Environmental Fate, Ecotoxicological Impacts and Remediation Strategies for Neonicotinoid Insecticides: A Systematic Review

Enock Mutepuka, Ferdinand Handavu, Bitwell Chibuye, Roxanne Mendere Gekonge

Abstract: *Neonicotinoid insecticides are systemic pesticides widely used in agricultural and non-agricultural pest control because of their efficacy against sucking and chewing insects. However, their high water solubility, persistence, plant translocation and mobility across environmental compartments have raised increasing concern regarding contamination of soil, water, pollen, nectar and non-target habitats. This review synthesizes current evidence on the environmental fate, ecological impacts and remediation strategies for neonicotinoid insecticides, with emphasis on aquatic systems, soil biota, pollinators, birds, humans and emerging clean-up technologies. Evidence from recent studies indicates that neonicotinoids can persist in soil, leach into surface and groundwater, impair aquatic invertebrates, disrupt pollinator behaviour and reproduction, and create indirect risks to food webs and ecosystem services. Remediation approaches, particularly microbial degradation, phytoremediation, advanced oxidation and nanomaterial-assisted removal, show promise but require further field validation. The review highlights the need for integrated pest management, routine environmental monitoring, stricter risk-based regulation and development of safer pest-control alternatives.*

Keywords: *Aquatic system; Neonicotinoid; Insecticides; Impact; Soil, pesticides.*

Enock Mutepuka (enockmutepuka1@gmail.com) Department of Environment and Climate Sciences, School of Agriculture and Environmental Sciences,Mukuba University ,Kitwe ,Zambia., https://orcid.org/0000-0002-1563-8723
Ferdinand Handavu, Department of Environment and Climate sciences, Mukuba University Kitwe, Zambia
Bitwell Chibuye, Department of Physical sciences, Mukuba University Kitwe, Zambia, https://orcid.org/0000-0002-6658-6695
Roxanne Mendere Gekonge, Institute of Biomedical Sciences, Mukuba University kitwe, Zambia
Correspondence: Enock Mutepuka*

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Introduction

Neonicotinoid insecticides (NNIs), a class of insecticides chemically related to nicotine, are extensively used in agriculture worldwide because of their high effectiveness in controlling a broad spectrum of crop pests. Since their introduction in the 1990s, NNIs have become the most widely used insecticides globally due to their efficiency and systemic mode of action (Wood & Goulson, 2017). These compounds are absorbed by plants and translocated throughout plant tissues, thereby providing prolonged protection against herbivorous insects (Wood & Goulson, 2017). Their insecticidal activity occurs through binding to nicotinic acetylcholine receptors in the insect nervous system, disrupting neural signaling pathways and ultimately causing paralysis and death in target pests (Kang et al., 2025; Strouhova et al., 2023; Naseema et al., 2024).

Although this mechanism is highly effective against pest species, it also poses risks to non-target insects, particularly pollinators, because similar receptor types occur across many insect taxa, as reported by Costas-Ferreira and Faro in 2021 and further demonstrated by Merivee et al. in 2025. Initially, NNIs were considered highly selective for insect receptors; however, subsequent studies revealed that these compounds can also interact with vertebrate receptors, albeit with lower affinity. This has raised concerns regarding their potential safety risks to mammals, as highlighted by Moeris et al. in 2021. Furthermore, the toxicological effects of NNIs are not restricted to insects alone, as they may adversely affect a wide range of non-target organisms and ecological systems (Mamy et al., 2023).

Despite their agronomic benefits, the extensive use of NNIs has resulted in their widespread accumulation in environmental matrices, generating growing concern regarding their impacts on non-target organisms and ecosystem health (Morta et al., 2024; Mamy et al., 2023). NNIs were initially promoted as safer alternatives to conventional insecticides such as organophosphates because of their comparatively low mammalian toxicity and high selectivity toward insects. Consequently, they have been widely adopted in agricultural production systems (Li et al., 2025; Thompson et al., 2020). Nevertheless, increasing evidence indicates that the persistent and intensive application of NNIs has contributed to their occurrence in soils, water bodies, and other environmental compartments, raising substantial environmental health concerns. Certain neonicotinoid compounds exhibit long environmental half-lives and may persist for several years after application (Mamy et al., 2023).

