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Persistence and distribution of imidacloprid in soil and manure pellet during incubation study

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Abstract

Pesticides behave differently in the environment based on the characteristics of the soil and any organic materials added. Imidacloprid is a common insecticide used in farming to control pests that suck plant juices. However, how long it stays in the soil and other organic materials can affect the environment and how well crops grow. This study looked at how long imidacloprid stays in soil and manure pellets under controlled conditions. The insecticide was tested at different levels and left to sit for up to 120 days. Samples were checked regularly to track how the pesticide breaks down and how much remains in both soil and manure pellets. The results showed that the amount of imidacloprid decreased over time. Manure pellets held onto the pesticide longer than soil because they have more organic material and places where the pesticide can stick. The study also found that organic materials have a big effect on how long pesticides stay around and how available they are. When looking at how the pesticide distributes itself, it was found to spread differently between soil and manure at different concentrations. The study shows that adding organic materials can help control how pesticides move and stay in the environment, which helps reduce pollution. These findings can help with managing pesticides in a more sustainable way and assessing risks to the environment.

Keywords: Imidacloprid, persistence, soil, manure pellet, residue analysis, incubation, pesticide degradation

1. Introduction

The growing need for more agricultural output has led to heavy use of pesticides to control insect pests, diseases, and weeds. Among the different types of insecticides, neonicotinoids have become very important because they work throughout the plant, are effective against a wide range of pests, and are less harmful to mammals. Imidacloprid, the first successful neonicotinoid, is widely used in many crops to fight pests like aphids, whiteflies, leafhoppers, jassids, and termites. Because it moves through the plant, imidacloprid stays active for a long time and offers good protection against these pests.

Imidacloprid works by attaching to receptors in the insect's nervous system, stopping the transmission of nerve signals and eventually causing the insect to become paralyzed and die. Its effectiveness even at low doses and compatibility with integrated pest management make it one of the most commonly used insecticides globally. However, its widespread use has sparked concerns about how long it stays in the environment and its effects on non-target organisms such as soil microbes, pollinators, aquatic life, and other beneficial insects. How imidacloprid moves through the environment depends on various physical, chemical, and biological processes in the soil. After application, it can stick to soil particles, break down, evaporate, move with water, be washed away, or be taken up by plants. The way these processes happen is influenced by factors like soil type, pH, organic content, moisture, temperature, and the presence of microbes. Therefore, understanding how imidacloprid behaves in different environments is vital for assessing its ecological impact and creating better ways to manage its use.

Soil organic matter plays a big role in how pesticides move and break down in the soil. It has various chemical groups that can attach to pesticide molecules, affecting their movement, how easily they can be used by organisms, how long they last, and how they break down. Higher levels of organic carbon usually help the soil hold on to pesticides, reducing their

movement and the chance of them entering water sources. However, strong binding can also slow down the breakdown of pesticides by microbes, making them stay longer in the soil. Organic amendments like farmyard manure, compost, vermicompost, and manure pellets are widely used in sustainable farming to improve soil health and structure. These materials add organic matter and support the growth of microbes. Earlier studies have shown that these amendments can change how pesticides are absorbed and break down in the soil by altering its chemical properties and microbial activity.

Manure pellets, in particular, have high organic content and porous structures that might help them absorb pesticides effectively. Way imidacloprid interacts with organic amendments is an important area of study because manure-based materials can act as temporary storage for pesticides, controlling their availability and movement. While better absorption can reduce the chance of pesticides moving into groundwater, it might also make the pesticides stay longer in the soil. Therefore, studying how imidacloprid distributes itself between soil and manure is key to understanding its environmental behavior and long-term effects. Research has shown that imidacloprid's persistence in the environment varies with different conditions. Its half-life ranges from a few weeks to several months, depending on soil type, weather, microbial activity, and farming practices. However, there is not much information on how imidacloprid behaves in manure pellets or how it spreads between soil and organic materials under controlled conditions. This information is crucial for making pesticide use more efficient and reducing environmental harm. For this reason, the current study was conducted to examine how long imidacloprid lasts, how much it stays in the soil and manure pellets, and how it moves between these materials under controlled conditions. The goal is to better understand the role of organic amendments in controlling pesticide behavior and to develop more sustainable practices for pesticide use.

