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Neonicotinoid Insecticides: Chemistry, Mode of Action, Uses, Environmental Fate and Ecological Consequences

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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Abstract

Neonicotinoids are systemic, nicotine-derived insecticides that act primarily as agonists of insect nicotinic acetylcholine receptors. Their selective activity against insect pests, broad-spectrum efficacy and versatility in seed, soil, foliar and trunk-injection applications have supported extensive use in agriculture, veterinary ectoparasite control and structural pest management. This review examines their chemistry and structural classification, mode of action, field applications, physicochemical behaviour, environmental fate, ecological consequences and available remediation approaches. The properties that support systemic movement, particularly high water solubility, relatively low soil sorption and persistence, also promote movement from treated sites into soil, groundwater, surface water and plant tissues. Evidence summarised in the manuscript indicates risks to non-target organisms, including pollinators, aquatic invertebrates, earthworms and birds, together with the potential for dietary and environmental exposure in mammals. Residue persistence varies markedly among compounds, soil conditions, plant species and methods of application, while repeated use can extend environmental exposure. Current remediation approaches include physicochemical treatment, microbial remediation and phytoremediation, although each has practical limitations related to cost, efficiency, treatment duration or secondary impacts. Overall, the reviewed evidence indicates that

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effective neonicotinoid pest management requires careful regulation, judicious application and integration with preventive and ecologically compatible pest-management strategies to reduce off-target contamination while retaining necessary crop-protection benefits.

Keywords: Neonicotinoids; nicotinic acetylcholine receptor; environmental fate; sorption-leaching; ecotoxicology; pollinator; decline; remediation.

1. Introduction

Chemical pesticides have substantially supported global agricultural productivity by protecting crops from weeds, insects, pathogens and rodents. Used appropriately, they remain an essential input for food security; however, their extensive and often indiscriminate use has resulted in soil and water pollution, harm to non-target organisms, and residue accumulation across the food chain (FAO, 2022).

The consumption pattern of pesticides in India diverges from the global trend. Insecticides account for the largest share of pesticide use in India (61.11 per cent), followed by herbicides (22.22 per cent) and fungicides (11.11 per cent), whereas globally herbicides dominate (52 per cent), followed by fungicides (23 per cent) and insecticides (18 per cent) (FAO, 2021). India, despite contributing only about 1 per cent of global pesticide use and applying a comparatively low 0.24 kg ha^{-1} in 2023 (FAO, 2023) - far below Brazil (12.63), Japan (10.61), the USA (2.78) and China (1.78 kg ha^{-1}) - continues to report elevated pesticide residues owing to unregulated and disproportionate usage patterns. Among the top ten pesticides used in the country, chlorpyrifos leads with 26 % share, followed by cypermethrin and malathion (11% each), quinalphos and fipronil (9% each), profenofos and monocrotophos (8 per cent each), and lambda-cyhalothrin, imidacloprid and thiamethoxam (6% each) (DPPQS, 2025). The prominence of imidacloprid and thiamethoxam - both neonicotinoids - in this list underscores their widespread field use despite growing environmental concern. Recent studies address imidacloprid efficacy and dissipation, non-target effects and associated environmental risks (Thodusu et al., 2024; Yasodha, 2024; Cao et al., 2024; Mandal et al., 2025; Li et al., 2025). This evidence remains dispersed across use, fate, toxicity and remediation. This review integrates these dimensions to frame safer-use and mitigation directions.

2. Neonicotinoids: Classification and Chemistry

2.1 History

Pest management through the mid-twentieth century relied heavily on organochlorines (e.g., DDT) and organophosphates, both later restricted owing to environmental persistence, mammalian toxicity, and rapidly developing pest resistance. Neonicotinoids emerged as an alternative offering greater target specificity, lower vertebrate toxicity and systemic action. Nithiazine, synthesised by Shell in the 1970s, was the first neonicotinoid-type compound but suffered from poor photostability, limiting field use; however, it served as the lead structure for later commercial compounds. Imidacloprid, introduced by Bayer in 1991, was the first commercially successful neonicotinoid, followed by nitenpyram (Sumitomo, 1995), acetamiprid (Nippon Soda, 1995), thiamethoxam (Syngenta, 1998), thiacloprid (Bayer, 2000), clothianidin (Bayer, 2001) and dinotefuran (Mitsui Chemicals, 2002) (Bass *et al.,* 2015). By 2014, neonicotinoids accounted for over 25 per cent of global insecticide sales, with imidacloprid, thiamethoxam and clothianidin together comprising nearly 85 per cent of neonicotinoid sales in crop protection as of 2012.