Although their relatively low toxicity to mammals contributed to their rapid adoption, the adverse effects of NNIs on non-target invertebrates, especially pollinators, have emerged as a major focus of scientific investigation (James et al., 2016). Current evidence also demonstrates significant ecological risks to aquatic invertebrates and other sensitive organisms exposed to neonicotinoid contamination (Garcia-Hernandez et al., 2025; Zhang et al., 2024).

This review aims to synthesize current evidence regarding the environmental occurrence, transport pathways, ecological impacts, and remediation of neonicotinoid insecticides, with particular emphasis on aquatic ecosystems, soil environments, pollinators, birds, human exposure pathways, and emerging remediation technologies. Unlike previous reviews that primarily focus on pollinator decline or aquatic toxicity, this review provides an integrated assessment across multiple environmental compartments, including soil, water, air, plants, pollinators, birds, and humans, while also linking these impacts to remediation strategies. Such an integrated perspective is essential because neonicotinoid contamination is rarely confined to a single environmental medium; rather, these compounds are transported through interconnected agroecosystems via processes such as leaching, surface runoff, plant uptake, dust drift, and trophic transfer within food webs.

Methodology

Study Design and Framework

This study was conducted as a systematic review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses PRISMA guidelines, which provide a standardized framework for identifying, selecting, appraising, and synthesizing relevant scientific evidence. The adoption of the PRISMA methodology ensured transparency, reproducibility, and methodological rigor in the review process.

The primary objective of this review was to synthesize existing literature on Environmental fate, ecotoxicological impacts and remediation strategies for neonicotinoid insecticides with a specific focus on the impact on the environmental media such as water,soil ,air and invertebrates coupled with exposure pathways , and remediation strategies .

Protocol and Registration

Although this study review was not prospectively registered in databases such as Prospero, the methodology was developed a priori and guided strictly by PRISMA recommendations to minimize bias. The protocol included predefined objectives, inclusion and exclusion criteria, search strategies, and data extraction procedures to ensure consistency throughout the review process.

Eligibility Criteria

The eligibility criteria for inclusion in this systematic review were defined using a modified framework tailored to environmental health and one health research.

Inclusion Criteria

Studies were included if they met the following criteria:Population: Studies on the impacts of Neonicotinoids insecticides focusing on the aquatic systems ,soil ,air and fauna and flora.Exposure: Studies reporting exposure to Neonicotinoid insecticides from agricultural uses that lead to contaminated soil, water, air, or food .Outcomes: Studies reporting clinical outcomes (e.g., acute and chronic effects of Neonicotinoid insecticides, environmental contamination levels, and remediation strategies. Study Design: Observational studies (cross-sectional, cohort, case-control), interventional studies, and relevant review articles.Language: Articles published in English.Publication Type: Peer-reviewed journal articles and credible institutional reports

Exclusion Criteria

The following studies were excluded:Animal or in vitro studies not directly applicable to Environmental impacts of Neonicotinoids.Studies conducted on Insecticides that have no contextual importance.Editorials, commentaries, and opinion pieces lacking primary or secondary data.Articles with insufficient methodological detail or incomplete data.Duplicate publications

Information Sources

A comprehensive literature search was conducted across multiple electronic databases to ensure broad coverage of relevant studies. The databases included: PubMed/MEDLINE,Scopus,Web of Science,Google Scholar and researchgate**.**In addition, reference lists of included articles were manually screened to identify additional relevant studies not captured during the initial search.

Study Selection Process

The study selection process followed the PRISMA flow structure and consisted of four stages. On Identification, a total of 300 records were identified through database searching.During Screening, removal of duplicate records and some studies were screened based on titles and abstracts.Eligibility: A total of 225 full-text articles were assessed for eligibility based on predefined inclusion criteria.Inclusion: Finally, 73 studies were included in the qualitative synthesis