2. Review of Literature

2.1 Imidacloprid and its Environmental Significance

Imidacloprid is a type of insecticide called a neonicotinoid, developed by Bayer in the early 1990s. It has become one of the most widely used insecticides globally because it works well against a range of insect pests that feed by sucking or piercing. The insecticide works by attaching to nerve receptors in the insects, which causes them to become paralyzed and eventually die. Because it is systemic, imidacloprid can be taken up by the roots of plants and move throughout the plant, offering long-term protection from pests. While it is useful for farming, there are worries about how long it stays in the environment and its effects on other living things like bees, soil creatures, water organisms, and helpful microbes. Recent research has found imidacloprid in soil, water, and crops, showing how important it is to keep monitoring its presence (Kathuria *et al.*, 2023; Akter *et al.*, 2023; Yang *et al.*, 2025) [10, 3, 24].

2.2 Persistence of Imidacloprid in Soil

How long imidacloprid stays in soil has been studied a lot because it can remain active for a long time and pose risks to the environment. Studies have found that the speed at which imidacloprid breaks down depends on several factors, including the type of soil, temperature, moisture, and the

presence of microbes. The time it takes for imidacloprid to reduce by half, known as the half-life, can vary from about 30 days to more than 200 days depending on these factors. Soils with high clay content and more organic matter tend to hold imidacloprid better, slowing its breakdown and movement. On the other hand, sandy soils with less organic matter tend to break down imidacloprid more quickly. Research has shown that environmental conditions strongly affect how long imidacloprid stays in agricultural soil (Sharma *et al.*, 2023; Majee and Reddy, 2024) [17, 13].

2.3 Influence of Organic Matter

The amount of organic matter in soil plays a big role in how imidacloprid behaves in the environment. Organic carbon in the soil helps hold pesticide molecules, making them less likely to move through the soil or end up in groundwater. Adding organic materials like manure, compost, worm castings, or crop leftovers can increase how much imidacloprid is held in the soil, reducing the risk of it spreading. Organic matter also improves soil structure and supports microbial life, which can help break down pesticides more effectively. Studies have found that soils with added compost retain more imidacloprid compared to those without, highlighting the effect of organic matter on how long the pesticide stays in the environment (Mahapatra and Adak, 2025; Majee and Reddy, 2024) [12, 13].

2.4 Role of Microorganisms

Microbes in the soil are important in breaking down imidacloprid. Many soil bacteria and fungi are able to use pesticide molecules as a source of energy and nutrients, leading to their breakdown and reducing their harmful effects. Some bacteria, like members of the genera *Bacillus*, *Pseudomonas*, *Rhizobium*, *Rhodococcus*, and *Burkholderia*, are especially good at degrading imidacloprid. Fungi also help by changing the chemical structure of the pesticide through enzyme activity. However, how fast the microbes break down the pesticide depends on conditions like temperature, moisture, and the availability of nutrients. Recent studies suggest that using microbes to help remove pesticide residues from polluted areas could be a useful strategy. But too much pesticide can harm soil microbes, affecting their diversity and their ability to support healthy soil systems (Randhawa, 2024; Akter *et al.*, 2023; Philippot *et al.*, 2024) [16, 3, 13].

2.5 Distribution between Soil and Organic Amendments

How imidacloprid moves between soil and organic materials like manure, compost, and crop leftovers is important for understanding its environmental impact. These organic materials can act as temporary storage for pesticide molecules, holding them in place and reducing their chance of moving into groundwater. The way imidacloprid interacts with these materials affects how available it is for microbes to break it down and how long it stays in the environment. Studies show that organic amendments can both hold pesticides longer and help microbes break them down more efficiently by supporting microbial activity and providing nutrients. Understanding how imidacloprid moves between soil and organic materials is crucial for creating better ways to manage pesticides and prevent environmental contamination (Mahapatra and Adak, 2025; Randhawa, 2024; Sharma *et al.*, 2023) [12, 16, 17].

