

Chapter

Pesticide-Contaminated Soils in Sudan: Environmental Fate, Microbial Biodegradation and Sustainable Remediation Strategies

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Abstract

Pesticides play a central role in agriculture by enhancing crop productivity; however, their intensive and poorly regulated use has raised environmental and health concerns, particularly in Sudan, where monitoring and management systems remain limited. Inappropriate application, unsafe handling, weak enforcement, and insufficient farmer training increase the risks of soil and water contamination, pesticide residues in food, biodiversity loss, and human exposure. These challenges are intensified by limited laboratory capacity, inadequate disposal practices, and scarce national data on pesticide use and environmental contamination. Strengthening regulatory enforcement, environmental monitoring, farmer awareness, and sustainable pest-management practices is essential to protect ecosystems, public health, and long-term agricultural productivity. This chapter synthesizes current knowledge on pesticide-contaminated soils in Sudan, focusing on environmental fate, soil–microbe interactions, microbial biodegradation, and sustainable remediation approaches. Key processes governing pesticide behavior in soil, including adsorption, desorption, leaching, volatilization, chemical transformation, and biodegradation, are examined in relation to soil physicochemical properties, climatic conditions, and microbial activity. These interacting factors regulate pesticide mobility, persistence, and bioavailability under semi-arid conditions. Evidence indicates that pesticides can significantly alter soil microbial biomass, diversity, and metabolic functions, with direct implications for soil fertility, nutrient cycling, and ecosystem stability. Atrazine is presented as a representative case study because of its persistence, mobility, and ecological relevance. Microbial biodegradation is identified as the primary and most sustainable pathway for pesticide dissipation. The chapter further highlights bioremediation, phytoremediation, and integrated soil-management strategies, alongside the need for improved regulation, greater farmer awareness, and wider adoption of integrated pest management (IPM).

Keywords: pesticide-contaminated soils, environmental fate of pesticides, soil–microbe interactions, microbial biodegradation, bioremediation, atrazine, soil health, sustainable agriculture, integrated pest management (IPM), Sudan

1. Introduction to pesticides and agricultural importance

1.1 Definition and classification of pesticides

Pesticides are substances or mixtures of substances used to prevent, destroy, repel, or control pests, including insects, weeds, fungi, and other harmful organisms that adversely affect agricultural production, stored products, and public health [1, 2]. In modern agricultural systems, the term also encompasses compounds applied to regulate plant growth, protect harvested commodities, and improve crop management efficiency, making pesticides a broad group of chemical and biological agents used to reduce biotic stress and support crop performance [1].

Pesticides can be classified using several complementary criteria. The most common classification is based on the target organism, such as insecticides, herbicides, fungicides, rodenticides, and nematocides. However, pesticides are also classified according to their chemical nature, environmental behavior, and toxicological characteristics, all of which are essential for understanding their persistence, mobility, and ecological effects [2–4]. Major chemical groups include organochlorines, organophosphates, carbamates, pyrethroids, and triazines, each differing in mode of action, degradation behavior, and risk profile in soil and water environments [5–7].

Mode-of-action classification is particularly important because it links pesticide function to biological response and environmental consequences. Herbicides may inhibit photosynthesis, amino acid biosynthesis, or other plant-specific metabolic pathways, whereas fungicides and insecticides interfere with essential biochemical and physiological processes in target organisms [8–10]. Increasingly, classification systems also consider environmental persistence, toxicity to non-target organisms, and implications for food safety and sustainable use, reflecting a broader shift toward risk-based pesticide assessment [1, 2].

1.2 Historical development of pesticide use

The use of substances for pest control dates back to early agricultural societies, when naturally occurring materials such as sulfur, ash, and plant extracts were used to protect crops. The development of modern pesticide use accelerated during the nineteenth and twentieth centuries with the introduction of inorganic compounds, followed by the synthesis of organic pesticides, which became central to agricultural intensification and large-scale pest control [2, 3].

The expansion of synthetic pesticide use contributed substantially to increased crop productivity, improved crop protection, and more reliable food production systems. Pesticides became important tools for reducing pre- and post-harvest losses and for supporting agricultural modernization under rising population pressure [1, 4, 11]. At the same time, growing evidence showed that many conventional pesticides could persist in the environment, accumulate in food chains, and affect non-target organisms, which raised major concerns regarding environmental contamination and human health [2, 7, 12].

As a result, pesticide science has progressively shifted toward safer and more sustainable approaches. Recent developments emphasize reduced-risk products, improved formulation technologies, precision application, integrated pest management (IPM), and biologically based alternatives such as microbial and nano-enabled products [13–15]. This transition reflects the increasing need to maintain agricultural productivity while reducing ecological disturbance and protecting human health [1, 16].

1.3 Role of pesticides in agriculture and public health

Pesticides play an important role in both agriculture and public health. In agriculture, they are used to control weeds, insects, and plant pathogens that would otherwise reduce crop yields, impair quality, and threaten food security. In public health, pesticides contribute to the control of disease vectors and other harmful organisms, thereby supporting sanitation and disease prevention programs [2, 4].

Their importance is especially evident in production systems exposed to high pest pressure, climatic stress, and limited management options. Under such conditions, pesticides can stabilize yields, reduce crop failures, and support farmers' livelihoods by limiting severe pest-related losses [1, 11]. Nevertheless, the value of pesticides must be considered together with their potential risks to humans and the environment.

Human exposure may occur through occupational handling, contaminated food, water, or environmental pathways, and may lead to acute or chronic toxicological effects. In addition, pesticides can contaminate soil and water, affect aquatic and terrestrial organisms, and alter soil microbial communities that are essential for nutrient cycling and soil health [9, 12, 17, 18]. Recent evidence further shows that increasing pesticide diversity and repeated use can impair soil microbial functions and ecological balance, reinforcing concerns about long-term ecosystem effects [19, 20].

Accordingly, pesticide use represents a clear risk-benefit trade-off. While pesticides remain important tools for crop protection and public health, their use should be guided by ecological principles, regulatory control, residue monitoring, and sustainable management practices to reduce adverse consequences [1, 2, 21].

1.4 Benefits of pesticide use in crop production

1.4.1 Increasing crop productivity

Pesticides are essential inputs in modern agriculture because they protect crops from weeds, insects, and diseases, thereby improving productivity and helping farmers maintain more stable yields and income [1, 11]. By reducing biotic stress, pesticides allow crops to use available nutrients, water, and light more efficiently and to express a greater proportion of their yield potential [4]. Their contribution to productivity is particularly important in intensive agricultural systems, where pest pressure can significantly constrain output if left unmanaged [2].

1.4.2 Reducing pest-related losses

Pesticides are also important for minimizing crop losses caused by insects, pathogens, and weeds throughout the growing season and during storage. By reducing pest-related damage, they help maintain both the quantity and quality of

agricultural production and contribute to greater food supply stability [1, 11]. This role becomes increasingly important under rising global food demand and limited possibilities for agricultural land expansion, where protecting existing production is essential for food system resilience [4, 16].

1.4.3 Improving food quality

Beyond yield protection, pesticides can improve food quality by reducing visible pest damage, lowering disease incidence, and preserving the marketability and storability of agricultural produce [1]. However, these benefits depend strongly on proper application and regulatory compliance, because misuse or excessive use may result in pesticide residues that compromise food safety and increase health risks [12, 21]. Therefore, the major challenge is not whether pesticides are useful but how to optimize their use within sustainable systems that integrate safer products, better timing and dosage, and complementary approaches such as IPM and green pest control technologies [2, 16].

1.5 Rationale for focusing on pesticide-contaminated soils in Sudan

Sudan represents an important case for examining pesticide-contaminated soils because pesticide behavior is strongly shaped by the country's agroecological diversity, semi-arid climate, and agricultural management constraints. Agricultural production occurs across irrigated schemes, semi-mechanized rainfed systems, and traditional rainfed farming, where pest pressure, rainfall variability, and limited management options influence pesticide dependence [22–24]. Under Sudanese conditions, high temperatures, seasonal rainfall, low or variable soil organic matter (SOM), and differences in soil texture may affect pesticide adsorption, desorption, leaching, volatilization, persistence, and biodegradation [6, 25–30]. These factors are particularly relevant because pesticide use in Sudan is often accompanied by weak monitoring systems, limited laboratory capacity, insufficient farmer training, and challenges in regulatory enforcement [1, 2, 12, 17, 21]. Therefore, this chapter uses international knowledge on pesticide fate and microbial degradation as a scientific foundation while interpreting these processes through the environmental, agricultural, and institutional conditions of Sudan.

2. Pesticide use and agricultural context in Sudan

2.1 Overview of agricultural systems in Sudan

Agriculture represents a fundamental pillar of Sudan's economy, contributing substantially to food security, employment, and rural livelihoods. The country encompasses diverse agroecological zones, ranging from arid and semi-arid environments in the north to more humid savanna systems in the south, which strongly influence cropping patterns, pest dynamics, and pesticide use intensity [22, 23]. These environmental gradients determine both agricultural productivity and vulnerability to pest outbreaks under changing climatic conditions.

Sudan's agricultural sector is broadly categorized into three main production systems: Irrigated agriculture, semi-mechanized rainfed farming, and traditional

rainfed subsistence farming. Irrigated systems, particularly large-scale schemes, support the cultivation of cash crops under a controlled water supply, while rainfed systems dominate the cultivated area and depend heavily on rainfall variability [22]. The predominance of rainfed agriculture exposes production systems to climatic uncertainty, which directly affects crop performance and pest dynamics.

Rainfed agriculture is especially vulnerable to drought, irregular rainfall, and increasing temperature variability. These climatic stresses not only reduce crop productivity but also influence pest population dynamics, often leading to increased pest pressure and greater reliance on pesticides [22, 24]. In semi-arid savanna systems, interactions between climate variability and anthropogenic pressures further exacerbate ecosystem instability, making pest management both more necessary and more complex [19, 23].

2.2 Commonly used pesticides in Sudanese agriculture

Pesticide use in Sudan reflects the structure of its agricultural systems, dominant crops, and prevailing pest pressures. Herbicides, insecticides, and fungicides are widely applied across both irrigated and rainfed systems, although their intensity, regulation, and management vary considerably [1, 2]. Herbicides are particularly important in mechanized rainfed systems, where weed competition significantly reduces yields, especially for staple crops such as sorghum and sesame.