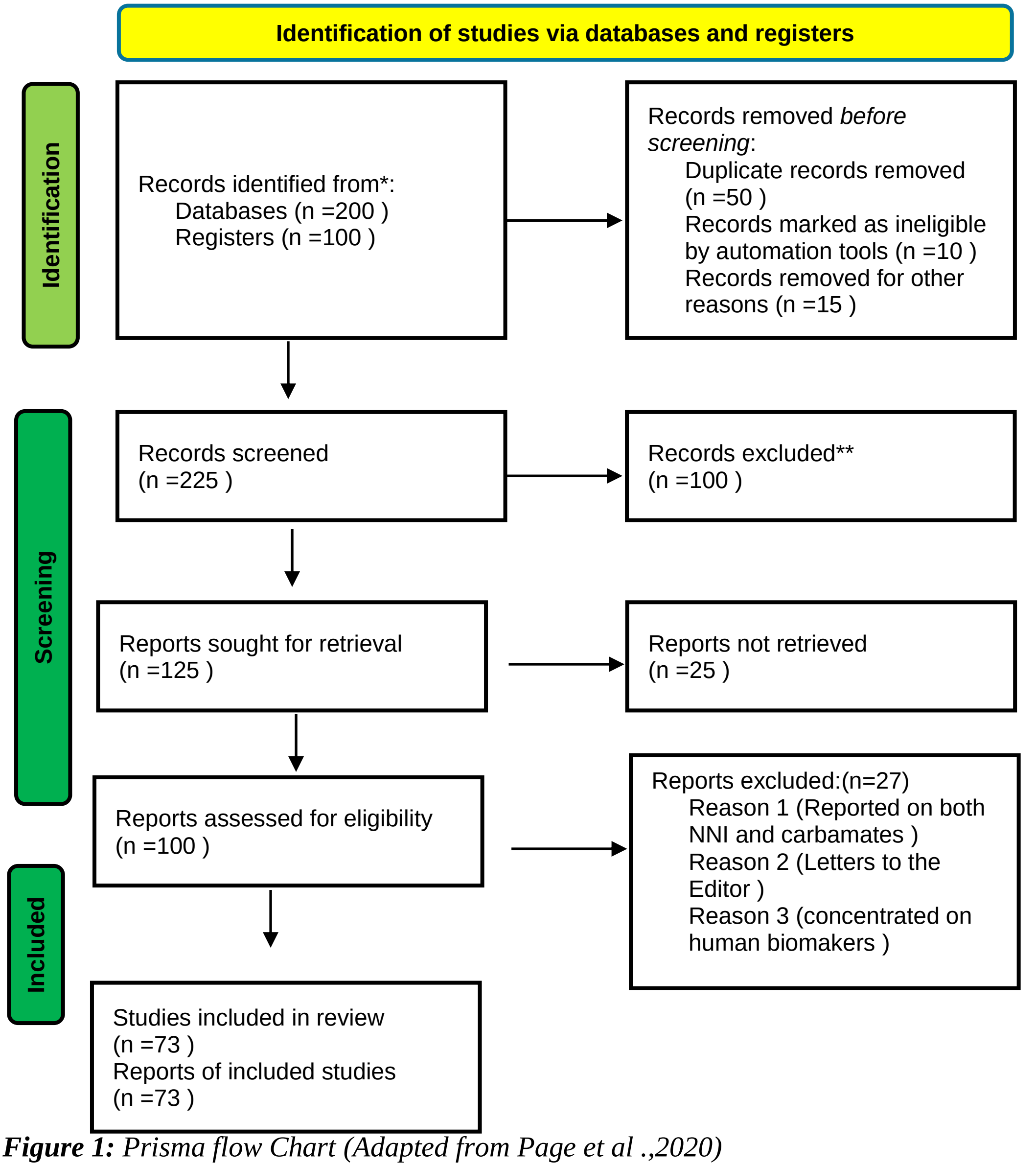

Figure 1: *Prisma flow Chart (Adapted from Page et al .,2020)*

Data Extraction

Data extraction was conducted systematically using a standardized extraction template developed for this review. The following variables were extracted from each study:Author(s) and year of publication,Study location (e.g., Global,african or local),Study design,Sample size and population characteristics,Source and pathway of lead exposure,Environmental contamination levels (soil, water, air) ,remediation strategies ,Key findings and conclusion.This ensured accuracy and consistency as extracted data were cross-checked and verified against the original articles.

Quality Assessment and Risk of Bias

The methodological quality of included studies were assessed using criteria adapted from established tools for observational studies.

