

OPINION

Pesticide Risk Assessment in a Changing World

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Correspondence: Mathilde L. Tissier (mathilde.tissier@iphc.cnrs.fr)**Received:** 11 December 2024 | **Revised:** 1 April 2025 | **Accepted:** 6 April 2025**Funding:** This work was supported by Canadian Network for Research and Innovation in Machining Technology, Natural Sciences and Engineering Research Council of Canada and Liber Ero Foundation.**Keywords:** global change | insect health | insecticides | neonicotinoids | nutrition**ABSTRACT**

Pesticide risk assessments currently rely on surrogate species and focus primarily on acute lethality metrics, failing to capture the broader impacts on non-target organisms and thus biodiversity. Under the directives of regulatory agencies worldwide, this traditional approach overlooks the complex interactions between multiple stressors, including climate change, land-use shifts, and pesticide transformation products. Pesticide risk assessments must therefore undergo a paradigm shift to account for these complex interactions, which disproportionately affect insect pollinators, other non-target species, and biodiversity at large. While prior work has highlighted the need to move beyond single-species models, emerging evidence on nonlinear stressor interactions and the ecological consequences of transformation products highlight critical gaps in current frameworks. Here, we synthesize insights from recent research to propose a holistic approach for environmental risk assessments that integrates ecological and evolutionary complexities in the context of global change.

1 | Reevaluating Toxicity Assessment for Biodiversity

Ecological risk assessments (ERAs) assess the likelihood that stressors, such as chemicals or invasive species, will adversely affect ecosystems and biodiversity. For pesticides, ERAs currently rely on extrapolating the toxicological responses of a few surrogate species to entire taxonomic groups. However, a paradigm shift is underway in ERAs, recognizing the inadequacy of relying on a limited number of surrogate species to accurately gauge pesticide toxicity for all biodiversity (Raine and Rundlöf 2024; Shahmohammadloo et al. 2024; Siviter et al. 2021, 2023; Topping et al. 2020). Honey bees, for instance, dominate pesticide toxicity studies in the world's largest knowledgebase (ECOTOX), which remains vital to the ERA process. While managed honey bees (*Apis* spp) are often used as a model organism

to inform policies, many other insects essential to agriculture are potentially more sensitive to widely used *neonicotinoids* (see Box 1: "Glossary") (Basu et al. 2024; Franklin and Raine 2019; Shahmohammadloo et al. 2024). In addition, variation in pesticide sensitivities exists not only between species but also within taxa. For example, the lethality of pesticides in honey bees (assessed by the *LD50*; Box 1) varies by up to six orders of magnitude within and among studies, which raises concerns about the accuracy of using them as surrogates for other species in risk assessments (Shahmohammadloo et al. 2024). Furthermore, domestic honey bees are not an ideal surrogate for other wild bees due to their domestication, eusocial structure, and genetic selection—while many wild bees are solitary and have very different ecological characteristics (Franklin and Raine 2019; Raine and Rundlöf 2024). This challenges the use of honey bees as a general surrogate for terrestrial arthropods in ERAs.

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BOX 1 | Glossary.