Among herbicides, compounds such as atrazine and glyphosate are commonly used due to their effectiveness, availability, and relatively low cost. However, these compounds are associated with persistence in soil and water systems, as well as risks of environmental contamination and bioaccumulation [6, 7, 21]. Insecticides, including organophosphates and pyrethroids, are extensively used to control crop pests and disease vectors, reflecting their dual role in agriculture and public health [4, 12].

Growing evidence indicates that pesticide residues are increasingly detected in agricultural products and environmental compartments. Studies have reported contamination of food systems and potential human exposure risks associated with pesticide misuse and inadequate regulation [12, 21]. Furthermore, pesticide application can significantly affect soil microbial communities, reducing microbial diversity and altering key ecological functions essential for soil fertility and nutrient cycling [17–19].

The widespread use of pesticides in Sudan is influenced by multiple interacting factors, including economic constraints, limited access to alternative pest control methods, and increasing pest pressure driven by climatic variability. However, pesticide selection and application are not always based on scientific recommendations, leading to inefficiencies, environmental contamination, and increased risks to human health [1, 2].

2.3 Regulatory framework and management challenges

Pesticide management in Sudan is guided by national regulations, supported by international principles for pesticide lifecycle management, including registration, distribution, application, and disposal. These frameworks aim to reduce risks to human health and the environment while maintaining effective pest control [1, 2].

Despite these regulatory structures, pesticide management in Sudan faces substantial challenges. Weak enforcement, limited institutional capacity, and inadequate monitoring systems contribute to widespread issues such as improper pesticide use, the circulation of unregistered products, and insufficient control of residues in food and environmental media [2, 12]. In addition, limited laboratory infrastructure constrains the routine monitoring of pesticide contamination in soil, water, and agricultural products.

Farmer awareness and technical training represent additional critical limitations. In many cases, pesticide use is based on experience rather than scientifically informed guidelines, resulting in over-application, incorrect dosing, and unsafe handling practices. These factors increase the risk of occupational exposure, environmental pollution, and the development of pest resistance [4, 17]. Furthermore, improper storage and disposal of pesticides contribute to long-term environmental contamination, particularly in regions with limited waste management systems [3].

From a sustainability perspective, these challenges highlight the urgent need for integrated pesticide management approaches. Strengthening regulatory enforcement, improving farmer education, enhancing monitoring systems, and promoting alternative strategies such as IPM and biological control are essential for reducing risks and improving pesticide use efficiency in Sudanese agricultural systems [2, 14, 16].

2.4 Pesticide-use practices and contamination pathways in Sudan

In Sudan, pesticide contamination of agricultural soils is closely linked to production systems, application practices, farmer awareness, and regulatory capacity. In irrigated agricultural schemes, pesticide residues may enter soils, drainage networks, canals, and groundwater through repeated application, irrigation return flow, runoff, and leaching processes [25, 31]. In semi-mechanized rainfed farming, herbicides are particularly important for weed control in large cultivated areas, especially where labor shortages and high weed pressure limit non-chemical management options [1, 2, 22]. In traditional rainfed systems, pesticide use may be less intensive, but risks remain high because application decisions are often influenced by farmer experience, pesticide availability, and limited technical guidance rather than formal recommendations [4, 17].

The main contamination pathways in Sudanese agricultural landscapes include direct deposition on soil during spraying, runoff after seasonal rainfall, leaching under irrigation or intense rainfall events, accidental spills during mixing, unsafe storage, and improper disposal of empty pesticide containers [2, 3, 12, 21]. These pathways are particularly concerning in areas where residue monitoring in soil, water, crops, and sediments is limited. The circulation of unregistered or misused pesticides, combined with weak enforcement and inadequate awareness, can increase the probability of environmental contamination and occupational exposure [1, 2, 12, 17]. Therefore, pesticide contamination in Sudan should be understood not only as a soil chemistry issue, but also as a combined problem of agricultural practice, regulation, monitoring, farmer education, and environmental management.

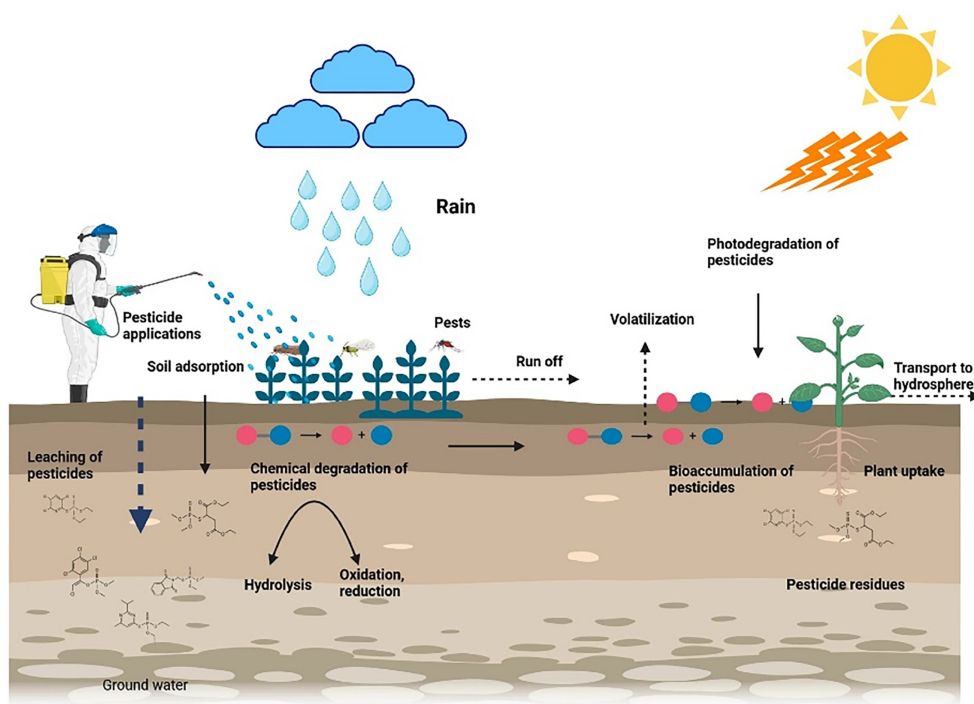


Figure 1. Schematic representation of pesticide behavior in the soil–plant–atmosphere system, showing processes such as adsorption, leaching, runoff, volatilization, photodegradation, plant uptake, and transport to groundwater and aquatic systems [32].

3. Environmental fate of pesticides in soil

3.1 Adsorption and desorption processes

The environmental fate of pesticides in soil is governed by a complex interaction of physicochemical and biological processes that control their retention, mobility, bioavailability, and persistence. Among these processes, adsorption–desorption dynamics represent a key mechanism regulating pesticide behavior in soil systems [25, 26].

The environmental fate of pesticides in soil involves multiple interconnected processes, including adsorption, leaching, volatilization, chemical degradation, plant uptake, and transport across environmental compartments (see **Figure 1**).

As illustrated in **Figure 1**, pesticide fate is governed by simultaneous and interacting processes that determine their distribution, persistence, and environmental impact. Within this system, adsorption refers to the binding of pesticide molecules to soil particles, particularly organic matter and mineral surfaces, whereas desorption describes their release back into the soil solution, making them available for transport or degradation.

SOM is a dominant factor influencing adsorption due to its high surface area and strong affinity for hydrophobic compounds. Pesticides with higher hydrophobicity tend to bind strongly to organic carbon, reducing their mobility but potentially increasing persistence in soil [27, 28]. Clay minerals and metal oxides also

contribute to adsorption through electrostatic interactions and surface complexation, further regulating pesticide partitioning between solid and liquid phases [6, 29]. In addition, soil pH significantly affects adsorption behavior, particularly for ionizable pesticides, by altering their chemical speciation and charge distribution [25, 30].

Adsorption processes are commonly described using isotherm models, such as the Freundlich and Langmuir equations, which quantify the relationship between pesticide concentration in soil solution and the amount adsorbed onto soil particles [6, 26]. Strong adsorption generally reduces leaching potential but may limit microbial accessibility, thereby slowing biodegradation. Conversely, weakly adsorbed pesticides remain more mobile and bioavailable, increasing both degradation potential and environmental contamination risk [25, 29].

Recent studies emphasize that adsorption is not a static process but is influenced by dynamic environmental conditions, including soil moisture, temperature, and land management practices. The presence of dissolved organic matter (DOM), fertilizers, and co-contaminants can further modify adsorption behavior, highlighting the complexity of pesticide–soil interactions under real field conditions [26, 28].

3.2 Leaching and groundwater contamination

Leaching is a major pathway through which pesticides are transported from the soil surface to deeper layers and ultimately into groundwater systems. This process occurs when percolating water carries dissolved pesticide residues through soil pores, particularly under conditions of high rainfall or irrigation [25, 31].

The extent of pesticide leaching is strongly influenced by both pesticide properties and soil characteristics. Compounds that are highly soluble, weakly adsorbed, and persistent are more prone to leaching, especially in coarse-textured soils with low organic matter content and limited adsorption capacity. In contrast, soils rich in clay and organic matter reduce leaching through enhanced adsorption and slower water movement [6, 29].

Environmental conditions, such as rainfall intensity, irrigation practices, and soil structure, also play a critical role in determining leaching potential. Preferential flow pathways, including macropores and cracks, can facilitate rapid pesticide transport, bypassing adsorption processes and increasing contamination risk [25]. Even relatively small fractions of applied pesticides can lead to groundwater contamination due to cumulative effects and persistence.

Groundwater contamination by pesticides represents a serious environmental and public health concern. Persistent herbicides, such as atrazine, are frequently detected in aquatic systems, reflecting their mobility and resistance to degradation [7, 21]. These findings highlight the importance of understanding leaching dynamics for effective risk assessment and sustainable pesticide management.

3.3 Volatilization and atmospheric transport

Volatilization is the process by which pesticides are transferred from soil and plant surfaces into the atmosphere in gaseous form. This pathway contributes to pesticide dissipation from agricultural fields and enables atmospheric transport over varying distances [1, 33].

The rate of volatilization depends on several factors, including pesticide vapor pressure, temperature, soil moisture, and application methods. High temperatures and low soil moisture conditions tend to increase volatilization by enhancing vapor pressure and reducing pesticide adsorption to soil particles. Surface-applied pesticides are generally more susceptible to volatilization compared to those incorporated into the soil [1].

