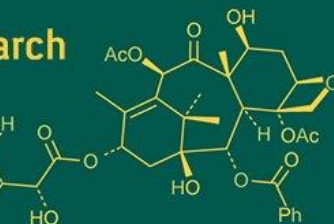
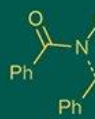


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The influence of soil type on residual pesticide toxicity: A review of fundamental mechanisms, environmental persistence, and remediation strategies

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Abstract

Pesticides play a crucial role in sustaining agricultural productivity; however, their extensive and repeated applications have been resulting in persistent residues in soil, posing serious environmental and human health concerns. Residual pesticide toxicity is governed by a complex interaction between the physicochemical properties of the pesticide and intrinsic soil characteristics such as texture, organic matter content, pH, and microbial activity.

The present review critically examines the fundamental mechanisms controlling pesticide persistence, mobility, and degradation in different soil types, with special emphasis on sorption-desorption dynamics, degradation pathways, and transport processes. Coarse-textured sandy soils favour leaching and ensuing groundwater contamination, whereas fine-textured clay soils enhance adsorption but increase the risk of surface runoff and long-term persistence. Soils rich in organic matter strongly immobilize pesticides, potentially reducing bioavailability but paradoxically prolonging residual toxicity.

Selected case studies on widely used pesticides illustrate how soil type influences environmental fate and ecological risk. The review also discusses contemporary mitigation and remediation strategies, including improved soil management practices, organic and inorganic amendments, as well as bioremediation approaches. Understanding soil-pesticide interactions is essential for designing site-specific management strategies to minimize residual toxicity, safeguard soil and water resources, while promoting sustainable agricultural systems.

Keywords: Degradation, environmental persistence, pesticide residues, residual toxicity, soil type, sorption

1. Introduction

Widespread use of pesticides has become an integral component of modern agriculture to ensure food security and crop protection ^[1]. Despite their benefits, pesticide applications inevitably leads to the accumulation of their residues in soil, water, and agricultural produce, raising concerns about long-term environmental sustainability, public health, and the broader environment ^[2]. According to the World Health Organization, pesticide residues include not only the parent compound but also its metabolites, degradation products, and impurities that may possess toxicological significance ^[3].

Residual toxicity refers to the capacity of these compounds to exert adverse biological effects long after application, either through acute exposure or chronic low-dose exposure over extended periods ^[4]. The persistence and behavior of pesticide residues are not uniform but are strongly influenced by soil characteristics and environmental conditions ^[5]. Soil acts both as a sink and a conduit for pesticides, regulating their retention, transformation, and movement within the agro-ecosystem ^[6].

The present review aims to elucidate existing knowledge on the influence of soil type on residual pesticide toxicity by integrating physicochemical, biological, and environmental perspectives. The article also highlights the mechanisms governing pesticide fate, discusses soil-specific risks, and evaluates current mitigation and remediation strategies relevant to sustainable agriculture ^[7].

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2. Fundamental properties governing pesticide fate in soil

The environmental fate of pesticides is determined by the interaction between intrinsic chemical properties of the specific pesticide and the physicochemical and biological attributes of particular soil [8]. Parameters such as water solubility, vapor pressure, soil adsorption coefficient (Koc), and half-life play a decisive role in determining mobility and persistence.

Pesticides with low Koc values are weakly adsorbed and exhibit high mobility, increasing the risk of leaching, particularly in sandy soils [9]. In contrast, compounds with high Koc values bind strongly to soil organic matter and clay minerals, reducing mobility but often increasing persistence.

2.1 Intrinsic Properties of the Pesticide

2.1.1 Key Physicochemical Characteristics

The organic carbon-water partitioning coefficient (Koc) is a fundamental parameter used to assess a pesticide's affinity for soil organic matter (SOM) [3]. Higher Koc values indicate stronger sorption to soil organic fractions, resulting in reduced mobility and a lower likelihood of downward

leaching through the soil profile.

For instance, Benomyl, which has a high Koc value of approximately 1,900, is regarded as strongly sorbed to soil particles, whereas Dicamba salt, with a very low Koc value of about 2, is highly mobile and prone to leaching. In addition to sorption behavior, water solubility plays a crucial role in determining pesticide transport. Pesticides with high solubility are more readily transported in the aqueous phase, increasing their potential movement through surface runoff and leaching into groundwater.