- **Antimetabolite:** Is a chemical that interferes with metabolism by preventing the use of a metabolite, which is an organic substance that is part of normal metabolism.
- **Glyphosate:** Is an herbicide, widely used in agriculture around the world to remove weeds. Increasing evidence shows that glyphosate or its transformation products impair the microbiota of many animals (including humans) and can disrupt the metabolism of aromatic amino acids like tryptophan, with important health consequences.
- **LD50:** Is the lethal dose at which 50% of the studied population is killed within a specific time frame (often 24–48 h). It is a common metric in ecotoxicology to assess the toxicity of a molecule.
- **nAChRs:** Nicotinic acetylcholine receptors: embedded in cell walls, they play an important role in cell signaling and cognitive processes. They are targeted by neonicotinoids, which saturate these receptors and block the fixation of the neurotransmitter acetylcholine (ACh) with deleterious consequences on the central and peripheral nervous systems. They are named after nicotine, a metabolite synthesized by plants from niacin or vitamin B3.
- **Neonicotinoids:** Are “new nicotine-like” insecticides, derived from the alkaloid nicotine. They primarily act on the central nervous system by binding to nAChRs, disrupting insects’ central nervous systems, leading to death. They are the most widely used insecticides worldwide. First introduced in the 1990s to fight insects damaging crops, they are also toxic to pollinators and other animals, including humans.
- **Nicotine:** Is an alkaloid, i.e., a plant metabolite called a “secondary compound”. It is produced by plants from nicotinic acid (vitamin B3, a primary compound). Like other alkaloids such as gramine or caffeine, it can have positive effects at low doses but can be toxic to insects at high doses.
- **Pyrethroids:** Are synthetic organic insecticides recreating the action of pyrethrins, a group of terpenoids with insecticidal activities produced by chrysanthemum flowers. Pyrethroids and pyrethrins target the central nervous system of insects. They are commonly used in crop protection, forestry, wood and textile industry, as well as in medicine (i.e., to protect against viruses transmitted from mosquitoes) and veterinary medicine.
- **Transformation products:** Once in the environment, a molecule can be degraded (i) by abiotic factors—such as sunlight or water (through chemical mechanisms like hydrolysis, photolysis, or redox reactions)—becoming a degradation product or (ii) metabolized by microorganisms present in the environment (biological mechanism), becoming a metabolite of the initial molecule. Recent research highlights environmental concerns about both degradation products and metabolites of pesticides.
- **Vitamin B3 or Niacin:** Are generic terms including nicotinic acid, nicotinamide, and nicotinamide riboside. In plants, nicotinic acid is the precursor of alkaloids like nicotine, anabasine, and gramine. In animals, vitamin B3 modulates hundreds of enzymes, while nicotinamide is the precursor of Nicotinamide Adenine Diphosphate (NAD), essential for cell respiration and ATP synthesis. All animals must obtain it from the diet or gut microbiota daily.

Given the alarming declines in biodiversity across insect groups, including pollinators such as wild bees and butterflies, as well as other crop auxiliaries like carabid beetles and ladybugs, and even aquatic invertebrates, there is growing concern that current ERAs are underestimating the ecological risks of pesticides (Cornelisse et al. 2025; Edwards et al. 2025; Guzman et al. 2024; Harvey et al. 2020; Siviter et al. 2023; Wan et al. 2025). Calls for a more holistic approach to ERAs highlight the importance of assays on non-*Apis* pollinators and other insects that prioritize metrics beyond acute lethality, such as chronic lethality and sublethal effects. These approaches should adopt a multi-stressor framework that integrates the synergistic or antagonistic impacts of temperature, pesticide exposure, and other ecological factors (Kenna et al. 2023; Raine and Rundlöf 2024; Siviter et al. 2023; Topping et al. 2020). Despite advancements in pesticide regulations, comprehensive approaches are not yet universally implemented in ERAs (Siviter et al. 2023). The recognition that (a)biotic drivers influence species sensitivities to pesticide exposure underscores the need to broaden assessments to include a diversity of taxa beyond managed bees (Kenna et al. 2023; Parreño et al. 2022; Topping et al. 2020). However, important knowledge gaps remain that hinder the widespread adoption of comprehensive and holistic ERAs. This piece identifies some leading contributors to these gaps and proposes future research avenues, particularly in understanding how ecological complexity and global change intersect to affect insects exposed to pesticides and their *transformation products* (TPs; Box 1).

2 | Moving Beyond LD50s and Honey Bees

Current data on pesticide toxicity largely focuses on honey bees and is strikingly incomplete, with significant gaps in understanding the sublethal effects (71% of pesticides), interactions among two or more molecules (for ~99% of pesticides) and effects on non-*Apis* insect pollinators (Basu et al. 2024; Bogo et al. 2025; Tosi et al. 2022). These gaps undermine the ecological relevance of ERAs, particularly for non-*Apis* pollinators exposed to pesticides in variable and synergistic environmental conditions. Regarding neonicotinoid impacts on honey bees, ECOTOX is dominated by studies on lethality and short-term behavioral changes related to pollination under pesticide exposure (Shahmohammadloo et al. 2024). Consequently, ERAs often overlook the sublethal and long-term, field-relevant effects of pesticides on non-target organisms (Shahmohammadloo et al. 2024; Tosi et al. 2022; Wan et al. 2025). Furthermore, pre-exposure to different climatic conditions, including both long-term climate change and geographical variability, can alter insect responses to pesticides. These factors can influence organisms’ physiology, which will affect individual’s sensitivity to pesticides (Maebe et al. 2021; Parreño et al. 2022). Populations from different regions potentially show distinct responses due to local environmental pressures, including genetic adaptations to those stressors (Hawkins et al. 2019). This highlights the need for risk assessments that account for these regional and genetic differences in how populations respond to pesticides and other stressors.