Once released into the atmosphere, pesticides may undergo chemical transformation or be transported over long distances before deposition through precipitation or dry settling. This process contributes to the redistribution of pesticides beyond their application sites and can result in the contamination of non-target ecosystems [2]. Consequently, volatilization plays an important role in the regional and global dispersion of pesticide residues.

3.4 Chemical degradation and hydrolysis

Chemical degradation represents an important abiotic pathway for pesticide transformation in soil systems. Key processes include hydrolysis, oxidation, reduction, and photochemical reactions, which contribute to the breakdown of pesticide molecules into simpler or more polar compounds [34, 35].

Hydrolysis is particularly significant for many pesticides and is strongly influenced by environmental factors such as soil moisture, temperature, and pH. The chemical structure of the pesticide also determines its susceptibility to hydrolytic reactions [34]. In addition, oxidation–reduction reactions mediated by soil minerals and redox conditions can further contribute to pesticide transformation.

Photodegradation occurs when pesticides are exposed to solar radiation, either directly or indirectly through interactions with DOM. Direct photolysis involves the absorption of light energy by pesticide molecules, leading to structural breakdown, while indirect photolysis involves reactive intermediates that accelerate degradation processes [35].

Despite these transformation pathways, chemical degradation alone is often insufficient to fully eliminate pesticide residues, and intermediate products may retain toxicity or mobility. Therefore, chemical processes must be considered alongside biological degradation when evaluating pesticide fate in soil environments.

3.5 Biodegradation processes

Biodegradation is the primary pathway for pesticide dissipation in most soil systems and plays a critical role in reducing environmental contamination. It involves the enzymatic transformation of pesticide compounds by microorganisms, including bacteria, fungi, and actinomycetes, into simpler and less toxic substances [36, 37]. Microorganisms degrade pesticides through diverse metabolic pathways, often utilizing them as sources of carbon or energy. Enzymes such as hydrolases and oxygenases play key roles in these processes, enabling the breakdown of complex organic molecules [38, 39]. In some cases, microbial communities adapt to repeated pesticide exposure, resulting in enhanced degradation efficiency over time [40].

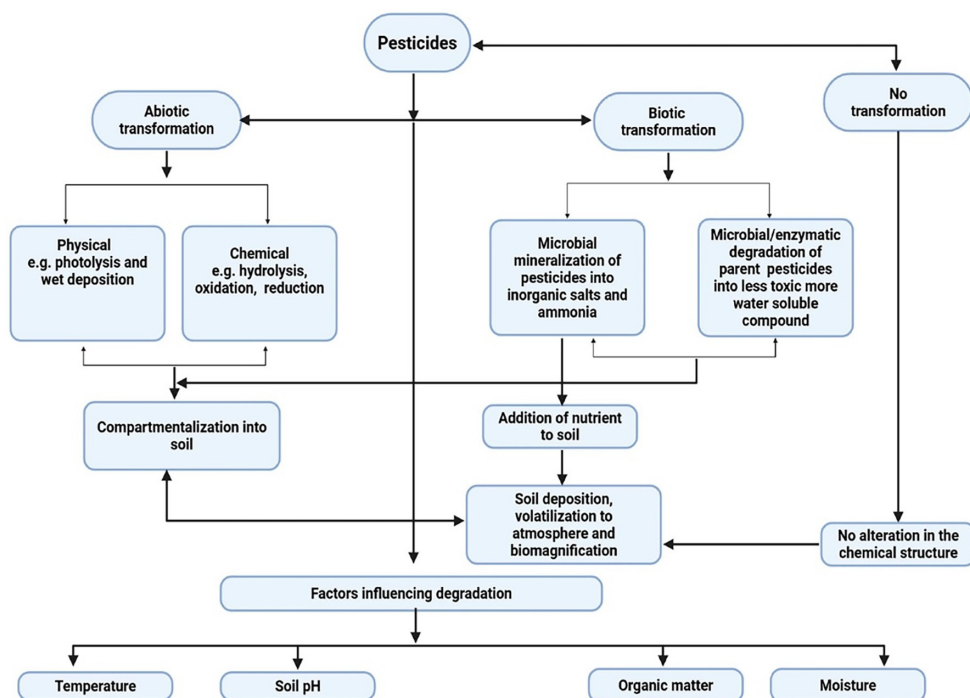


Figure 2.

Conceptual framework illustrating the environmental fate of pesticides in soil, including abiotic (physical and chemical) and biotic (microbial) transformation pathways, mineralization processes, and the influence of key environmental factors such as temperature, soil pH, organic matter, and moisture [32].

The environmental fate of pesticides in soil is governed by a combination of abiotic and biotic transformation processes, alongside environmental controls that regulate degradation pathways and persistence (see **Figure 2**).

As shown in **Figure 2**, pesticide fate is controlled by the interaction between transformation processes and environmental factors, which collectively determine persistence, mobility, and ecological impact. Within this framework, microbial degradation is strongly influenced by environmental conditions, including soil moisture, temperature, pH, organic matter content, and nutrient availability. Favorable conditions enhance microbial activity and enzymatic processes, whereas adverse conditions, such as drought or nutrient limitation, can slow degradation and prolong pesticide persistence [30, 41].

However, biodegradation is not always complete. Partial degradation may lead to the formation of metabolites that are more mobile or retain toxicity, emphasizing the need to consider both primary compounds and their transformation products in environmental assessments [31, 42].

Recent advances in microbial ecology, genomics, and biotechnology have significantly improved the understanding of pesticide biodegradation mechanisms and enabled the identification of functional genes and metabolic pathways involved in degradation processes. These developments provide new opportunities for enhancing bioremediation strategies and improving environmental sustainability [43, 44].

Under Sudanese agroecological conditions, pesticide fate is likely to be highly seasonal and strongly controlled by interactions among soil properties, climate, irrigation, and rainfall timing. During dry periods, limited soil moisture can suppress microbial activity and reduce biodegradation, thereby prolonging pesticide persistence in soil [30, 36, 37, 41]. Conversely, rainfall events after pesticide application may accelerate runoff and leaching, particularly in fields with low vegetation cover, compacted surfaces, coarse-textured soils, or low organic matter content [25, 29, 31]. In irrigated systems, repeated water application may enhance downward movement of soluble or weakly adsorbed pesticides and increase the risk of contamination in drainage water and groundwater [25, 31]. High temperatures may also increase volatilization losses for susceptible compounds and modify chemical transformation rates [1, 33, 34]. As a result, pesticide contamination risks in Sudan are not constant throughout the year but may increase during specific hydrological windows, especially after pesticide application followed by rainfall or irrigation.

4. Factors influencing pesticide degradation in soil

4.1 Soil physical and chemical properties

Pesticide degradation in soil is governed by interactions between pesticide physicochemical properties and the soil environment, which together determine pesticide availability for transformation processes. Soil physical and chemical properties, particularly texture, structure, pH, cation exchange capacity (CEC), and mineral composition, play a central role in regulating pesticide persistence and degradation pathways [25, 26].

Pesticide degradation is influenced by a complex interplay of physical, chemical, biological, environmental, and geological factors, which collectively determine degradation rates, persistence, and environmental behavior (see **Figure 3**).

As illustrated in **Figure 3**, these factors do not operate independently but interact dynamically, resulting in spatial and temporal variability in pesticide degradation across different soil systems. Within this integrated framework, soil physical and chemical properties represent key controls that regulate pesticide retention, mobility, and transformation processes.

Soil texture strongly influences water movement and sorption capacity. Coarse-textured soils, such as sandy soils, typically exhibit low adsorption capacity and high permeability, which enhances pesticide mobility but may reduce residence time and limit degradation. In contrast, fine-textured soils rich in clay minerals provide a larger reactive surface area, increasing adsorption and reducing mobility, but potentially prolonging persistence by limiting microbial accessibility [6, 29].

Soil pH is another critical factor, particularly for ionizable pesticides. Variations in pH alter pesticide speciation, solubility, and charge distribution, thereby influencing adsorption–desorption equilibria and degradation kinetics. In addition, CEC affects the retention of charged pesticide molecules and mediates interactions with soil colloids, further influencing pesticide fate [25, 30].

Overall, soil physicochemical properties interact dynamically rather than acting independently, creating complex and spatially variable degradation

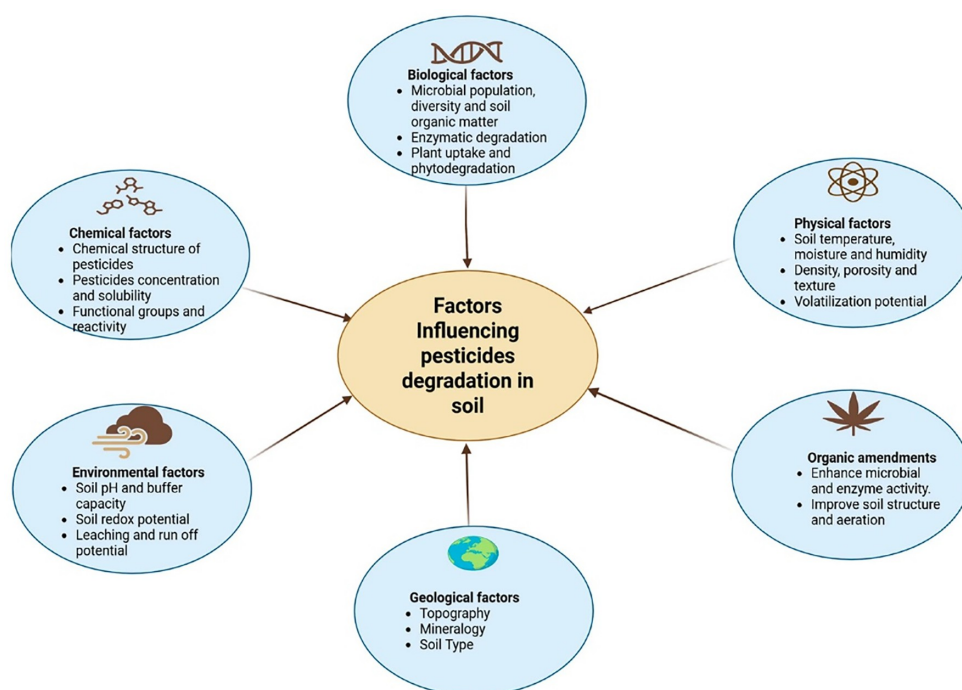


Figure 3.

