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Environmental Toxicology and Chemistry, 2026, **45**, 2056–2090
https://doi.org/10.1093/etojnl/vgag069
Published: March 21, 2026
Critical Review

The impact of environmental pollution on dragonflies and damselflies (Odonata) and the role of climate change as an interactive stressor

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Abstract

Globally, 16% of dragonfly and damselfly species (Odonata) are threatened with extinction, primarily due to the loss and degradation of freshwater habitats. These threats are exacerbated by environmental pollution, particularly from pesticides and heavy metals, and are further compounded by climate change. Despite their recognized value as bioindicators of environmental pollution, comprehensive assessments of the impacts of widespread and hazardous pesticides and heavy metals on Odonata remain limited. The available studies often focus narrowly on either dragonflies or damselflies, specific species, particular life stages, or individual contaminants, resulting in fragmented evidence and substantial knowledge gaps. This review synthesizes findings from 54 peer-reviewed articles to assess the effects of pesticide and heavy metal pollution on Odonata across their life cycle, while also considering potential synergistic interactions between these pollutants and climate change. Three categories of impact were assessed: (1) community composition and diversity metrics, (2) mortality and sublethal effects, and (3) behavioral endpoints. Across these categories, broad-spectrum neurotoxic insecticides—particularly neonicotinoids (e.g., imidacloprid), phenylpyrazoles (e.g., fipronil), and pyrethroids—emerged as the most harmful pesticide groups. Among heavy metals, copper was consistently identified as the most toxic. Evidence for synergistic interactions between environmental pollution and climate change, particularly warming, was mixed, with both additive and synergistic effects commonly reported. Notably, research on behavioral endpoints and the impacts of multiple concurrent stressors remains scarce. This review concludes that climate change, particularly warming, is likely to exacerbate pollution-related pressures on Odonata, potentially resulting in synergistic effects that could accelerate local population declines and increase species' extinction risk.

Keywords pesticides, heavy metals, temperature, global warming, ecotoxicology

Introduction

Freshwater ecosystems are experiencing increasing degradation as a result of environmental pollution, primarily driven by anthropogenic activities such as agricultural intensification, industrial effluents, urban expansion, and wastewater discharges (Amoatey & Baawain, 2019; Kumaraswamy et al., 2020; Mushtaq et al., 2019). Climate change further intensifies this degradation by disrupting hydrological processes within these ecosystems, mainly through rising temperatures and altered precipitation patterns (Kundzewicz, 2008). The increasing frequency and severity of extreme weather events, particularly droughts, are expected to exacerbate water quality deterioration by reducing the volume and flow of water available to dilute contaminants (Mosley, 2015; van Vliet et al., 2023). These combined stressors have contributed to substantial biodiversity loss in freshwater habitats, with current species extinction rates comparable to those of past mass extinction events (Sayer et al., 2025; Williams-Subiza & Epele, 2021). Among freshwater taxa, dragonflies and damselflies (Odonata) face severe extinction risks and population declines, with estimates indicating that 16% of species are threatened and 37% have shown reductions in abundance (Sánchez-Bayo & Wyckhuys, 2019; Sayer et al., 2025). The primary drivers of these declines are freshwater habitat loss and degradation, with declining water quality due to pollution representing a major, although not exclusive, contributing factor (Samways et al., 2025; Sánchez-Bayo & Wyckhuys, 2019; Villalobos-Jimenez et al., 2016). Despite growing recognition of the detrimental effects of pollution on odonates, the impacts of specific contaminants remain poorly understood. Most existing research has largely focused on either dragonflies or damselflies, often at the level of individual species, and has typically examined only a single life stage—either the nymph or the adult. The latter approach can be particularly limiting, as contaminant

Received: November 5, 2025. **Revised:** February 26, 2026. **Accepted:** March 10, 2026

exposure pathways and body burdens can vary considerably across life stages (Cetinić et al., 2021). To address these knowledge gaps, this review evaluates current evidence on the effects of the most widespread and hazardous contaminants—particularly pesticides and heavy metals—on Odonata across their life cycle, while also considering potential synergistic interactions between these pollutants and climate change.

Odonates are recognized as valuable biological indicators of environmental quality and provide essential ecosystem services through their role as predators of disease vectors and agricultural pests (May, 2019; Miguel et al., 2017; Priyadarshana & Slade, 2023). By preying on mosquito larvae, odonates contribute to the control of vector-borne diseases such as dengue, malaria, and Zika virus (Choo et al., 2021; Priyadarshana & Slade, 2023; Sebastian et al., 1990). In agricultural systems, odonates support natural and sustainable pest management by regulating populations of certain crop pests, particularly species within Diptera and Lepidoptera (May, 2019; Neal & Whitcomb, 1972). Beyond pest control, odonates play a crucial role in maintaining the structure and stability of both aquatic and terrestrial food webs; research has shown that their suppression or exclusion can trigger trophic cascades, which ultimately destabilize ecosystems (Knight et al., 2005; Moon & Silva, 2013). Given their ecological importance, understanding the impacts of environmental pollution on odonates across their life cycle is essential, not only to evaluate their effectiveness as bioindicators but also to inform conservation strategies aimed at preserving their populations and the ecosystem services they provide (Samways et al., 2025).

In addition to environmental pollution, climate change constitutes an increasingly important stressor for odonate populations. Rising water temperatures affect the geographic distribution, species composition, morphology, and phenology of freshwater invertebrates (Anderson et al., 2019; Baranov et al., 2020; Bonacina et al., 2023). In odonates, temperature increases have been linked to shifts in geographic range, altered phenology, changes in morphology, and increased mortality (Hassall et al., 2007; Pélissié et al., 2022; Starr & McIntyre, 2020). However, the relationship between climate change and range shifts is complex: while most species are expected to move poleward, some may experience range expansions, whereas others may undergo contractions (Jaeschke et al., 2013; Pélissié et al., 2022). As primarily ectothermic organisms, odonates are particularly sensitive to fluctuations in temperature, exhibiting accelerated development, reduced body size at emergence, and increased mortality under warmer conditions (De Block & Stoks, 2003; McCauley et al., 2015; Starr & McIntyre, 2020). Accelerated development can result in earlier emergence, potentially leading to phenological mismatches with prey and disruptions to food availability and trophic interactions (Damien & Tougeron, 2019; Visser & Both, 2005). While odonates' generalist feeding behavior may mitigate some of these effects, smaller body size at emergence can constrain prey consumption, as feeding capacity and diet breadth are often size-dependent (Thompson, 1978).

Beyond rising water temperatures, the increasing frequency and severity of extreme weather events associated with climate change, such as storms and droughts, may impose additional stress on odonates, particularly during vulnerable periods such as the egg stage and during emergence. Strong winds and heavy rainfall can reduce adult flight activity, and strong winds in particular have been linked to increased mortality due to damage incurred during emergence (Goforth, 2010; Jakob & Suhling, 1999). Adult odonates may also exhibit behavioral responses to extreme weather, such as abandoning ponds prior to storms, although such responses can be confounded by concurrent changes in light conditions (Goforth, 2010). Drought reduces water availability, which can lead to egg desiccation and increased mortality, particularly in species that lack drought tolerance adaptations that enable survival in seasonal ponds (Hassall & Thompson, 2008). Drought has also been associated with declines in local odonate abundance (Vilenica et al., 2024) and reductions in genetic diversity (Herzog & Hadrys, 2017). Given that many freshwater habitats are already compromised by pollution, the combined effects of rising water temperatures, extreme weather events, and contaminant exposure are likely to intensify stress on odonates.

While poor water quality caused by environmental pollution is a well-established threat to odonates, the precise impacts of specific contaminants across their life cycle—from aquatic nymphs to terrestrial adults—remain to be synthesized (see Box 1 for an overview of their life cycle and ecology). Studies have identified several hazardous compounds, particularly pesticides and heavy metals, that can negatively affect odonates (Perron & Pick, 2020; Tazunoki et al., 2022; Villalobos-Jimenez et al., 2016). However, the available research remains fragmented, and the extent to which climate change may intensify the harmful impacts of these contaminants on odonates remains unclear. This review addresses these knowledge gaps by synthesizing and critically evaluating existing research, focusing on two key questions:

1) How does pesticide and heavy metal pollution impact Odonata across their life cycle?
2) Does climate change synergistically amplify the impact of pesticide and heavy metal pollution on Odonata?

Literature search

This review synthesizes current research on the impacts of pesticide and heavy metal pollution on Odonata throughout their life cycle, as well as the potential synergistic interactions between these environmental pollutants and climate change. Relevant studies were identified using Google Scholar, ResearchGate, and CataloguePlus (the online library of the University of Amsterdam). To locate studies examining the effects of pesticide and heavy metal pollution on Odonata, search terms included combinations of "impact(s)," "effect(s)," "influence," "pesticide(s)," "heavy metal(s)," "pollution," "contamination," "Odonata," "odonate(s)," "dragonfly(ies)," and "damselfly(ies)." In cases where initial searches did not retrieve sufficient information on specific compounds of interest, additional searches were conducted using the names of individual pesticides and metals, such as "fipronil" and "zinc." For studies exploring the interactions between climate change and these pollutants, the previously mentioned search terms were supplemented with additional keywords, including "climate change," "temperature(s)," "warming," "heatwave(s)," and "drought(s)." Only peer-reviewed research articles were included in this review, while meta-analyses and books were excluded.

Box 1 Overview of the life cycle and ecology of Odonata.

Odonates undergo incomplete metamorphosis, transitioning from eggs to aquatic nymphs (naiads) before emerging as terrestrial adults (Suhling et al., 2015; Truman, 2019). This complex life cycle requires adaptation to both aquatic and terrestrial environments, rendering odonates sensitive to changes in water quality (Perron & Pick, 2020) as well as to alterations in terrestrial vegetation and habitat structure that influence emergence, perching, and foraging (Hykel et al., 2020; Rouquette & Thompson, 2007). Both nymphs and adults are generalist predators (Silsby, 2001). Nymphal development typically lasts from 6 months to 5 years, while adult lifespans range from a few weeks to several months (Corbet, 1999; Silsby, 2001). True dragonflies (Anisoptera) and damselflies (Zygoptera) differ across a suite of morphological, physiological, and ecological traits that likely mediate their responses to environmental contaminants. Dragonflies are generally larger and possess greater lipid reserves than damselflies, characteristics that may promote increased bioaccumulation of lipophilic contaminants (Landrum & Fisher, 1999). Moreover, larger body size has been negatively correlated with sensitivity to pesticides across freshwater arthropods (Rico & Van den Brink, 2015; Rubach et al., 2012). Respiratory morphology represents another key distinction between the suborders: damselfly nymphs possess external caudal gills, whereas dragonfly nymphs breathe via internal rectal gills (Silsby, 2001). External respiratory structures increase surface area available for both active and passive contaminant uptake and have been associated with higher pesticide uptake rates (Buchwalter et al., 2002; Rubach et al., 2012). Differences in microhabitat preference may further influence exposure pathways. Dragonfly nymphs are primarily associated with benthic or sediment habitats, whereas damselfly nymphs are more closely linked to aquatic and riparian vegetation (Corbet, 1999; Merritt et al., 2019). Consistent with these habitat associations, damselfly richness increases with greater riparian vegetation cover, whereas dragonfly richness and abundance are comparatively higher in habitats characterized by reduced riparian vegetation (Oliveira-Junior & Juen, 2019; Silva et al., 2021).

A total of 54 research articles published between 1974 and 2024 were retrieved (Figure 1A). To facilitate a structured review, these studies were categorized into three groups based on the variables assessed: community composition and diversity metrics (n = 13), mortality and sublethal effects (n = 36), and behavioral endpoints (n = 11; Figure 1B). Six studies were counted in multiple categories due to overlapping endpoints. Efforts were made to achieve a geographically representative sample and a balance between field and laboratory studies. However, there was a notable lack of field studies (n = 12), whereas laboratory-based research was far more prevalent (n = 42). This review is structured into three main sections: impacts of pesticides (n = 28), impacts of heavy metals (n = 18), and interactions between climate change and these pollutants (n = 8). The latter remains an emerging field of research and has received comparatively limited attention. The geographic distribution of studies was broad, with at least two papers per continent, except Antarctica (Figure 1C). Most studies (69.6%) reported negative effects of poor water quality on Odonata, while a smaller proportion yielded ambiguous results (19.6%) or found no impact (8.7%), and only one study (2.2%) reported a positive effect (Figure 1D; see Table 1 for a complete list and summaries of included studies). Studies examining interactions between climate change and pollutants (n = 8) were excluded from Figure 1D, as they assessed the presence or absence of synergistic interactions rather than the impacts of poor water quality on odonates, which are represented in that panel.

The impact of environmental pollution on Odonata

Pesticides

Pesticides are chemical compounds commonly used in agriculture to protect crops from pests, increase agricultural productivity, and enhance food safety (Carvalho, 2017; Khan et al., 2023). Despite these benefits, pesticide application can often lead to unintended environmental consequences when these chemicals disperse beyond their target crops and adversely affect non-target organisms (Serrão et al., 2022). Although several harmful and persistent pesticides have been banned in recent years, residues from both legacy use and recent applications continue to persist, contaminating freshwater ecosystems and even infiltrating the human food chain (Carvalho, 2017; Khan et al., 2023). Pesticides can enter freshwater ecosystems through various pathways, including direct application to control aquatic weeds and other pests, spray drift, industrial wastewater discharge, atmospheric deposition, and runoff or leaching from agricultural fields (Figure 2; Riaz et al., 2021; Tudi et al., 2021). Pesticides can be broadly classified as biological or synthetic pest control agents. Biological pesticides are derived from naturally occurring sources, such as plants, fungi, and microorganisms, and are often considered safer alternatives to synthetic compounds (Ayilara et al., 2023). In contrast, synthetic pesticides are artificially formulated and involve more complex synthesis processes (Fenibo & Matambo, 2025). Despite their distinct origins, biological and synthetic pesticides can function as insecticides, herbicides, or fungicides, depending on the groups of agricultural pests they target.