Beyond honey bees, impacts of pesticide exposure on non-target organisms include reduced reproductive success, impaired foraging, and hindered individual and colony growth (Sgolastra et al. 2020; Siviter et al. 2021; Tosi et al. 2022; Wan et al. 2025).

While foraging behavior has received some attention, other critical behaviors remain underexplored in comparison (Bogo et al. 2025; Tosi et al. 2022). For instance, the herbicide *glyphosate* (Box 1) can disrupt collective thermoregulation in the brood of bumble bees, altering reproductive output and colony development without affecting individual mortality, while it is lethal for stingless bees like *Melipona quadrifasciata* (Basu et al. 2024; Weidenmüller et al. 2022).

Given the importance of behavior and reproduction for organism health, colony and population persistence, and pollination or biological control efficiency, these traits should play a more prominent role in ERAs on pesticide risks to insects.

3 | Risk Assessment of Pesticide Toxicity Is Missing Ecology

Insect populations are declining worldwide (Cornelisse et al. 2025; Edwards et al. 2025; Forister et al. 2021; Hallmann et al. 2017). Their decline is believed to be driven by the cumulative effects of habitat loss, agricultural intensification, and climate change. These stressors interact to impair reproductive and behavioral health, reduce immunity, and ultimately compromise pollinator resilience and ecosystem function (Bogo et al. 2025; Kenna et al. 2023; Maebe et al. 2021; Parreño et al. 2022). Habitat loss, conventional agricultural practices, and climate change are interactively leading to elevated pesticide exposure, malnutrition, and pathogen spillover, with detrimental consequences for non-target organisms such as pollinators, other crop auxiliaries, or aquatic invertebrates (Cornelisse et al. 2025; Forister et al. 2016; Guzman et al. 2024; Van Deynze et al. 2024; Wan et al. 2025).

While an increasing number of studies attempt to address the effects of two environmental stressors—such as temperature and pesticide exposure, or pathogens and pesticide interactions—on insects (Albacete et al. 2023; Costa et al. 2022; Esquivel-Román et al. 2025; Straub et al. 2022), these stressors have predominantly been studied in isolation. Consequently, ecotoxicological data informing ERAs are dominated by studies that focus on a single type of stressor (i.e., exposure to one pesticide, or temperature alone or a cocktail of pesticides) rather than considering stressors in interaction (e.g., heat stress, malnutrition, and pesticide exposure combined). This limitation hampers our ability to have a holistic approach that assesses risks in an ecologically relevant context, subjected to seasonal and annual variations in both biotic and abiotic factors. Those rare studies examining the interactive effects of rising temperatures and pesticide exposure (Kenna et al. 2023; Maebe et al. 2021), or the interaction between pesticide exposure and nutrition (Costa et al. 2022), illustrate the complexity and non-linear effects of climate and nutrition on bee sensitivity to pesticides (Figure 1a-c).

4 | Moving Toward a Multi-Stressor Framework

4.1 | Interaction Between Climate and Pesticides

Pesticide risk is a combination of exposure and sensitivity, both of which are influenced by geographical factors (spatial component), such as local pesticide use, climate conditions, and