3. Materials and Methods

3.1 Experimental Site

The study was carried out in the Soil Science Laboratory at PGP College of Agricultural Sciences, Namakkal, Tamil Nadu, India, during the academic year 2025-2026. The research was done in a controlled lab setting to check how long imidacloprid residues stay in soil and manure pellets. The lab environment was kept stable with consistent temperature and moisture levels throughout the incubation period.

3.2 Collection and Preparation of Samples

Surface soil samples (from 0 to 15 cm depth) were collected from the experimental farm at PGP College of Agricultural Sciences, Namakkal. The soil was air-dried in the shade, then gently crushed using a wooden mallet and passed through a 2 mm sieve to remove any stones, plant parts, or other unwanted materials. The soil was mixed well and stored in clean polyethylene containers until it was needed for the experiment. Manure pellets were made from well-decomposed organic materials taken from local farmyard manure and composted waste. The organic materials were dried, ground into a fine powder, mixed evenly, and then formed into pellets using a pellet-making machine. The pellets were then dried in the shade and stored under lab conditions until the experiment started.

3.3 Experimental Design

The experiment involved incubating soil and manure pellets with imidacloprid. The treatments were arranged in a Completely Randomized Design with several replications. Imidacloprid was applied at the recommended dosage, and its residue levels were checked at set intervals during the incubation. Untreated samples were used as controls for comparison. Samples from each treatment were collected regularly to measure residue levels and track how the pesticide broke down. This setup allowed for the evaluation of imidacloprid's longevity under different conditions.

3.4 Incubation Study

A laboratory-based incubation study was carried out by placing a known amount of soil and manure pellets into separate containers. Imidacloprid was evenly applied to the

containers and mixed thoroughly to ensure even distribution. The moisture level was kept around 60% of the field capacity by adding distilled water as needed. The containers were kept at a temperature of 25 ± 2 °C. Samples were collected at fixed time intervals, such as 0, 15, 30, 45, 60, and 90 days after the pesticide was applied, to monitor how long the residue lasted and how it degraded. The collected samples were stored properly until they were tested for residues.

3.5 Residue Extraction and Analysis

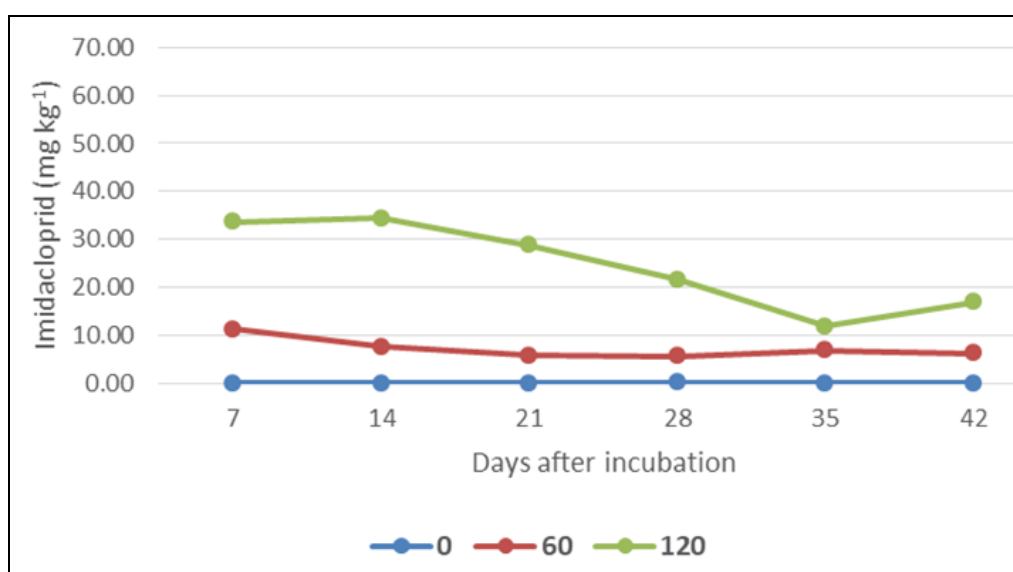
Imidacloprid residues were extracted from soil and manure pellet samples using standard solvent extraction methods. A specific amount of sample was weighed and extracted with organic solvents like acetonitrile following standard analytical procedures. The extracts were then filtered and cleaned to remove any interfering substances. The amount of imidacloprid was measured using High Performance Liquid Chromatography (HPLC) depending on what equipment was available. Standard solutions of pure imidacloprid were made, and the concentration in the samples was calculated by comparing the peak areas from the sample and the standard. The percentage of imidacloprid that degraded was calculated using the following formula: $\text{Degradation (\%)} = \frac{(\text{Initial residue} - \text{Residual residue})}{\text{Initial residue}} \times 100$. The half-life (DT50) of imidacloprid was calculated based on first-order kinetics.