Integrated framework of factors influencing pesticide degradation in soil, including physical, chemical, biological, environmental, and geological controls [32].

patterns. This variability is especially pronounced in heterogeneous dryland soils, where differences in texture, mineralogy, and nutrient status can lead to significant variations in pesticide persistence across short spatial scales [19, 23].

In Sudan, the degradation of pesticides is likely to vary considerably among irrigated clay soils, semi-mechanized rainfed soils, sandy soils, and savanna soils because each system differs in texture, organic matter, moisture availability, and microbial activity. Clay-rich soils may increase pesticide adsorption and reduce leaching, but strong adsorption can also reduce bioavailability and slow microbial degradation [6, 25, 29]. In contrast, sandy or low-organic-matter soils may allow greater pesticide mobility, increasing the risk of leaching and off-site transport [25, 29, 31]. SOM is particularly important under Sudanese conditions because it supports microbial biomass and enzymatic activity, while also influencing pesticide sorption and bioavailability [27, 28, 45, 46]. Therefore, improving SOM through compost, manure, crop residues, and conservation practices may represent a practical strategy to enhance microbial degradation and reduce pesticide mobility in Sudanese agricultural soils [47, 48].

4.2 SOM and microbial activity

SOM is a key factor in controlling pesticide degradation due to its dual role in sorption processes and the stimulation of microbial activity. High SOM content

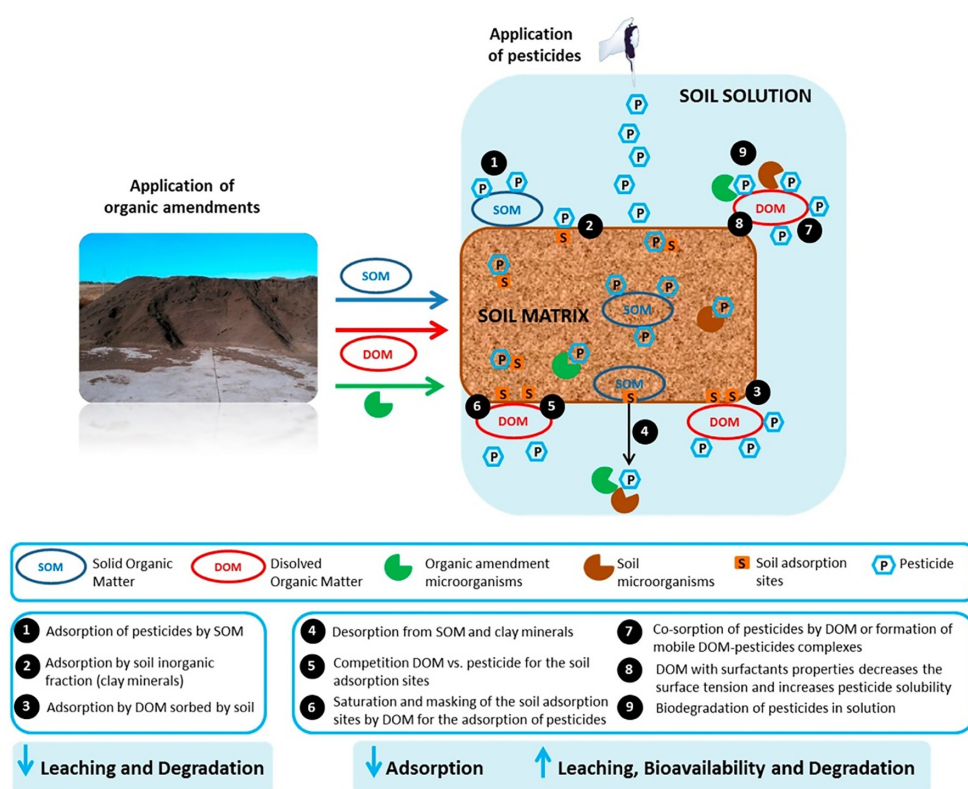


Figure 4. Conceptual diagram illustrating the role of solid organic matter (SOM) and dissolved organic matter (DOM) in controlling pesticide fate in soil, including adsorption, desorption, co-sorption, competition for binding sites, enhanced solubility, microbial degradation, and their combined effects on leaching, bioavailability, and degradation processes [46].

enhances microbial biomass and activity by providing energy and nutrient sources, thereby promoting biodegradation processes [27, 45]. In addition, DOM contributes to pesticide dynamics by influencing solubility, mobility, and interactions with soil particles.

SOM and DOM jointly regulate pesticide fate by affecting adsorption, desorption, bioavailability, and microbial degradation processes (see **Figure 4**).

As illustrated in **Figure 4**, the interaction between SOM and DOM creates a dynamic balance between pesticide retention and mobility, ultimately controlling their bioavailability and degradation potential in soil systems. This balance determines whether pesticides remain strongly sorbed and persistent or become more mobile and accessible for microbial transformation.

Organic amendments, such as crop residues, compost, and manure, can significantly increase pesticide degradation rates by stimulating microbial populations and enzymatic activity. The addition of organic materials and fertilizers has been shown to enhance the breakdown of pesticides by improving soil biological activity and nutrient availability [47, 48].

However, the relationship between SOM and pesticide degradation is not strictly linear. Increased organic matter can also enhance pesticide adsorption, reducing bioavailability and potentially limiting microbial access to the compound. This

creates a trade-off between enhanced microbial activity and reduced substrate availability [6, 25].

Microbial activity itself is a primary driver of pesticide degradation. Soil microorganisms, including bacteria, fungi, and actinomycetes, possess diverse metabolic pathways that enable the transformation and mineralization of pesticide compounds. The structure and diversity of microbial communities strongly influence degradation efficiency, and adapted communities may exhibit enhanced degradation capacity following repeated pesticide exposure [38, 40].

Thus, pesticide degradation is best understood as the result of interactions between SOM-mediated sorption processes and biologically driven transformation mechanisms, rather than purely chemical or biological processes alone.

4.3 Temperature and moisture conditions

Temperature and soil moisture are primary environmental controls on pesticide degradation, mainly through their influence on microbial activity and chemical reaction rates. Temperature regulates enzymatic activity, microbial growth, and reaction kinetics, with degradation rates generally increasing as temperature rises up to an optimal threshold [34, 49].

At low temperatures, microbial metabolism slows due to reduced enzyme activity and limited substrate transport, resulting in slower degradation. Conversely, excessively high temperatures can inhibit microbial activity or lead to microbial mortality, thereby reducing degradation efficiency. These effects are particularly pronounced in dryland environments, where temperature extremes are common [34].

Soil moisture plays an equally critical role by regulating microbial activity, oxygen availability, and solute transport. Adequate moisture enhances microbial metabolism and pesticide diffusion in the soil solution, thereby promoting degradation. However, excessive moisture can create anaerobic conditions, altering degradation pathways and potentially slowing the breakdown of certain compounds [30, 41].

The interaction between temperature and moisture is especially important in semi-arid ecosystems, where fluctuating environmental conditions create pulsed degradation patterns. Microbial activity and pesticide degradation often increase rapidly following rainfall events but decline during dry periods, resulting in highly variable degradation dynamics over time [22, 24].

4.4 Pesticide chemical structure and concentration

The intrinsic chemical properties of pesticides are fundamental determinants of their degradability, persistence, and environmental behavior. Molecular structure influences solubility, polarity, volatility, and susceptibility to chemical and biological transformation processes. For example, structurally complex and hydrophobic compounds tend to be more resistant to degradation and may persist in soil environments for extended periods [7, 17].

In contrast, more polar and structurally simple compounds are generally more susceptible to microbial degradation and chemical transformation. Functional groups such as esters, amides, and halogen substitutions play a key role in determining degradation pathways, including hydrolysis, oxidation, and enzymatic breakdown [34, 35].

Pesticide concentration also significantly affects degradation dynamics. At low concentrations, pesticides may be rapidly degraded due to efficient microbial utilization. However, at higher concentrations, toxic effects can inhibit microbial activity, leading to slower degradation rates and prolonged persistence [2, 37].

Repeated pesticide applications may lead to microbial adaptation, resulting in enhanced degradation over time. While this process can reduce pesticide persistence, it may also decrease pesticide effectiveness, creating challenges for long-term pest management strategies [38, 40].

5. Effects of pesticides on soil microbial communities

5.1 Impacts on microbial biomass and diversity

Soil microbial communities form the foundation of terrestrial ecosystem functioning, playing essential roles in organic matter decomposition, nutrient cycling, and soil structure formation. The introduction of pesticides into soil systems represents a significant chemical disturbance that can alter microbial biomass, diversity, and community composition [2, 17]. These effects depend on pesticide characteristics such as type, concentration, persistence, and application frequency, as well as soil properties and environmental conditions.

Pesticides can exert both inhibitory and stimulatory effects on soil microorganisms. Toxic compounds may reduce microbial biomass and selectively eliminate sensitive taxa, leading to decreased diversity and altered community composition. This is particularly evident for broad-spectrum pesticides that affect non-target organisms, including beneficial bacteria and fungi [9, 50]. In contrast, some microorganisms are capable of utilizing pesticides as carbon or energy sources, resulting in the enrichment of specialized degrading populations and shifts in microbial community structure [36, 38].

Recent studies indicate that pesticide exposure often results in microbial community restructuring rather than complete suppression. Resistant or adaptive species may become dominant, leading to reduced functional diversity and increased dependence on a narrower range of microbial taxa. Long-term or repeated pesticide application can, therefore, produce persistent shifts in microbial community composition, particularly in intensively managed agricultural systems [19, 20].

The effects of pesticides on soil microbial communities are especially important in Sudan because soil biological activity is already constrained in many areas by high temperatures, moisture limitations, and low organic carbon. Pesticide exposure may further reduce microbial biomass, alter microbial diversity, and disrupt enzyme activities involved in carbon, nitrogen, and phosphorus cycling [17–20, 51, 52]. These effects can have direct implications for soil fertility because microorganisms regulate organic matter decomposition, nutrient mineralization, soil aggregation, and plant–microbe interactions [2, 23, 53]. However, repeated exposure to specific pesticides may also select for adapted microbial populations capable of degrading pesticide residues more efficiently [36, 38, 40]. This suggests that Sudanese agricultural soils may contain indigenous pesticide-degrading microorganisms that could be isolated, characterized, and developed for locally adapted bioremediation strategies [39, 43].