ecological characteristics. These factors are further subjected to climate influences, which can amplify or alter the effects of pesticides. Landscape configuration impacts insect exposure by shaping when and where pesticides are applied, while climate impacts insect exposure by modulating the timing of insect activity in those areas. Under future climate change, we expect activity patterns to shift and likely to show significant variability between species (Maebe et al. 2021; Raine and Rundlöf 2024). Additionally, insect sensitivity to pesticides varies with temperature as shown in bees (Albacete et al. 2023; see also Figure 1b), beetles (Esquivel-Román et al. 2025), fruit flies (Gandara et al. 2024), parasitoids (Abbes et al. 2015) and plant bugs from the *Miridae* family (largely used as biological control agents; Ricupero et al. 2020), including daily temperature fluctuations (Verheyen et al. 2022). The U-shaped relationship between temperature and pesticide toxicity observed in honey bees (Figure 1b) may be due to changes in how agrochemicals are metabolized at different temperatures or to the direct effects of temperature on organism resilience. This reduced resilience makes organisms less capable of coping with multiple stressors (Maebe et al. 2021; Parreño et al. 2022). Moreover, the interaction between temperature and pesticides can differ depending on the specific pesticide or trait being observed (e.g., mortality, reproduction, behavior), and even the type of behavior (Kenna et al. 2023). Climate change is also expected to affect precipitation patterns, leading to increased flooding and drought events. Drought has been shown to increase the sensitivity of several collembola to some pesticides (Xie et al. 2024). Not surprisingly, these interactions have mostly been studied in the context of insect pests, less in the context of ERAs (e.g., Khodaverdi et al. 2016; Matzrafi 2019). These important variations support the need for a holistic approach that assesses multiple endpoints related to both individual and colony performance (for social species), as previously highlighted (Sgolastra et al. 2020; Topping et al. 2020).

4.2 | Interaction Between Nutrition and Pesticides

Studies conducted on insect pollinators emphasize the complex effects of nutrition on sensitivity to pesticides (Costa et al. 2022; Parreño et al. 2022; Richman et al. 2022; Stevenson et al. 2017). Beyond the quantity of nectar or pollen, the interplay between specific nutrients (e.g., flavonoids like quercetin, alkaloids like caffeine or *nicotine* (Box 1), or other active biomolecules) and pollinators' response to pesticides is particularly important (Figure 1c). For instance, an appropriate diet can alleviate or buffer the detrimental effects of some insecticides on bees (Costa et al. 2022; Parreño et al. 2022). Conversely, secondary plant metabolites—naturally found in nectar and pollen—can show benefits in the absence of pesticides but may magnify the negative effects of pesticides when combined (Richman et al. 2022; Stevenson et al. 2017) (Figures 1c and 2). The extent to which the costs and benefits of these secondary compounds on insect resilience to pesticides will be altered by climate change remains uncertain and warrants further investigation.

4.3 | Interaction Between Climate and Nutrition

Nutrition also modulates insect sensitivity to climate, particularly to heat stress. Nutritional stress can have direct effects on