2.1.2 Persistence and Half-Life ($T_{1/2}$)

Pesticide persistence in soil is commonly quantified using the half-life ($T_{1/2}$), defined as the time required for 50% of the initially applied pesticide to degrade in the soil environment [5]. Based on half-life values, pesticides are generally classified as non-persistent (less than 30 days), moderately persistent (30-100 days), or persistent (more than 100 days).

However, the half-life of a pesticide is not a fixed property and can vary widely depending on environmental conditions such as soil temperature, moisture content, aeration, and the level of microbial activity.

Table 1: Soil adsorption coefficient and half-life of selected pesticides

Common Name	Trade Name	Soil Adsorption Coefficient, Koc (mL/g)	Half-life, $T_{1/2}$ (Days)
Acephate	Orthene	2	3
Dicamba	Banvel	2	14
Atrazine	AAtrex	100	60
Alachlor	Lasso	170	15
Carbaryl	Sevin	300	10
Chlorpyrifos	Lorsban	6,070	30
Glyphosate	Roundup	24,000	47
Paraquat	Gramoxone	1,000,000	1,000

2.2 Soil Physicochemical and Biological Properties

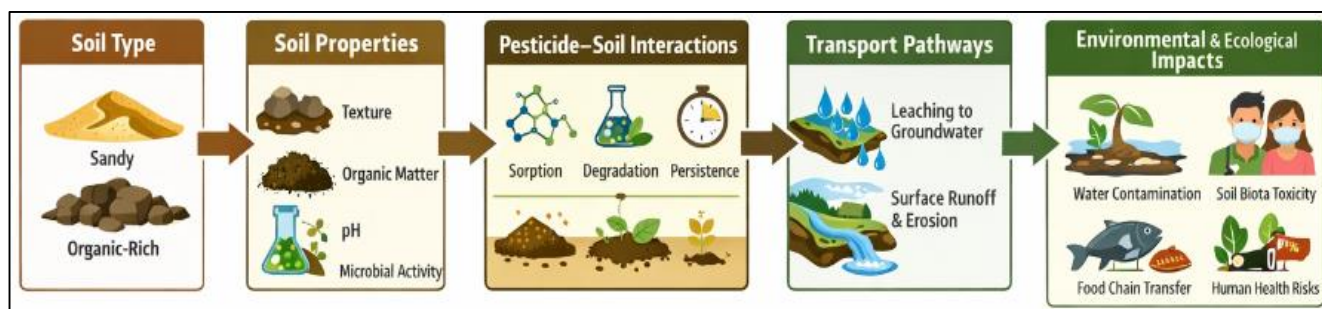


Fig 1: Soil and pesticide interaction flowchart

2.2.1 Influence of Soil Texture and Structure

Soil texture significantly affects pesticide transport and retention [10]. Sandy soils, characterized by large pore spaces and low surface area, facilitate rapid water movement and enhance leaching of soluble pesticides into groundwater. Clay-rich soils possess high surface area and adsorption capacity, resulting in strong pesticide retention but increased susceptibility to surface runoff and erosion-mediated transport.

2.2.2 Role of Soil Organic Matter

Soil organic matter (SOM) is the most influential factor controlling pesticide adsorption [11]. Hydrophobic pesticides preferentially partition into organic matter, reducing their bioavailability and immediate toxicity. However, strong

sorption may also shield pesticides from microbial degradation, leading to prolonged persistence and chronic exposure risks. This dual role of SOM underscores the complexity of soil-mediated pesticide behavior.

2.2.3 Effect of Soil pH and Microbial Activity

Soil pH influences the ionization state and stability of many pesticides, thereby affecting adsorption and degradation rates [12]. Alkaline conditions often reduce the degradation of certain herbicides, increasing their persistence. Microbial communities play a central role in pesticide degradation, with bacteria and fungi metabolizing pesticides under favorable moisture, temperature, and aeration conditions [13]. Repeated applications of the same pesticide may induce enhanced biodegradation through microbial adaptation.