The environmental impact of pesticides depends on how these chemicals interact with crops and pests. Pesticides can be classified based on their mobility within plant tissues as systemic or nonsystemic, and according to their specificity toward pests as broad-spectrum or narrow-spectrum (Table 2). Systemic pesticides can be absorbed and transported through the vascular system of plants, providing protection to the entire plant, including protection against pests that do not come into direct contact with the application site (Ahmad et al., 2024). In contrast, nonsystemic pesticides have limited mobility within the vascular system of plants, remaining localized at the site of

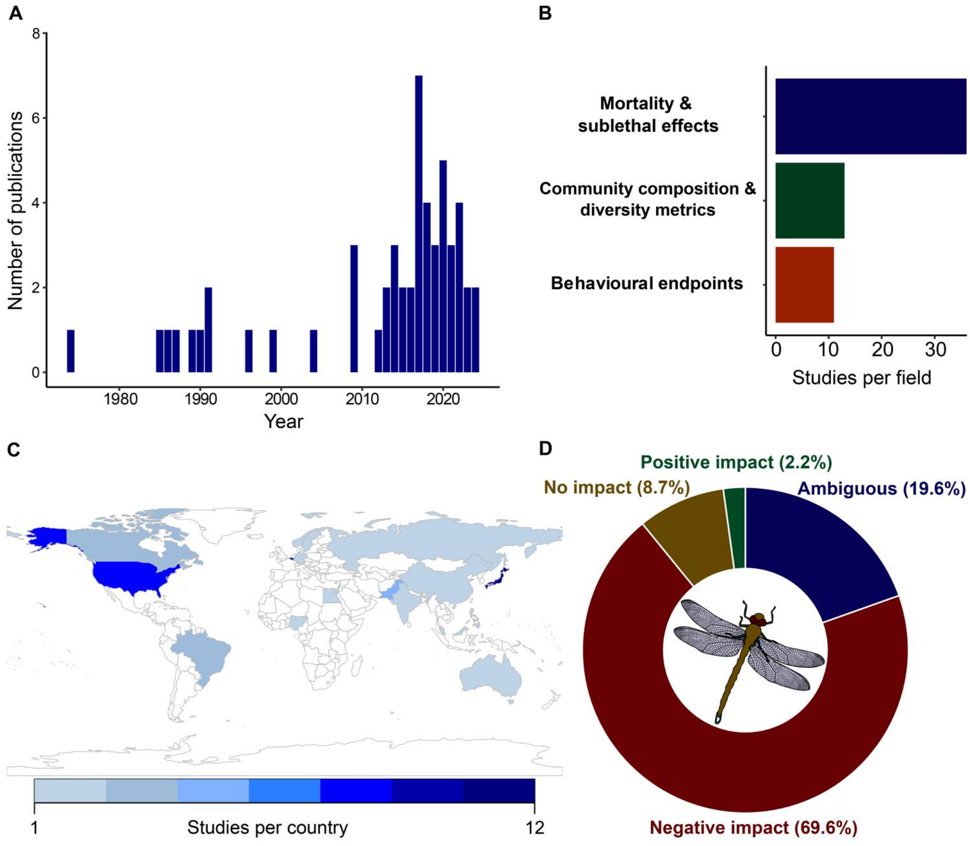

Figure 1 Summary of the publications considered in the literature review (see Table 1). (A) The number of peer-reviewed publications per year. (B) The number of studies per category according to the variables assessed. (C) The geographic range of the research articles considered. (D) Main outcomes from each study.

application and affecting only pests that come into direct contact with the treated area (Ahmad et al., 2024). Beyond mobility, pesticides can also be categorized based on their specificity toward pests. Broad-spectrum pesticides act on physiological processes or chemical receptors that are common across various taxa, making them effective against a wide range of pests but inadvertently causing adverse effects on non-target organisms, including beneficial taxa such as pollinators (Parween & Jan, 2019; Woodcock et al., 2017). In some cases, broad-spectrum pesticide use can lead to undesirable outcomes such as competitive release among pest species, secondary pest outbreaks, or diminished abundance of the natural enemies of the target pest (Hill et al., 2017; Wilson et al., 1998). In contrast, narrow-spectrum pesticides are designed to target specific pests, thereby minimizing the potential for unintended impacts on non-target organisms (Parween & Jan, 2019). Consequently, the environmental consequences of pesticide application are largely dependent on the type of pesticide used, specifically whether it is systemic or nonsystemic and whether it is broad-spectrum or narrow-spectrum.

Pesticide contamination in freshwater ecosystems can severely impact invertebrate communities, causing substantial shifts in community composition, species abundance, and the ecosystem functions they support (Berenzen et al., 2005; Liess & Ohe, 2005; Münze et al., 2017). Freshwater invertebrates are particularly vulnerable to pesticide exposure, experiencing both direct effects from insecticides, molluscicides, or other chemical agents and indirect effects through herbicide-induced changes in aquatic and riparian vegetation (Sánchez-Bayo, 2021; Schäfer et al., 2012). The responses of odonates to pesticide pollution are influenced by the environmental fate of these chemicals, which is shaped by factors such as their chemical and physical properties, application rates, and the geological, geographic, and climatic characteristics of freshwater habitats (Gavrilescu, 2005; Schäfer et al., 2011). Pesticides with high water solubility and low environmental persistence, such as phosphonates (e.g., glyphosate), are generally subject to rapid biodegradation and are less likely to accumulate in sediments or bioaccumulate in organisms (Lushchak et al., 2018). In contrast, pesticides with low water solubility and high environmental persistence, such as phenylpyrazoles, tend to accumulate in sediments and pose a higher risk of bioaccumulation in organisms (Lushchak et al., 2018). Pesticides target organisms through various modes of action, including disruption of the nervous system by neonicotinoids, phenylpyrazoles, and pyrethroids or inhibition of essential enzymes by organophosphates and phosphonates (e.g., glyphosate; Sousa et al., 2020; Sparks & Nauen, 2015). This review categorized pesticide groups based on the most commonly studied compounds in odonate-focused ecotoxicological research (see Tables 1 and 3). For instance, imidacloprid served

Table 1 Summary of the publications included in the literature review.

Contaminants	Dragonflies (Anisoptera)		Damselflies (Zygoptera)		Taxa	Variables	Results summary	Reference
	Nymphal stage	Adult stage	Nymphal stage	Adult stage				
Pesticides								
3 insecticides, 4 herbicides, and 5 fungicides	X		X		5 Odonata species	Community composition (abundance and species richness)	Downstream sites surrounded by rice fields that were subjected to aerial spraying of pesticides had the lowest abundance and species richness of odonate nymphs.	Takamura et al. (1991)
8 insecticides, 5 herbicides, and 7 fungicides		X		X	30 Odonata species	Community composition (abundance)	The concentrations of the insecticides acephate, clothianidin, dinotefuran, flubendiamide, pymetrozine, and thiamethoxam were negatively associated with the abundance of lentic and benthic odonate species.	Tazunoki et al. (2022)
9 insecticides		X			*Sympetrum frequens*	Community composition (population density)	There was a significant negative association between the annual increase in the use ratio of systemic insecticides and the annual population growth rate of *S. frequens*.	Nakanishi et al. (2020)
Fipronil (Phenylpyrazole)		X		X	27 Odonata species	Community composition (abundance)	Following fipronil application near the surveyed site, a significant decline in the abundance of *S. eroticum* and one lotic benthic species was observed. Conversely, the abundance of most lentic species increased.	Kita et al. (2020)
Bacillus thuringiensis israelensis (Bti) (biological larvicide)	X		X		Aeshnidae Libellulidae Coenagrionidae	Community composition (abundance)	The composition of benthic macroinvertebrate communities shifted in Bti-treated mesocosms, primarily due to a decline in the abundance of chironomid larvae, as well as Libellulidae and Coenagrionidae nymphs.	Gerstle et al. (2023)
5 herbicides	X		X		13 Odonata species	Community composition (abundance and species richness)	Herbicide-treated experimental rice plots supported higher species richness (up to 12 species) compared to control plots (8 species).	Md Rawi et al. (2012)

(continued)

Table 1 (continued)

Contaminants	Dragonflies (Anisoptera)		Damselflies (Zygoptera)		Taxa	Variables	Results summary	Reference
	Nymphal stage	Adult stage	Nymphal stage	Adult stage				
Imidacloprid and dinotefuran (Neonicotinoids)	X				*Crocothemis servilia* *Lyriothemis pachygastra* *Orthetrum albistylum*	Community composition: abundance, species richness, and Shannon-Wiener's diversity index (H′)	Imidacloprid treatment (10 kg/ha) significantly reduced the abundance of *C. servilia* and *L. pachygastra* nymphs, while the abundance of *O. albistylum* slightly increased. In contrast, dinotefuran treatment (10 kg/ha) did not cause declines in the abundance of any odonate species.	Kobashi et al. (2017)
15 insecticides			X		*Ischnura senegalensis*	Acute toxicity (EC50 value)	Nymphs demonstrated the greatest sensitivity to pyrethroid insecticides, followed by decreasing sensitivity to phenylpyrazoles, organophosphates, carbamates, neonicotinoids, diamide, and nereistoxin.	Sugita et al. (2018)
Deltamethrin and esfenvalerate (Pyrethroids)	X		X		*Lestes sponsa* *Cordulia aenea*	Mortality (96-hr LC50 value)	Odonata nymphs were less sensitive to pyrethroids than Ephemeroptera nymphs, with variation among species; *L. sponsa* was considerably more sensitive than *C. aenea*.	Beketov (2004)
Deltamethrin and esfenvalerate (Pyrethroids)			X		*Coenagrion puella*	Predatory ability, mobility, and three physiological biomarkers: glutathione S-transferase activity (a detoxification enzyme), activity of the electron transport system, and formation of malondialdehyde	Exposure to deltamethrin reduced predatory ability but did not affect mobility. In contrast, esfenvalerate had no significant effect on either predatory ability or mobility. Glutathione S-transferase activity was induced after single exposure to esfenvalerate and low concentrations of deltamethrin, but was inhibited after high-concentration deltamethrin exposure or combined exposure to both pyrethroids.	Kunce et al. (2017)
Deltamethrin and cypermethrin (Pyrethroids)	X		X		*Trithemis aurora*	Midgut histopathology	Pyrethroid exposure caused structural damage to midgut tissues.	Chand (2014)

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Table 1 (continued)

Contaminants	Dragonflies (Anisoptera)		Damselflies (Zygoptera)		Taxa	Variables	Results summary	Reference
	Nymphal stage	Adult stage	Nymphal stage	Adult stage				
Chlorpyrifos (Organophosphate)					*Enallagma cyathigerum*	Mortality, growth, and bioenergetic variables	Chlorpyrifos exposure nearly halved survival rates and significantly reduced growth, primarily due to reduced energy conversion efficiency.	Van Dievel et al. (2019)
Chlorpyrifos (Organophosphate)	X				*Pantala flavescens*	Mortality and activity of detoxifying enzymes (acetylcholinesterase and glutathione S-transferase activity)	Chlorpyrifos exposure resulted in 20% mortality among *P. flavescens* nymphs and significantly increased the activity of acetylcholinesterase and glutathione S-transferase.	Mohammed et al. (2022)
Chlorpyrifos (Organophosphate)			X		*Enallagma cyathigerum*	Growth, energy storage molecules, RNA: DNA ratio, and body stoichiometry	Chlorpyrifos exposure reduced growth rates, decreased energy reserves, altered RNA: DNA ratios, and changed elemental stoichiometry.	Janssens et al. (2017)
Chlorpyrifos (Organophosphate)	X				*Anax junius*	Head capsule cholinesterase activity and foraging behavior	Chlorpyrifos exposure had no significant effect on cholinesterase activity or foraging behavior.	Brewer and Atchison (1999)
Imidacloprid (Neonicotinoid) and avermectin (macrocyclic lactone)			X		*Copera annulata*	Mortality and fluctuating asymmetry	There was no significant difference in nymph mortality across three increasing insecticide concentrations. However, fluctuating asymmetry in two traits increased with higher insecticide concentrations.	Chang et al. (2008)
Imidacloprid (Neonicotinoid) and fipronil (Phenylpyrazole)	X				*Sympetrum infuscatum*	Mortality and emergence patterns	The fipronil treatment resulted in 100% nymph mortality, with no nymphal emergence observed. The imidacloprid treatment exhibited 84.8% mortality and a mean emergence rate of 12.1%.	Jinguji et al. (2013)
Imidacloprid (Neonicotinoid) and fipronil (Phenylpyrazole)	X	X			*Sympetrum frequens*	Mortality, emergence patterns, nymphal development, and length of adult wings	The fipronil treatment experienced 100% nymph mortality. Imidacloprid treatment showed a 40% reduction in nymph abundance compared to controls. Surviving nymphs exposed to imidacloprid exhibited reduced growth rates, lower emergence, and shorter adult wing lengths.	Jinguji et al. (2009)

(continued)

Table 1 (continued)

Contaminants	Dragonflies (Anisoptera)		Damselflies (Zygoptera)		Taxa	Variables	Results summary	Reference
	Nymphal stage	Adult stage	Nymphal stage	Adult stage				
Clothianidin (Neonicotinoid), chlorantraniliprole (Anthranilic diamide), and fipronil (Phenylpyrazole)	X				*Crocothemis servilia* *Orthetrum albistylum*	Abundance and emergence patterns	*C. servilia* nymphs were significantly less abundant in the fipronil treatment, while emergence was significantly reduced in all insecticide treatments. *O. albistylum* nymphs were significantly less abundant in all treatments, with emergence significantly reduced under clothianidin and completely absent under fipronil.	Kasai et al. (2016)
Imidacloprid dinotefuran (Neonicotinoids), fipronil (Phenylpyrazole), and cartap hydrochloride (Nereistoxin analogue)	X				*Sympetrum frequens*	Mortality, emergence patterns, and growth	The imidacloprid and fipronil treatment caused 100% nymph mortality. Nymph survival was significantly lower in the dinotefuran treatment than in the control and cartap treatments. While emergence rates did not differ significantly, nymph head widths were significantly narrower in the dinotefuran treatment.	Jinguji and Uéda (2015)
Deltamethrin, cypermethrin, lambda-cyhalothrin (Pyrethroids), chlorpyrifos, dichlorvos (Organophosphates), and acetamiprid (Neonicotinoid)	X		X		*Ischnura elegans* *Trithemis aurora*	Mortality (48-hr LC90 value)	*I. elegans* and *T. aurora* were most sensitive to lambda-cyhalothrin and least sensitive to chlorpyrifos, with overall sensitivity rankings of lambda-cyhalothrin > acetamiprid > deltamethrin > cypermethrin > dichlorvos > chlorpyrifos (*I. elegans*) and lambda-cyhalothrin > acetamiprid > cypermethrin > deltamethrin > dichlorvos > chlorpyrifos (*T. aurora*).	Ilahi et al. (2020a)
Glyphosate (Phosphonate) and Roundup (Glyphosate-based herbicide)			X		*Coenagrion pulchellum*	Mortality, growth, energy storage, muscle mass, acetylcholinesterase activity, foraging behavior, and escape swimming speed	Herbicide exposure increased mortality and food intake, while reducing growth, energy reserves, muscle mass, and escape swimming speed. Roundup caused stronger adverse effects than glyphosate alone, with increased mortality and reduced muscle mass observed only under Roundup exposure.	Janssens and Stoks (2017)

(continued)

Table 1 (continued)