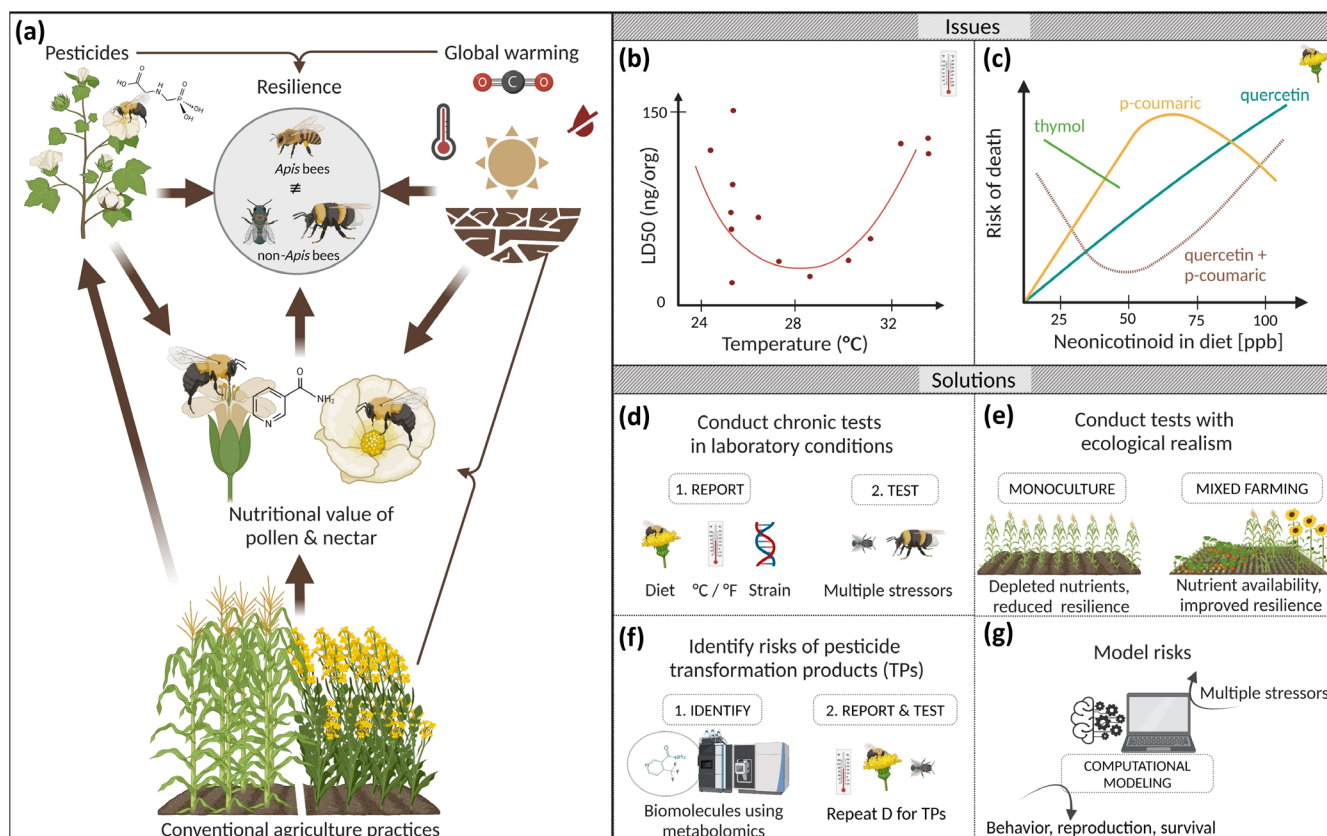


FIGURE 1 | Non-linear interactive effects of (a) biotic drivers and pesticide exposure on lethality: Issues and solutions for ERAs. (a) Global warming, nutrition, and pesticides individually and synergistically impact bees, affecting their resistance to heat stress, pathogens, and pesticide exposure, though significant differences of sensitivity have been recorded between *Apis* and non-*Apis* bees. (b) Bimodal relationship between ambient temperature and LD50 in domestic honey bees exposed to imidacloprid. Neonicotinoid toxicity increases from 24°C to 28°C, then decreases up to 33°C. (c) Non-linear effects of dietary biomolecules and imidacloprid dietary content on the risk of death in domestic honey bees. The trends represent significant differences at various concentrations of neonicotinoids in diet. (b) and (c) were assembled from metadata presented in studies from ECOTOX (see (Shahmohammadloo et al. 2024) for more details). In (b) data on imidacloprid LD50 toxicity for temperatures outside the 24°C–33°C range were absent from ECOTOX. These temperatures do not capture the full range experienced by wild bees (e.g., cold northern region or the tropics). (c) Was complemented by (Richman et al. 2022) for thymol. (d–g) Solutions for implementing a holistic framework in ERAs, supporting the resilience of pollinator populations and the sustainability of ecosystems they support, are shown. (d) When conducting test under laboratory conditions: (1) analyze and report meta-data, including dietary composition, ambient temperature, and the strains or origins for honey bees and commercial bumble bees (due to artificial selection); (2) experimentally test for interactions between pesticides and other frequently encountered stressors to understand the effects of temperature or plant metabolites on toxicity.

organisms by heightening sensitivity to heat, while high-quality resources may alleviate it (Parreño et al. 2022; Vanderplanck et al. 2019). Climate also influences the biochemical composition of plants, altering plant-pollinator interactions (Hoover et al. 2012; Walters et al. 2024), which not only impacts an organism's sensitivity to pesticides among geographical areas but could further affect insect sensitivity to pesticides in a changing climate (Figure 1c). In addition, insect sensitivity to precipitations or extreme weather events like cold snaps or heat waves—which are expected to increase in occurrence with climate change—is not equal between species (Ewald et al. 2015). Consequently, studies examining insect responses to a single pesticide or a cocktail of molecules under nutritional equilibrium and within a narrow temperature range cannot capture the full complexity of pesticide exposure in natural environments, where pollinating insects and other organisms are exposed to nutritional stress, temperature change, and pathogens.