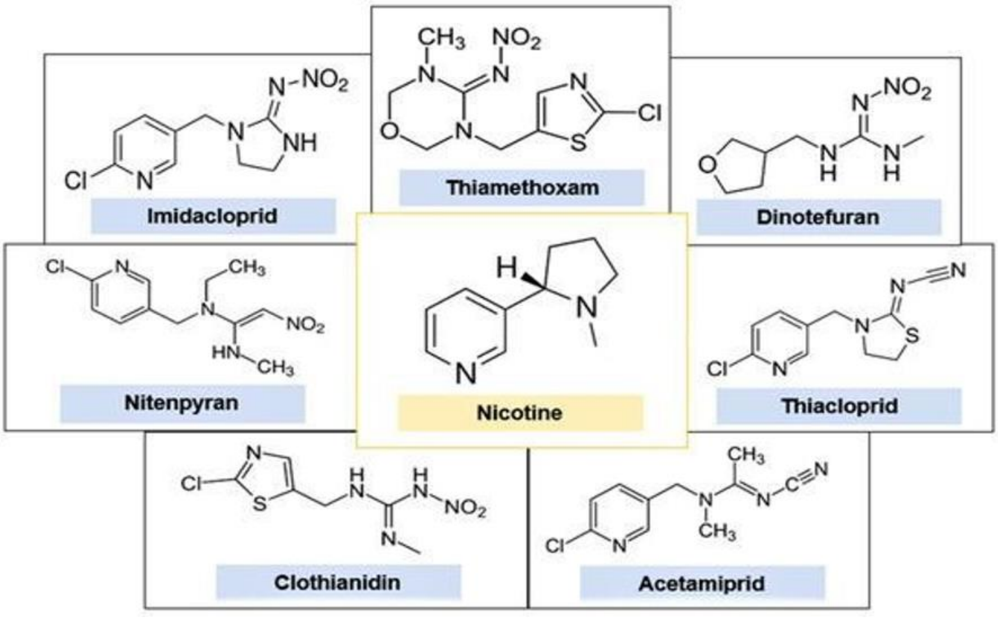

Fig. 1. Chemical structures of nicotine and neonicotinoid insecticides. (Costas-Ferreira Ferreira & Faro, 2021)

2.2 Chemistry and Structural Classification

Neonicotinoids are synthetic analogues of nicotine, engineered for selective affinity towards insect nAChRs over vertebrate receptors. Structurally, they comprise three key elements: a chloropyridinyl, chlorothiazolyl, or tetrahydrofuryl group (X), a heterocyclic or acyclic spacer (Y), and an electronegative moiety (Z) (Seifert, 2014). Based on this framework, neonicotinoids are classified into three chemical generations:

• Chloropyridinyl compounds / chloronicotinyls (first generation): imidacloprid, nitenpyram, acetamiprid, thiacloprid
• Chlorothiazolyl compounds / thianicotinyls (second generation): thiamethoxam, clothianidin
• Tetrahydrofuryl compounds / tefurylnicotinyls (third generation): dinotefuran

The second generation arose from combining the heterocycle 2-chloro-5-methylthiazole with a 4-nitroimino-N-5-methyl-1- oxa-3,5-diazine spacer, while the third generation replaced the chloropyridine/chlorothiazole ring with a (±)-tetrahydro-3- furylmethyl (furanicotinyl) moiety, yielding dinotefuran (Bhattacherjee *et al.,* 2020).

3. Mode of Action

Nicotinic acetylcholine receptors (nAChRs) are ligand-gated ion channels (Na^+, K^+, Ca^{2+}) located on postsynaptic neurons that mediate nerve impulse transmission in response to acetylcholine (ACh) binding. Neonicotinoids act as nAChR agonists, mimicking ACh but resisting hydrolysis by acetylcholinesterase (AChE) in contrast to organophosphates and carbamates, which act by inhibiting AChE. Persistent receptor activation by neonicotinoids blocks normal impulse transmission, causing ACh accumulation, hyperexcitation, convulsions, paralysis and eventual death of the insect (Anadón et al., 2020). Their selectivity for insects over mammals arises from structural distinctions in receptor binding: neonicotinoids are uncharged and carry an electronegative nitro or cyano pharmacophore that binds a unique cationic subsite on insect receptors, whereas nicotine (protonated) binds vertebrate receptors via a cation-π interaction (Kundoo *et al.,* 2018). Additionally, structural and functional differences between insect and mammalian nAChR subunits contribute to insect selectivity; in vertebrates, neonicotinoids show preferential, though limited, affinity for the brain receptor subtypes $\alpha4\beta2$ and $\alpha7$, with minimal activity at peripheral nAChRs (Gupta *et al.,* 2019).

4. Efficacy and Field Applications

4.1 Efficacy

Neonicotinoid insecticides are among the most effective chemical classes used for the management of a wide range of sucking insect pests, including aphids, whiteflies, leafhoppers, planthoppers and thrips, as well as certain microlepidopteran and coleopteran pests. They are also used for the control of ectoparasites in companion animals and cattle, in addition to household and public health pests such as cockroaches, houseflies and termites. Their broad spectrum of activity, combined with their ability to selectively target insect nicotinic acetylcholine receptors (nAChRs), systemic action in plants, prolonged efficacy and diverse application methods, has contributed substantially to the widespread adoption and success of this insecticide group (Elbert et al., 2008).

Neonicotinoids show strong acute and residual efficacy against piercing-sucking pests like aphids, whiteflies, leafhoppers, planthoppers, thrips, mites, leaf miners as well as certain microlepidoptera and coleopterans, across vegetables, fruit crops, rice, cotton, corn, canola, potato, sugar beet, oilseed rape and soybean. A major characteristic responsible for the effectiveness of neonicotinoids is their systemicity in plants. When applied to soil or used as seed treatments, these compounds are absorbed through the roots and subsequently translocated throughout the plant, providing sustained protection against sucking pests. Following foliar application, neonicotinoids can penetrate the leaf tissues and exhibit translaminar activity, enabling them to control pests feeding on the underside of leaves. In addition, their acropetal movement through the xylem allows them to reach newly developing plant tissues and shoots, thereby extending protection to emerging growth (Elbert et al., 2008). They are also effective against selected chewing and soil-dwelling insects, including beetles, wireworms and other coleopteran pests.