Contaminants	Dragonflies (Anisoptera)		Damselflies (Zygoptera)		Taxa	Variables	Results summary	Reference
	Nymphal stage	Adult stage	Nymphal stage	Adult stage				
Atrazine (triazine)	X				*Pachydiplax longipennis*	Immune function (hemocyte count and phenyloxidase (PO) activity in the hemolymph, cuticle, and gut)	Exposure to environmentally relevant concentrations of atrazine significantly altered indicators of immune function, including hemocyte count and PO activity in both hemolymph and cuticle.	St. Clair and Fuller (2018)
Bacillus thuringiensis israelensis (Bti) (biological larvicide)	X	X			*Erythemis simplicicollis*	Nymphal mortality, development, morphology, adult size, and flight capability	Bti exposure, through both external (contaminated water) and internal (contaminated prey) pathways, had no significant effects on mortality, nymphal development, morphology, adult size, or flight capability.	Painter et al. (1996)
Bacillus thuringiensis israelensis (Bti) and *Bacillus sphaericus* (biological larvicides)	X		X		*Enallagma civile* *Tarnetrum corruptum*	Longevity, emergence patterns, and predation rate	Exposure to Bti and *B. sphaericus* through the consumption of contaminated mosquito larvae did not significantly affect the longevity, emergence, or predation rate of *T. corruptum* and *E. civile*.	Aly and Mulla (1987)
Imidacloprid (Neonicotinoid)			X		*Lestes congener*	Learned recognition of a predator odor	Imidacloprid exposure impaired the ability of nymphs to learn or recognize a novel predator odor, reducing antipredator responses.	Wickramasingha et al. (2024)
Imidacloprid (Neonicotinoid), fipronil and fipronil sulfone (Phenylpyrazoles)	X				*Sympetrum infuscatum* *Sympetrum frequens*	Feeding behavior (quantity of prey items consumed and the time taken to capture prey items)	Exposure to fipronil and fipronil sulfone reduced prey consumption (*S. infuscatum*) and increased prey capture time (*S. frequens*), with fipronil sulfone significantly impairing feeding at all tested concentrations. Imidacloprid affected feeding only at 1,000 µg/L. Fipronil sulfone was more toxic than fipronil.	Jinguji et al. (2018)
Glyphosate (Phosphonate)	X				*Pantala flavescens* *Trithemis aurora* *Libellula fulva*	Predatory performance (consumption of mosquito larvae)	Exposure to glyphosate weakened the predatory performance of nymphs from all three dragonfly species against mosquito larvae.	Khan et al. (2022)

(continued)

Table 1 (continued)

Contaminants	Dragonflies (Anisoptera)		Damselflies (Zygoptera)		Taxa	Variables	Results summary	Reference
	Nymphal stage	Adult stage	Nymphal stage	Adult stage				
Heavy metals								
27 heavy metals and metalloids	X		X		16 Odonata genera	Community composition (abundance and taxonomic composition)	Urban ponds had lower dragonfly species richness and abundance, lower damselfly abundance, and overall lower Odonata diversity compared to natural ponds.	Perron and Pick (2020)
Copper, zinc, iron, manganese, and nickel	X		X		18 Odonata genera	Community composition (abundance, genus composition, richness, Shannon-Wiener diversity index, and Pielou's evenness index)	A negative relationship was observed between Pielou's evenness and the concentrations of nickel, copper, zinc, and manganese. In contrast, there were significant positive associations between iron and abundance, genus richness, and Shannon-Wiener diversity.	Bruno et al. (2022)
Zinc, manganese, cadmium, lead, and gold	X		X		12 Odonata genera	Community composition (abundance)	There was a significant negative correlation between the abundance of Odonata and lead concentrations.	Ehikhamele and Ogbogu (2016)
Copper, zinc, iron, and lead		X			27 Odonata species	Community composition (abundance and species richness) and bioaccumulation	The abundance of dragonflies was negatively associated with iron levels in water, while species diversity exhibited a significant positive relationship with iron concentrations in sediments. Moreover, the bioaccumulation of metals varied considerably among different body parts across species.	Noor-Ul-Islam et al. (2021)
Mine tailings (without a specific breakdown of metal elements)		X		X	16 Odonata genera	Community composition (abundance, species richness, and endemism)	Sites without mine tailings showed greater Odonata abundance, species richness, and endemism compared to sites with mine tailings.	Quisil et al. (2014)
Copper, zinc, nickel, cadmium, and lead	X				*Aeshna* spp.	Genotoxicity	There was a significant correlation between the levels of zinc in the sediment and DNA damage.	Meland et al. (2019)
Copper, zinc, manganese, cadmium, and lead		X			*Austroaeschna inermis*	Oxidative stress biomarkers	Lead showed positive correlations with oxidative stress biomarkers, while other metals exhibited significant negative correlations.	Ihechiluru et al. (2015)

(continued)

Table 1 (continued)

Contaminants	Dragonflies (Anisoptera)		Damselflies (Zygoptera)		Taxa	Variables	Results summary	Reference
	Nymphal stage	Adult stage	Nymphal stage	Adult stage				
Cadmium, lead, and aluminum			X		*Enallagma* sp.	Mortality (96-hr LC50 value)	*Enallagma* sp. showed the least sensitivity to heavy metal exposure when compared to filter feeders, scrapers, and shredders. Among the three metals examined, cadmium was the most toxic to the odonate.	Mackie (1989)
Cadmium			X		*Ischnura heterosticta*	Mortality (96-hr LC50 value)	The nymphs showed less sensitivity to high cadmium concentrations compared to a species of Amphipoda and Ephemeroptera.	Thorp and Lake (1974)
Aluminum	X				*Somatochlora cingulata*	Oxygen consumption, ammonia excretion, and O: N ratios	No significant differences were observed between exposure to low pH and aluminum concentrations compared to low pH alone, indicating that aluminum exposure itself did not exert a toxic effect.	Correa et al. (1985)
Lead	X				*Libellula depressa* *Libellula quadrimaculata* *Aeshna cyanea*	Bioaccumulation and oxidative enzyme activity	Lead did not accumulate in the brain, but considerable accumulation was observed in the midgut, fat body, rectum, and cuticle. Additionally, lead exposure suppressed the activity of oxidative enzymes in the brain.	Meyer et al. (1986)
Aluminum	X				*Libellula julia*	Oxygen consumption	Exposure to low pH alone did not depress respiratory rates as greatly as low pH and aluminum combined.	Rockwood et al. (1990)
Aluminum	X				*Libellula julia*	Water balance, ionic regulation, and acid-base balance (hemolymph pH)	Exposure to aluminum and low pH had a synergistic effect, resulting in significant disruptions to water balance, ionic regulation, and acid-base balance (hemolymph pH).	Rockwood and Coler (1991)
Copper, cadmium, and lead	X				*Pachydiplax longipennis* *Erythemis simplicicollis*	Mortality and bioaccumulation	Dragonfly nymphs accumulated high concentrations of cadmium, lead, and copper, primarily in their exoskeletons. Mortality rates were low with cadmium and lead exposure; however, nymphs were significantly more sensitive to copper, exhibiting increased mortality at lower concentrations.	Tollett et al. (2009)

(continued)

Table 1 (continued)

Contaminants	Dragonflies (Anisoptera)		Damselflies (Zygoptera)		Taxa	Variables	Results summary	Reference
	Nymphal stage	Adult stage	Nymphal stage	Adult stage				
Copper, manganese, mercury, and cadmium	X				*Tramea cophysa*	Mortality (48-hr LC50 value)	*T. cophysa* exhibited varying sensitivity to metals, with the highest sensitivity to copper, followed by equal sensitivity to cadmium and mercury, and then manganese.	dos Santos Lima et al. (2019)
Copper, zinc, mercury, cadmium, and lead	X				*Tramea cophysa*	Mortality	*T. cophysa* showed the highest mortality when fed mosquito larvae contaminated with mercury, followed by larvae exposed to lead, cadmium, copper, and zinc.	Akhtar et al. (2021)
Copper, cadmium, and lead	X		X		*Ischnura elegans* *Trithemis aurora* *Pantala flavescens*	Mortality (7-day LC50 value) and feeding rate	Among the metals assessed, copper exhibited the greatest toxicity across odonate species, as evidenced by the lowest LC50 values. While exposure to all heavy metals significantly reduced the feeding rate of *P. flavescens*, only copper exposure led to significant reductions in the feeding rate of *I. elegans* and *T. aurora*.	Ilahi et al. (2020b)
Copper, manganese, mercury, and cadmium	X				*Tramea cophysa*	Feeding rates and food preference	Nymphal food preferences remained unchanged after exposure to each metal salt, but feeding rates decreased after exposure to all metal salts except manganese sulphate.	dos Santos Lima et al. (2021)
Interactions between climate change, pesticides, and heavy metals								
Two temperatures (20 °C and 24 °C) and zinc			X	X	*Ischnura elegans*	Nymphal mortality, growth rate, development time, and emergence success, as well as adult mass at emergence and lifespan	Zinc exposure caused strong delayed effects in *I. elegans*, reducing post-exposure survival, growth, mass at emergence, and adult lifespan. Synergistic interactions between zinc and warming occurred only in low-latitude damselflies, where elevated temperatures intensified the adverse effects of zinc on survival, growth, emergence, and adult lifespan.	Debecker et al. (2017)

(continued)

Table 1 (continued)

Contaminants	Dragonflies (Anisoptera)		Damselflies (Zygoptera)		Taxa	Variables	Results summary	Reference
	Nymphal stage	Adult stage	Nymphal stage	Adult stage				
Two temperatures (20 °C and 24 °C) and zinc			X		*Ischnura elegans*	Mortality, growth rate, and food intake	Zinc exposure reduced survival, growth, and food intake in *I. elegans*, with effects exacerbated at the higher temperature. Considerable zinc-induced mortality at 24 °C occurred only in high-latitude nymphs.	Dinh et al. (2013)
Warming (+4 °C) and fipronil (Phenylpyrazole)	X		X		Libellulidae Aeshnidae Zygoptera	Community composition (abundance)	The fipronil treatment significantly reduced odonate nymph abundance, while the warming treatment had no effect. The combined fipronil and warming treatment caused a greater decline than either treatment alone, indicating a synergistic interaction.	Ishiwaka et al. (2024)
Heatwave (29 °C for two days) and esfenvalerate (Pyrethroid)			X	X	*Lestes sponsa*	Nymphal mortality, development, and growth rate, as well as adult heat tolerance, total fat content, and flight muscle mass	The heatwave had no significant effects on nymphs but reduced adult fat reserves and flight muscle mass in odonates from the central-latitude population. Esfenvalerate exposure reduced nymphal growth rate, prolonged development time, and decreased adult flight muscle mass. No synergistic interaction between the two stressors was observed.	Sniegula et al. (2017)
Seven mean temperatures (12 °C to 34 °C), daily temperature fluctuations (0 °C or 7.6 °C), and chlorpyrifos (Organophosphate)			X		*Ischnura elegans*	Mortality, growth rate, and activity of acetylcholinesterase	Chlorpyrifos had no effects at 20–24 °C, but reduced growth at ≤16 °C (more strongly in high-latitude nymphs) and drastically lowered survival, growth, and activity of acetylcholinesterase at ≥28 °C. Daily temperature fluctuations further intensified survival losses at 34 °C. Toxicity increased with temperature, even as degradation rates of chlorpyrifos were nearly seven times higher at 34 °C compared to 12 °C.	Verheyen and Stoks (2023)

(continued)

Table 1 (continued)

Contaminants	Dragonflies (Anisoptera)		Damselflies (Zygoptera)		Taxa	Variables	Results summary	Reference
	Nymphal stage	Adult stage	Nymphal stage	Adult stage				
Two temperatures (20 °C and 24 °C) and chlorpyrifos (Organophosphate)			X		*Ischnura elegans*	Mortality, growth rate, activity of acetylcholinesterase, and oxidative damage	Chlorpyrifos exposure significantly increased mortality and physiological stress in nymphs, particularly at the lower temperature (20 °C). Adverse effects—including reduced growth, oxidative damage, and suppressed acetylcholinesterase activity—were more pronounced in high-latitude populations and largely absent at 24 °C, where faster chlorpyrifos degradation mitigated toxicity.	Op de Beeck et al. (2017)
Two temperatures (20 °C and 24 °C) and chlorpyrifos (Organophosphate)			X		*Ischnura elegans* *Ischnura pumilio*	Mortality, growth rate, heat tolerance, and activity of acetylcholinesterase	Chlorpyrifos reduced survival and growth in both species, but *I. elegans* was considerably more sensitive than *I. pumilio*, particularly at 20 °C, where pesticide accumulation was higher.	Op de Beeck et al. (2018)
Two temperatures (20 °C and 24 °C) and chlorpyrifos (Organophosphate)			X		*Ischnura elegans*	Predator behavior (mobility, foraging) and antipredator behavior (activity reductions under predation risk and escape swimming performance)	Chlorpyrifos exposure impaired predator behaviors (walking, head orientations, and feeding strikes), with stronger adverse effects on head orientations and feeding strikes at 24 °C. It also disrupted antipredator behaviors (escape swimming speed and activity reduction in response to predator cues), though these effects were independent of temperature. Behavioral impairments were consistent across nymphs from low- and high-latitude populations.	Dinh et al. (2014)

as the representative compound for neonicotinoids, as most studies on neonicotinoid effects in odonates focus on this compound (see Table 1).

Community composition and diversity metrics

Research on the impact of pesticide pollution on odonate nymph and adult communities in freshwater habitats remains scarce, with most available studies conducted in Japan. Takamura et al. (1991) investigated odonate nymph abundance and species richness across different sections of a Japanese river system. Their sampling design compared upstream sites near rice fields without aerial pesticide spraying, midstream sites adjacent to both sprayed and unsprayed fields, and downstream sites bordered by sprayed fields. Their results showed that downstream sites had the lowest nymph abundance and species richness, suggesting a potential link between aerial pesticide application and altered odonate communities. Building on this, Nakanishi et al. (2020) examined the impact of systemic insecticide use on adult populations of the dragonfly *Sympetrum frequens* across four Japanese prefectures between 2009 and 2016. Their analysis found a significant negative association between the annual increase in the use ratio of systemic insecticides and the annual population growth rate of *S. frequens*. Similarly, Tazunoki et al. (2022) assessed the effects of various insecticides, herbicides, and fungicides on adult odonate abundance in ponds located across agricultural and nonagricultural areas in Japan. Consistent with prior research, their findings showed a significant negative relationship between insecticide concentrations and odonate abundance. Collectively, these field studies indicate that freshwater habitats exposed to high concentrations of pesticides, particularly insecticides, are consistently associated with lower odonate abundance and diversity.

Insecticides can exert various negative impacts on odonate community composition, and it is commonly assumed that biological narrow-spectrum insecticides are safer for non-target organisms, including odonates, compared to their synthetic broad-spectrum counterparts (Ayilara et al., 2023; Harun-Ur-Rashid & Imran, 2025). However, recent evidence challenges this assumption, revealing that both insecticide types can produce similarly disruptive ecological effects, despite differences in their chemical properties and target specificities. A comparison of two recent studies—Kita et al. (2020) and Gerstle et al. (2023)—underscores this point. Kita et al. (2020) monitored odonate communities along a river before and after the application of the synthetic broad-spectrum insecticide fipronil in nearby paddy fields. Their findings indicated significant alterations in odonate community composition, particularly a marked decline in the abundance of the Libellulidae species *Sympetrum eroticum*. In a similar vein, Gerstle et al. (2023) examined the effects of the biological narrow-spectrum insecticide *Bacillus thuringiensis israelensis* (Bti) on macroinvertebrate communities, with a focus on odonate nymphs. Although Bti does not directly harm odonate nymphs, the study reported a 54% reduction in the emergence rates of Libellulidae in Bti-treated mesocosms. This decline was attributed to a trophic cascade: Bti reduced populations of chironomid larvae, an essential prey resource, leading to decreased food availability and increased intraguild predation among odonate nymphs. Together, these studies demonstrate that both synthetic broad-spectrum and biological narrow-spectrum insecticides can exert comparable effects on odonate community composition, depending on the ecological context. Consequently, the assumption that biological narrow-spectrum insecticides are safer than their synthetic broad-spectrum alternatives may not hold when indirect ecological consequences, such as the disruption of trophic interactions, are taken into account.