4.4 | Consequences of These Interactions for the ERA Process

Climate and pesticides interactively affect pollinators, and both of these stressors interact with nutrition (Figure 1). These interactive effects are non-linear, making it critical to consider reaction norms associated with pesticide exposure in conjunction with other environmental variables like temperature or nutrition (Figure 1a). Understanding how plant chemistry interacts additively or synergistically with dietary exposure to pesticides is crucial for accurately assessing toxicity, and therefore risk (Costa et al. 2022; Stevenson et al. 2017). This is especially true considering that plant-insect mutualism, along with the value of food rewards for pollinators, are expected to be altered by climate change (Hoover et al. 2012; Walters et al. 2024), with considerable heterogeneity to be expected. Climate-induced changes are predicted to show significant

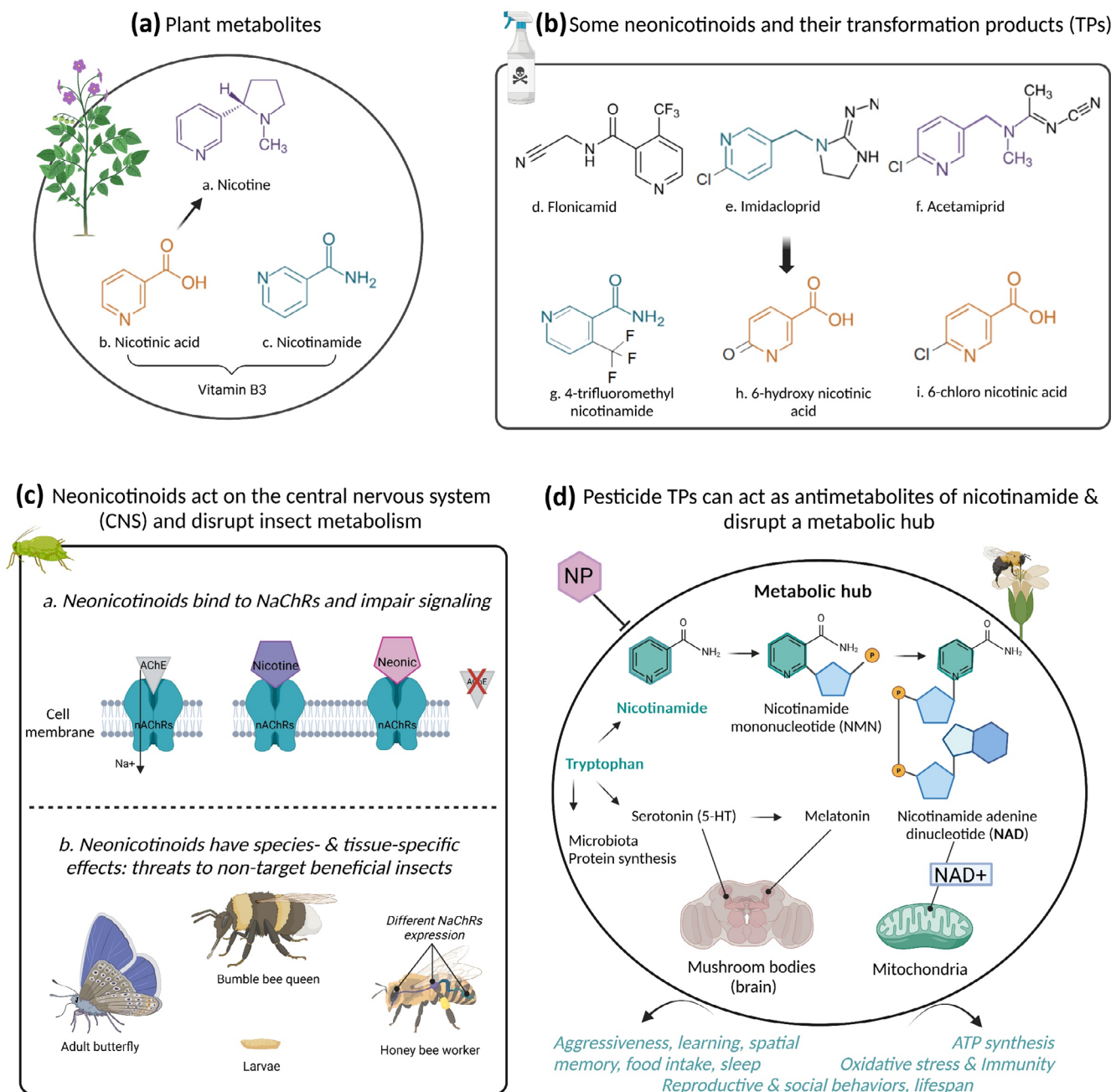


FIGURE 2 | Relationships between plant metabolites, transformation products of pesticides and a metabolic hub in bees. (a) Plant metabolites: A. nicotine (purple), b. nicotinic acid (orange), c. nicotinamide (blue). (b) Structures of some neonicotinoids in a.-c. and their transformation products (TPs, in g.-i.), which share structural similarities with vitamin B3 (color-coded as in (a)); each neonicotinoid molecule is located above its TP. (c) Pathways of neonicotinoid action: A. Neonicotinoids bind to nAChRs (Box 1). b. nAChRs are differentially expressed across life stages, organs and species. (d) A metabolic hub modulating key functions, susceptible to disruption by pesticide transformations products including neonicotinoid metabolites shown in (b). Functions affected by disruption of this metabolic hub are highlighted in italic blue.

variability across geographic areas and taxa, not only because temperature and precipitation changes are unevenly distributed globally but also because pollinating insects from tropical and northern regions are overall more sensitive to pesticides than domestic honey bees (Basu et al. 2024; Bogo et al. 2025; Shahmohammadloo et al. 2024), whose sensitivity has been primarily assessed in temperature ranges typical of temperate regions (see Figure 1b). Despite the greater sensitivity of tropical bees than honey bees, negative effects of pesticides on non-target organisms have been found to be