Domains Assessed

Selection Bias: Representativeness of study populations.Measurement Bias: Accuracy of exposure and outcome measurements.Confounding: Control of potential confounders.Reporting Bias: Completeness and transparency of reported results

Data Synthesis

Because of the importance of heterogeneity in:Study designs,Population characteristics,Exposure measurements and Outcome reporting.A quantitative meta-analysis was not feasible.Instead, a narrative synthesis approach was adopted, structured around key thematic areas: Impact on the aquatic system,soil,air quality, birds ,humans and remediation.Findings were compared and integrated across studies to identify consistent patterns, trends, and gaps in knowledge.

Ethical Considerations

As this study is a review based on previously published data, no direct ethical approval was required. However, all included studies were assumed to have adhered to ethical standards as reported in their respective publications.

Limitations of Methodology

Several methodological limitations were identified such as restriction to English-language publications which may introduce language bias.Potential publication bias due to reliance on peer-reviewed literature,heterogeneity of included studies limited the ability to perform quantitative synthesis and limited availability of longitudinal studies.Despite these limitations, efforts were made to ensure a comprehensive and unbiased review of available evidence.

Strengths of the Methodology

Use of PRISMA guidelines ensured transparency and rigor,Comprehensive database search enhanced coverage.Inclusion of multiple study designs provided broad insights.Systematic data extraction improved consistency.

Environmental fate and transport of neonicotinoids

The vocalization of neonicotinoids from treated crops and soils introduces these compounds into the atmosphere, facilitating their dispersal over considerable distances and increasing the potential for inhalation exposure among non-target organisms. Atmospheric transport contributes to the deposition of neonicotinoids onto non-agricultural lands and aquatic environments, thereby extending the geographical range of environmental contamination and associated ecological risks. This widespread atmospheric dissemination highlights the importance of comprehensive monitoring programs aimed at evaluating airborne concentrations and deposition patterns of neonicotinoid insecticides across diverse ecosystems. In addition, atmospheric degradation products of neonicotinoids may exhibit toxicities that differ from, and in some cases exceed, those of the parent compounds, thereby complicating environmental risk assessment models. Furthermore, interactions between airborne neonicotinoids and other atmospheric pollutants or particulate matter may generate novel toxicological profiles capable of intensifying both environmental and human health impacts.

Neonicotinoids are readily absorbed by plants and subsequently translocated into pollen and nectar, resulting in direct exposure of pollinators to these compounds, as reported by Bjorge in 2021. Even at low concentrations, neonicotinoids can alter pollinator behavior, impair physiological systems, and interfere with larval development. Such effects may ultimately contribute to colony collapse in bees, as observed by Kreick et al. in 2025.

In addition, neonicotinoids can persist in soil and aquatic environments for extended periods, leading to their widespread detection in environmental samples. This persistence raises significant ecological concerns because of the potential impacts on terrestrial and aquatic organisms, as highlighted by Nedrich et al. in 2024 and Wu et al. in 2024. Certain neonicotinoids exhibit prolonged degradation times, ranging from several months to multiple years, which facilitates their accumulation in soils, plants, nectar, and pollen, including in non-agricultural areas. For example, clothianidin has been reported to exhibit degradation periods ranging from 148 to 6,931 days (Orčić et al., 2022). Such persistence enables these insecticides to disperse into habitats adjacent to agricultural fields, where they may adversely affect beneficial insect populations, as noted by Tetlie and Harmon-Threatt in 2024.

Moreover, the occurrence of neonicotinoids in soil and water systems enhances their environmental mobility and long-term distribution, thereby increasing the likelihood of chronic exposure among non-target organisms (Norton et al., 2023; Tetlie & Harmon-Threatt, 2024). Prolonged exposure to Sublethal concentrations of neonicotinoids has been associated with a range of adverse effects in pollinators, including altered movement patterns, tremors, impaired navigation, and reduced foraging efficiency.

