

## **RESTORING CHLORPYRIFOS-CONTAMINATED LAND: A REMEDICATION RENAISSANCE**

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### **ABSTRACT**

Chlorpyrifos, a widely used organophosphate insecticide, has greatly increased agricultural output, but poses significant environmental challenges due to its persistence, ecotoxicity, and potential impacts on human health. Its significant sorption to soil particles, variable persistence, and potential for off-site transfer by runoff, erosion, and metabolite production extend risks beyond treated areas into interconnected terrestrial and aquatic ecosystems. Conventional remediation techniques frequently give little thought to long-term ecosystem restoration in favour of concentrating mostly on the removal of contaminants. The occurrence, environmental behavior, and remediation of chlorpyrifos-contaminated soils are summarized in this review, with a focus on new restoration-oriented approaches. The mechanics, effectiveness, and suitability of various remediation methods—such as microbial degradation, phytoremediation, biostimulation, and integrated ecological approaches—are evaluated critically. The impact of environmental elements such as soil characteristics, microbial interactions, and pesticide bioavailability on degrading performance is highlighted by a comparison of laboratory and field research. The review also addresses how integrated soil management techniques, plant-microbe interactions, and microbial consortia can improve degradation efficiency while fostering ecosystem rebound. This study highlights the necessity of interdisciplinary approaches that integrate biotechnology, soil science, and ecological restoration principles by placing remediation within the larger framework of sustainable land restoration. These tactics can enable sustainable management of pesticide-contaminated landscapes and help build more resilient agroecosystems.

**Keywords:** Chlorpyrifos, Degradation, Organophosphate, Pesticide, Remediation, Restoration

## **INTRODUCTION**

Modern agriculture relies heavily on synthetic pesticides to increase crop output and ensure global food security. Since its introduction in the 1960s, chlorpyrifos (O, O-diethyl O-3,5,6-trichloro-2-pyridyl phosphorothioate), an organophosphate pesticide, has been one of the most widely used substances worldwide. In addition to non-agricultural contexts, including termite management and public health initiatives, it has been used to manage a wide range of insect pests in cereals, cotton, fruits, vegetables, and plantation crops (Racke 1993; Singh and Walker 2006). Because of its toxicity, endurance, and non-selective mode of action, chlorpyrifos has become a significant environmental contaminant despite its agronomic advantages. Acetylcholinesterase activity is inhibited by chlorpyrifos, which causes neurotoxicity in insects and non-target creatures such as people, birds, aquatic animals, and soil biota (Costa 2006). Chronic exposure to chlorpyrifos has been associated with developmental neurotoxicity, endocrine disruption, and negative reproductive and cognitive impacts, especially in children, according to growing epidemiological and toxicological evidence (Rauh et al. 2011; Eaton et al. 2008). The urgency of addressing legacy pollution in agricultural soils has increased as a result of these concerns, which have led to strict regulatory actions and partial or complete bans in numerous countries.

Long-term chlorpyrifos residues in soils have been demonstrated to impair nutrient cycling, disturb microbial diversity, and suppress beneficial enzymatic activities (phosphatase, dehydrogenase), all of which led to soil degradation and ecosystem malfunctioning (Cycoñ et al. 2010; Johnsen et al. 2001). Soil degradation is a pressing global environmental issue that undermines the sustainability of ecosystems and poses significant threats to food security, public health, and overall ecological integrity (Dar et al. 2019; Srivastava and Kumar 2023). These detrimental effects on soil health have cascading impacts on agricultural productivity, potentially jeopardizing global food supplies and exacerbating malnutrition, particularly in regions where agriculture is the primary source of sustenance (Atuchin et al. 2023). The interconnection between soil health and human well-being is further underscored by the potential for soil contaminants to enter the food chain, posing direct risks to public health through the consumption of contaminated crops or livestock (Hassan Al-Taai 2021). The importance of addressing soil degradation is also emphasized by its inclusion in the UN Decade on Ecosystem Restoration, a global initiative aimed at preventing, halting, and reversing the degradation of ecosystems worldwide (Gómez-Sagasti et al. 2018; Srivastava and Kumar 2023). Therefore, addressing pesticide contamination in soils is increasingly seen as a crucial part of larger land restoration initiatives meant to maintain agricultural production and ecosystem services, in addition to being a pollution management concern.