less pronounced in tropical regions than in temperate ones (Wan et al. 2025). Regional ERAs that integrate temperature, precipitation, risk of extreme weather events (i.e., heatwaves, cold-snaps, droughts, and flooding), and species sensitivity to pesticides should be prioritized. Additionally, since pesticide TPs (see Box 1) can impair the metabolism of key biomolecules and disrupt insect metabolism, behavior, and reproduction (Figure 2), it is essential for pesticide toxicity studies to consider not only the toxicity of the primary molecules but also the *antimetabolite* (Box 1) potential of their by-products

(i.e., their ability to disrupt or block the metabolism of essential biomolecules, necessary to the organism's proper functioning). The complexity of the multiple interactions between nutrition \times pesticide \times climate is thus likely going to be exacerbated by climate change. By altering the biochemical composition of plants pollen and nectar—and thus the value of the rewards for pollinators—climate change is expected to further increase the complexity of the interactions between plants secondary metabolites and pesticide TPs, making their effects on insects highly uncertain and the implementation of continental or global ERAs inadequate.

5 | Pesticide Transformation Products: A Hidden Risk

Research on pesticide risks often focuses on the effects of primary molecules and rarely considers their TPs. These TPs, generated through abiotic and biotic processes, can be equally or even more toxic than their parent compounds. A notable example involves neonicotinoids, known to cause lethal and sublethal effects in bees, including impaired learning, spatial memory, and various reproductive and metabolic disorders (e.g., disrupted food intake and sleep) (Parreño et al. 2022; Siviter et al. 2021; Tosi et al. 2022). Neonicotinoids recreate the action of nicotine, a “natural insecticide” (Figure 2a,b). Their direct and most studied mode of action is their impact on neurotransmission (Figure 2c). However, neonicotinoids and their TPs (Figure 2b,d–i) can also have indirect effects on insect health, acting as *antimetabolites* of *vitamin B3* (Box 1). As such, they can disrupt a metabolic hub that involves key biomolecules that are nicotinamide and tryptophan, and their metabolites (Figure 2d). Both tryptophan and nicotinamide are essential for animals: sourced daily from diet or gut microbiota, they play crucial roles in regulating reproductive, behavioral, and immune functions. These include ATP synthesis, sleep, food intake, memory, spatial learning, aggressiveness, reproductive, and social behaviors (Figure 2d). Deficiencies or disruptions in their metabolism, as observed in humans, livestock, and wildlife, can lead to reproductive disorders, behavioral changes, and death (Tissier et al. 2017, 2023; Zhang et al. 2022).