5.2 Changes in microbial metabolic activity

In addition to structural changes, pesticides significantly influence microbial metabolic activity, which governs key soil biochemical processes. Microbial metabolism is commonly assessed using indicators such as respiration rates, enzyme activities, and nutrient transformation processes. Exposure to pesticides can inhibit enzymatic functions involved in carbon, nitrogen, and phosphorus cycling, thereby disrupting soil biochemical functioning [17, 51].

Enzymes such as dehydrogenases, phosphatases, and ureases are particularly sensitive to pesticide stress. Reductions in enzyme activity reflect impaired microbial metabolism and a reduced capacity for organic matter decomposition and nutrient mineralization. However, under certain conditions, microbial activity may temporarily increase due to stress-induced responses or the use of pesticides as metabolic substrates, particularly at low concentrations [37, 41].

Recent research shows that pesticide-induced changes in microbial metabolism can significantly affect biogeochemical cycling processes, especially nitrogen dynamics. Alterations in microbial functional groups involved in nitrification, denitrification, and nitrogen fixation may influence nutrient availability and soil fertility [19, 52]. These effects are often context-dependent and influenced by environmental conditions, pesticide characteristics, and microbial adaptation.

5.3 Implications for soil fertility and ecosystem functions

The effects of pesticides on soil microbial communities have broader implications for soil fertility and ecosystem functioning. Soil microorganisms regulate essential processes such as organic matter decomposition, nutrient cycling, soil aggregation, and plant-microbe interactions. Disruption of these processes can lead to reduced soil productivity and long-term degradation of soil quality [2, 23].

Pesticide exposure not only affects microbial degradation processes but also alters microbial community structure and soil biochemical functions, leading to cascading impacts on nutrient cycling, organic matter decomposition, and overall soil productivity (see **Figure 5**).

As illustrated in **Figure 5**, the cumulative effects of pesticide exposure extend beyond microbial degradation, influencing key soil ecosystem functions and potentially leading to long-term declines in soil health and agricultural productivity. These impacts are primarily mediated through changes in microbial activity and community composition.

One of the most significant consequences of pesticide-induced microbial changes is the alteration of nutrient cycling. Reduced microbial activity can limit the mineralization of organic nutrients, thereby decreasing the availability of nitrogen, phosphorus, and other essential elements for plant uptake. In addition, shifts in microbial community composition may affect symbiotic interactions, such as those involving nitrogen-fixing bacteria and plant growth-promoting microorganisms, ultimately influencing plant growth and ecosystem stability [14, 53].

Pesticides may also indirectly affect soil structural properties by disrupting microbial processes involved in soil aggregation and stabilization. Reduced microbial activity can weaken soil structure, increase susceptibility to erosion, and decrease water retention capacity, particularly in fragile, dryland environments [27, 28].

Furthermore, pesticide impacts extend beyond soil systems to influence broader ecosystem processes, including biodiversity, trophic interactions, and ecological

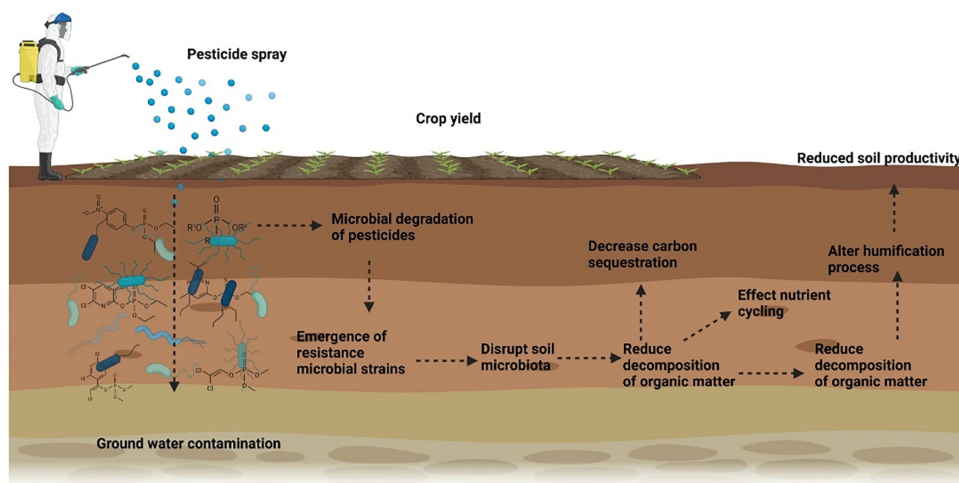


Figure 5.
Effects of pesticide application on soil microbial communities and ecosystem functions, illustrating microbial degradation, the emergence of resistant strains, the disruption of soil microbiota, and subsequent impacts on nutrient cycling, organic matter decomposition, and soil productivity [32].

resilience. Changes in microbial communities can cascade through the ecosystem, affecting higher trophic levels and overall ecosystem stability [2, 19].

From a sustainability perspective, these findings emphasize the importance of managing pesticide use within an ecosystem-based framework. Sustainable approaches should integrate ecological principles, microbial conservation, and improved management practices, including reduced pesticide inputs, organic amendments, and biological pest control strategies to maintain soil health and long-term productivity [14, 16].

6. Atrazine as a case study of persistent herbicides

6.1 Chemical characteristics and agricultural applications

Atrazine is one of the most widely used selective herbicides worldwide, particularly in the cultivation of cereal crops such as maize and sorghum. It belongs to the triazine group of herbicides and functions primarily by inhibiting photosystem II (PSII), thereby disrupting electron transport during photosynthesis and ultimately causing plant death [7, 54]. Its effectiveness, relatively low cost, and broad-spectrum weed control have contributed to its widespread adoption in both developed and developing agricultural systems [1].

From a physicochemical perspective, atrazine is characterized by moderate water solubility, low volatility, and relatively high chemical stability. These properties enhance its agronomic efficiency but also contribute to its persistence in the environment [6, 34]. Its sorption behavior is strongly influenced by SOM and clay content, while its mobility increases in soils with low adsorption capacity, particularly sandy soils [25, 29]. Consequently, atrazine exhibits dual behavior, being

retained in some soil conditions while remaining sufficiently mobile to pose contamination risks in others.

Atrazine is particularly relevant to Sudanese agriculture because herbicides are widely used in rainfed and mechanized farming systems, where weed competition strongly affects crop productivity, including crops such as sorghum and other field crops [1, 2, 22]. Its moderate solubility, persistence, and mobility make it environmentally important in semi-arid and irrigated landscapes, where rainfall pulses and irrigation may transport residues from treated fields into deeper soil layers, drainage canals, and aquatic systems [6, 7, 21, 25, 31]. Under dry or nutrient-limited conditions, atrazine degradation may be delayed because microbial activity is constrained by moisture and organic matter availability [30, 34, 55]. At the same time, repeated exposure may promote enhanced biodegradation through the selection of specialized microbial populations carrying atrazine-degrading pathways [38–40, 43]. For Sudan, this highlights the need for local studies on atrazine residues, degradation rates, metabolites, and indigenous degrading microorganisms under Sudanese soil and climate conditions [55–61].

6.2 Environmental persistence and mobility

Atrazine is widely recognized for its persistence and mobility in soil and aquatic systems, making it one of the most frequently detected herbicides in the environment. Its half-life in soil varies widely depending on environmental conditions, including temperature, moisture, soil type, and microbial activity [55, 56].

A defining characteristic of atrazine is its tendency to leach into groundwater and be transported into surface water systems. Due to its moderate solubility and relatively weak adsorption in soils with low organic matter content, atrazine is particularly susceptible to leaching under conditions of high rainfall or irrigation [6, 25]. As a result, it has been detected in rivers, groundwater, and other aquatic environments, raising concerns about environmental contamination and water quality [7, 21].

Atrazine persistence is further influenced by environmental constraints on degradation processes. In dry or nutrient-limited soils, degradation rates are reduced, leading to prolonged environmental residence. This is particularly relevant in semi-arid and savanna ecosystems, where fluctuating moisture conditions and high temperatures create complex and often delayed degradation dynamics [24, 34].

6.3 Toxicological effects on ecosystems and human health

Atrazine has been extensively studied for its ecological and human health impacts. In aquatic environments, exposure to atrazine has been shown to affect physiological and developmental processes in aquatic organisms, including invertebrates and vertebrates [9, 57]. These effects are linked to its interference with biological processes, raising concerns about ecosystem health.

In terrestrial ecosystems, atrazine can affect non-target plant species and soil microbial communities, potentially altering biodiversity and ecosystem functioning. Its persistence and mobility increase the likelihood of exposure beyond target areas, contributing to unintended ecological impacts [17, 18].

From a human health perspective, atrazine exposure may occur through contaminated drinking water, food, or occupational contact. Pesticide residues in agricultural products and environmental media raise concerns regarding long-term exposure and potential health risks, particularly in vulnerable populations [12, 21]. These concerns have led to increasing regulatory scrutiny and restrictions on atrazine use in several regions.

6.4 Metabolic pathways of atrazine degradation in soil

Atrazine degradation in soil occurs through both chemical and biological processes, with microbial degradation representing the dominant pathway under most conditions. This process involves a sequence of enzymatic reactions that transform atrazine into less complex and more polar compounds [58, 59].

The primary microbial degradation pathway begins with dealkylation reactions, producing intermediate metabolites such as deethylatrazine (DEA) and deisopropylatrazine (DIA). These intermediates may subsequently undergo hydrolysis to form hydroxyatrazine, followed by ring cleavage and eventual mineralization into carbon dioxide, ammonia, and other inorganic products [60, 61].

The efficiency of atrazine degradation is strongly influenced by soil properties and environmental conditions. Factors such as microbial activity, temperature, soil moisture, and nutrient availability play critical roles in determining degradation rates. Soils with higher organic matter content and active microbial communities generally exhibit faster degradation, whereas dry or nutrient-poor soils tend to show prolonged persistence [30, 55].

An important phenomenon associated with atrazine degradation is enhanced biodegradation, in which repeated exposure leads to the development of specialized microbial populations capable of rapidly degrading the compound. While this process can reduce environmental persistence, it may also reduce herbicide effectiveness over time, creating challenges for pest management [38, 40].