3.6 Statistical Analysis

The data from the residue analysis were statistically analyzed using Analysis of Variance (ANOVA), which is suitable for a Completely Randomized Design. Treatment averages were compared using the Least Significant Difference (LSD) test at a 5% significance level. All statistical analyses were done using standard software, and the impact of different treatments on imidacloprid persistence and degradation was assessed using standard statistical techniques.

4. Results

4.1 Persistence of Imidacloprid in Soil During Incubation



Residue of imidacloprid in soil

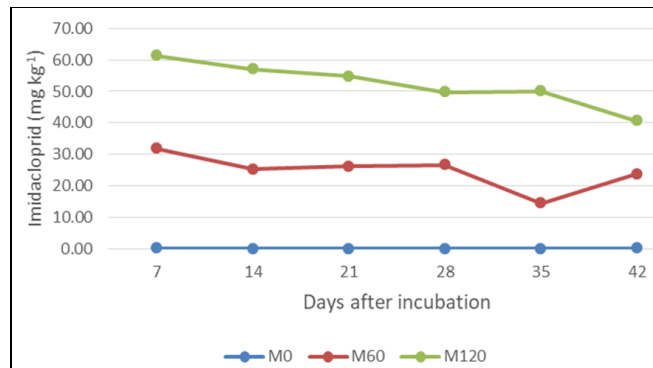
The persistence of imidacloprid in soil was monitored over the incubation period. A gradual decline in residue concentration was observed with increasing incubation duration. The highest concentration was recorded immediately after application, followed by a progressive reduction throughout the study period. This decline may be attributed to a combination of microbial degradation, chemical hydrolysis, adsorption-desorption processes, and transformation into metabolites.

The dissipation pattern indicates that imidacloprid undergoes continuous degradation under incubation conditions. Soil microorganisms play a major role in pesticide degradation by utilizing pesticide molecules as sources of carbon and energy. Increased microbial activity during incubation accelerates pesticide transformation and mineralization.

The observed reduction in residue concentration is consistent with previous findings that reported gradual degradation of imidacloprid in agricultural soils. According to Cox (2001) [5], imidacloprid persistence varies depending on environmental conditions, with degradation being influenced by temperature, moisture content, and microbial population. Similarly, Bonmatin *et al.* (2015) [4] reported that imidacloprid residues decline progressively due to biological and physicochemical processes occurring within soil systems.

The present findings suggest that although imidacloprid exhibits moderate persistence, continuous degradation occurs under favorable incubation conditions, thereby reducing environmental accumulation over time.

4.2 Retention of Imidacloprid in Manure Pellets



Retention of imidacloprid in Manure Pellet

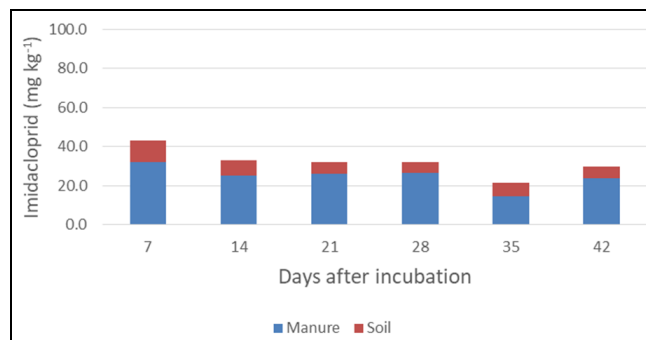
The retention study revealed that manure pellets retained greater amounts of imidacloprid throughout the incubation period compared with soil. Although residue concentrations gradually declined with time, the rate of decline was slower in manure pellets. This indicates that organic substrates possess a stronger capacity to adsorb pesticide molecules.