Shedding light on how herbicides may influence odonate community composition, Md Rawi et al. (2012) examined the effects of five herbicides (propanil, quinclorac, molinate/propanil, 2,4-D amine, and bensulfuron) on odonate abundance and diversity in experimental rice plots. Their study found that herbicide-treated plots supported higher species richness (up to 12 species) compared to control plots (eight species). Species abundances also varied, with *Ischnura* spp. being the most abundant in treated plots, whereas *Agriocnemis* spp. were the most abundant in control plots. The authors attributed the observed increase in odonate diversity to potentially greater prey availability, likely resulting from the decomposition of weeds and subsequent enrichment of the water with organic matter. In another study, Kobashi et al. (2017) assessed the effects of two neonicotinoid insecticides, imidacloprid and dinotefuran, on aquatic insect assemblages in experimental mesocosms. Imidacloprid-treated mesocosms (10 kg/ha) showed significant reductions in the nymph abundance of *Crocothemis servilia* and *Lyriothemis pachygastra*, whereas dinotefuran-treated mesocosms (10 kg/ha) showed no declines in the abundance of any odonate species. These findings suggest that although both insecticides are broad-spectrum systemic neonicotinoids applied at equal rates, odonate nymphs may be more sensitive to imidacloprid than to dinotefuran.

The studies reviewed on the impact of pesticide pollution on odonate nymph and adult communities indicate that freshwater habitats exposed to higher pesticide concentrations are generally associated with lower odonate abundance and species richness. However, this relationship may be confounded by other unmeasured environmental factors, limiting the ability to infer a clear causal relationship. Despite this, studies employing controlled experimental designs, such as those by Gerstle et al. (2023) and Kobashi et al. (2017), provide strong evidence for the adverse effects of insecticides on odonate nymph communities. Moreover, the findings reviewed in this section suggest that some pesticide classifications—whether broad- or narrow-spectrum—can be poor predictors of ecological impact. Both types can alter odonate community composition, although typically via different mechanisms: broad-spectrum insecticides tend to cause direct toxicity, whereas narrow-spectrum insecticides may exert indirect effects by disrupting trophic interactions. Notably, pesticides do not always lead to immediate negative outcomes. In some cases, herbicides may temporarily enhance odonate diversity by increasing prey availability through the enrichment of water with organic matter from the decomposition of weeds. Finally, comparisons of insecticides within the same class (e.g., neonicotinoids) applied at the same rates have shown that their impacts on odonate communities can vary substantially. Taken together, these results suggest that broad pesticide categories may offer limited predictive value for assessing

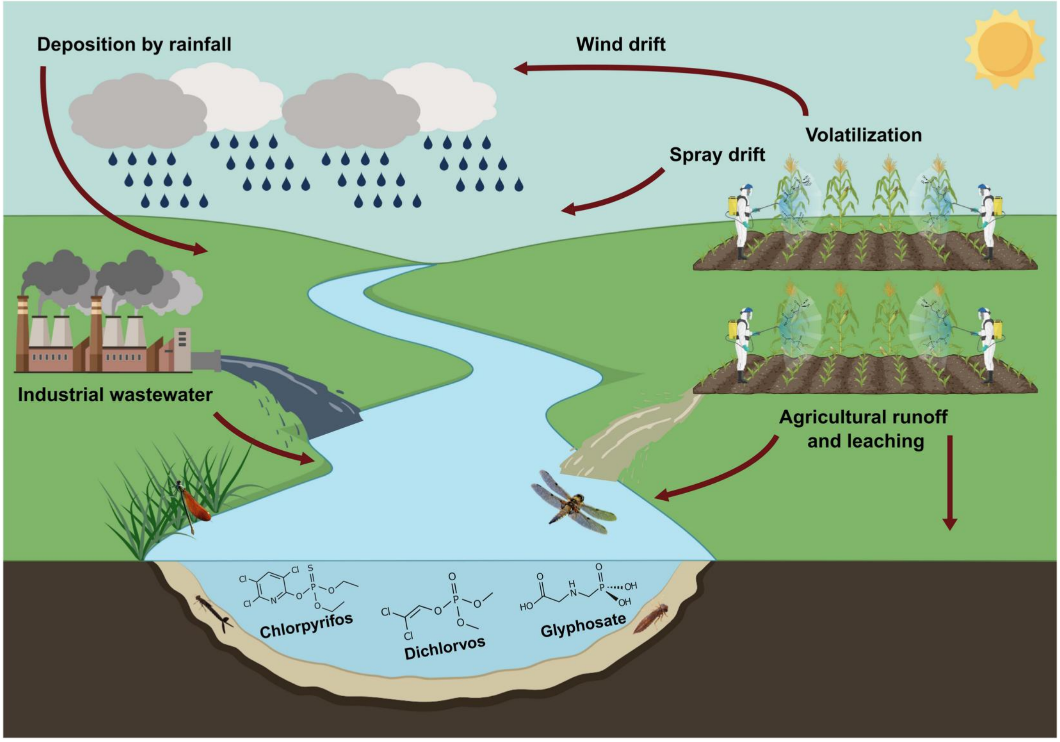

Figure 2. Primary sources of pesticide contamination in freshwater ecosystems. Made with BioRender.

Table 2. Classification of pesticides based on their mobility within plant tissues and spectrum of activity.

	Broad-spectrum	Narrow-spectrum
Systemic	Moves within the plant vascular system and affects a broad range of taxa	Moves within the plant vascular system and affects a narrow range of taxa
Nonsystemic	Does not move within the plant vascular system and affects a broad range of taxa	Does not move within the plant vascular system and affects a narrow range of taxa

Table 3. Classification of commonly studied pesticide groups in odonate-focused ecotoxicological research, based on their mobility within plant tissues, spectrum of activity, water solubility, environmental persistence, and mode of action. The characteristics of each pesticide group are generalized from a representative compound (indicated in parentheses), selected for its frequent use in odonate-focused ecotoxicological studies. The Chemical Abstracts Service Registry Number (CAS RN) for each representative compound is also included. Data were compiled from chemical profiles reported in Lewis et al. (2016), Mestres and Mestres (1992), Simon-Delso et al. (2015), Sparks and Nauen (2015), and Tišler et al. (2009).

Pesticide group	Mobility	Spectrum of activity	Solubility in water	Environmental persistence	Mode of action	CAS RN
Neonicotinoids (Imidacloprid)	Systemic	Broad-spectrum	Moderate	Moderate to High	Neurotoxic	138261-41-3
Phenylpyrazoles (Fipronil)	Systemic	Broad-spectrum	Low	Moderate to High	Neurotoxic	120068-37-3
Phosphonates (Glyphosate)	Systemic	Broad-spectrum	High	Low to Moderate	Enzyme inhibitor	1071-83-6
Organophosphates (Chlorpyrifos)	Nonsystemic	Broad-spectrum	Low	Low to Moderate	Enzyme inhibitor	2921-88-2
Pyrethroids (Deltamethrin)	Nonsystemic	Broad-spectrum	Low	Low	Neurotoxic	52918-63-5

the consequences of pesticide pollution on odonate community composition.

Mortality and sublethal effects

Pyrethroid insecticides are extensively employed for the control of various agricultural and household pests (Matsuo, 2019). These nonsystemic, neurotoxic compounds are favored for their relatively low toxicity to mammals and rapid environmental degradation, which contributes to minimal environmental persistence and contamination (Matsuo, 2019; Tang et al., 2018). Despite their widespread use, field-based studies on the effects of pyrethroids and other insecticides on odonate mortality and sublethal endpoints remain limited. Nevertheless, an expanding body of laboratory research has provided important insights into these effects. For instance, Sugita et al. (2018) assessed the acute toxicity of 15 insecticides on nymphs of *Ischnura senegalensis*, determining median effect concentrations (EC50) after a 24-hr exposure followed by a 48-hr post-treatment observation. Nymphs were classified as either “immobilized” (dead or unresponsive to stimuli) or “alive” (swimming or responsive to stimuli), and EC50 values were calculated accordingly. The study found that odonate nymphs were most sensitive to pyrethroids (etofenprox, EC50 = 0.647 μg/L), followed by phenylpyrazoles (fipronil, EC50 = 1.835 μg/L), organophosphates (fenitrothion, EC50 = 7.871 μg/L), carbamates (benfuracarb, EC50 = 28.290 μg/L), and neonicotinoids (imidacloprid, EC50 = 112.300 μg/L). Notably, *I. senegalensis* demonstrated greater sensitivity to neonicotinoids than *Daphnia magna*, a species commonly used in ecotoxicological risk assessments. Similarly, Beketov (2004) conducted 96-hr acute toxicity tests to determine lethal concentration (LC50) values for the pyrethroids deltamethrin and esfenvalerate in various aquatic insects. While odonate nymphs were generally less sensitive to pyrethroids than ephemeropteran nymphs, the study revealed considerable interspecific variation among odonates. *Lestes sponsa* exhibited the highest sensitivity (LC50 = 0.015 μg/L for deltamethrin; 0.012 μg/L for esfenvalerate), whereas *Cordulia aenea* showed lower sensitivity (LC50 = 0.760 μg/L for deltamethrin; 0.262 μg/L for esfenvalerate). These findings indicate that *L. sponsa* is approximately 51 times more sensitive to deltamethrin and 22 times more sensitive to esfenvalerate than *C. aenea*. Interestingly, *D. magna* was again among the least sensitive species tested, ranking as the second least sensitive species after *C. aenea*.

Concerning sublethal endpoints, Kunce et al. (2017) investigated the physiological responses of *Coenagrion puella* nymphs to individual and combined exposures of two pyrethroid insecticides—deltamethrin and esfenvalerate. Their study focused on three biomarkers: glutathione S-transferase activity (a detoxification enzyme), electron transport system activity (a proxy for metabolic rate), and malondialdehyde formation (indicative of oxidative damage). Among these, glutathione S-transferase activity showed the most marked response. Specifically, glutathione S-transferase activity increased in response to esfenvalerate (0.069 and 0.130 μg/L) and deltamethrin (0.065 μg/L) but was suppressed at higher deltamethrin concentrations (0.130 μg/L) and under combined exposure to both pyrethroids (0.067 μg/L deltamethrin and 0.120 μg/L esfenvalerate). These results suggest that while low-level pyrethroid exposure may activate detoxification mechanisms, higher or combined exposures may inhibit them. Similarly, Chand (2014) examined the impact of 40-hr exposures to two pyrethroid insecticides—deltamethrin (2.500 μg/L) and cypermethrin (0.027 μg/L)—on the midgut tissues of *Trithemis aurora* nymphs. Both insecticides caused severe structural damage to midgut tissues, implying impaired digestive function and potential developmental disruption. Collectively, these studies demonstrate that even sublethal concentrations of pyrethroids can compromise key physiological systems in odonate nymphs, including detoxification and gut integrity.

Organophosphate insecticides, esters of phosphoric acid, are widely used in agricultural pest management due to their broad-spectrum activity and relatively rapid environmental degradation (Sidhu et al., 2019). This rapid breakdown has contributed to their perception as more environmentally benign compared to more persistent pesticides (Sidhu et al., 2019). However, their primary mode of action—the inhibition of acetylcholinesterase, a key enzyme for normal nervous system function—raises concerns regarding their impact on non-target organisms (Sparks & Nauen, 2015). Despite their lower environmental persistence, organophosphates such as chlorpyrifos can cause both lethal and sublethal effects in odonates. For example, Van Dievel et al. (2019) examined the individual and combined effects of chlorpyrifos exposure (2.140 μg/L) and predation risk on the survival and growth of *Enallagma cyathigerum* nymphs. Chlorpyrifos exposure nearly halved nymph survival rates and significantly reduced growth, primarily due to decreased energy conversion efficiency (the proportion of assimilated energy converted into body mass). Predation risk exerted additive negative impacts, highlighting the potential for natural ecological stressors to amplify pesticide-induced physiological stress. Similarly, Janssens et al. (2017) exposed *E. cyathigerum* nymphs to a lower concentration of chlorpyrifos (1.000 μg/L) alongside predator cues, leading to declines in growth and energy reserves, as well as disruptions in RNA: DNA ratios and body stoichiometry. Notably, these impacts were more pronounced in the presence of predator cues, underscoring the importance of ecological context when assessing pesticide toxicity. The authors noted that the observed pesticide-induced changes in body stoichiometry could have broader implications for nutrient cycling in freshwater communities.

Emerging evidence also points to interspecific variation in chlorpyrifos sensitivity among odonate species. Mohammed et al. (2022) assessed the acute effects of chlorpyrifos exposure (0.040 μg/L) on mortality and detoxification enzyme activity in mosquito larvae and their aquatic predators, including ephemeropteran and *Pantala flavescens* nymphs. Among the species assessed, *P. flavescens* exhibited the lowest sensitivity, with a mortality rate of 20%. Chlorpyrifos exposure induced significant increases in acetylcholinesterase and glutathione S-transferase activity in these nymphs, indicating the activation of detoxification pathways that may contribute to their relative tolerance. In contrast, Brewer and Atchison (1999) found no significant changes in head capsule cholinesterase activity in *Anax junius* nymphs after a 24-hr exposure to higher concentrations of chlorpyrifos (0.200, 0.600, and 1.000 μg/L), suggesting potential species-specific sensitivities. Although no significant enzymatic alterations were noted, the authors cautioned that the same chlorpyrifos concentrations could still indirectly affect odonates by decreasing prey availability. Overall, the evidence indicates that while some odonate species may possess the capability to detoxify chlorpyrifos to some extent, others suffer severe physiological and developmental disruptions. Crucially, studies that incorporate ecological stressors, particularly predation risk, consistently reveal that pesticide toxicity is context-dependent. Therefore, studies that omit such interactions may underestimate the ecological risks posed by chlorpyrifos and other insecticides to odonate populations in freshwater habitats.

Neonicotinoid and phenylpyrazole insecticides represent two major classes of systemic, broad-spectrum neurotoxic compounds with similar physicochemical properties (Lewis et al., 2016; Simon-Delso et al., 2015). Since their market introduction in the 1990s, these compounds have become some of the most widely used insecticides worldwide, with various applications in agriculture, aquaculture, and veterinary medicine (Lewis et al., 2016; Simon-Delso et al., 2015). Collectively, neonicotinoids and the phenylpyrazole fipronil account for roughly one-third of global insecticide use (Simon-Delso et al., 2015). Due to their widespread application, environmental persistence, and similar physicochemical characteristics, these insecticides are often studied together in research assessing their impacts on odonate mortality and sublethal endpoints. For instance, Jinguji et al. (2009) employed a micro-paddy lysimeter (MPL) system to investigate the effects of fipronil and the neonicotinoid imidacloprid on the mortality, development, and emergence of *S. frequens* nymphs. Granular formulations of each insecticide were applied at field-relevant rates (0.89 g/m^2) per lysimeter. The results indicated that fipronil-treated lysimeters experienced 100% nymph mortality, while those treated with imidacloprid showed a nearly 40% reduction in nymph abundance compared to controls. Furthermore, surviving nymphs in the imidacloprid-treated lysimeters exhibited significantly lower growth rates, reduced emergence, and shorter adult wing lengths relative to controls. In a subsequent study, Jinguji et al. (2013) used a similar MPL system to assess the impacts of fipronil and imidacloprid on the mortality and emergence of a congeneric species, *Sympetrum infuscatum*. After the application of the insecticides, peak concentrations in paddy water were measured at 1.300 μg/L for fipronil and 52.800 μg/L for imidacloprid. Nine days post-application, fipronil-treated lysimeters showed 100% nymph mortality with no emergence, whereas imidacloprid-treated lysimeters experienced 84.8% nymph mortality and only 12.1% emergence, compared to 66.7% in control lysimeters. Collectively, these studies underscore the potential of both neonicotinoid and phenylpyrazole insecticides to cause severe lethal and sublethal effects in odonates, even when applied in accordance with standard agricultural practices.