Different neonicotinoids have been developed for specific crop-protection requirements. For example, thiamethoxam has been used as a foliar treatment, soil application and seed treatment and has been registered for a wide range of crops including vegetables, potato, rice, cotton, fruits, tobacco and cereals. Acetamiprid has been used in crops such as cotton, vegetables, potato, orchards, vines, citrus, tea and ornamentals, whereas thiacloprid has been employed against both sucking and chewing pests in fruit, cotton, vegetables, oilseed rape, cereals, potato, rice and ornamental crops.

In veterinary medicine, neonicotinoid insecticides are primarily used for the control of ectoparasites, particularly fleas in dogs and cats. Among the neonicotinoids, imidacloprid, nitenpyram and dinotefuran have been used as flea adulticides because of their rapid insecticidal activity and selective action on insect nicotinic acetylcholine receptors. Imidacloprid is widely used as a topical spot-on treatment in dogs and cats, providing rapid and prolonged control of adult fleas; it is also formulated in combination with permethrin for tick and flea control and with moxidectin for the prevention of heartworm disease and control of gastrointestinal nematodes and mites. Nitenpyram is administered orally for rapid, short-term flea control, with fleas beginning to fall from treated animals within approximately 30 minutes, whereas dinotefuran is used as a topical treatment and provides rapid knockdown and residual activity against fleas. Thus, neonicotinoids have become important veterinary ectoparasiticides because of their rapid flea-killing activity and effectiveness in reducing flea- associated problems such as flea-bite allergic dermatitis and flea-transmitted diseases (Vo et al., 2010).

The application of neonicotinoids has extended beyond agriculture into household and professional pest management. Their efficacy against cockroaches, ants and termites has encouraged the development of formulations specifically designed for indoor and structural pest control. Imidacloprid, for example, has been incorporated into bait formulations for cockroach management, while thiamethoxam has been formulated as bait for ant control (Jeschke et al., 2011).

Neonicotinoids are also used for termite management, particularly because their systemic and transfer properties can facilitate exposure of insects that encounter the treated substrates. Imidacloprid has been used for the control of termites such as *Reticulitermes* spp., while neonicotinoid-based formulations have also been investigated for other structural and household pests (Jeschke et al., 2011).

One of the important indirect uses of neonicotinoids in crop protection is the management of insect vectors responsible for transmitting plant viruses. Because compounds such as imidacloprid, thiamethoxam and clothianidin are systemic, they can suppress important vectors such as aphids, whiteflies and other hemipteran insects, thereby reducing secondary spread of plant viruses. For instance, neonicotinoid treatments have been associated with control of aphid-transmitted barley yellow dwarf virus in cereals, beet mild yellow virus in sugar beet, tomato yellow leaf curl virus through whitefly management, and tomato spotted wilt virus through management of thrips. Thus, their importance in plant protection extends beyond direct suppression of insect populations to disease-vector management and reduction of virus transmission (Jeschke et al., 2011).

4.2 Methods of Application

Neonicotinoids are applied via seed treatment (dressing, coating, pelleting), soil application (injection, granules, drip/drench irrigation), foliar spray, and trunk or bud injection in perennial crops. Clothianidin, imidacloprid and thiamethoxam are predominantly used in seed dressings, while thiacloprid and acetamiprid are mainly applied as sprays; thiamethoxam, clothianidin and imidacloprid can also be sprayed. Imidacloprid (Confidor, Admire, Gaucho) is registered for over 140 crop uses in more than 120 countries, acetamiprid (Mospilan, Assail, Chipco, Tristar) is used on cotton, vegetables, potatoes, vines, citrus, tea and ornamentals, as well as in termite and household control, thiamethoxam (Actara, Platinum, Cruiser) covers 115 crop uses in at least 65 countries, thiacloprid (Calypso) targets sucking and chewing pests on fruit, cotton, vegetables, oilseed rape, cereals, potatoes, rice and ornamentals, clothianidin (Poncho, Dantotsu, Dantop) is active against Coleoptera, Diptera, Hemiptera and select Lepidoptera, and dinotefuran (Safari, Venom) is applied on ornamentals, fruit, cotton, potatoes and vegetables. Approximately 60 per cent of current neonicotinoid use is through soil or seed application, with the remainder applied as sprays, reflecting their high water solubility, which facilitates rapid root and foliar uptake and systemic translocation (Kundoo *et al.,* 2018).

A major factor contributing to the success of neonicotinoids is their versatility in application. Unlike many conventional contact insecticides that depend largely on direct deposition on the target insect, systemic neonicotinoids can be introduced into plants through several routes. The major application methods include foliar spraying, seed treatment, soil application, soil drenching, chemigation and, for woody plants, trunk injection (Thompson *et al.*, 2020).