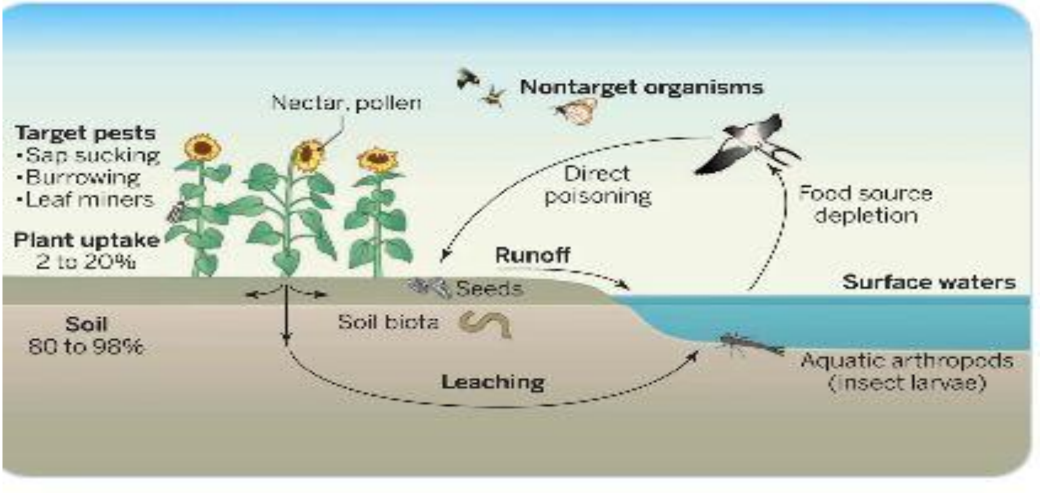

Figure 2: The impact of Neonicotinoids Insecticides on the Environment**.** (Adapted from:Sanchez-Bayo &Francisco,2014)

Neonicotinoid insecticides pose significant environmental concerns due to their widespread occurrence in soil and aquatic ecosystems and their adverse effects on non-target organisms. Their persistence and mobility in environmental matrices contribute to contamination of terrestrial and aquatic habitats, thereby threatening biodiversity and ecosystem stability. Numerous studies have demonstrated that exposure to neonicotinoids can negatively affect a wide range of organisms, including pollinators, aquatic invertebrates, birds, and other wildlife.

Addressing neonicotinoid contamination requires the implementation of effective management and remediation strategies aimed at reducing environmental exposure and minimizing ecological risks. Sustainable agricultural practices, improved pesticide regulation, environmental monitoring, and the development of safer pest-control alternatives are essential to mitigate their environmental impacts. Furthermore, protecting soil quality, water resources, and biodiversity should remain a priority in order to maintain healthy and resilient ecosystems.

Although neonicotinoid contamination represents a major environmental challenge, coordinated scientific, regulatory, and agricultural efforts can contribute to reducing their ecological impacts and promoting environmental sustainability. Figure 2 illustrates the major environmental impacts associated with neonicotinoid insecticides (NNIs).

Table 1. Areas contaminated by NNI and subsequent accumulations

Areas contaminated by NNI	Accumulations
Agricultural fields	soils
Natural habitats	Pollen and nectar
Aquatic systems	water

Neonicotinoid insecticides (NNIs) contaminate a wide range of environments, including agricultural fields, natural habitats, and aquatic ecosystems, where they accumulate in various environmental compartments such as soils, water, pollen, and nectar. The presence of these compounds in such environments poses significant ecological concerns because it affects soil-dwelling organisms, aquatic biota, and pollinators that rely on contaminated pollen and nectar. Since these organisms play essential roles in maintaining ecosystem functioning, biodiversity, nutrient cycling, and plant reproduction, neonicotinoid contamination may disrupt ecological balance and compromise overall ecosystem health.

Movement of neonicotinoid in the environment

Low-level exposures to these chemicals can alter animal behavior, particularly learning and memory processes essential for survival. Surveys across multiple countries have detected these chemicals in surface waters, indicating that conventional wastewater treatment fails to effectively degrade them or their harmful byproducts.

Neonicotinoids, which persist in the environment and are highly water-soluble, frequently contaminate aquatic systems. They pose risks to non-target insects critical to ecosystem function and biodiversity. For instance, studies show that neonicotinoids bioaccumulate in aquatic organisms, disrupting physiological processes. This accumulation transfers through the food web, potentially impacting humans who consume seafood.

Chemicals such as imidacloprid and thiacloprid exhibit high mobility in water, facilitating their global dispersal into ecosystems. Their persistence and solubility exacerbate risks to non-target aquatic species. Beyond water, neonicotinoids contaminate soil, air, and even bird feathers, underscoring their ubiquity.