3. Transport and Mobility

3.1 Leaching to Groundwater

Leaching refers to the downward movement of soluble or weakly adsorbed pesticides through the soil profile ^[14]. The risk of leaching is greatest in highly permeable sandy soils and for pesticides characterized by high water solubility and low K_{oc} values ^[3]. Once pesticides enter groundwater aquifers, which are typically cold and low in oxygen, degradation processes slow down considerably, resulting in prolonged persistence and long-term contamination of water resources ^[15].

3.2 Surface Runoff and Erosion

Surface runoff occurs when rainfall or irrigation exceeds the soil's infiltration capacity, transporting dissolved pesticides across the land surface into adjacent streams, rivers, and other water bodies. This pathway is particularly significant in fine-textured and compacted soils, where infiltration rates are low ^[4]. In addition, soil erosion facilitates the movement of pesticide-laden soil particles, representing a major off-site transport mechanism for pesticides that are strongly adsorbed on soil solids.

4. Influence of specific soil types on residual toxicity

4.1 Porous, Coarse-Textured Soils (e.g., Sandy Loams)

Porous, coarse-textured soils exhibit high infiltration rates and rapid water percolation. Due to their low surface area

and limited sorption capacity, these soils present a high potential for pesticide leaching into groundwater ^[16]. Studies conducted on Brazilian soils have shown that in Typic Quartzipsamment soils, rapid water movement results in elevated leaching potential, posing a significant risk of water contamination, particularly for highly mobile pesticides ^[17].

4.2 Fine-Textured, Clay-Rich Soils (e.g., Vertisols)

In contrast, fine-textured, clay-rich soils are characterized by low infiltration rates and a high capacity to adsorb pesticides. Strong adsorption reduces the likelihood of extensive leaching; however, low permeability enhances surface runoff, thereby increasing the risk of contamination of surface water bodies ^[14]. For pesticides that bind strongly to soil particles, erosion further augments the potential for off-site transport.

4.3 Soils with High Organic Matter Content (e.g., Histosols)

Soils dominated by organic materials are highly effective in adsorbing non-ionic pesticides, making soil organic matter (SOM) the most important factor in reducing pesticide mobility and leaching potential ^[8]. As discussed in Section 3.1, strong sorption may reduce microbial accessibility, thereby prolonging residual toxicity and increasing the risk of forming persistent contaminant reservoirs in soil ^[8].

Table 2: Influence of soil type on pesticide behaviour, transport pathways and environmental risk

Soil type	Key characteristics	Dominant pesticide behaviour	Major transport pathway	Primary environmental risk
Sandy/coarse-textured soils	Low clay, low organic matter, high permeability	Weak sorption, high mobility	Leaching to groundwater	Groundwater contamination
Clay-rich soils (Vertisols)	High clay content, low permeability	Strong sorption, slow degradation	Surface runoff & erosion	Surface water contamination
Organic matter-rich soils (Histosols)	High SOM, high adsorption capacity	Immobilization, prolonged persistence	Particle-bound transport	Long-term residual toxicity
Compacted soils	Low infiltration, poor structure	Limited leaching	Surface runoff	Off-site contamination

5. Pesticide persistence and environmental impact

5.1 Case Study 1: Atrazine

Atrazine is a widely used herbicide known to persist for extended periods in high-pH soils due to reduced chemical and microbial degradation ^[9]. Studies have reported the presence of atrazine residues in drinking water supplies in intensive agricultural regions, highlighting concerns over groundwater and surface water contamination ^[15]. In areas with karst geology (landscapes formed by dissolution of soluble bedrock), preferential flow pathways may allow contaminants to bypass natural soil filtration processes, facilitating direct entry into water resources ^[17].

5.2 Case Study 2: Glyphosate

Glyphosate exhibits strong adsorption to soil particles, particularly clay minerals and organic matter, which generally limits its leaching potential ^[4]. However, studies have demonstrated that rapid transport can still occur through preferential flow pathways, such as macropores formed by earthworms or decayed root channels, especially under no-tillage systems ^[14]. This challenges the assumption that strong sorption alone is sufficient to prevent leaching.