Foliar spraying is one of the conventional methods of applying neonicotinoids. After deposition on leaves, the active ingredient can penetrate the leaf cuticle and move within the leaf tissues. Their translaminar activity enables control of pests feeding on the lower surface of leaves, while systemic and acropetal movement can provide protection to newly developing tissues. Formulation technologies have further improved leaf spreading, penetration and rainfastness of foliar-applied neonicotinoids (Jeschke et al., 2011).

Soil application is particularly important for systemic neonicotinoids because the active ingredient can be absorbed by plant roots and subsequently transported through the vascular system. Soil drenching and soil injection are useful where foliar application is difficult or where prolonged systemic protection is desired. The supplied review identifies soil application as one of the major application techniques contributing to the success of neonicotinoids. Soil application may also be delivered through irrigation or chemigation systems, including drip irrigation and drench systems. Such approaches have been used in vegetables and tobacco seedlings and can provide prolonged protection against aphids and whiteflies (Jeschke et al., 2011).

Seed treatment is one of the most important and distinctive uses of neonicotinoids. Treating seeds with a systemic insecticide places the active ingredient close to the emerging root system, allowing it to be absorbed during germination and subsequently transported into developing plant tissues. This provides protection during early crop establishment against both above-ground and soil-associated pests. Neonicotinoids such as thiamethoxam and clothianidin have been extensively associated with seed-treatment applications. The supplied review identifies seed treatment and soil application as particularly important application routes, with approximately 60% of neonicotinoid applications reported in the reviewed period being associated with soil or seed treatments (Jeschke et al., 2011).

Trunk injection represents a more targeted method of delivering systemic insecticides to woody plants. In this technique, the insecticide is introduced directly into the trunk or vascular system, allowing subsequent movement through the xylem to foliage and other plant tissues. Imidacloprid has been used through trunk injection for management of tree pests, including the emerald ash borer, while thiamethoxam and other systemic insecticides have also been investigated for tree- pest management (Berger & Laurent, 2019). Compared with foliar spraying or soil application, trunk injection can reduce spray drift and provide more direct delivery into the plant vascular system. It has therefore been considered particularly useful for high-value trees, urban landscapes and situations where conventional spraying is difficult or undesirable (Archer *et al.*, 2022).

The versatility of neonicotinoids also permits their application through irrigation water, drip systems, drenches and basal treatments, depending on the active ingredient and formulation. These approaches exploit the systemic movement of the compounds within plants and can provide prolonged protection while reducing the need for repeated foliar spraying (Jeschke et al., 2011).

Table 1. Dosage of application of neonicotinoid insecticides (DPPQS, 2025)

Chemical	Dosage (a.i./ha)	Formulation type(s)	Waiting period (days)
Imidacloprid	21-63 g/ha	70% WG, 48% FS, 30.5% SC, 17.8% SL, 70% WS, 0.3% GR	3-40
Acetamiprid	10-20 g/ha	20% SP, 25% + Bifenthrin 25% WG, 20% + Chlorantraniliprole 20% WG	3-15
Thiamethoxam	1-300 g/ha (seed & foliar)	30% FS, 70% WS, 25% WG, 75% SG	5-60
Thiacloprid	24-180 g/ha	21.7% SC	5-52
Clothianidin	10-250 g/ha	0.5% GR, 50% WDG	1-76
Dinotefuran	25-250 g/ha	20% SG, 70% WG	7-32
Nitenpyram	1.0 mg/kg (as oral dose for dogs and cats)	50% WDG, 50% WP,10% SL, 20% SL, SL 10%, SL 25%	1-2

5. Physicochemical Properties and Environmental Fate

5.1 Properties Governing Persistence and Mobility

Neonicotinoids are characterised by systemic transport, high persistence, high water solubility, high leaching potential, low soil sorption affinity, and low volatility. Solubility ranges widely, from 184 mg L^{-1} (thiacloprid) to 570,000 mg L^{-1} (nitenpyram), with clothianidin, imidacloprid and thiamethoxam at 327, 610 and 4,100 mg L^{-1} respectively (PPDB, 2025). Soil half-lives range from about 1 day to nearly 4 years depending on conditions, and residues can accumulate in soil following repeated use. Low vapour pressures (1.3×10^{-7} to 0.001 mPa at 25°C) indicate limited volatilisation potential (Bonmatin *et al.*, 2015).

Leaching potential, expressed through the Ground Ubiquity Score (GUS), is high for dinotefuran (4.85) and clothianidin (3.74), and elevated for imidacloprid (3.69) and thiamethoxam (3.58); acetamiprid and thiacloprid degrade more readily, lowering their leaching risk. All three of the most widely used agricultural neonicotinoids (imidacloprid, clothianidin, thiamethoxam) exceed a GUS index of 3.5, and their low soil sorption coefficients reflect greater potential for mobility within the soil profile (PPDB, 2025).

5.2 Physicochemical Processes Governing Behaviour

Pesticide fate in the environment is governed by the interplay of sorption, desorption, degradation, volatilisation and leaching. Sorption to soil particles and organic matter regulates mobility and bioavailability; compounds with higher sorption coefficients show reduced leaching, while weakly sorbed compounds are more prone to groundwater contamination. Degradation proceeds via abiotic pathways (hydrolysis, photolysis, oxidation) and microbial biotransformation, the latter capable of mineralising residues to CO_2, water and biomass. Volatilisation, influenced by vapour pressure, temperature, moisture and wind, contributes to atmospheric dispersion and off-target drift, while leaching, the vertical movement of pesticides through the soil profile, is a major driver of groundwater contamination risk, particularly for highly soluble, weakly sorbed compounds (Agnihotri, 2023).