Building on earlier studies, Jinguji and Ueda (2015) examined the effects of fipronil and imidacloprid, along with two comparatively more selective insecticides—dinotefuran and cartap hydrochloride—on the survival, development, and emergence of *S. frequens* using a MPL system. As in previous experiments, granular formulations were applied to rice seedlings at manufacturer-recommended rates (50 g per nursery box), which were then transplanted into individual MPLs. After transplantation, 50 newly hatched *S. frequens* nymphs were introduced into each system. After 30 days, complete mortality was observed in both the fipronil- and imidacloprid-treated MPLs, as indicated by the absence of surviving nymphs or exuviae. Dinotefuran-treated MPLs exhibited significantly lower survival (mean of 6.3 nymphs) compared to cartap treatments (mean of 27.0 nymphs) and controls (mean of 31.0 nymphs). Although emergence rates did not differ significantly among dinotefuran, cartap, and control groups, nymphs exposed to dinotefuran displayed significantly narrower head widths, suggesting developmental impairment. These results indicate that while dinotefuran and cartap may pose lower acute risks than fipronil and imidacloprid, they can still induce notable sublethal effects. In a related study, Kasai et al. (2016) evaluated the impacts of fipronil, clothianidin (a neonicotinoid), and chlorantraniliprole (an anthranilic diamide) on aquatic communities in paddy mesocosms, again using field-relevant application rates (50 g per nursery box). Treated rice seedlings were transplanted into mesocosms 24 hr post-application, resulting in initial water concentrations of 0.394 μg/L (fipronil), 2.690 μg/L (clothianidin), and 2.060 μg/L (chlorantraniliprole). Over a nearly 2-month monitoring period, the abundance and emergence of *C. servilia* and *Orthetrum albistylum* were assessed. For *C. servilia*, nymph abundance was unaffected by clothianidin and chlorantraniliprole but was significantly reduced by fipronil. However, emergence rates were significantly lower across all treatments. For *O. albistylum*, nymph abundance declined significantly under all insecticides, with emergence completely absent under fipronil, significantly reduced by clothianidin, and unaffected by chlorantraniliprole. These findings further emphasize that field-relevant concentrations of these insecticides can cause substantial harm to non-target odonates, with fipronil consistently inflicting the most severe negative effects.

Biological insecticides are often considered safer alternatives to synthetic insecticides due to their lower toxicity to non-target organisms and their rapid environmental degradation, which minimizes the risk of environmental contamination (Ayilara et al., 2023; Chowański et al., 2014). However, the impact of these pest control agents on odonates remains poorly understood, as research is still limited. Painter et al. (1996) investigated the effects of Bti on nymphal mortality, development, morphology, and adult size in *Erythemis simplicicollis*. In their experiment, nymphs were exposed weekly to 1,200 μg/L Bti, with treatment groups receiving either external exposure or both external and internal exposure through ingestion of Bti-contaminated prey. The study found no significant effects of Bti exposure on any of the measured endpoints. Similarly, Aly and Mulla (1987) assessed the impact of Bti and *Bacillus sphaericus* on the longevity and emergence of *Tarnetrum corruptum* and *Enallagma civile* nymphs. Nymphs were fed for four consecutive days with *Culex quinquefasciatus* mosquito larvae previously exposed to commercial larvicide formulations (1 g/L). Despite the high toxin content in the prey, no adverse effects on odonate longevity or emergence were observed. These laboratory studies, which suggest minimal impacts of biological insecticides on odonates, contrast sharply with more recent field research. For example, Gerstle et al. (2023) reported a 54% reduction in the emergence rates of Libellulidae in Bti-treated mesocosms. This discrepancy likely stems from the artificial conditions of these earlier laboratory experiments, where nymphs were supplied with a stable and abundant food source. Such conditions do not reflect the prey scarcity that can occur in contaminated environments. In the field, insecticide-induced reductions in prey availability may lead to food limitation and increased intraguild predation among odonates (e.g., Gerstle et al., 2023). Consequently, while these laboratory studies provide valuable insights into the direct toxicity of biological insecticides, they may substantially underestimate the broader ecological impacts mediated through trophic interactions.

Herbicides are the most extensively used category of pesticides globally, accounting for nearly half of all pesticide applications (De et al., 2014). Their widespread use has resulted in considerable environmental contamination, negatively impacting a variety of non-target organisms (Bamal et al., 2024). In addition to affecting their intended plant targets, several commonly used herbicides have been shown to impair immune function and induce genotoxic effects across a broad range of taxa (Cavas, 2011; Yang et al., 2021). Despite these recognized threats, the effects of herbicide exposure on odonates remain poorly understood, particularly when compared to the more extensively researched effects of insecticides. Addressing this knowledge gap, St. Clair and Fuller (2018) investigated how long-term exposure to environmentally relevant concentrations of the herbicide atrazine affects immune function in nymphs of the dragonfly *Pachydiplax longipennis*. Over 3- and 6-week periods, nymphs were exposed to atrazine at concentrations of 0, 1, 5, and 10 μg/L. The study revealed that atrazine significantly altered multiple indicators of immune strength, including hemocyte count and phenoloxidase activity in both the hemolymph and cuticle. The authors suggested that these changes could compromise pathogen tolerance and disrupt developmental processes in natural odonate populations. Complementing these findings, Janssens and Stoks (2017) compared the effects of the commercial herbicide Roundup and its active ingredient glyphosate on mortality, growth, and physiological condition in *Coenagrion pulchellum* nymphs. Exposure to environmentally relevant herbicide concentrations (1,000 and 2,000 μg/L) increased mortality and reduced growth rates, energy reserves, and muscle mass. Notably, Roundup caused more pronounced adverse effects than glyphosate, with some impacts, such as increased mortality and reduced muscle mass, observed only under Roundup exposure. These results underscore the importance of including commercial formulations in risk assessments, as co-formulants can enhance the toxicity of commercial products beyond that of the active ingredient alone.

Behavioral endpoints

Limited research has been conducted on the impact of pesticide exposure on behavioral endpoints in odonate nymphs and adults. Nevertheless, Kunce et al. (2017) examined the effects of two pyrethroid insecticides—deltamethrin and esfenvalerate—on the predatory ability and mobility of *C. puella* nymphs. Deltamethrin significantly reduced predatory ability at both tested concentrations (0.065 μg/L and 0.130 μg/L), whereas mobility remained unaffected. In contrast, exposure to esfenvalerate (0.069 μg/L and 0.130 μg/L) had no significant effect on either behavioral endpoint. Similarly, Brewer and Atchison (1999) investigated the effects of the organophosphate insecticide chlorpyrifos on various aspects of foraging behavior in *A. junius* nymphs. Nymphs were exposed for 24 hr to environmentally relevant chlorpyrifos concentrations (0.200, 0.600, and 1.000 μg/L) across a range of prey densities. Chlorpyrifos exposure resulted in mostly nonsignificant differences in foraging behavior compared to controls. However, prey density strongly influenced behavior: higher prey availability led to more orientations, pursuits, strikes, and ingestions regardless of insecticide treatment. Although Brewer and Atchison (1999) reported limited direct behavioral effects of chlorpyrifos exposure, their findings revealed a strong influence of prey density on odonate foraging behavior. This points to a potential indirect pathway through which insecticides could affect odonate behavior—namely, by reducing prey density. This pathway once again underscores the importance of considering both direct and indirect ecological consequences of pesticide contamination.

Jinguji et al. (2018) assessed sublethal behavioral effects of the insecticides imidacloprid (a neonicotinoid), fipronil (a phenylpyrazole), and its metabolite fipronil sulfone on the predatory behavior of two odonates, *S. infuscatum* and *S. frequens*. After a 48-hr exposure period, feeding inhibition was measured using species-specific behavioral endpoints: the number of prey consumed by *S. infuscatum* and the time taken to capture prey by *S. frequens*. In *S. infuscatum*, prey consumption was significantly reduced at 1,000 μg/L imidacloprid, ≥10 μg/L fipronil, and at all tested concentrations of fipronil sulfone (0.01–1,000 μg/L). In *S. frequens*, nymphs exposed to 1,000 μg/L imidacloprid failed to capture prey, and capture times increased significantly at ≥10 μg/L fipronil and ≥1 μg/L fipronil sulfone. These behavioral disruptions may represent one mechanism by which these insecticides contribute to the high mortality rates reported in prior studies. Notably, fipronil sulfone was substantially more toxic than its parent compound. In addition to impairing odonate behavior as predators, insecticides can also disrupt their behavior as prey. Wickramasingha et al. (2024) examined the impact of a 10-day imidacloprid exposure (0, 0.1, 1.0, or 10.0 μg/L) on the ability of *Lestes congener* nymphs to learn and respond to a novel predator odor. After the exposure period, nymphs were conditioned to associate the novel odor with conspecific alarm cues. Nymphs exposed to 0 or 0.1 μg/L imidacloprid displayed appropriate learned antipredator behaviors. In contrast, those exposed to 1.0 or 10.0 μg/L failed to do so, indicating that higher concentrations of imidacloprid interfered with either the chemical integrity of the conditioning cues or the cognitive processes required for associative learning. Collectively, these studies demonstrate that insecticides at environmentally relevant concentrations can profoundly disrupt odonate behavior, compromising their roles as both predators and prey.

Research on the behavioral impacts of herbicide exposure in odonates remains notably scarce. However, two recent studies have begun to address this gap. Khan et al. (2022) investigated how exposure to the phosphonate herbicide glyphosate influences the predatory performance of nymphs from three odonate species—*P. flavescens*, *T. aurora*, and *Libellula fulva*—when preying on mosquito larvae. In 24-hr feeding trials, glyphosate exposure significantly reduced prey consumption. Specifically, predatory performance declined at concentrations of 1,000, 2,500, and 5,000 μg/L for *P. flavescens*, at 2,500 and 5,000 μg/L for *T. aurora*, and at 5,000 μg/L for *L. fulva*. Similarly, Janssens and Stoks (2017) examined the sublethal behavioral effects of both glyphosate and the glyphosate-based commercial formulation Roundup on *C. pulchellum* nymphs, focusing on foraging activity and escape swimming speed at concentrations of 1,000 and 2,000 μg/L. Roundup exposure significantly increased foraging activity and reduced escape swimming speed at both concentrations, whereas glyphosate alone altered these behaviors only at the higher concentration. Although both of these studies explored similar behavioral responses to glyphosate, their findings diverge: Khan et al. (2022) observed a reduction in predatory performance, whereas Janssens and Stoks (2017) reported an increase in foraging activity. This contrast may reflect species-specific differences in behavioral responses to herbicide exposure. Importantly, the increased foraging activity observed in *C. pulchellum* occurred alongside a range of adverse effects, including increased mortality and reduced growth rates, indicating that such behavioral changes are not necessarily beneficial. Taken together, and consistent with previous findings, these studies demonstrate that herbicides, despite being designed to target plants, can exert direct sublethal effects on odonates at environmentally relevant concentrations.

Section summary

The reviewed literature demonstrates that environmentally relevant concentrations of pesticides adversely affect odonate community composition, survival, physiology, and behavior. Laboratory studies provide substantial evidence of both acute and chronic toxicity, particularly with respect to mortality and sublethal endpoints; however, field-based assessments and research on pesticide effects on community composition and behavioral endpoints remain limited. Studies on community composition and taxonomic diversity metrics indicate that freshwater habitats exposed to high pesticide concentrations, particularly insecticides, exhibit lower odonate abundance and species richness, as well as altered community composition. Among insecticides, neurotoxic compounds such as pyrethroids, neonicotinoids, and phenylpyrazoles are especially harmful, with pyrethroids and the phenylpyrazole fipronil identified as the most acutely toxic. Nonetheless, sensitivity to these compounds varies across species. Beyond mortality, insecticides at environmentally relevant concentrations induce a wide range of sublethal effects, including midgut tissue damage, reduced growth rates, decreased emergence success, and shortened adult wing lengths. Studies using commercial formulations of insecticides applied at field-relevant rates consistently highlight fipronil and imidacloprid as considerable threats to non-target odonates. Furthermore, studies on behavioral endpoints indicate that insecticide exposure compromises odonates' ecological roles as both predators and prey, resulting in reduced predatory performance against mosquito larvae, feeding inhibition, and impaired learning and response to novel predator cues. While herbicides are primarily designed to target plants, several studies have reported direct lethal and sublethal effects on odonates, including increased mortality, reduced growth rates, and compromised immune function at environmentally relevant concentrations. Crucially, pesticide toxicity often appears context-dependent, with stronger adverse outcomes observed in the presence of additional ecological stressors (e.g., predation risk), commercial formulations, or pesticide metabolites. These findings underscore the limitations of studies focusing on single compounds and isolated stressors.

Heavy metals

The contamination of freshwater ecosystems by heavy metals has become a substantial global concern due to their environmental persistence, propensity for bioaccumulation within food webs, and toxicity (Ali et al., 2019; Briffa et al., 2020; Edo et al., 2024). Heavy metals can enter freshwater ecosystems through both natural and anthropogenic pathways. Natural sources include volcanic eruptions and the weathering of metal-bearing rocks, whereas anthropogenic sources comprise mining, industrial processes, and sewage effluents (Figure 3; Ali et al., 2019; Briffa et al., 2020; Edo et al., 2024). Additionally, agricultural activities contribute as a secondary source of heavy metal contamination, as pesticides and phosphate fertilizers often contain elevated concentrations of these compounds (Figure 3; Ali et al., 2019; Briffa et al., 2020). Heavy metals can be classified as either essential or nonessential to living organisms. Essential metals, such as copper (Cu), zinc (Zn), iron (Fe), manganese (Mn), and nickel (Ni), function as micronutrients that support biochemical and physiological processes when present within tolerable concentrations (Ali & Khan, 2019; Rinken & Kivirand, 2019). In contrast, nonessential metals, such as mercury (Hg), cadmium (Cd), lead (Pb), arsenic (As), and aluminum (Al), are not required for normal biological functions and can pose severe toxicological risks even at extremely low concentrations, as most organisms lack mechanisms for their metabolism or excretion (Ali & Khan, 2019; Rainbow, 2002; Rinken & Kivirand, 2019). High concentrations of heavy metals in the environment are particularly harmful to freshwater invertebrate communities, as prolonged exposure results in significant shifts in community composition, with marked declines in species richness and abundance (Marqués et al., 2003; Qu et al., 2010; Rico-Sánchez et al., 2022).