Recent advances in microbial ecology and molecular biology have identified key genes and enzymes involved in atrazine degradation. These insights improve the understanding of microbial adaptation mechanisms and provide opportunities for developing targeted bioremediation strategies aimed at reducing environmental contamination [39, 43].

7. Microbial biodegradation and sustainable remediation of pesticide-contaminated soils

7.1 Microbial degradation mechanisms

Microbial degradation represents one of the most effective and environmentally sustainable pathways for the removal of pesticide residues from soil systems. This process involves the enzymatic transformation of pesticide compounds by microorganisms, including bacteria, fungi, and actinomycetes, into less toxic or fully mineralized products such as carbon dioxide, water, and inorganic nutrients [36, 37].

Microorganisms degrade pesticides through diverse metabolic pathways, often utilizing them as sources of carbon, nitrogen, or energy. Enzymatic systems, such as oxygenases, hydrolases, and dehydrogenases, catalyze key reactions, including oxidation, hydrolysis, dealkylation, and ring cleavage, converting complex xenobiotic compounds into simpler intermediates that can be incorporated into microbial metabolic cycles [39, 59].

A critical aspect of microbial degradation is metabolic versatility and adaptation. Microbial communities exposed to repeated pesticide applications can develop enhanced degradation capabilities through genetic adaptation, including the acquisition of degradative genes or metabolic pathways. This phenomenon, often referred to as enhanced biodegradation, demonstrates the dynamic interaction between microbial communities and environmental contaminants [38, 40].

However, degradation efficiency is strongly influenced by environmental conditions. Factors such as soil moisture, temperature, pH, oxygen availability, and nutrient status regulate microbial activity and enzyme function. Under suboptimal conditions, degradation rates may be significantly reduced, resulting in prolonged pesticide persistence in soil [30, 41].

7.2 Bioremediation strategies

Bioremediation refers to the use of biological systems, primarily microorganisms, to detoxify contaminated environments. It is widely recognized as a cost-effective, environmentally friendly, and sustainable alternative to conventional physical and chemical remediation approaches [37, 62].

Bioremediation strategies are generally classified into *in situ* and *ex situ* approaches. *In situ* bioremediation treats contaminated soil directly at the site, minimizing disturbance and reducing operational costs, whereas *ex situ* approaches involve excavation and treatment under controlled conditions, allowing optimization of environmental factors such as temperature, moisture, and nutrient availability [44, 63].

Several techniques are used to enhance bioremediation efficiency. Biostimulation involves the addition of nutrients, such as nitrogen and phosphorus, to stimulate microbial growth, while environmental optimization, such as aeration and moisture management, creates favorable conditions for microbial activity. These strategies aim to accelerate pesticide degradation by enhancing microbial metabolic processes [48, 64].

Bioremediation has been successfully applied to various pesticide-contaminated environments, demonstrating its capacity to reduce environmental risks while maintaining soil functionality. However, its effectiveness depends on site-specific conditions, including soil characteristics, contaminant properties, and the composition of native microbial communities [2, 36].

For Sudan, microbial biodegradation is one of the most promising approaches for managing pesticide-contaminated soils because it is relatively low-cost, environmentally compatible, and adaptable to local soil conditions. However, its success depends on the survival and activity of pesticide-degrading microorganisms under high temperatures, fluctuating moisture, variable pH, and limited organic matter conditions [30, 36, 37, 41]. Biostimulation through organic amendments, fertilizers, aeration, and moisture management may improve degradation by increasing microbial

biomass, nutrient availability, and enzymatic activity [47, 48, 64]. Bioaugmentation using indigenous pesticide-degrading bacteria or fungi may also be more suitable than introducing non-native strains because local microorganisms are already adapted to Sudanese environmental conditions [36, 39, 43]. Therefore, future bioremediation programs in Sudan should prioritize the isolation of native degraders, testing of microbial consortia, and field validation under realistic dryland and irrigated agricultural conditions.

7.3 Phytoremediation and bioaugmentation approaches

Phytoremediation and bioaugmentation represent advanced biological strategies for enhancing pesticide degradation in soil systems. These approaches utilize plant-microbe interactions and targeted microbial interventions to improve the efficiency of contaminant removal under environmentally sustainable conditions.

Phytoremediation involves the use of plants and their associated microbial communities (the phytomicrobiome) to remove, degrade, or stabilize contaminants. Plant roots release exudates that stimulate microbial activity in the rhizosphere, creating a biologically active zone that enhances pesticide degradation. In addition, some plants can directly uptake and transform pesticide compounds, contributing to contaminant removal [53, 65].

Phytoremediation may be particularly useful in Sudan, where low-cost and ecologically based remediation options are needed for agricultural soils. Plants can enhance pesticide degradation by stimulating rhizosphere microorganisms through root exudates, increasing microbial activity, and improving soil structure [53, 65]. In pesticide-contaminated Sudanese soils, plant-assisted remediation could be combined with organic amendments to improve soil moisture retention, microbial activity, and pesticide bioavailability [45, 47, 48]. However, plant selection should consider drought tolerance, rooting depth, biomass production, compatibility with local cropping systems, and the ability to support beneficial rhizosphere microorganisms. Combining phytoremediation with bioaugmentation using indigenous pesticide-degrading microorganisms may provide a practical and sustainable strategy for improving degradation efficiency under Sudanese semi-arid conditions [39, 53, 65].

Bioaugmentation involves the introduction of specific pesticide-degrading microorganisms into contaminated soils to enhance degradation rates. Microorganisms such as *Pseudomonas*, *Bacillus*, and *Rhodococcus* possess specialized metabolic pathways that enable the breakdown of complex pesticide compounds [39]. Recent advances in microbial selection and genetic engineering have enabled the development of highly efficient, engineered microbial strains with enhanced degradation capabilities, significantly improving bioremediation performance.

As illustrated in **Figure 6**, the integration of microbial selection, genetic optimization, and gene-editing technologies enables the development of high-performance degraders capable of efficiently transforming persistent pesticide compounds. These engineered microbial systems offer promising solutions for contaminated environments where natural degradation processes are limited or insufficient.

The success of bioaugmentation depends on several factors, including the survival and adaptation of introduced microorganisms, competition with native

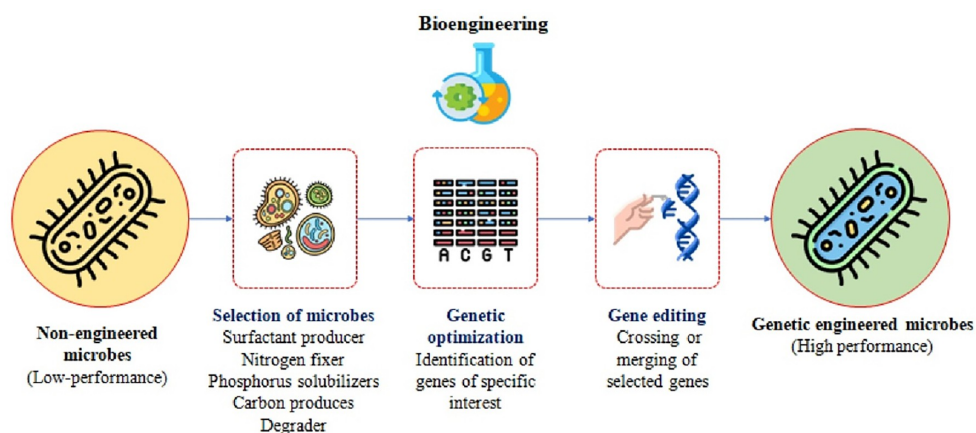


Figure 6.

Development of engineered microbial strains for enhanced pesticide biodegradation, including microbial selection, genetic optimization, and gene editing processes leading to high-performance degraders [66].

microbial communities, and prevailing environmental conditions. Advances in biotechnology have further enabled the development of robust microbial strains with enhanced degradation capabilities, offering effective solutions for highly contaminated environments [43, 67].

Despite their considerable potential, both phytoremediation and bioaugmentation require careful design and monitoring to ensure effectiveness, ecological compatibility, and long-term sustainability within soil ecosystems.

7.4 Integrated sustainable soil remediation strategies

Sustainable management of pesticide-contaminated soils requires an integrated approach that combines biological, chemical, and agronomic strategies. Rather than relying on a single remediation technique, integrated systems aim to optimize multiple processes to achieve long-term environmental restoration and soil health improvement [1, 2].

One effective strategy involves combining bioremediation with organic amendments such as compost, crop residues, and biochar. These amendments improve soil structure, increase nutrient availability, and stimulate microbial activity, thereby enhancing pesticide degradation while improving soil fertility [28, 68].

Another key approach is the implementation of IPM, which reduces reliance on chemical pesticides by incorporating biological control, crop rotation, resistant varieties, and precision application technologies. IPM minimizes environmental contamination while maintaining effective pest control and promoting ecological balance [4, 16].

Emerging technologies, including nanobiopesticides and advanced delivery systems, provide additional opportunities to improve pesticide efficiency and reduce environmental impacts. These innovations enable targeted application, reduced dosages, and improved degradation dynamics, contributing to more sustainable agricultural systems [14, 15].

Ultimately, sustainable remediation requires a holistic perspective that integrates soil science, microbiology, agronomy, and environmental management. The goal is

Sudan-specific factor	Effect on pesticide behavior	Environmental implication	Recommended action	Supporting references
Semi-arid climate and high temperature	May increase volatilization and affect chemical transformation	Loss to the atmosphere and altered persistence	Evaluate pesticide half-lives under Sudanese temperature regimes	[1, 33, 34]
Seasonal rainfall	Promotes runoff and leaching after pesticide application	Transport to canals, lowlands, and aquatic systems	Avoid applications before heavy rainfall	[25, 31]
Irrigated agriculture	Enhances vertical transport and drainage movement	Potential groundwater and drainage-water contamination	Monitor irrigation return flows and groundwater	[22, 25, 31]
Semi-mechanized rainfed farming	Large cultivated areas increase herbicide exposure	Diffuse soil contamination risk	Promote IPM and precision application	[1, 2, 16, 22]
Low or variable organic matter	Reduces microbial activity and may increase mobility	Slower biodegradation and higher leaching risk	Add compost, manure, and crop residues	[27, 28, 45, 47, 48]
Variable soil texture	Controls adsorption, retention, and leaching	Spatial variation in persistence and contamination	Map soil-specific pesticide risk	[6, 25, 29]
Weak monitoring capacity	Residues may remain undetected	Limited risk assessment and policy response	Establish residue monitoring programs	[1, 2, 12, 21]
Farmer awareness gaps	Incorrect dosage, unsafe handling, poor disposal	Occupational exposure and environmental contamination	Strengthen extension and safe-use training	[3, 4, 17]
Limited local microbial studies	Weak basis for bioremediation design	Dependence on international evidence	Isolate native pesticide-degrading microbes	[36, 39, 43]
Climate variability	Alters pest pressure and pesticide demand	Increased reliance on chemical control	Promote climate-smart IPM	[14, 16, 22–24]

Table 1.
Sudan-specific factors influencing pesticide contamination, fate, and remediation in agricultural soils.

not only to remove contaminants but also to restore soil health, maintain ecosystem functions, and ensure long-term agricultural sustainability [2, 23].