5.3 Fate in the Soil-Water System

Pesticides enter aquatic environments primarily through agricultural and urban activity, with secondary inputs from wastewater treatment plant effluent and sludge, atmospheric deposition, and drainage. Pathways include surface runoff, leaching through drainage systems, spray/dust drift and subsequent wet/dry deposition, volatilisation during application, and seepage into groundwater and surface water, with groundwater, surface water, plants and, ultimately, humans as key receptors.

Comparative sorption mobility studies illustrate substantial variation among neonicotinoids and soil types. Aseperi *et al.* (2020), studying four neonicotinoids across contrasting UK soils, found thiamethoxam the least sorbed and thiacloprid the most sorbed (up to 186 fold greater adsorption), with organic matter content strongly influencing sorption. Column leaching confirmed a high groundwater contamination risk from thiamethoxam, particularly in low organic matter soils. Majee and Reddy (2024), examining imidacloprid sorption in Deccan plateau soils, reported a two-stage kinetic process (rapid uptake within 3 h, equilibrium by 16 h), with adsorption capacity strongly correlated to clay content, cation exchange capacity and specific surface area; black cotton soils retained imidacloprid far more strongly than red soil. Banerjee *et al.* (2008), working with thiamethoxam across sandy-loam, clay and silty-clay Indian soils, found adsorption driven mainly by organic carbon and clay content, with silty-clay soil releasing over 90 per cent of adsorbed residues on desorption, indicating largely reversible, moderately mobile behaviour.

Persistence studies further highlight the influence of moisture and pH. Singh (2013) reported clothianidin half-lives in water ranging from 237.6 days (pH 9.2) to 367.0 days (pH 4.0), confirming high aquatic persistence. Gupta and Gajbhiye (2007) found acetamiprid dissipated fastest under field capacity and submerged conditions (half-lives 15.7-17.4 and 19.2- 29.8 days, respectively) but persisted markedly longer under air dry conditions (<40 per cent dissipation by day 60), consistent with reduced microbial activity under low soil moisture.

Table 2. Properties and environmental persistence of major neonicotinoids (PPDB, 2025)

Neonicotinoids	Vapour pressure (mPa, 20°C)	Water solubility (mg/L, 20°C)	Log Kow	Log Koc	Log Kd	Soil DT50 (days)	Water-sediment DT50 (days)	Water photolysis DT50 (days)	Water hydrolysis DT50 (days)
IMI	4.0×10^{-7}	610	0.57	2.19-2.90	1.20	191 (104-228)	30-129 (stable)	< 1; 0.2 (fast)	365 (stable)
THM	6.6×10^{-7}	4100	−0.13	1.75	0.37	50 (7-72)	31-40 (stable)	2.7-39.5 (mod. fast)	11.5 (stable)
CLO	1.3×10^{-7}	340	0.91	2.08	1.20	545 (13-1386)	40-56 (stable)	< 1; 0.1 (fast)	14.4 (stable)
ACE	1.0×10^{-3}	2950	0.80	2.3	1.32	3 (2-20)	4.7 (mod. fast)	34 (stable)	420 (stable)
THA	3.0×10^{-7}	184	1.26	3.67	1.45	15.5 (9-27)	8-28 (stable)	10-63 (stable)	n/a (stable)

5.4 Persistence in Plant Systems

The persistence of neonicotinoid residues in plants varies considerably, ranging from rapid dissipation within a few weeks to prolonged retention over several years, depending on the active ingredient, mode of application, plant species and tissue characteristics. In general, soil-applied neonicotinoids exhibit greater persistence than those applied to foliage, while woody perennial plants tend to retain residues for longer periods than annual crops. Neonicotinoid residues derived from seed treatments generally exhibit a pronounced decline in annual crop tissues as plants progress from the vegetative to reproductive stages. In corn, clothianidin concentrations decreased by 97.8 –99.3% from the seedling to reproductive stage across different application rates, while imidacloprid concentrations in cotton declined by approximately 99.6% over the corresponding sampling period. Similarly, thiamethoxam and clothianidin residues in cotton leaves declined by 99.9–100% by flowering, with comparable reductions of more than 99% reported in soybean. These findings indicate that residues originating from seed treatments generally decline substantially as annual crops develop, potentially reducing exposure to pollinators during later growth stages (Whalen *et al.*, 2021). In paddy ecosystems, imidacloprid, thiamethoxam and clothianidin showed initial concentrations of 19.3, 9.36 and 52.6 µg g^{-1}, respectively, in plant tissues, followed by dissipation that conformed to first-order kinetics (Liu *et al.*, 2024). In chrysanthemum production systems, neonicotinoids exhibited degradation half-lives of approximately 20–36 days in soil, while leaves and soil represented the major compartments for residue accumulation (Wang, Fu, *et al.*, 2023). These findings demonstrate that dissipation in annual and herbaceous crops can be relatively rapid, although the persistence of residues varies according to the compound, application method, plant species and environmental conditions.