Freshwater invertebrates accumulate heavy metals primarily through two mechanisms: direct absorption from contaminated water and sediments via their exoskeletons or body surfaces, and dietary intake through the consumption of contaminated prey or plant material (Gall et al., 2015; Heikens et al., 2001). Odonates, particularly during their nymphal stages, are known to bioaccumulate various heavy metals, including Cu, Zn, Cd, Pb, and As, due to their close association with bottom sediments (Fletcher et al., 2017; Lesch & Bouwman, 2018; Nasirian & Irvine, 2017). In other aquatic invertebrates, the accumulation of these metals has been linked to a range of biochemical and physiological disturbances, including DNA damage, oxidative stress, reduced oxygen consumption, developmental inhibition, and increased mortality (Jeong et al., 2023; Jorge et al., 2013). Heavy metal exposure can also induce behavioral changes, such as reduced locomotion and suppressed feeding activity, the latter of which is often attributed to the inhibition of digestive enzymes (Lebrun & Gismondi, 2020). Although odonates are frequently found to be less sensitive to heavy metal exposure than other freshwater invertebrates, such as mollusks, amphipods, and ephemeropterans (Mackie, 1989; Thorp & Lake, 1974; Tollett et al., 2009), considerable interspecific variation in sensitivity exists. This variation stems in part from species-specific differences in the types of metals accumulated and the body parts in which these metals are sequestered (Fletcher et al., 2017; Hamid & Jumaat, 2023; Noor-Ul-Islam et al., 2021). Habitat preferences also influence accumulation patterns, as species closely

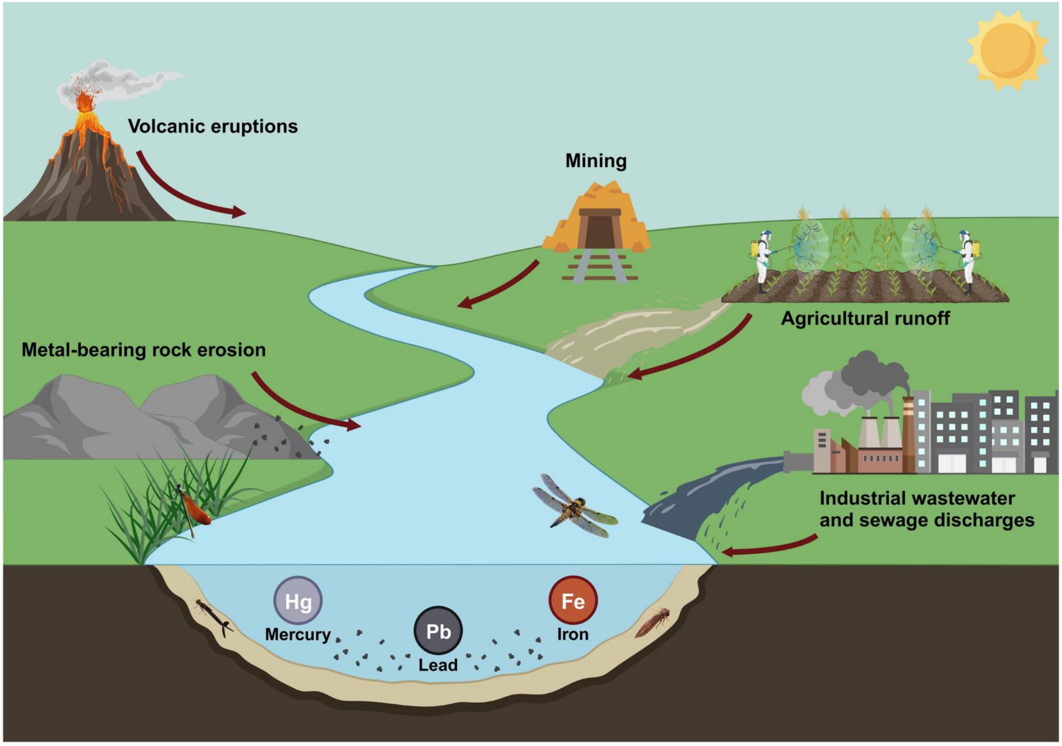

Figure 3. Primary sources of heavy metal contamination in freshwater ecosystems. Made with BioRender.

associated with bottom sediments tend to accumulate higher concentrations of metals (Fletcher et al., 2020). However, greater accumulation does not necessarily correspond to increased toxicological risk, since some species with substantial metal loads exhibit relatively lower sensitivity (Noor-Ul-Islam et al., 2021). Therefore, the broad characterization of odonates as less sensitive to heavy metal exposure likely oversimplifies a complex, species-dependent phenomenon. A critical review of the literature is thus necessary to better understand the impacts of heavy metal exposure across odonates.

Community composition and diversity metrics

Research on the impact of heavy metal pollution on odonate nymph communities in freshwater habitats remains limited. Perron and Pick (2020) compared urban and natural ponds and found significantly higher concentrations of chloride, heavy metals, and metalloids in urban ponds. Their study revealed that urban ponds had lower dragonfly species richness and abundance, reduced damselfly abundance, and overall lower odonate diversity compared to natural ponds. Moreover, dragonfly community composition differed between environments: genera such as *Leucorrhinia* and *Sympetrum* were more prevalent in natural ponds, whereas *Aeshna* and *Anax* were more common in urban ponds with elevated heavy metal concentrations, particularly Zn and As. Similarly, Ehikhamele and Ogbogu (2016) reported a significant negative correlation between odonate nymph abundance and water Pb concentrations in two Nigerian water reservoirs. The most comprehensive field study to date, conducted by Bruno et al. (2022), examined sediment heavy metal content across 12 streams and its associations with nymph assemblage composition. Their findings indicated a negative relationship between taxa evenness and Cu, Zn, Mn, and Ni concentrations, while Fe was positively related to odonate abundance and genus richness. Despite the positive association between sediment Fe concentration and nymph abundance, elevated Cu, Zn, Mn, and Ni concentrations reduced taxa evenness, favoring less sensitive species. Given that natural environments rarely experience contamination from a single metal, these findings collectively suggest that heavy metal pollution can significantly disrupt nymph community assemblages by selectively reducing the abundance and richness of sensitive taxa.

The influence of heavy metal pollution on adult odonate communities in freshwater habitats has received comparatively less attention. Quisil et al. (2014) assessed species richness, abundance, and endemism across eight sampling sites, four of which were contaminated by mine tailings—a known source of heavy metal pollution (Abraham & Susan, 2017). Their study found that sites unaffected by mine tailings supported higher species richness, abundance, and endemism, suggesting that heavy metal pollution strongly influences adult odonate community composition. In another study on adult odonate communities, Noor-Ul-Islam et al. (2021) investigated the bioaccumulation of heavy metals in various odonate body parts and analyzed the relationship between water and sediment metal concentrations and dragonfly species richness and abundance. Their results revealed significant variation in Cu, Zn, Fe, and Pb concentrations across sampling sites, with dragonfly abundance being negatively correlated with Fe levels in water bodies. In contrast, species diversity was positively correlated with Fe concentrations in sediments. Additionally, species-specific differences in metal sensitivity were observed, with *Neurothemis tullia* and

Orthetrum anceps displaying lower sensitivity to high metal loads. These findings highlight the potential for certain species to persist in contaminated environments while others may be more vulnerable, leading to shifts in odonate community composition. Collectively, these studies indicate that heavy metal pollution influences species richness and abundance in odonate communities at both nymphal and adult stages.

Mortality and sublethal effects

Research on the sublethal effects of heavy metal pollution on odonates in freshwater environments remains limited. Meland et al. (2019) investigated the association between DNA damage in *Aeshna* spp. dragonfly nymphs and heavy metal concentrations in both highway sedimentation ponds and natural ponds. Their study identified a significant positive correlation between DNA damage and sediment Zn concentrations. In a complementary study, Ihechiluru et al. (2015) assessed oxidative stress biomarkers in *Austroaeschna inermis* across five study sites and analyzed their relationships with sediment concentrations of Cu, Zn, Mn, Cd, and Pb. Their results revealed a significant positive correlation between oxidative stress biomarkers and Pb, whereas correlations with Cu, Zn, Mn, and Cd were significantly negative. Although field studies on odonate sublethal endpoints remain scarce, these findings suggest that heavy metal exposure can lead to genotoxic effects. However, the variable responses of oxidative stress biomarkers complicate the interpretation of the impact of heavy metals on oxidative stress in odonates.

Compared to field studies, laboratory research on heavy metal toxicity in odonates is more prevalent, particularly in assessing LC50 values and sublethal effects in nymphal stages. For instance, Mackie (1989) conducted 96-hr toxicity tests to determine the lethal concentrations of Cd, Pb, and Al in benthic macroinvertebrates from four functional groups. The study found that the predatory odonate *Enallagma* sp. was less sensitive to these metals than filter feeders, scrapers, and shredders. Among the three metals tested, Cd was the most toxic, with 96-hr LC50 values ranging from 7.05 to 10.66 mg/L across a pH range of 3.5 to 4.5. In a similar study, Thorp and Lake (1974) conducted 96-hr toxicity tests of Cd with a range of selected freshwater invertebrates. Their results revealed that the odonate *Ischnura heterosticta* was considerably less sensitive to Cd compared to the tested amphipod and ephemeropteran species. The reported 96-hr LC50 Cd value for *I. heterosticta* was 233 mg/L, approximately 26 times greater than the 96-hr LC50 Cd value for *Enallagma* sp. determined by Mackie (1989).

In another acute toxicity study, dos Santos Lima et al. (2019) assessed the sensitivity of *Tramea cophysa* and other invertebrates to Cu, Mn, Hg, and Cd. Their results indicated that *T. cophysa* was generally less sensitive to heavy metals than the other tested invertebrates. Nevertheless, among the metals examined, *T. cophysa* exhibited the highest sensitivity to Cu, followed by Cd, Hg, and Mn, with recorded 48-hr LC50 values of 0.611 mg/L (Cu), 0.845 mg/L (Cd), 0.846 mg/L (Hg), and 323 mg/L (Mn). Similarly, Ilahi et al. (2020b) investigated the effects of a 7-day exposure to Cu, Cd, and Pb on the mortality of *I. elegans*, *T. aurora*, and *P. flavescens* nymphs. Their results corroborated the findings of dos Santos Lima et al. (2019), indicating that Cu was the most toxic metal tested. The 7-day LC50 values reported for *I. elegans*, *T. aurora*, and *P. flavescens* were, respectively, 148.2 mg/L, 101.8 mg/L, and 173.6 mg/L for Cu; 618.4 mg/L, 417.6 mg/L, and 1441.7 mg/L for Cd; and 762.7 mg/L, 712.1 mg/L, and 923.9 mg/L for Pb. A direct comparison between these studies reveals considerable interspecific differences in sensitivity to heavy metals. For example, the 48-hr LC50 value for Cd reported by dos Santos Lima et al. (2019) for *T. cophysa* (0.845 mg/L) suggests that this species is about 1,706 times more sensitive to Cd than *P. flaviscens*, for which Ilahi et al. (2020b) reported a 7-day LC50 of 1,441.7 mg/L. These findings suggest that variation in heavy metal sensitivity among odonate species can far exceed the variation in sensitivity of a single species to different metals.

Building on these acute toxicity studies, Tollett et al. (2009) conducted a laboratory study to evaluate the bioaccumulation and toxicity of Cu, Cd, and Pb in dragonfly nymphs over a 7-day exposure period. Their results demonstrated that dragonfly nymphs accumulated high concentrations of these metals, primarily in their exoskeleton. While nymphs exhibited low sensitivity to Cd and Pb—showing no significant mortality at concentrations below 100 mg/L and 185 mg/L, respectively—they were markedly more sensitive to Cu, with significant mortality occurring at concentrations as low as 0.15 mg/L. To expand our understanding of heavy metal–induced mortality beyond direct exposure to metal-spiked water, Akhtar et al. (2021) examined the effects of trophic transfer through dietary intake. Their experiment involved feeding *T. cophysa* nymphs with *Aedes aegypti* mosquito larvae that had been previously exposed to Cu (0.6 mg/L), Zn (3.5 mg/L), Hg (0.3 mg/L), Cd (0.3 mg/L), and Pb (0.2 mg/L). Among these metals, Hg-contaminated prey induced the highest mortality in *T. cophysa* (51.6% on average), followed by Pb, Cd, Cu, and Zn. These findings highlight trophic transfer as an important but often understudied pathway of heavy metal toxicity in odonates.

The reviewed laboratory studies on the sensitivity of odonate nymphs to heavy metal exposure indicate that nonessential heavy metals, such as Hg and Cd, can induce mortality in odonates. Moreover, even essential metals such as Cu were revealed to be toxic to odonates at comparatively lower concentrations. However, when evaluating the toxicity of heavy metals in odonates, it is essential to consider the influence of water pH, as metal solubility increases under acidic conditions (Rostern, 2017; Saalidong et al., 2022). Environmental acidification events, including acid rain and acid mine drainage, further intensify this issue by mobilizing metals from the environment and increasing their bioavailability (Hogsden & Harding, 2012; Rostern, 2017). Consequently, heavy metal concentrations deemed relatively safe in laboratory settings may pose substantial risks to odonate populations in freshwater habitats that are simultaneously subjected to heavy metal pollution and acidification (Hogsden & Harding, 2012; Rostern, 2017; Saalidong et al., 2022).

Numerous laboratory studies have considered the physiological consequences of heavy metal exposure in odonates. Meyer et al. (1986) investigated Pb bioaccumulation and its impact on the oxidative properties of various organs in dragonfly nymphs. After 6 weeks of exposure to 0.02 mg/L Pb, substantial accumulation of Pb was observed in the midgut, fat body, rectum, and cuticle. Although Pb did not accumulate in the brain, oxidative enzyme activity in this organ was significantly reduced. Additionally, energy metabolism in midgut cells was disarranged, potentially impairing nutrient absorption and transfer to the hemolymph. Rockwood and Coler (1991) examined the combined effects of low pH and Al exposure on *Libellula julia* nymphs, exposing them to pH levels of 4.0 and 2.3 alongside Al concentrations of 0, 0.3, 3, and 30 mg/L over 96 hr. While exposure to pH 2.3 alone caused severe disruptions in water balance, ionic regulation, and acid-base balance, these physiological disturbances were comparatively significantly exacerbated when combined with high Al concentrations (30 mg/L). The study suggested a synergistic interaction between low pH and Al, leading to pronounced changes in hemolymph osmolality, Cl^- and Na^+ concentrations, and hemolymph pH. Similarly, Correa et al. (1985) exposed *Somatochlora cingulata* nymphs to acidic conditions (pH 4.2) and high Al concentrations (30 mg/L). Their findings indicated several adverse effects, including reduced oxygen consumption rates and decreased excretion of harmful metabolites such as ammonia. However, Correa et al. (1985) found no significant differences between nymphs exposed to low pH alone and those exposed to both low pH and Al, suggesting Al itself did not exert a toxic effect. In contrast, Rockwood et al. (1990) studied *L. julia* nymphs under similar conditions (30 mg/L Al at pH 4.0) and found that Al significantly reduced oxygen uptake and that pH alone did not depress respiratory rates as greatly as Al and low pH combined. The authors proposed that the decline in oxygen consumption could be attributed to mechanical blockage of the gills due to mucus denaturation and the accumulation of Al hydroxide precipitates.