The enhanced retention observed in manure pellets may be attributed to their high organic carbon content and porous structure. Organic matter contains numerous functional groups capable of binding pesticide molecules through hydrogen bonding, van der Waals forces, and hydrophobic interactions. Consequently, a substantial portion of the applied imidacloprid remained associated with the manure matrix.

The strong adsorption of pesticides by organic materials has been widely documented. Ahmad *et al.* (2006) [1] reported that increasing organic carbon content significantly

enhanced pesticide adsorption and reduced mobility. Similar findings were reported by Spark and Swift (2002) [19], who observed increased retention of pesticides in organic-amended soils due to stronger sorption mechanisms. The present study demonstrates that manure pellets act as an effective reservoir for imidacloprid, thereby influencing its persistence and availability in agricultural systems.

4.3 Distribution of Imidacloprid at 60 mg kg⁻¹ Level



Distribution at 60 mg / kg level

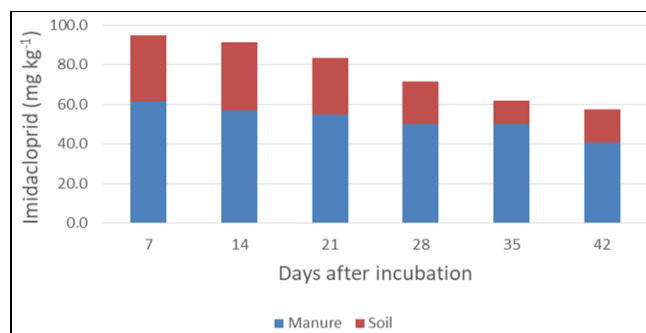
The distribution study conducted at the 60 mg kg⁻¹ application level indicated differential partitioning of imidacloprid between manure pellets and soil. During the initial stages of incubation, a greater proportion of the pesticide was retained within the manure fraction compared with soil.

The higher retention in manure may be attributed to stronger adsorption resulting from elevated organic matter content. As incubation progressed, residue concentrations gradually declined in both fractions due to degradation and transformation processes. However, manure consistently retained higher amounts of imidacloprid throughout the incubation period.

The observed distribution pattern supports the findings of Gupta and Gajbhiye (2007) [8], who reported that organic amendments enhance pesticide adsorption and reduce leaching losses. The strong affinity of imidacloprid toward organic carbon results in preferential accumulation within organic substrates.

These findings suggest that manure amendments can reduce the mobility of imidacloprid and potentially lower groundwater contamination risks.

4.4 Distribution of Imidacloprid at 120 mg kg⁻¹ Level



Distribution at 120 mg / kg level

At the higher application rate of 120 mg kg⁻¹, a similar distribution pattern was observed. Manure pellets retained a greater proportion of imidacloprid than soil throughout the

incubation period. The increased concentration enhanced adsorption opportunities within the organic matrix, resulting in prolonged persistence.

The stronger retention observed at higher application rates may be associated with greater pesticide-organic matter interactions. However, despite higher initial concentrations, progressive dissipation occurred during incubation, indicating active degradation mechanisms.

According to Singh and Singh (2014) [18], pesticide degradation in organic substrates occurs through microbial transformation, enzymatic reactions, and physicochemical breakdown. The results of the present study are consistent with these observations and demonstrate that organic amendments regulate pesticide behavior even under elevated contamination levels.

The findings further indicate that organic amendments may serve as temporary sinks for pesticides, reducing immediate environmental exposure while allowing gradual degradation.

4.5 Mechanisms Influencing Persistence and Distribution

The persistence and distribution of imidacloprid observed in this study were governed by several interacting mechanisms:

1. Adsorption onto organic matter and soil colloids.
2. Microbial degradation and mineralization.
3. Hydrolysis and oxidation reactions.
4. Diffusion within soil and manure matrices.
5. Moisture-mediated transformation processes.