In contrast to annual crops, woody perennial plants can retain neonicotinoid residues for considerably longer periods. Residues have been detected in woody plants for more than one year following a single application, and soil application of imidacloprid to maple trees has been reported to provide pest protection for several years (Bonmatin et al., 2015; Goulson, 2013). In citrus, imidacloprid and thiamethoxam remained at concentrations sufficient for pest suppression for approximately five months following a single application (Goulson, 2013). However, foliar application of imidacloprid to citrus resulted in no quantifiable residues in pollen or nectar one year after treatment, suggesting substantially faster dissipation compared with soil-applied treatments (Martínez-Ferrer, 2019). Persistence can also vary considerably among compounds and delivery methods in woody plants. Dinotefuran residues were detected in nectar at 235–1191 ng g^{-1} following application during summer, indicating prolonged movement and persistence within woody plants (Mach, 2018). In palm endotherapy, imidacloprid remained detectable for up to three months, whereas thiamethoxam was detected only up to 10 days following injection (Chihaoui-Meridja *et al.*, 2020). These observations highlight the importance of plant type, chemical properties and application technique in determining the persistence and dissipation behaviour of neonicotinoids in plant systems. Neonicotinoid persistence in plants is governed by a combination of application technique, plant characteristics, compound-specific physicochemical properties and metabolic transformation. Soil and seed applications generally favour prolonged systemic exposure, whereas foliar applications tend to dissipate more rapidly (Martínez-Ferrer, 2019; Mach, 2018). At the same time, differences among plant species, tissues and individual neonicotinoids can substantially modify residue distribution and persistence (Havers et al., 2024; Wang, Fu, et al., 2023). Importantly, the formation of persistent or biologically active metabolites may extend the period of ecological relevance beyond that indicated by the dissipation of the parent compound alone (Wu et al., 2019; Wang, Fu, et al., 2023).

6. Environmental Consequences

Neonicotinoids were initially regarded as an environmentally favourable alternative to older insecticide classes owing to their low application rates and insect-selective toxicity. However, their high persistence and water solubility, the very traits behind their commercial success, now underlie major environmental concerns, enabling accumulation in ecosystems and contamination of water bodies, including rivers, lakes and temporary water sources. Of the roughly 15,000 registered neonicotinoid products applied across 120+ countries and 450+ crops, only about 5 per cent of applied active ingredient is estimated to reach target pests, with over 90 per cent entering soil and subsequently water and sediment (Anadón *et al.,* 2020).

6.1 Impact on Non-Target Organisms

Neonicotinoids have been strongly implicated in pollinator decline and Colony Collapse Disorder (CCD). Even at sublethal concentrations, they impair foraging efficiency, navigation, olfactory memory and learning in bees, threatening colony survival. This evidence led the European Commission to restrict clothianidin, imidacloprid and thiamethoxam use in 2013, followed by a complete outdoor ban from 30 May 2018, restricting use to permanent greenhouses (Strouhova *et al.,* 2023). Wintermantel *et al.* (2020), analysing nectar from 291 oilseed rape fields in France over five years under the EU moratorium, found imidacloprid residues persisting without decline, with simulation models indicating continued acute and chronic mortality risk to bees, which was attributed to residual soil contamination. In a local study, Boli (2013) evaluated new-generation insecticides against bee pollinators at Trivandrum district of Kerala and found neonicotinoids posed the highest risk, with imidacloprid causing near-total mortality (100 per cent) in *Apis mellifera* and *Trigona iridipennis*, and thiacloprid and clothianidin similarly highly toxic.

Aquatic invertebrates also show marked sensitivity, with Ephemeroptera, Trichoptera and Chironomidae particularly vulnerable, while *Daphnia magna* is comparatively tolerant. Global surface water surveys show neonicotinoid concentrations frequently exceeding ecological safety thresholds of 0.2 µg L^{-1} (acute) and 0.035 µg L^{-1} (chronic), impairing survival, growth, emergence and behaviour in sensitive taxa even at or below 1 µg L^{-1} acute / 0.1 µg L^{-1} chronic (Morrissey et al., 2015; Zhang et al., 2020).

Table 3. Acute LC50/LD50 values for non-target organisms exposed to neonicotinoids

Research object	Taxon	LC50 / LD50 (Neonicotinoid)	Reference
Crustaceans	Aquatic organism	0.59 mg L^{-1} (IMI); 0.62 (THC); 0.84 (CLO); 1.27 (ACE); 8.87 (TMX); 37.75 (DIN)	Morrissey *et al.* (2015)
Aquatic insects	Aquatic organism	mg L^{-1} (IMI); 0.03 (THC); 0.03 (CLO); 0.04 (ACE); 0.04 (TMX); 0.23 (DIN)	Morrissey *et al.* (2015)
Fish	Aquatic organism	1.2-241 mg L^{-1} (IMI); 93.6 mg L^{-1} (CLO)	Gibbons *et al.* (2015)
Bees	Non-target insect	Oral 3.7, contact 81 ng/bee (IMI); oral 5, contact 24 ng/bee (TMX); oral 3.8, contact 28 ng/bee (CLO)	EFSA (2013a, 2013b,2013c)
Mallards	Birds	283 mg kg^{-1} (IMI); 98 (ACE); 576 (TMX); 752 (CLO)	Mineau and Palmer (2013)
Rats	Mammals	Oral 450 (IMI); 182 (ACE); 1563 (TMX); 5000 (CLO); 640 (THC); 2400 mg kg^{-1} (DIN)	Sheets *et al.* (2016)

