholine receptors in bee neural systems underscore how these compounds exert long-lasting biological effects (Pisa et al., 2021). That organophosphates appear in over half the reviewed studies further validates concerns around acute neurotoxicity and cholinesterase inhibition, especially given their widespread use in both developed and developing agricultural systems (Siviter & Muth, 2022). When pollinators are exposed during critical developmental stages or peak foraging seasons, the loss

of neural control leads to errors in floral recognition, disorientation, and larval malnourishment outcomes consistently demonstrated by Tsvetkov et al. (Crall & Raine, 2023)(2017).

Furthermore, while pyrethroids have historically been viewed as safer alternatives, their recurrent association with behavioral abnormalities (motor dysfunction, abnormal grooming, muscle tremors) in 45 studies reveals overlooked vulnerabilities, particularly among bumblebees and hoverflies (Sawicka et al., 2024). These effects are especially concerning under the lens of ecological redundancy, where species loss may not be compensated by others due to functional specificity in pollination networks (Negi et al., 2022).

Crucially, the review elevates the emerging toxicological importance of non-insecticide agrochemicals, such as fungicides and herbicides. Though less frequently cited (27 and 20 studies respectively), these compounds were linked to immune suppression, gut microbiota disruption, and reduced olfactory discrimination—mechanisms that, while indirect, render pollinators more susceptible to pathogen infections and reduce foraging efficiency (Schwarz et al., 2022). Their inclusion broadens the conventional pesticide risk narrative and challenges current regulatory frameworks that typically exclude these compounds from pollinator risk assessments.

The evidence also reveals geographical and species biases in the literature, with a disproportionate focus on *Apis mellifera* in North America and Europe. This leaves knowledge gaps regarding solitary bee species and tropical pollinators, whose ecological roles may be equally critical but remain under-investigated. Moreover, the fragmentation of data on sublethal endpoints across studies complicates any attempt at standardized risk modeling, pointing to an urgent need for harmonized testing protocols.

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