Organic matter was identified as the most influential factor affecting pesticide retention. The manure pellets provided numerous adsorption sites that increased residue persistence while reducing mobility.

Previous investigations by Racke (1993) [15] and Sparks (2019) [20] have emphasized that soil organic matter strongly controls pesticide fate in terrestrial ecosystems. The present findings further confirm that organic amendments significantly influence pesticide persistence and environmental behavior.

5. Discussion

The results clearly demonstrate that imidacloprid persistence decreases with increasing incubation period, while manure pellets enhance residue retention compared with soil. The differential distribution observed between manure and soil fractions highlights the importance of organic matter in controlling pesticide behavior.

The study confirms that organic amendments can modify pesticide adsorption, persistence, and degradation pathways. Increased retention within manure pellets may reduce immediate pesticide mobility and groundwater contamination. However, prolonged retention may also extend the duration of pesticide presence within agricultural systems. Therefore, understanding pesticide-organic matter interactions is essential for developing sustainable pesticide management strategies that maximize pest control efficiency while minimizing environmental risks.

5.1 Persistence of Imidacloprid in Soil

The incubation study revealed a progressive decline in imidacloprid concentration with increasing incubation period. The highest residue levels were observed immediately after application, followed by gradual dissipation over time.

The reduction in residue concentration may be attributed to microbial degradation, adsorption-desorption processes, volatilization, and chemical transformation. Similar observations have been reported by earlier researchers studying neonicotinoid degradation under laboratory conditions.

5.2 Retention of Imidacloprid in Manure Pellets

Manure pellets exhibited greater retention of imidacloprid compared with soil throughout the incubation period. The higher organic carbon content of manure pellets provided additional adsorption sites for pesticide molecules.

The increased retention observed in manure pellets demonstrates the important role of organic matter in regulating pesticide availability and mobility. Organic substrates effectively reduced pesticide movement and enhanced adsorption.

5.3 Distribution of Imidacloprid Between Soil and Manure

The distribution study indicated differential partitioning of imidacloprid between manure pellets and soil. At both concentration levels, manure retained a larger fraction of the applied pesticide during the early stages of incubation.

The preferential retention within manure pellets suggests stronger adsorption mechanisms involving organic functional groups. As incubation progressed, gradual redistribution and degradation contributed to declining residue concentrations.

5.4 Effect of Incubation Period

The incubation period significantly influenced pesticide persistence. Residues consistently decreased from initial application to the final incubation stage.

This reduction reflects the combined effects of microbial activity, hydrolysis, oxidation, and adsorption-desorption equilibrium. Extended incubation facilitated greater degradation and reduced residual toxicity.

5.5 Environmental Implications

The findings indicate that organic amendments can substantially modify pesticide behavior in soil systems. Increased retention within manure pellets may reduce leaching losses and groundwater contamination. However, prolonged persistence within organic matrices may also influence long-term residue dynamics.

Appropriate management of organic amendments is therefore essential for maximizing pesticide efficiency while minimizing environmental risks.

6. Summary

The present investigation assessed the persistence and distribution of imidacloprid in soil and manure pellets under incubation conditions.

Major findings include

- Imidacloprid residues decreased progressively with incubation period.
- Manure pellets exhibited higher retention than soil.
- Organic matter significantly influenced adsorption and persistence.
- Distribution patterns demonstrated differential partitioning between soil and manure fractions.

- Incubation promoted gradual degradation and dissipation of residues.
- Organic amendments may reduce pesticide mobility and environmental contamination.

7. Conclusion

The study demonstrated that imidacloprid persistence is strongly influenced by the nature of the substrate. Manure pellets showed superior adsorption and retention capacity compared with soil due to their higher organic matter content. Residue concentrations declined steadily throughout incubation, indicating on-going degradation processes. The distribution behavior confirmed that organic amendments play a significant role in regulating pesticide fate and environmental persistence. These findings emphasize the importance of integrating organic amendments into sustainable pesticide management strategies for improving environmental safety and agricultural productivity.