In Sudan, this integrated approach is particularly important because pesticide contamination, environmental fate, and remediation potential are shaped by the semi-arid climate, seasonal rainfall, irrigated and rainfed farming systems, variable SOM, farmer-use practices, monitoring limitations, and regulatory challenges. The major Sudan-specific factors influencing pesticide contamination, fate, and remediation in agricultural soils are summarized in **Table 1**.

8. Environmental and regulatory aspects of pesticide management

8.1 Environmental impact of non-degraded pesticides

Non-degraded pesticides represent a significant environmental concern due to their persistence, mobility, and capacity to cause long-term ecological disruption. Once released into the environment, these compounds can accumulate in soil, water, and air, interacting with physical, chemical, and biological systems across multiple spatial and temporal scales [1, 2]. Persistent pesticide residues may adsorb to soil particles, volatilize into the atmosphere, leach into groundwater, or accumulate in aquatic sediments, thereby creating multiple exposure pathways for non-target organisms [6, 25].

These processes typically result in chronic rather than acute environmental effects, characterized by cumulative impacts on ecosystem structure and function. Non-target organisms, including soil microorganisms, invertebrates, plants, and vertebrates, may experience physiological stress, reduced reproductive capacity, and altered population dynamics [9, 12]. At the ecosystem level, these impacts can lead to biodiversity loss, disruption of trophic interactions, and impairment of essential ecosystem services such as nutrient cycling and soil formation [19, 23]. Furthermore, the persistence of pesticide residues increases the likelihood of secondary contamination, where compounds are remobilized under changing environmental conditions, thereby extending their ecological footprint [25].

8.2 Bioaccumulation

Bioaccumulation is a key process through which pesticide residues concentrate in living organisms, particularly within aquatic ecosystems. This process occurs through bioconcentration, direct uptake from water, and biomagnification, where pesticide concentrations increase progressively along food chains [21, 42].

Pesticides can enter aquatic ecosystems through leaching and runoff, where they are transferred from agricultural soils into water bodies and subsequently incorporated into aquatic food webs (see **Figure 7**).

As illustrated in **Figure 7**, pesticide residues can be transferred across trophic levels, resulting in biomagnification and increased exposure risks for higher organisms, including humans. This process highlights the strong connectivity between terrestrial agricultural practices and aquatic ecosystem contamination.

The extent of bioaccumulation is largely determined by the physicochemical properties of pesticides, especially their lipophilicity and partitioning behavior. Lipophilic compounds exhibit a strong affinity for fatty tissues and, therefore, accumulate in organisms over time, increasing their persistence within biological systems [1, 7]. As these compounds move through trophic levels, from primary producers to higher-level consumers, their concentrations can increase significantly, posing risks to both wildlife and humans.

The implications of bioaccumulation are substantial. In aquatic systems, higher trophic-level organisms may experience toxic effects even at relatively low environmental concentrations. For humans, exposure occurs primarily through the consumption of contaminated food, particularly fish and other aquatic organisms, raising concerns about long-term health impacts [12, 21]. Thus, bioaccumulation

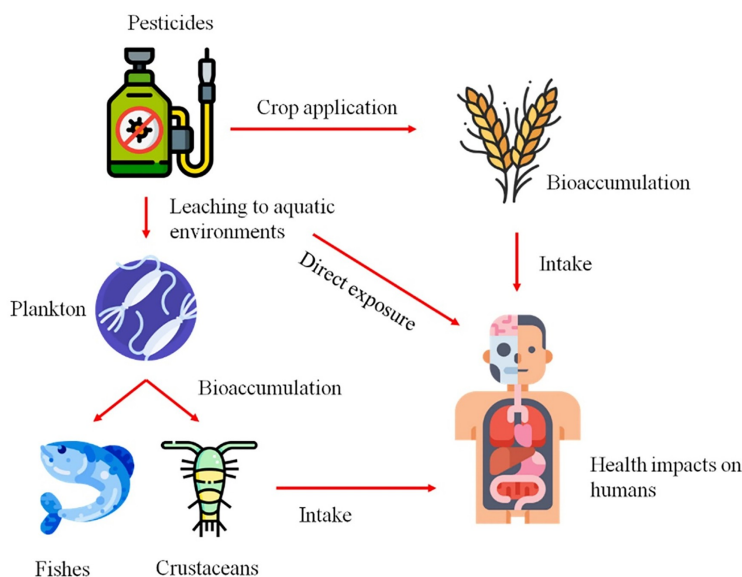


Figure 7.
 Schematic representation of pesticide transport and bioaccumulation pathways from agricultural application to aquatic ecosystems and humans, illustrating trophic transfer from plankton to higher organisms (fish and crustaceans) and subsequent human exposure through food intake and direct environmental contact [66].

represents a critical pathway linking environmental contamination to ecological and human health risks.

8.3 Impact on groundwater and ecosystems

Pesticides can enter aquatic systems through multiple pathways, including surface runoff, leaching, spray drift, and drainage flows. Once introduced into these systems, they can significantly affect groundwater quality and aquatic ecosystems [25, 31]. Groundwater contamination is particularly concerning due to its role as a primary source of drinking water and its limited capacity for natural attenuation.

In aquatic environments, pesticide exposure affects a wide range of organisms, including fish, mollusks, and benthic invertebrates. These effects may include physiological stress, reproductive impairment, and disruption of metabolic processes, ultimately leading to population declines and altered community structure [9, 57]. Sediment-associated pesticides can act as long-term reservoirs, releasing contaminants back into the water column under changing environmental conditions, thereby prolonging exposure risks [6].

Beyond individual species, pesticide contamination can disrupt key ecosystem processes such as nutrient cycling, primary productivity, and trophic interactions. The loss of sensitive species and the dominance of tolerant organisms may reduce ecosystem resilience and functional stability [2, 19]. These impacts highlight the need for sustainable pesticide management practices to protect both groundwater resources and ecosystem integrity.

Human exposure to pesticides occurs through multiple direct and indirect pathways, including ingestion, inhalation, dermal contact, and transfer through environmental media such as water, plants, and food systems (see **Figure 8**).

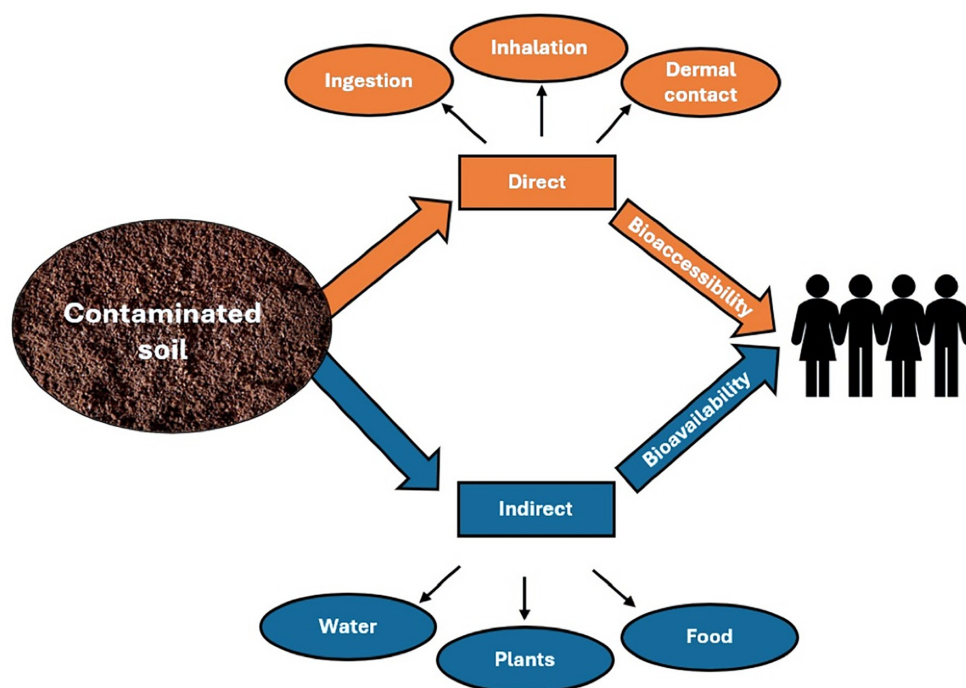


Figure 8.

Pathways of human exposure to pesticides originating from contaminated soils, illustrating both direct routes (ingestion, inhalation, dermal contact) and indirect routes through environmental media such as water, plants, and food, mediated by bioavailability and bioaccessibility processes [69].

As illustrated in **Figure 8**, human exposure to pesticide residues is governed by both direct contact and indirect pathways mediated through environmental compartments, emphasizing the importance of controlling soil contamination to protect public health.

8.4 Regulations and environmental standards

Effective pesticide regulation is essential for minimizing environmental and human health risks while maintaining agricultural productivity. Regulatory frameworks typically govern the entire pesticide lifecycle, including registration, labeling, distribution, application, storage, disposal, and the establishment of residue limits in food and environmental media [1, 2].

Environmental quality standards are also used to define acceptable concentrations of pesticides in water and soil systems, providing benchmarks for environmental protection and risk assessment. These standards are supported by monitoring programs and scientific evaluations of pesticide behavior, toxicity, and persistence [21, 42].