The impact of pesticide TPs on insects remains largely unexplored. As products of microbial or chemical transformations, TPs are persistent in the environment, often found at higher frequencies and concentrations than neonicotinoids (Codling et al. 2016). Some TPs are more toxic than their parent compounds, while others exhibit reduced acute toxicity but have additive or synergistic effects to the primary pesticide molecules, including important chronic or sub-lethal effects on non-target organisms like bees, butterflies, or aquatic invertebrates (Malev et al. 2012; Qiao et al. 2022; Wan et al. 2025; Zhang et al. 2025). Beyond neonicotinoids, other pesticides—e.g., glyphosate, *pyrethroids* (Box 1)—and their TPs, or even antibiotics, can disrupt the tryptophan-nicotinamide metabolic hub in many species (Figure 2d; Tissier et al. 2023; Zhang et al. 2022). By disrupting the metabolism of key biomolecules like tryptophan, serotonin, or vitamin B3, pesticide TPs can act as “disrupters” or “blockers” of these molecules, leading to sublethal effects such as cognitive and sleep impairments or reproductive disorders (Figure 2d). These effects are exemplified by monocultures, as several crops

or plants are deficient in tryptophan and vitamin B3, already causing behavioral and reproductive disorders in pollinators and mammals (Matsuzaki et al. 2023; Tissier et al. 2023; Zhang et al. 2022). In this context, existing nutrient deficiencies could be aggravated by the presence of antimetabolites from pesticide TPs, and vice-versa. This also suggests that TPs may exacerbate the effects of primary pesticides, particularly under climate-induced stressors like heat waves and resource scarcity. The ecological implications of TPs remain understudied, representing a critical frontier for pesticide risk assessments. Addressing this gap requires not only identifying major TPs in environmental matrices but also assessing their chronic and sublethal effects under realistic field conditions.

6 | Taking a Holistic Approach Toward Risk Assessment

Despite the increasing recognition that global change can influence the risks posed by pesticides to non-target organisms, ERAs currently do not explicitly incorporate these climate-pesticide interactions, let alone the complex climate–nutrition–pesticide interactions essential for understanding how pesticides affect pollinator populations, their sensitivity to different climatic conditions, and their resilience to climate change. Addressing nonlinear effects (Figure 1) and considering the antimetabolite potential of pesticides' main metabolites (i.e., their ability to act as “disrupters” or “blockers” of biomolecules crucial to the organism's functioning; Figure 2), alongside genetic and plastic/evolutionary effects, is crucial for risk assessments. While gathering and integrating such comprehensive data into ERAs may be a long-term endeavor, the use of “multi-omics” approaches offers a promising pathway forward (Matsuzaki et al. 2023; Zhang et al. 2022).

We propose the implementation of the following steps to support a holistic framework in ERAs (Figure 1d–g), building up on the work presented here, together with previously proposed reformed pesticide regulation and tools to promote safer pesticide use (Fisher et al. 2023; Matsuzaki et al. 2023; Siviter et al. 2023; Zhang et al. 2022):

- *Report and test for multi-stressors*: Begin with chronic studies under controlled laboratory conditions to assess pesticide risks. Address interactions between multiple stressors (Figure 1d).
- *Reflect ecological complexity* by conducting toxicological assessments under (semi)natural conditions within realistic and changing environmental contexts, including those multiple stressors (Figure 1e).
- *Identify pesticide transformation products and evaluate their effects*. Measuring the lethal and sub-lethal effects of major transformation products found in the environment (in pollen, nectar, soil, and water) is crucial to accurate risk assessments (Figure 1f).
- *Model risks*: Tackling multi-stressor effects can be a complex endeavor, which can be simplified by the use of computational models, such as supervised learning, to analyze nonlinear interactions among multiple environmental stressors, manage uncertainty, and assess risks using

multivariate responses, including both lethal and sublethal endpoints (Figure 1g; e.g., Anandhi and Lyapparaja 2024; Bernardes et al. 2022). While doing so, consider addressing geographical variability of climate-induced effects of pesticides by implementing regional ERAs, integrating species sensitivity proxies (e.g., relative responses compared to well-studied surrogate species), ambient temperatures, as well as predicted extreme weather events.

Author Contributions

Mathilde L. Tissier: conceptualization, data curation, resources, visualization, writing – original draft. **René S. Shahmohammadloo:** conceptualization, resources, software, writing – review and editing. **Laura Melissa Guzman:** conceptualization, formal analysis, resources, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed for this article.

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