References

- Ahmad R, Kookana RS, Alston AM, Skjemstad JO. The nature of soil organic matter affects sorption of pesticides. *Aust J Soil Res.* 2006;44(2):131-142.
- Aktar MW, Sengupta D, Chowdhury A. Impact of pesticides use in agriculture: their benefits and hazards. *Interdiscip Toxicol.* 2009;2:1-12.
- Akter S, Hulugalle NR, Jasonsmith J, Strong CL. Changes in soil microbial communities after exposure to neonicotinoids: a systematic review. *Environ Microbiol Rep.* 2023;15(6):431-444.
- Bonmatin JM, Giorio C, Girolami V, Goulson D, Kreutzweiser DP, Krupke C, *et al.* Environmental fate and exposure of neonicotinoids and fipronil. *Environ Sci Pollut Res.* 2015;22:35-67.
- Cox C. Imidacloprid: toxicology and environmental fate. *J Pestic Reform.* 2001;21:15-21.
- Food and Agriculture Organization. Guidelines for pesticide residue analysis in agricultural soils. Rome: FAO; 2024.
- Gupta PK. Pesticide exposure and environmental pollution. Jodhpur: Agrobios Publications; 2018.
- Gupta S, Gajbhiye VT. Adsorption-desorption behavior of imidacloprid in soils amended with organic materials. *Chemosphere.* 2007;66:1473-1478.
- Jeschke P, Nauen R, Schindler M, Elbert A. Overview of the status and global strategy for neonicotinoids. *J Agric Food Chem.* 2011;59:2897-2908.
- Kathuria D, Bhattu M, Bankar A, Puri P. A review on methods for the elimination of imidacloprid: 2018-2022. *ChemistrySelect.* 2023;8(34):e202302293.
- Kumar S, Singh N, Sharma S. Persistence of neonicotinoid insecticides in agricultural soils. *J Environ Manage.* 2021;290:112-120.
- Mahapatra B, Adak T. Effect of the presence of carbendazim on imidacloprid degradation in a biological organic mixture. *Int J Environ Anal Chem.* 2025;105(9):2131-2145.
- Majee P, Reddy PHP. Sorption-desorption behaviour of imidacloprid in agricultural soils of the Deccan Plateau of Southern India: kinetics and thermodynamic analysis. *Int J Environ Anal Chem.* 2024;104(20):8570-8584.
- Organisation for Economic Co-operation and Development. Test guidelines for evaluation of pesticide persistence and degradation in soil. Paris: OECD; 2025.
- Racke KD. Environmental fate of pesticides. Madison (WI): Soil Science Society of America; 1993.
- Randhawa JS. Microbial-assisted remediation approach for neonicotinoids from polluted environment. *Bull Natl Res Cent.* 2024;48:70.
- Sharma R, *et al.* Persistence, sorption, and forced degradation of imidacloprid in environmental matrix. *Mater Today Proc.* 2023;78:849-857.
- Singh BK, Singh K. Microbial degradation of pesticides and environmental sustainability. *Appl Microbiol Biotechnol.* 2014;98:329-341.
- Spark KM, Swift RS. Effect of soil composition and dissolved organic matter on pesticide sorption. *Sci Total Environ.* 2002;298:147-161.
- Sparks DL. Environmental soil chemistry. 3rd ed. New York: Academic Press; 2019.
- Tomizawa M, Casida JE. Neonicotinoid insecticide toxicology: mechanisms of selective action. *Annu Rev Pharmacol Toxicol.* 2005;45:247-268.
- Tomlin CDS, editor. The pesticide manual. 18th ed. Alton (UK): British Crop Protection Council; 2018.
- United States Environmental Protection Agency. Ecological risk assessment of imidacloprid. Washington (DC): US EPA; 2023.
- Yang JY, Chen H, Song KW, *et al.* Environmental behaviors and ecotoxicity of imidacloprid: a comprehensive review on fate, degradation processes, and ecological risks. *Front Microbiol.* 2025;16:1724551.