6.2 Soil Contamination

Neonicotinoids enter soils through seed dressings, drenches, irrigation and incorporation of treated crop residues, persisting for over 2.5 years in some cases and interacting with soil biota across macro-, meso- and micro-scales, with potential to degrade soil health and function (Potts *et al.,* 2023). Alves *et al.* (2013), assessing three seed treatment insecticides and two fungicides on the earthworm *Eisenia andrei*, found imidacloprid the only compound causing acute mortality (LC_{50} = 25.53 mg kg^{-1}), while all compounds impaired reproduction, with imidacloprid most toxic (EC_{50} = 4.07 mg kg^{-1}) and its chronic LOEC (0.75 mg kg^{-1}) close to predicted environmental concentrations, indicating substantial ecological risk to soil invertebrates.

Ge et al. (2018), who evaluated the avoidance behaviour of earthworms (*Eisenia fetida*) against six neonicotinoids (NEOs) (acetamiprid, dinotefuran, clothianidin, thiacloprid, nitenpyram, imidacloprid) demonstrated that neonicotinoid contamination in soil can adversely affect earthworms even at low concentrations. *Eisenia fetida* showed clear avoidance responses, with EC_{50} values of 0.14 -7.87 mg kg^{-1}, indicating that avoidance behaviour was more sensitive than acute toxicity for detecting neonicotinoid-contaminated soils. Chronic exposure also significantly reduced cocoon production and hatchability, with EC_{50} values of 0.37 - 3.57 mg kg^{-1} after 56 days. These findings suggest that environmentally occurring neonicotinoid residues in soil may pose ecological risks to earthworms and soil health.

6.3 Surface Water and Groundwater Contamination

High water solubility and moderate-to-high persistence (up to 545 days for clothianidin) enhance neonicotinoid mobility away from application sites via leaching into groundwater and runoff into surface water. Hladik *et al.* (2014), surveying Iowa streams across an intensive corn-soybean growing region, detected clothianidin in 75 per cent of samples (max. 257 ng L^{-1}), thiamethoxam in 47 per cent (max. 185 ng L^{-1}) and imidacloprid in 23 per cent (max. 42.7 ng L^{-1}), with concentrations peaking during planting season and detections persisting even before new applications, indicating residue contamination. While generally below acute benchmarks, many detections exceeded proposed chronic thresholds for aquatic invertebrates.

Studies from different regions have confirmed the widespread occurrence of neonicotinoids in surface waters. In the Pearl River, China, concentrations ranged from 92.6–321 ng L^{-1}, with imidacloprid, thiamethoxam and acetamiprid detected in all samples (Yi *et al*., 2019). In the central Yangtze River, imidacloprid showed the highest median concentration (4.37 ng L^{-1}) (Mahai *et al*., 2019). Similarly, rivers around Sydney, Australia, had multiple neonicotinoids in 93% of samples, with concentrations ranging from 0.06 - 4.5 µg L^{-1} (Sánchez-Bayo & Hyne, 2014). Globally, imidacloprid was the most frequently detected neonicotinoid, with a mean concentration of 119.5 ng L^{-1}, followed by nitenpyram (88.1 ng L^{-1}) and thiamethoxam (59.8 ng L^{-1}), highlighting the widespread contamination of aquatic environments by neonicotinoid pesticides (Wang, Yin, et al., 2023).

A global study of 97 bottled water samples from five continents by Chen et al. (2025) detected at least one neonicotinoid in all samples, confirming widespread contamination of drinking water. Total neonicotinoid residues were highest in Asia (62.56 ± 39.56 ng L^{-1}) and were significantly higher in purified bottled water (70.71 ± 42.29 ng L^{-1}) than in natural mineral water (19.15 ± 14.75 ng L^{-1}). Residues were higher during the dry season and positively correlated with pesticide use. Although infants showed the highest estimated exposure (4.28 ± 1.14 ng kg^{-1} day^{-1}), all estimated intakes remained below the reference dose, indicating low but widespread human exposure to neonicotinoids through bottled drinking water.

6.4 Dietary Exposure

Chen *et al.* (2014) found imidacloprid, acetamiprid, thiamethoxam, clothianidin and thiacloprid to be the most frequently detected residues in food commodities, with several samples approaching or exceeding maximum residue limits (Zhang et al., 2024), while average dietary exposure remained within acceptable daily intake for most populations, children and other vulnerable groups face relatively higher cumulative exposure risk. Ikenaka et al. (2019) assessed neonicotinoid exposure among 46 children living in communities where thiacloprid was used for pine wilt disease control. Urine and atmospheric particulate samples collected before, during, and after spraying were analysed by LC–ESI– MS/MS. Thiacloprid was detected in about 30% of urine samples, while N-dm-acetamiprid, thiamethoxam, dinotefuran and clothianidin were also detected. Although the estimated daily intakes were below the acceptable daily intake (ADI) limits, the study confirmed daily exposure to multiple neonicotinoids among children, indicating potential concerns regarding repeated environmental exposure.