While designed to target pest insects, neonicotinoids adversely affect beneficial species like bees and birds. Persistent residues in soil and water harm resident biota, with compounds like imidacloprid and thiamethoxam entering the food chain and affecting predators. These widespread impacts extend to human health, as dietary exposure through contaminated food may pose risks.

Further research is essential to quantify neonicotinoid effects on wildlife, their food web dynamics, and potential human health implications.

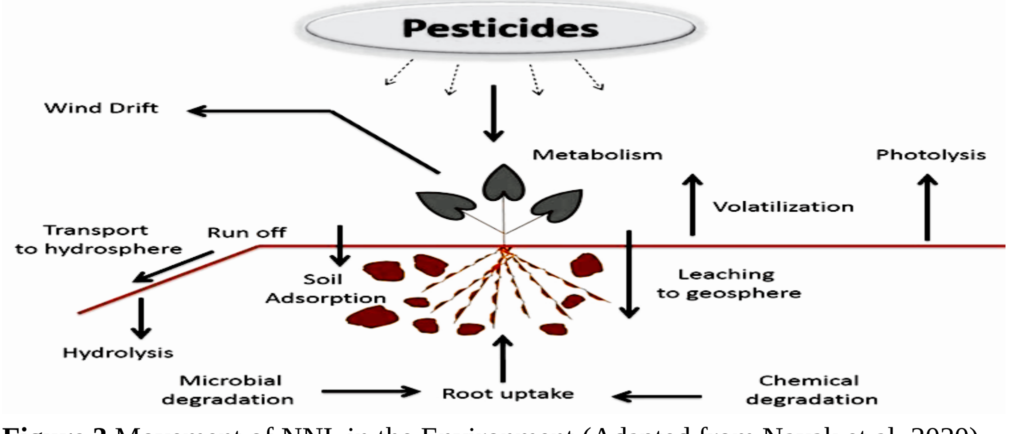

Figure 3 Movement of NNI in the Environment (Adapted from Nayak et al.,2020)

Occurrence in aquatic systems

Neonicotinoids, a class of systemic insecticides, threaten aquatic ecosystems due to their high water solubility and environmental persistence (Lexmond et al., 2014). Their widespread use and inherent toxicity to aquatic invertebrates have caused severe impacts on these fragile environments (Bonmatin et al., 2014). Specifically, these compounds correlate with declines in aquatic insect communities key food sources for higher trophic levels, including fish and birds (Bonmatin et al., 2012). For example, imidacloprid concentrations in certain California aquatic systems have exceeded U.S. Environmental Protection Agency ecological risk thresholds by factors of 10 to 100 (Norton et al., 2020). Such elevated levels highlight the ubiquity of neonicotinoids and their potential for broad ecotoxicological effects (Kurwadkar & Evans, 2016).

Beyond direct lethality, Sublethal neonicotinoid exposure induces reproductive impairment and developmental anomalies in aquatic organisms, undermining population viability and ecosystem function (Buckingham et al., 2017). Their persistent detection in diverse aquatic habitats, from fresh waters to coastal regions, underscores the scope of this contamination (Mamy et al., 2023).

Table 2.Impact of Neonicotinoids on the Aquatic system

Neonicotinoids	Impacts on the aquatic system
Imidacloprid	Altered reproductive success
clothianidine	Threat to aquatic life
Thiamethoxam	Toxicity to aquatic invertebrat
Acetamiprid	Developmental anomalis

Effects on soil organisms and microbial communities

Neonicotinoids pose a substantial risk to soil ecosystems, with over 80% of applied neonicotinoid seed treatments remaining in the soil, leading to elevated exposure for soil invertebrates (Mamy et al.,2023). This residual accumulation can result in concentrations exceeding established no-effect levels for organisms like earthworms and spring-tails, consequently inducing chronic toxicity and detrimental effects on soil biota (Norton et al .,2023). For example, reproductive harm in earthworms has been observed even at very low concentrations of neonicotinoids in contaminated soils (Norton et al., 2023). The high persistence of certain neonicotinoids, such as clothianidin and imidacloprid, with half-lives extending from 187 days to over 500 days, contributes to their ubiquitous presence and potential long-term environmental health concerns (Mamy et al.,2023) . Moreover, even after the cessation of their application, neonicotinoids can persist in soils for several years, creating a continuous source of exposure for soil-dwelling organisms and enabling their transport into wider environmental compartments (Wood & Goulson,2017) This persistent soil contamination thereby facilitates their leaching into groundwater and surface waters, further propagating their detrimental effects across diverse ecosystems. This pervasive contamination is exacerbated by various dispersal mechanisms, including dust generated during the drilling of treated seeds and runoff into surface and groundwaters (Sluijs et al.,2014)