Despite the existence of regulatory systems, significant challenges remain, particularly in developing countries. Weak enforcement, limited monitoring capacity, and insufficient farmer awareness contribute to issues such as pesticide misuse, over-application, and environmental contamination [2, 12]. Inadequate

infrastructure for residue analysis and regulatory control further limits the effectiveness of pesticide governance.

Addressing these challenges requires strengthening institutional capacity, improving enforcement mechanisms, enhancing farmer education, and promoting sustainable pest management approaches. Strategies such as IPM, precision agriculture, and reduced-risk pesticide use are essential for balancing agricultural productivity with environmental protection [1, 16].

9. Synthesis, knowledge gaps, and future perspectives

9.1 Integrated synthesis of pesticide–soil–ecosystem interactions

The environmental behavior of pesticides in soil is governed by a complex network of interacting physicochemical, biological, and climatic processes that jointly determine their fate, transport, and ecological impact. Pesticide dynamics cannot be understood in isolation but must be evaluated within an integrated system linking soil properties, environmental conditions, microbial activity, and management practices [2, 25]. Adsorption–desorption processes regulate pesticide availability, while transport mechanisms such as leaching and volatilization determine their spatial redistribution across soil and atmospheric compartments [1, 6]. At the same time, chemical and biological degradation pathways control persistence and transformation into intermediate or mineralized products [34, 37].

A key synthesis emerging from this analysis is that bioavailability represents the central control point in pesticide dynamics. Soil properties, such as organic matter content, texture, and pH, influence both pesticide retention and microbial accessibility, thereby regulating degradation rates [28, 29]. Environmental drivers, particularly temperature and moisture, further control these processes by influencing microbial activity and reaction kinetics [31, 24]. In dryland and savanna ecosystems, where climatic variability is pronounced, pesticide behavior is highly dynamic and often characterized by pulsed degradation patterns linked to rainfall variability and soil moisture fluctuations [22, 24].

The case of atrazine exemplifies the complexity of pesticide–soil interactions. Its moderate solubility, persistence, and susceptibility to both microbial and chemical transformation make it a representative compound for understanding herbicide behavior in soil systems [7, 55]. The interaction between its mobility, degradation pathways, and ecological impacts highlights the need for integrated, system-level approaches to pesticide management.

The interactions between pesticide sources, soil processes, transport mechanisms, and biological systems can be conceptualized as a continuum linking environmental contamination to human health outcomes (see **Figure 9**).

As illustrated in **Figure 9**, pesticide contamination is not an isolated process but a continuum that links soil processes to ecological and human health outcomes, emphasizing the need for integrated management strategies.

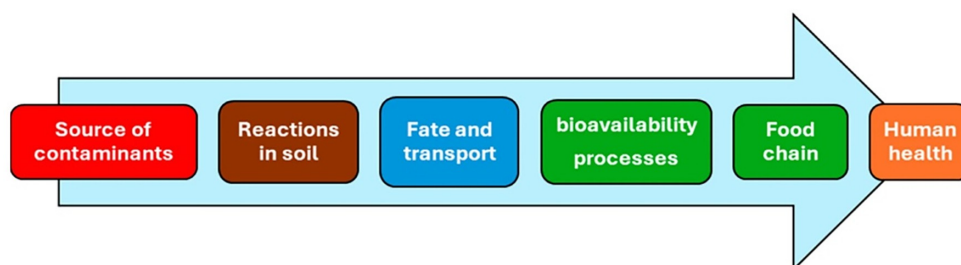


Figure 9.

Conceptual continuum illustrating the pathway from pesticide sources to human health impacts, highlighting key stages including soil reactions, environmental fate and transport, bioavailability processes, transfer through the food chain, and ultimate effects on human health [69].

9.2 Key knowledge gaps and research needs

Despite substantial progress in pesticide science, several critical knowledge gaps remain, limiting accurate prediction and sustainable management of pesticide behavior in soil systems.

First, there is a need for improved understanding of multi-scale interactions between pesticides, soil properties, and climatic drivers. Many studies are conducted under controlled laboratory conditions, which may not adequately capture the spatial heterogeneity and temporal variability of field environments, particularly in dryland ecosystems [2, 25].

Second, the role of microbial community dynamics and functional genes in pesticide degradation remains insufficiently resolved. Although advances in molecular biology have identified key degradation pathways, linking microbial diversity to functional performance under varying environmental conditions remains a major challenge [39, 43].

Third, the environmental behavior of pesticide mixtures is still poorly understood. In real agricultural systems, multiple pesticides are often applied simultaneously or sequentially, leading to interactions that may alter degradation rates, mobility, and toxicity. Current risk assessment frameworks often evaluate individual compounds, potentially underestimating cumulative and synergistic effects [19, 42].

Fourth, there is limited knowledge of the long-term ecological impacts of pesticide residues and their metabolites. Transformation products may differ significantly from parent compounds in terms of toxicity, persistence, and mobility, yet they are often insufficiently monitored or incorporated into regulatory frameworks [21, 31].

Finally, regional data gaps, particularly in Sub-Saharan Africa, including Sudan, remain a major limitation. Site-specific studies that consider local soil conditions, climate variability, and agricultural practices are essential for developing context-specific and evidence-based management strategies [2, 22].

9.3 Future directions for sustainable pesticide management

Addressing these challenges requires a transition toward more sustainable and integrated pesticide management strategies that combine advances in soil science, microbiology, and technological innovation.

One promising direction is the adoption of precision agriculture technologies, which enable targeted pesticide application based on spatial variability in crop conditions and pest distribution. These approaches can significantly reduce pesticide inputs while maintaining effectiveness [16].

The expansion of biopesticides and bio-based solutions represents another important pathway. Microbial formulations, plant-derived compounds, and biologically based pest control strategies offer environmentally friendly alternatives to synthetic pesticides, although challenges related to scalability and consistency remain [13, 14].

Advances in microbial biotechnology and genetic engineering provide opportunities to enhance biodegradation processes through the development of specialized microbial strains and optimized metabolic pathways. These innovations can improve the efficiency of bioremediation strategies in contaminated soils [43, 44].

In addition, the integration of IPM approaches is essential for reducing reliance on chemical pesticides. IPM combines biological, cultural, and mechanical control methods with optimized chemical use, promoting ecological balance and long-term sustainability [1, 4].

From a policy perspective, strengthening regulatory frameworks, improving monitoring systems, and enhancing farmer education are critical for ensuring safe and effective pesticide use. International collaboration and knowledge exchange are also necessary to address global challenges related to pesticide contamination and environmental protection [1, 2].

9.4 Future directions for sustainable pesticide management

Future research on pesticide-contaminated soils in Sudan should move from general risk description toward systematic field-based evidence. First, national and regional surveys are needed to quantify pesticide residues in agricultural soils, irrigation canals, groundwater, crop products, and sediments, especially in intensively cultivated and irrigated areas [1, 2, 12, 21]. Second, pesticide-use inventories should be developed to identify the most frequently applied active ingredients, application rates, farmer practices, storage conditions, and disposal pathways [2–4, 17]. Third, local degradation studies are required to estimate pesticide half-lives under Sudanese soil, temperature, moisture, pH, salinity, and organic matter conditions [25, 26, 30, 34]. Fourth, microbial studies should focus on isolating indigenous pesticide-degrading bacteria and fungi and evaluating their performance under semi-arid field conditions [36, 38–40, 43]. Fifth, risk assessment should integrate soil contamination, food safety, occupational exposure, water quality, and ecosystem effects [12, 17, 19, 21]. Finally, Sudan requires stronger institutional coordination among agricultural authorities, environmental agencies, research institutions, and extension services to support pesticide monitoring, farmer training, regulatory enforcement, and sustainable pest management [1, 2, 14, 16].

10. Conclusion

Pesticides remain important tools for supporting agricultural production, pest control, and food security; however, their increasing and sometimes poorly regulated use in Sudan raises significant concerns for soil quality, water resources,

food safety, microbial functioning, and ecosystem integrity. This chapter demonstrates that pesticide-contaminated soils cannot be understood only through the chemical properties of pesticides but must be interpreted within the country's specific agroecological, agricultural, and management context. Soil texture, organic matter, pH, temperature, moisture availability, irrigation practices, seasonal rainfall, pesticide-use patterns, and microbial activity interact to determine pesticide adsorption, mobility, persistence, volatilization, leaching, transformation, and biodegradation pathways.

The synthesis presented in this chapter shows that pesticide fate in agricultural soils is highly context-dependent and seasonally variable. In semi-arid and dryland systems, limited moisture and low organic matter may constrain microbial activity and slow biodegradation, whereas rainfall events and irrigation may increase runoff, leaching, and the transport of residues to drainage systems, groundwater, and nearby aquatic environments. Persistent and mobile compounds, such as atrazine, illustrate the broader risks associated with repeated herbicide application under conditions where residue monitoring, regulation, farmer awareness, and remediation capacity remain limited.

Soil microbial communities are central to pesticide dissipation and soil health. Microbial biodegradation emerges as one of the most promising and sustainable pathways for reducing pesticide residues, but its practical application remains underdeveloped. Greater attention is needed for indigenous pesticide-degrading microorganisms, microbial consortia, functional degradation pathways, SOM management, and field validation under local climatic and soil conditions. Biostimulation, bioaugmentation, phytoremediation, and organic amendments offer practical opportunities for enhancing degradation efficiency while also restoring soil fertility, microbial activity, and ecosystem functions.

Sustainable pesticide management, therefore, requires an integrated strategy that combines scientific monitoring, stronger regulatory enforcement, farmer training, safe pesticide handling, improved disposal practices, and wider adoption of IPM. Reducing unnecessary reliance on chemical inputs should be supported by biological control, crop rotation, resistant varieties, precision application, organic amendments, and climate-smart pest management approaches. These measures are essential for reducing contamination risks while maintaining agricultural productivity and protecting rural livelihoods.

Future research should prioritize field-based studies under Sudanese agroecological conditions, including pesticide-residue surveys, pesticide-use inventories, degradation-rate experiments, metabolite monitoring, microbial isolation, and risk assessment across soil, water, crops, ecosystems, and human exposure pathways. Ultimately, protecting Sudanese agricultural soils requires linking pesticide science, soil and microbial ecology, regulatory capacity, and practical farm-level management. Such integration is essential for safeguarding soil health, water resources, food safety, ecosystem stability, and long-term agricultural sustainability in Sudan.

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Conflict of Interest

The authors declare no conflict of interest.

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