6.5 Human Health Risks and Bioaccumulation

Although initially considered low-risk to mammals owing to selective insect receptor affinity, accumulating epidemiological, clinical and experimental evidence indicates that neonicotinoids can pose neurological, reproductive, developmental and endocrine risks in mammals following chronic exposure.

Table 4. Sublethal effects of neonicotinoid insecticides reported in mammalian studies

Classification	Research object	Neonicotinoid (concentration)	Sublethal effect	Reference
Reproductive & developmental toxicity	Developing/adult rats, rabbits	IMI (0.5-45 mg kg^{-1}), CLO (2-32 mg kg^{-1}), ACE (30 mg kg^{-1})	Reproductive system injury, oxidative stress	Bal *et al.* (2012, 2013)
Neurotoxicity	Rats	IMI (20-90 mg kg^{-1}), TMX/CLO (2-5 mmol L^{-1}), TMX (50-1,100 mg kg^{-1})	Reduced locomotor activity, increased anxiety, biochemical alterations	Lonare *et al.* (2014); Bhardwaj *et al.* (2010); Rodrigues *et al.* (2010)
Genotoxicity	Human lymphocytes and other cells	IMI (0.05-0.5 mg L^{-1}), THC (75-480 mg L^{-1}), CLO (20-80 mg kg^{-1}), ACE (4.6 mg kg^{-1})	DNA fragmentation/damage, chromosome aberration	Kocaman *et al.* (2014); Guo *et al.* (2017)
Visceral toxicity	Infant/adult rats, kidney	IMI (4, 15, 20 mg kg^{-1}), TMX (12 mg kg^{-1})	Histopathological changes, biochemical alterations	Ozsahin *et al.* (2014); Arfat *et al.* (2014)

Vohra *et al.* (2014) reported that oral imidacloprid administration (20 mg kg^{-1} day^{-1}) in female albino rats over 60 days caused reduced feed intake, decreased relative heart and spleen weight, and hepatocyte degeneration with central vein congestion, while the lower dose (10 mg kg^{-1} day^{-1}) produced no adverse effect (NOEL). Yang *et al.* (2023) found thiamethoxam bioaccumulated primarily in zebrafish brain tissue, with the highest bioconcentration factor observed at the lowest exposure concentration (0.1 µg L^{-1}), indicating disproportionate uptake even at trace exposure levels.

Individual compound risk profiles vary: imidacloprid combines high soil persistence (DT50 ≈ 191 days) and high leaching potential (GUS 3.69) with extreme bee toxicity (oral LD_{50} 0.0037 µg/bee) and organ-level human health concern; clothianidin shows the longest soil persistence (DT50 545 days) and severe pollinator toxicity; thiamethoxam poses high leachability and extreme bee toxicity alongside possible carcinogenicity concern; thiacloprid is flagged for endocrine- disrupting and suspected carcinogenic potential; and dinotefuran combines high leachability with extreme sensitivity in bees and earthworms (PPDB, 2025).

7. Remediation Technologies

Given that over 90 per cent of applied pesticides do not reach target pests and instead enter soil and water systems, remediation approaches are essential complements to preventive management. Natural attenuation occurs via sorption- desorption, chemical and photodegradation, microbial biodegradation and phytoaccumulation. Engineered remediation strategies fall into three broad categories: physicochemical methods (adsorption, oxidation, advanced oxidation processes), which can achieve complete mineralisation but are often costly, complex, and may generate more toxic intermediates (particularly photocatalysis); microbial remediation, which relies on bacterial, fungal or microalgal biotransformation and is cost-effective with low secondary pollution, though limited by efficiency, which researchers are addressing through microbial consortia combined with physicochemical treatments; and phytoremediation, constrained by contaminated biomass disposal, long treatment duration and comparatively low efficiency (Wei et al., 2023; Zhang et al., 2023).

8. Conclusion

Neonicotinoids have become important tools in pest management because of their systemic action, selective activity against insect nicotinic acetylcholine receptors and flexible application routes. However, the same physicochemical properties that favour uptake and sustained activity can also promote persistence, leaching and movement into non-target environmental compartments. The evidence reviewed in this manuscript shows that residues may occur in soil, surface water, groundwater and plant tissues and may affect pollinators, aquatic invertebrates, earthworms and other non-target organisms. Mammalian studies also indicate the importance of considering repeated and sublethal exposure when evaluating potential health risks. Although physicochemical, microbial and phytoremediation approaches provide options for residue removal, their practical use is constrained by differences in efficiency, cost, treatment duration and possible secondary impacts. Accordingly, risk reduction should prioritise judicious and regulated use, appropriate application methods, protection of sensitive ecosystems and greater integration of neonicotinoids within Integrated Pest Management. Such measures can support necessary pest control while reducing environmental loading and avoidable ecological exposure.

9. Limitations

As a narrative review, this manuscript synthesises findings reported across studies that differ in compounds, formulations, application methods, environmental conditions, exposure durations and test organisms. These differences limit direct comparison among reported persistence, toxicity and residue values. In addition, evidence is uneven across environmental compartments and neonicotinoid compounds, with some agents and exposure pathways represented more extensively than others. Accordingly, the conclusions should be interpreted as an integrated assessment of the reviewed literature rather than as a quantitative estimate of uniform risk across all uses and environments.

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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