Neonicotinoids pose a substantial threat to pollinator populations, particularly honey bees, due to their systemic nature and high toxicity (Naseema et al.,2024) . This widespread impact stems from various exposure routes, including contaminated pollen, nectar, guttation fluids, and soil, leading to both Sublethal and lethal effects in these crucial organisms (Bakker et al.,2020) .For instance, studies have documented impaired foraging behavior, reduced reproductive success, and compromised immune function in bees exposed to even minute concentrations of these insecticides (Pisa et al.,2017) . More alarmingly, the intensive use of neonicotinoids during flowering stages has been implicated as a major contributing factor to colony collapse disorder in various predator and pollinator species (Ahmad et al.,2021)

Table 3. Common effects of NNI to Humans and Insects (pollinators)

Effects on humans	Effects on insects (Pollinators)
Behavioural alteration	Colony collapse
Impaired learning	Altered movement
Memory loss	Impaired foraging behaviour
Neurological deficiency	Brood development in bees

Effects on birds and vertebrates

Avian populations face significant risks from neonicotinoid exposure, primarily through the consumption of contaminated seeds and insects. These systemic insecticides, initially perceived as low in vertebrate toxicity, have been found in numerous surface waters, including those outside of agricultural areas, further expanding potential avian exposure pathways (Ertl et al.,2018) . Specifically, ingestion of neonicotinoid-treated seeds can lead to acute toxicity, characterized by severe neurological impairment, reduced feeding, and reproductive deficiencies in various bird species. While vertebrates are generally less susceptible than arthropods, concentrations applied as seed coatings have been demonstrably high enough to elicit acute toxic effects on birds prior to their registration (Ihara et al.,2017) . However, recent literature indicates that neonicotinoids exert substantial negative indirect effects on avian populations, particularly insectivorous birds, by diminishing their food supply through pesticide-mediated reductions in insect abundance, despite relatively low direct acute toxicity compared to older pesticide classes (Graves et al.,2022) . Beyond direct consumption of treated seeds, birds can also be exposed to neonicotinoids indirectly through the consumption of contaminated invertebrates, which accumulate these compounds through contact with treated plants or soil (James et al.,2016)

Human exposure pathways and health concerns

The pervasive presence of neonicotinoids in the environment, particularly in water systems, raises considerable concerns regarding human health, with studies indicating potential links to immunosuppression, hormone disruption, and Neurodevelopmental issues (Shareefdeen & Elkamel,2024) . Beyond direct human exposure, the widespread contamination of aquatic environments with neonicotinoids, notably at concentrations as low as 0.01 to 0.1 μg L^{-1}, significantly alters aquatic invertebrate communities and trophic interactions, which can indirectly impact human food webs and ecosystem services(Frame et al .,2020;Sanchez-Bayo et al .,2016) . Additionally, due to their systemic nature and high water solubility, these insecticides are readily translocated into various plant tissues and products, posing a risk of chronic exposure for non-target organisms and potentially entering the human food chain through agricultural produce (Parizadeh et al .,2021;Shareefdeen & Elkamel,2024). This widespread contamination underscores the urgent need for comprehensive risk assessments that consider both direct and indirect exposure pathways to humans (Ahmad et al.,2021) . Given their persistence and widespread use, understanding the full scope of neonicotinoid impacts on human health necessitates further research into their bioaccumulation potential and long-term toxicological effects across diverse populations. Furthermore, recent investigations highlight that the half-life of neonicotinoids in the environment can range from 1 day to almost 19 years, depending on the specific compound and environmental conditions, leading to continuous human exposure through various pathways (Costas-Ferreira & Faro,2021)