The reviewed studies indicate that heavy metal exposure disrupts essential biochemical and physiological processes in odonates. However, species-specific sensitivity varies considerably, as demonstrated by the divergent responses of *S. cingulata* and *L. julia* to equal Al concentrations under comparable pH conditions (Correa et al., 1985; Rockwood et al., 1990; Rockwood & Coler, 1991). Odonates accumulate heavy metals across various organs, and both waterborne exposure and dietary intake can induce lethal and sublethal effects, including oxidative stress, metabolic disturbances, and impaired respiratory function. Yet, the substantial variation in toxicity—sometimes by factors of 1,000 or more—underscores the limitations of single-species studies in assessing broader ecological risks. Nevertheless, prolonged heavy metal exposure, particularly when combined with acidification events that increase metal solubility and toxicity, poses a serious threat to odonate populations. Synergistic interactions can render otherwise tolerable metal concentrations hazardous, reducing individual fitness and compromising community resilience. Future research should focus on identifying the physiological and genetic mechanisms underlying species-specific metal tolerance and assessing the long-term impacts of chronic metal exposure across multiple generations.

Behavioral endpoints

Few laboratory studies have examined the behavioral effects of heavy metal exposure in odonates. Ilahi et al. (2020b) investigated the impact of a 7-day exposure to Cu (10 mg/L), Cd (40 mg/L), and Pb (40 mg/L) on the feeding rates of *I. elegans*, *T. aurora*, and *P. flavescens* nymphs. Their findings revealed a significant reduction in feeding rates for *P. flavescens* under all heavy metal treatments, while Cu at 10 mg/L significantly reduced feeding rates in *I. elegans* and *T. aurora*. As previously reported, Ilahi et al. (2020b) determined the LC50 values for Cu in *I. elegans* (148.2 mg/L), *T. aurora* (101.8 mg/L), and *P. flavescens* (173.6 mg/L), indicating that considerably lower concentrations, such as 10 mg/L, nearly 17 times below the LC50 threshold for *P. flavescens*, can still induce significant behavioral disruptions. Such reductions in feeding rates may have long-term consequences for individual fitness. The behavioral effects observed by Ilahi et al. (2020b) were corroborated by dos Santos Lima et al. (2021), who also found that heavy metal exposure disrupted odonate feeding behavior. Their study assessed the effects of four metal salts, copper sulphate (10 mg/L), manganese sulphate (100 mg/L), mercury chloride (10 mg/L), and cadmium chloride (10 mg/L), on the food preference and feeding rates of *T. cophysa* nymphs. While food preference remained unchanged, feeding rates declined for all metal salts except manganese sulphate. These studies suggest that exposure to sublethal concentrations of heavy metals can significantly disrupt feeding behavior in odonate nymphs.

Section summary

The reviewed literature underscores the considerable yet understudied impact of heavy metal pollution on odonate community composition, survival, physiology, and behavior. Despite growing recognition of these effects, research remains limited, with one-third of studies predating 2000. This scarcity of recent work has contributed to the broad characterization of odonates as less sensitive to heavy metals. However, much of this understanding is based on single-species studies (dos Santos Lima et al., 2019; Mackie, 1989; Thorp & Lake, 1974), whereas available evidence demonstrates considerable interspecific variation, which often exceeds intraspecific differences across different heavy metals. Studies on community composition reveal that heavy metal contamination is associated with notable shifts in odonate assemblages, often favoring less sensitive species while reducing or eliminating sensitive taxa. These community shifts can persist from the nymphal to the adult stage, raising concerns about long-term community restructuring. Acute toxicity studies consistently identify Cu as one of the most harmful metals to odonates, frequently exhibiting greater toxicity than non-essential metals such as Cd and Pb. Beyond direct mortality, odonates bioaccumulate metals in various tissues beyond their exoskeletons, leading to physiological disruptions, including oxidative stress, impaired respiration, altered energy metabolism, and dysregulation of water balance. These chronic sublethal effects may reduce individual fitness and weaken community resilience, particularly in acidified environments where metal toxicity is exacerbated. Although behavioral studies remain scarce, available research suggests that sublethal metal exposure can significantly alter feeding behavior, potentially impacting trophic interactions, growth, and survival. Future research should focus on varying field-relevant conditions and investigate interactive stressors, such as pH fluctuations and multi-metal exposures, to better assess the ecological risks posed by heavy metal pollution on odonates in freshwater ecosystems.

Interactions between climate change, pesticides, and heavy metals

Climate change has the potential to exacerbate pesticide and heavy metal contamination in freshwater ecosystems through mechanisms such as rising temperatures, altered precipitation patterns, and more frequent extreme weather events (Biswas et al., 2018; Oyewo et al., 2020; Tudi et al., 2021). These climatic changes are expected to disrupt the hydrological and biogeochemical processes that regulate the degradation, transformation, and particularly the mobility of pesticides and heavy metals (Figure 4; Biswas et al., 2018; Oyewo et al., 2020; Tudi et al., 2021). For instance, elevated temperatures can increase pesticide volatilization, accelerate microbial degradation and hydrolysis, and enhance the solubility of heavy metals in aquatic environments, which in turn affects the persistence and bioavailability of these pollutants (Biswas et al., 2018; Tudi et al., 2021). At the same time, warming can reduce soil organic matter and cation exchange capacity, diminishing the soil's ability to retain heavy metals and promoting their mobilization through erosion (Oyewo et al., 2020). Changes in precipitation patterns also influence the transport of contaminants. Increased rainfall can facilitate the wet deposition of volatilized pesticides and intensify surface runoff, thereby increasing the movement of eroded pollutants into freshwater bodies (Biswas et al., 2018). Extreme weather events further shape these processes. Droughts reduce water volume and flow, concentrating pollutants and, in some cases, causing acidification that enhances the solubility of heavy metals (Mosley, 2015; Mosley et al., 2014). Conversely, storms and floods may dilute contaminants but can simultaneously accelerate soil erosion and intensify runoff, thereby increasing contaminant transport (Biswas et al., 2018; Oyewo et al., 2020). Nonetheless, the effects of climate change on contaminant mobility are highly region-specific, shaped by local climatic conditions and landscape features, which complicates predictions of future pollution trends (Oyewo et al., 2020; Tudi et al., 2021). Despite this regional variability, rising global temperatures represent a pervasive driver of change that is likely to alter the environmental behavior of pesticides and heavy metals and may contribute to synergistic interactions between pollution and climate-related stressors.

Beyond influencing the environmental behavior of contaminants, climate warming has already caused pronounced shifts in odonate phenology and geographic distributions over recent decades, including earlier emergence times and poleward range expansions (Hassall et al., 2007; Hickling et al., 2005). As primarily ectothermic organisms, odonates are particularly sensitive to temperature fluctuations. Warmer conditions have been shown to accelerate development, reduce body size at emergence, and increase mortality rates (De Block & Stoks, 2003; McCauley et al., 2015; Starr & McIntyre, 2020; see also Hassall & Thompson, 2008). These physiological responses to warming raise concerns about odonates' capacity to persist under ongoing climate change, especially since elevated temperatures can synergistically enhance the toxicity of pollutants such as pesticides and heavy metals, which often become more toxic at higher temperatures (Noyes et al., 2009; Sokolova & Lannig, 2008). To investigate odonate responses to the combined pressures of warming and pollution, several studies have employed space-for-time substitution approaches by sampling populations of the same species across natural latitudinal temperature gradients (e.g., Debecker et al., 2017; Dinh et al., 2013; Sniegula et al., 2017). This method enables comparisons between low-latitude populations, which currently experience thermal conditions similar to those projected for higher latitudes under future climate scenarios, and high-latitude populations. By experimentally exposing both low-latitude and high-latitude populations to elevated temperatures and contaminants, researchers can assess whether warming synergistically increases pollutant toxicity and whether thermal adaptation in low-latitude populations mitigates these effects. Low-latitude odonates, adapted to warmer environments, are expected to allocate less energy to coping with thermal stress, thereby enabling greater investment in detoxification and repair processes. In contrast, high-latitude populations may experience these same temperatures as physiologically stressful, potentially diverting energy away from detoxification processes and thereby increasing their vulnerability to pollutants. These latitudinal comparisons thus provide a valuable framework for assessing whether climate warming amplifies the toxicity of pesticides and heavy metals in odonates, and whether gradual thermal adaptation can mitigate these compounded risks.

Interactions between climate change and pesticides

The potential for climate warming to exacerbate pesticide toxicity in freshwater invertebrates has garnered increasing scientific attention in recent years. However, empirical evidence specific to odonates remains limited and, in some cases, inconclusive. Despite their recognized value as bioindicators of environmental pollution, few studies have examined how rising temperatures influence odonate community responses to pesticide exposure. To address this gap, Ishiwaka et al. (2024) investigated the individual and combined effects of warming and pesticide exposure on odonate nymph abundance using experimental rice paddy mesocosms. Their study simulated a 4 °C increase in water temperature—consistent with the IPCC's (2021) SSP5-8.5 climate projection for this century—and applied the phenylpyrazole insecticide fipronil at field-relevant rates (50 g per nursery box) using a commercial granular formulation. The experimental design consisted of four treatment groups: a control, fipronil alone, warming alone (+4 °C), and a combination of fipronil and warming (+4 °C). Fipronil exposure alone significantly reduced nymph abundance, whereas warming alone had no statistically significant effect. Notably, the combination of fipronil and elevated temperature resulted in a more substantial decline in nymph abundance due to a synergistic interaction. These findings provide experimental evidence that warming, as projected under high-emission scenarios, may intensify the adverse effects of pesticide pollution on odonate nymph communities.

Compared to the relatively limited research on the combined effects of warming and pesticide exposure on odonate community composition, a more extensive body of work has examined how these stressors interact to influence mortality and sublethal endpoints. For instance, Sniegula et al. (2017) conducted a common garden experiment to assess the delayed and combined effects of a simulated heatwave during the egg stage and subsequent exposure to the pyrethroid esfenvalerate during the

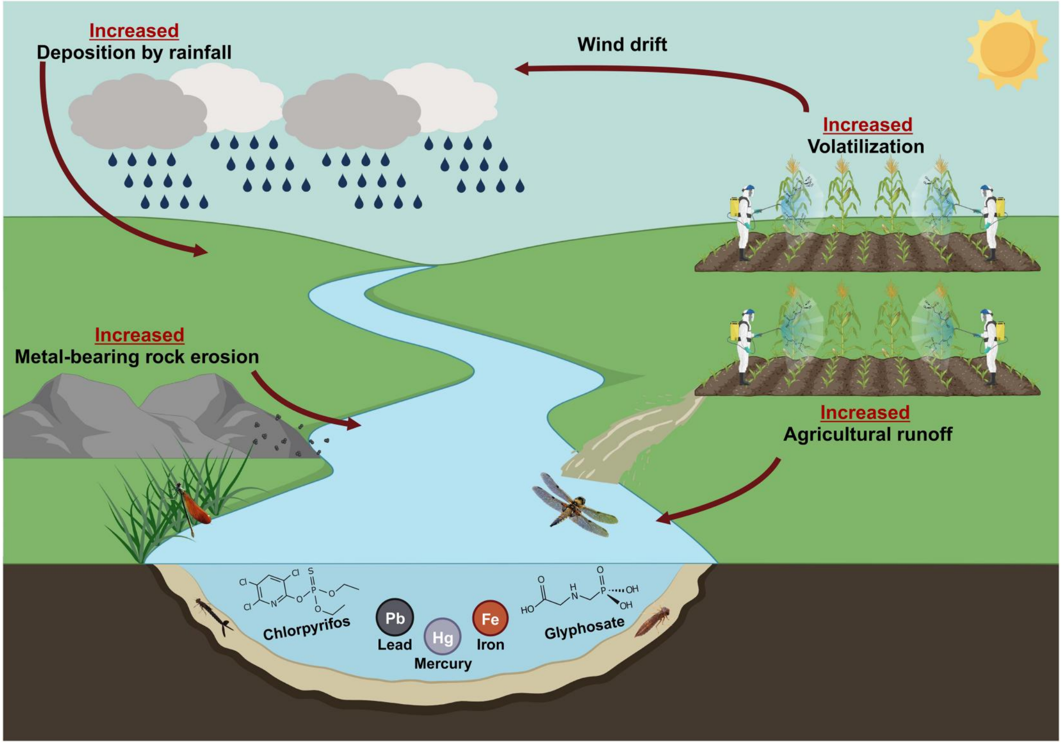

Figure 4. Mobility of pesticides and heavy metals in freshwater ecosystems under climate change. Made with BioRender.

nymphal stage on the life history and physiological traits of the damselfly *L. sponsa*. Eggs from populations at two latitudes—central (northern Poland) and high (northern Sweden)—were reared under identical laboratory conditions in a full factorial design incorporating three factors: population origin (central or high latitude), the presence or absence of a heatwave (29 °C for two days) during the egg stage, and the presence or absence of esfenvalerate exposure (0.081 μg/L) during the final nymphal instar. Although the simulated heatwave did not produce detectable effects on nymphal survival, development time, or growth, it imposed carry-over costs in adults by reducing fat reserves and flight muscle mass—effects observed only in nymphs of the central-latitude population. Esfenvalerate exposure independently reduced nymphal growth, prolonged development, and decreased adult flight muscle mass, with delayed emergence again restricted to the central-latitude group. Importantly, no synergistic interactions between the two stressors were detected. In contrast, Verheyen and Stoks (2023) reported strong synergisms between warming and the organophosphate chlorpyrifos in *I. elegans*. In their common garden experiment, nymphs from low-latitude (southern France) and high-latitude (Denmark and southern Sweden) populations were reared across seven mean temperatures (12–34 °C), under either a constant or a fluctuating thermal regime (±3.8 °C daily), and exposed to 1.000 μg/L chlorpyrifos or a control. While chlorpyrifos had no effect at intermediate temperatures (20–24 °C), it reduced growth at low temperatures (≤16 °C), particularly in high-latitude nymphs, and caused substantial declines in survival, growth, and acetylcholinesterase activity at high temperatures (≥28 °C). Moreover, daily temperature fluctuations further exacerbated reductions in survival at 34 °C. Notably, this increased toxicity at elevated temperatures occurred despite chlorpyrifos degrading nearly seven times faster at 34 °C than at 12 °C.

In contrast to the pronounced temperature-dependent synergisms reported by Verheyen and Stoks (2023), Op de Beeck et al. (2017, 2018) found that more moderate warming can mitigate, rather than exacerbate, the toxic effects of chlorpyrifos on damselfly nymphs. A key methodological difference may account for this apparent discrepancy: Verheyen and Stoks (2023) employed a static renewal regime with daily medium replacement, thereby limiting pesticide accumulation, whereas Op de Beeck et al. (2017, 2018) used a non-renewal regime, allowing for pesticide accumulation and thus more environmentally realistic exposure conditions. In their common garden experiment, Op de Beeck et al. (2017) investigated whether population-level thermal adaptation and temperature-dependent pesticide degradation could influence chlorpyrifos toxicity in *I. elegans*. Nymphs from low-latitude (southern France) and high-latitude (Denmark and southern Sweden) populations were reared from the egg stage at 20 °C and 24 °C—temperatures corresponding to the mean summer water temperatures of their respective native ranges. The study employed a nested full factorial design incorporating three factors: population origin (low or high latitude), rearing temperature (20 °C or 24 °C), and the presence or absence of pesticide exposure (administered as four sequential pulses of 1.000 μg/L chlorpyrifos over 7 days). At 24 °C, chlorpyrifos degraded more rapidly, resulting in approximately half the accumulated pesticide concentration compared to 20 °C.