5.3 Case Study 3: DDT

DDT, a Persistent Organic Pollutant (POP), serves as a classical example of long-term residual pesticide toxicity

^[15]. DDT and its metabolites (DDE and DDD) strongly adhere to fine soil particles and organic matter, limiting downward migration in most soil types. Nevertheless, under specific conditions such as acidic sandy soils, an increased risk of contamination of shallow aquifers has been reported ^[17].

6. Ecological and environmental consequences of residual pesticide toxicity

6.1 Impact on Non-Target Soil Organisms

Pesticide residues adversely affect a wide range of non-target organisms, including beneficial soil microorganisms and fauna across multiple trophic levels. Several studies have documented negative effects of pesticides on growth, reproduction, and physiological functions of non-target organisms in both terrestrial and aquatic ecosystems ^[10, 15]. Certain herbicides disrupt nitrogen-fixing bacteria and exert toxic effects on mycorrhizal fungi essential for plant nutrient uptake ^[10].

6.2 Risks to Water Resources

The contamination of water resources remains a global environmental concern ^[15]. Soil type plays a decisive role in determining dominant transport pathways: porous sandy soils facilitate rapid leaching to groundwater, whereas

compacted or clay-rich soils promote surface runoff into streams and rivers ^[3, 14].

7. Mitigation and remediation strategies

To mitigate residual pesticide toxicity, a range of preventive and remedial management strategies have been developed.

7.1 Enhanced Soil Management Practices

The use of cover crops during fallow periods enhances soil microbial activity and organic matter content, thereby accelerating microbial degradation of pesticides in surface soils ^[11]. Such practices reduce pesticide persistence and limit their transfer to groundwater. Reduced tillage systems further promote microbial biomass and soil organic matter accumulation, contributing to enhanced degradation and reduced soil erosion ^[11].

7.2 Soil Amendments

Biochar, a carbon-rich amendment, has emerged as an effective option for immobilizing pesticides in soil due to its large surface area and high adsorption capacity ^[16]. While biochar reduces pesticide bioavailability and leaching potential, strong sorption may also prolong persistence by limiting microbial degradation ^[8]. Organic amendments such as manure or compost, if contaminated, may inadvertently introduce persistent pesticide residues into agricultural soils ^[17].

7.3 Bioremediation Techniques

Bioremediation employs living organisms to transform hazardous pesticides into less toxic compounds. Approaches include stimulation of native microbial populations through nutrient amendment and the introduction of specific microbial strains with known degradation capabilities ^[11, 17]. Such biological strategies offer eco-friendly and sustainable solutions for the remediation of pesticide-contaminated soils.

8. Conclusion

Residual pesticide toxicity is a multifaceted environmental issue governed by intricate interactions between pesticide properties and soil characteristics. Soil texture, organic matter content, pH, and microbial activity collectively determine pesticide persistence, mobility, and ecological risk. While certain soil properties reduce immediate contamination risks, they may contribute to long-term persistence and chronic exposure. Therefore, site-specific soil management strategies coupled with judicious use of pesticides are essential for minimizing adverse impacts. Continuous monitoring, farmer awareness, and adoption of sustainable remediation strategies are vital to ensure environmental safety and food security.

9. Future Perspectives

Future research on residual pesticide toxicity should focus on developing predictive, soil-specific risk assessment models that integrate soil physicochemical properties, climate variables, and pesticide use patterns ^[17]. Advances in sensor-based monitoring, precision agriculture, and decision-support systems can help optimize pesticide application rates and timing, thereby reducing unnecessary residue build-up. Greater emphasis should be placed on understanding the long-term behavior of pesticide mixtures

and their transformation products, which are often more persistent and toxic than parent compounds.

The potential of emerging remediation technologies, including engineered biochar, microbial consortia, phytoremediation, and nano-enabled delivery systems, warrants systematic evaluation under field conditions. Additionally, strengthening regulatory frameworks, promoting farmer-centric extension programs, and encouraging the adoption of eco-friendly pest management strategies will be crucial for mitigating residual toxicity. Integrating soil health management with sustainable pest management approaches offers a promising pathway toward environmentally resilient and safe agricultural systems.

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11. Conflict of interest

The authors declare no conflict of interest.

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