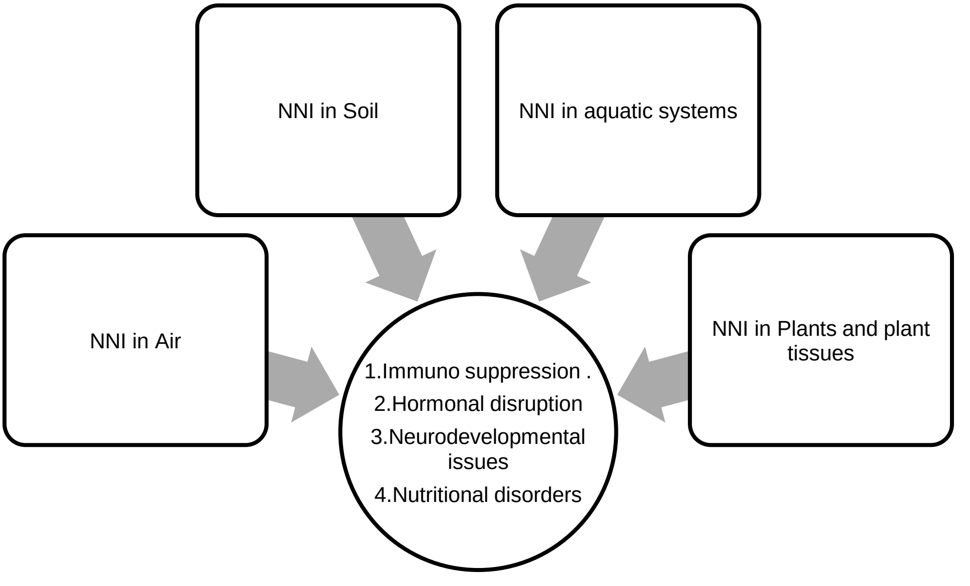

Figure 4 Exposure Pathways and health concerns.

Human exposure to neonicotinoids may occur through residues in food, drinking water, household insecticides and occupational contact. Although neonicotinoids were initially considered to have relatively low mammalian toxicity, emerging toxicological evidence suggests the need for caution, particularly regarding chronic low-dose exposure, developmental effects and possible endocrine or neurological outcomes. However, current human evidence remains less conclusive than ecological evidence; therefore, future studies should prioritize bio-monitoring, exposure assessment and epidemiological investigations in highly exposed populations.

Remediation technologies

Remediation of neonicotinoid-contaminated environments requires technology selection based on matrix type, contaminant concentration, cost, scalability and ecological safety. Microbial degradation is attractive because it can transform neonicotinoids under environmentally compatible conditions, but its field performance depends on microbial survival, soil chemistry, moisture, temperature and the toxicity of transformation products. Advanced oxidation processes and adsorption-based approaches may be more suitable for water treatment, while phytoremediation and microbial-assisted remediation may be more applicable to contaminated agricultural soils. Future remediation studies should therefore evaluate not only removal efficiency but also metabolite toxicity, field stability and cost-effectiveness.

Research gaps and future directions

Neonicotinoid insecticides remain important pest-control tools, but their persistence, systemic behaviour and mobility across environmental compartments have created significant ecological concerns. Evidence reviewed in this manuscript shows that neonicotinoids can contaminate soil, surface water, groundwater, pollen and nectar, with adverse implications for aquatic invertebrates, pollinators, birds and wider ecosystem functioning. Although human-health evidence is still developing, potential exposure through food, water and occupational pathways warrants continued monitoring. Remediation technologies such as microbial degradation, phytoremediation, adsorption and advanced oxidation show promise, but most require further validation under realistic field conditions. Future management should prioritize integrated pest management, reduced prophylactic use, environmental monitoring, compound-specific risk assessment and development of safer alternatives.

Conclusion

The environmental persistence, mobility and biological activity of neonicotinoids indicate that their use requires careful risk management rather than simplistic elimination. Regulatory decisions should be guided by compound-specific toxicity, environmental persistence, exposure pathways, availability of safer alternatives and the agronomic need for pest control. Sustainable mitigation should combine reduced reliance on prophylactic use, integrated pest management, improved application practices and remediation of contaminated sites where necessary.

Declaration of competing interests

The authors declare no conflicts of interests in the present study.

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