Consequently, exposure at the lower temperature led to significantly higher mortality, reduced growth, and increased lipid oxidative damage, with these adverse effects disproportionately affecting high-latitude nymphs. Chlorpyrifos also suppressed acetylcholinesterase activity, with reductions more pronounced at 20 °C and in high-latitude nymphs, suggesting that both temperature and population-specific thermal adaptation modulate sensitivity.

Building on these findings, Op de Beeck et al. (2018) explored interspecific differences in thermal and pesticide sensitivity between two congeneric damselfly species, *Ischnura pumilio* and *I. elegans*, which differ in life history and physiological traits. The former is smaller, develops more rapidly, and has a higher metabolic rate, whereas the latter is larger, develops more slowly, and has a lower metabolic rate. Using a factorial design similar to that of their previous work, the authors assessed survival, growth, and physiological responses at two temperatures (20 °C and 24 °C), with or without chlorpyrifos exposure (administered in four pulses of 1.000 μg/L). Chlorpyrifos exposure reduced survival and growth in both species, but the magnitude of these effects varied with species and temperature. Sensitivity was lower in *I. pumilio* than in *I. elegans*, potentially due to higher baseline levels of detoxification and antioxidant enzymes, acetylcholinesterase activity, and fat reserves. In *I. pumilio*, pesticide effects on survival and growth were minimal and did not vary considerably across temperatures. In contrast, *I. elegans* experienced pronounced reductions in survival and growth, particularly at 20 °C, where slower chlorpyrifos degradation led to greater accumulation. These results suggest that, under environmentally realistic, non-renewal, pulse-based exposure scenarios, warming can mitigate chlorpyrifos toxicity by accelerating its degradation. Nonetheless, as demonstrated by Verheyen and Stoks (2023), elevated temperatures can also increase physiological stress, intensifying toxicity even at lower pesticide concentrations. Taken together, these studies further underscore the importance of species-specific physiological traits and population-specific thermal adaptation in shaping odonate sensitivity to pesticide exposure under warming scenarios.

Limited research has investigated whether warming exacerbates the behavioral disruptions caused by pesticide exposure in odonates. To address this gap, Dinh et al. (2014) conducted a common garden experiment using *I. elegans* nymphs from low-latitude (southern France) and high-latitude (southern Sweden) populations to examine how temperature and chlorpyrifos exposure affect both predator and antipredator behaviors. Nymphs were reared at 20 °C and 24 °C and exposed for 6 days to chlorpyrifos at concentrations of 0, 1.500, or 3.000 μg/L. Chlorpyrifos significantly suppressed all measured predator behaviors, including walking, head orientations toward prey, and feeding strikes. Notably, reductions in head orientations and feeding strikes were more pronounced at 24 °C, suggesting that warming can amplify the adverse effects of chlorpyrifos on foraging behavior. For antipredator responses, chlorpyrifos exposure reduced escape swimming speed and weakened the typical activity reduction in response to predator cues; however, these behavioral alterations were independent of temperature. Behavioral impairments in *I. elegans* were consistent across nymphs from both latitudinal origins, providing no evidence that local thermal adaptation mitigates chlorpyrifos toxicity under warmer conditions. Overall, the study supports previous findings that environmentally realistic pesticide exposure impairs odonate behavior as both predator and prey and suggests that climate warming may intensify specific behavioral disruptions.

Interactions between climate change and heavy metals

Few studies have examined how warming may interact with heavy metal contamination to influence the development and survival of odonates. Debecker et al. (2017) investigated the combined effects of zinc exposure and elevated temperature on fitness-related traits across the life stages of the damselfly *I. elegans*. In a common garden experiment, nymphs from low-latitude (southern France) and high-latitude (southern Sweden) populations were reared at 20 °C or 24 °C and exposed to zinc (100 mg/L) or control conditions for 6 days during the final nymphal instar. While zinc exposure had minimal immediate effects, it caused pronounced delayed impacts in nymphs from both populations, including reduced post-exposure survival, decreased growth, lower mass at emergence, and shortened adult lifespan. Synergistic interactions between zinc exposure and warming were observed only in low-latitude damselflies, where elevated temperatures exacerbated the adverse effects of zinc exposure on survival, growth, emergence success, and adult lifespan. Supporting these findings, Dinh et al. (2013) also demonstrated temperature-dependent zinc sensitivity in *I. elegans*. In a similar common garden experiment, nymphs from low-latitude (southern France), central (Belgium), and high-latitude (southern Sweden) populations were reared at 20 °C or 24 °C and exposed to three zinc concentrations (0, 50, and 150 mg/L) for 6 days. At 20 °C, survival remained high across all zinc treatments; however, at 24 °C, mortality at the highest zinc concentration increased sharply, particularly among high-latitude nymphs. Additionally, zinc exposure reduced growth rates and food intake in nymphs from all populations, with the most pronounced effects observed at 24 °C. Notably, high-latitude nymphs experienced the steepest zinc-induced decline in food intake at the higher temperature. Together, these studies suggest that although thermal adaptation may influence odonate responses to heavy metal pollution under elevated temperatures, current evidence remains inconclusive as to whether it consistently mitigates the compounded stress of warming and contaminant exposure.

Section summary

The reviewed literature indicates that climate change, particularly rising temperatures, can amplify the adverse effects of pesticide and heavy metal pollution on odonates, with synergistic interactions reported in five out of eight studies (62.5%). However, these interactions are context-dependent; some studies have observed additive or, less frequently, antagonistic interactions, and synergisms were often endpoint-specific. The combined stress of elevated temperatures and pollutant exposure has been shown to impair odonate survival, growth, physiology, and behavior, with compounds such as fipronil, chlorpyrifos, and zinc demonstrating increased toxicity at higher temperatures. Latitudinal comparisons yielded mixed results, revealing that both low-latitude and high-latitude populations can be more susceptible to warming and pollutant exposure. This variability suggests that local thermal adaptation may not always provide a buffer against the enhanced toxicity of pollutants under warming conditions. Importantly, higher temperatures can also accelerate the degradation of certain pesticides (e.g., chlorpyrifos), potentially mitigating their toxicity under environmentally realistic exposure scenarios. However, this mitigating effect is compound-specific, as different pesticides exhibit distinct temperature-dependent degradation profiles (Ding et al., 2023). A major limitation of the current literature is its narrow taxonomic scope, with most studies (62.5%) concentrating exclusively on the damselfly *I. elegans*, which limits the generalizability of the findings. The only study that explicitly explored interspecific variation found considerable differences in susceptibility to pollutant–temperature interactions across species, underscoring the need for broader taxonomic coverage. Overall, the evidence suggests that climate change, particularly rising temperatures, is likely to exacerbate pollution-related pressures on odonates, potentially accelerating local population declines and extinctions.

Future research directions

This review synthesizes current literature on the impacts of environmental pollution, particularly from pesticides and heavy metals, on Odonata across their life cycle and assesses the potential synergistic interactions between these pollutants and climate change. Across the reviewed studies, several consistent research biases have emerged (Figure 1). Geographically, research is concentrated in Europe and Asia, with 12 of 54 studies originating from Japan and focusing primarily on pesticide effects. Notably, six of the eight studies investigating pollutant–climate interactions were conducted in Belgium. A pronounced taxonomic bias is also evident: five of these eight studies focused exclusively on the damselfly *I. elegans*. This narrow scope is concerning, as the only study to explicitly examine interspecific variation (Op de Beeck et al., 2018) reported substantial differences in susceptibility to pollutant–temperature interactions across species. These findings underscore the urgent need for broader taxonomic representation in future studies of climate–pollution interactions. The combination of geographic and taxonomic biases limits the generalizability of current findings. Variation in freshwater habitat types and agricultural practices across regions complicates extrapolation from well-studied areas such as Europe, North America, and Asia to underrepresented regions, including Africa, Central America, and South America. Methodologically, the dominance of laboratory-based studies (n = 42) has skewed the evidence base toward short-term, acute responses measured under controlled conditions, often using pollutant-spiked water and focusing on mortality and sublethal effects. As a result, our understanding of how pollution influences odonate community composition and diversity in freshwater ecosystems remains limited. Among the most critical and underexplored areas are behavioral endpoints—both in response to pollutants and in combination with climate-related stressors. Given the cascading effects of behavioral disruptions on predator–prey interactions and fitness-related traits, addressing this gap should be a priority for future research.

In addition to these research biases, several limitations in experimental design further constrain the environmental relevance of the existing studies. Most laboratory studies focus exclusively on waterborne exposure, neglecting dietary intake as an important route of contaminant exposure and bioaccumulation (Suedel et al., 1994). This is problematic, as many odonate prey species—particularly benthic taxa such as chironomids—can bioaccumulate pollutants from sediments (Béchard et al., 2008), thereby facilitating trophic transfer to predatory nymphs. Consequently, even studies that use environmentally relevant pollutant concentrations may underestimate total exposure and associated risks. Furthermore, laboratory setups often provide constant, abundant food, overlooking pollution-induced changes in prey availability. Pesticide contamination can reduce prey abundance or alter prey community composition, thereby disrupting trophic interactions and limiting food intake. These indirect effects—while difficult to replicate in laboratory settings—are essential for understanding how contaminants influence odonate growth, development, and survival in environmentally realistic contexts. Another limitation is the prevalence of single-stressor experimental designs. Most studies test individual pesticides or heavy metals in isolation, despite odonates in freshwater habitats frequently encountering complex contaminant mixtures (Bruno et al., 2022; Perron & Pick, 2020; Tazunoki et al., 2022). This lack of multi-contaminant research presents a substantial barrier to achieving environmentally realistic exposure scenarios, especially given emerging evidence that pollutants can act additively or synergistically with one another and with ecological stressors—such as predation risk—to exacerbate adverse effects (Cedergreen, 2014; Janssens et al., 2017; Van Dievel et al., 2019). These interactions may also differ between commercial pesticide formulations and isolated active ingredients, with formulations often producing stronger effects at equivalent concentrations (Janssens & Stoks, 2017). Future research should prioritize experimental designs that incorporate realistic multi-stressor conditions that reflect those in freshwater environments.

Expanding the scope of climate stressor research to include more environmentally realistic conditions is equally important. Most current studies simulate warming using a constant temperature increase—typically 4 °C, consistent with the IPCC's (2021) SSP5-8.5 climate projection—yet natural environments are characterized by fluctuating thermal regimes. To our knowledge, few studies have investigated how daily temperature fluctuations interact with contaminant exposure under warming scenarios, but available evidence suggests that such fluctuations can intensify the adverse effects of contaminants at higher mean temperatures (Verheyen et al., 2022). Similarly, interactions between pollutants and acute thermal stress events, such as heatwaves, remain largely unexplored, despite their potential to impose severe physiological stress and alter contaminant toxicity (Dinh et al., 2022). Incorporating heatwaves into experimental designs represents an important avenue for future work. Addressing these research gaps—in geographic and taxonomic representation, exposure pathways, behavioral endpoints, multi-stressor scenarios, and the inclusion of extreme weather events beyond warming—is essential to improve the predictive capacity of ecological risk assessments. As environmental change accelerates, a more comprehensive and ecologically realistic understanding of how pollution and climate change interact to affect odonate populations will be crucial to informing conservation and management strategies across diverse freshwater ecosystems.

Conclusions

This review addresses two primary questions: (1) How does pesticide and heavy metal pollution impact Odonata across their life cycle? and (2) Does climate change synergistically amplify the impact of pesticide and heavy metal pollution on Odonata? In response to the first question, research indicates that both pesticide and heavy metal contamination negatively affect odonates across multiple levels of biological organization—from individual physiology to community composition. These contaminants lead to reductions in odonate abundance and diversity, alterations in species composition, and impairments in critical life history traits such as growth, emergence success, and adult morphology. Among pesticides, broad-spectrum neurotoxic insecticides—particularly neonicotinoids (e.g., imidacloprid), phenylpyrazoles (e.g., fipronil), and pyrethroids—are identified as the most hazardous, causing both lethal and sublethal effects. These effects include diminished nymphal growth, lower emergence rates, shorter adult wing lengths, and internal tissue damage. Copper consistently emerges as the most acutely toxic heavy metal, often surpassing the toxicity of nonessential metals such as cadmium and lead. Heavy metals were shown to bioaccumulate in tissues beyond the exoskeleton, disrupting vital physiological processes such as respiration, oxidative balance, and energy metabolism, which may ultimately reduce odonate fitness and survival. Behaviorally, exposure to both pesticides and heavy metals compromises feeding efficiency and predator avoidance, undermining odonates' ecological roles as both predators and prey. Notably, neonicotinoids and phenylpyrazoles are not only among the most harmful insecticides identified in this review, but also among those with the highest environmental persistence (Lewis et al., 2016). Their prolonged presence in soils, sediments, and aquatic environments, lasting from months to years (Bonmatin et al., 2015), increases the risk of chronic exposure for odonate nymphs in freshwater habitats.

Regarding the second question—whether climate change synergistically amplifies the impact of pesticide and heavy metal pollution on Odonata—current evidence indicates that rising temperatures generally enhance the toxicity of these contaminants. Most studies demonstrate that warming exacerbates lethal and sublethal effects, resulting in greater reductions in survival and growth, disrupted physiological functions, and intensified behavioral impairments. However, it is essential to note that these interactions are often endpoint-specific. While synergistic effects are prevalent, some studies report additive impacts, and a limited number of studies observe instances of partial mitigation. In those cases, elevated temperatures accelerate pesticide degradation, thereby reducing their adverse effects. Nonetheless, this mitigating effect is compound-specific, as pesticides vary in their temperature-dependent degradation profiles (Ding et al., 2023). Overall, the dominant trend in the literature indicates that climate change, particularly rising temperatures, is likely to amplify pollution-related stress on odonate populations. Although some authors argue that odonates have survived previous episodes of global warming and may therefore possess a degree of tolerance to current and future temperature increases (Castillo-Pérez et al., 2022), it is important to recognize that past climatic shifts were more gradual and occurred in the absence of widespread anthropogenic pollution. The current combination of rapid climate warming and pervasive environmental contamination thus represents a fundamentally novel and more severe challenge for odonate populations.

Author contributions

Daniel Guerra (Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing—original draft), Thomas Blankers (Conceptualization, Writing—review & editing), Michiel H.S. Kraak (Conceptualization, Writing—review & editing), and Emily Rose Burdfield-Steel (Conceptualization, Supervision, Writing—review & editing)

Funding

The authors did not receive support from any organization for the submitted work.

Conflicts of interest

The authors declare no competing interests.

Disclaimer

Michiel H. S. Kraak holds the position of editorial board member for *Environmental Toxicology and Chemistry* and has not peer reviewed or made any editorial decisions for this paper.

Data availability

There are no new data associated with this article.

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Environmental Toxicology and Chemistry, 2026, 45, 2056–2090
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Critical Review