For large-scale agricultural landscapes, conventional remediation techniques for pesticide-contaminated soils, such as excavation, landfilling, soil washing, and chemical neutralization, are frequently expensive, environmentally disruptive, and unfeasible (Vidali 2001). As a result, more

focus has been placed on environmentally friendly and sustainable remediation methods that integrate ecological recovery with pollutant removal. Because they use natural biological processes to break down pollutants, lower their bioavailability, and encourage soil restoration, biological remediation techniques like phytoremediation and bioremediation have become attractive alternatives (Singh et al. 2011; Cycoń and Piotrowska-Seget 2016b). The knowledge of chlorpyrifos breakdown routes has been greatly increased by recent developments in microbial ecology, molecular biology, and systems-based environmental approaches. The potential of biological remediation techniques has been increased by the discovery of various bacterial and fungal strains that are able to metabolize chlorpyrifos, as well as knowledge of functional genes involved in organophosphate degradation (Li et al. 2010; Yang et al. 2019). Additionally, the creation of plant-microbe synergistic systems and microbial consortia has shown encouraging promise for enhancing degradation efficiency and promoting soil ecological recovery. The "remediation renaissance," in which pesticide remediation is increasingly incorporated within larger frameworks of sustainable agriculture, soil health restoration, and land degradation neutrality, might be attributed to these developments.

In this regard, the goal of the current review is to summarize what is currently known about the ecological effects, environmental behavior, and remediation techniques related to soils polluted with chlorpyrifos. This review aims to find integrated and environmentally sustainable solutions that turn remediation from a limited pollution-control strategy into a more comprehensive opportunity for long-term soil restoration and sustainable land management by critically analyzing both traditional and cutting-edge remediation approaches.

## **METHODOLOGY FOR LITERATURE SEARCH**

This review was conducted using a systematic literature search method to ensure accuracy and reliability. Major scientific databases such as Web of Science, Scopus, PubMed, and Google Scholar were utilized to gather peer-reviewed publications. Publications from 1990 to 2025 were included in the search with keywords like "organophosphate pesticide contamination," "chlorpyrifos degradation," "chlorpyrifos bioremediation," "3,5,6-trichloro-2-pyridinol (TCP)," "soil remediation," and "integrated restoration approaches" to cover both early and recent developments in chlorpyrifos research.

Research was included if it examined the fate, transport, toxicity, or remediation of chlorpyrifos in soil systems; presented data from experiments, fields, or models; and the works were published in English. We have excluded studies that only addressed non-soil matrices or had unclear methodology. Conceptual synthesis was the main use of review articles.

## **Environmental Impact and Ecotoxicity of Chlorpyrifos**

Chlorpyrifos not only serves its intended purpose of pest control but also emerges as a significant environmental pollutant with multi-faceted ecotoxicological implications. Table 1 encapsulates the broad spectrum of detrimental effects attributed to chlorpyrifos, emphasizing the urgent need to adopt effective remediation strategies.

### **i. Ecological Risks in Terrestrial and Aquatic Habitats**

The hydrophobic organophosphate insecticide chlorpyrifos (O, O-diethyl O-3,5,6-trichloro-2-pyridyl phosphorothioate) is heavily influenced by its physicochemical characteristics and interactions with soil constituents. The strong sorption of chlorpyrifos to clay minerals and soil organic matter reduces its immediate mobility but increases its persistence, particularly in dry or low-microbial activity conditions (Racke et al. 1996; Singh et al. 2003). Strong sorption typically restricts its vertical mobility but increases permanence in surface soils, particularly in dry and low-microbial environments. Its breakdown is influenced by a number of variables, including soil pH, temperature, moisture regime, and microbial community composition (Racke et al. 1996; Fenner et al. 2013). While acidic and organic-rich soils frequently show longer persistence, alkaline soils typically promote rapid hydrolysis.

A major byproduct of chlorpyrifos degradation is 3,5,6-trichloro-2-pyridinol (TCP), which is more mobile, persistent, and equally or more hazardous to soil microbes than the parent compound. Chlorpyrifos can be carried outside of application locations by surface runoff and erosion, especially if it is bonded to sediments, despite its low solubility. Concerns regarding off-site pollution and cumulative ecological consequences at the landscape scale have been raised by studies that have shown its frequent detection in nearby water bodies and sediments (Mackay et al. 2014; Stehle and Schulz 2015). As a result, although chlorpyrifos may seem static in soil profiles, its environmental behavior is dynamic and intimately related to hydrological processes and land management techniques.

**Table 1: Environmental behaviour and ecological consequences of chlorpyrifos in soil and agroecosystems**

<b>Types of consequences</b>	<b>Key characteristics</b>	<b>Observed ecological effects</b>	<b>Implications for land degradation and restoration</b>	<b>References</b>
<b>Degradation pathways</b>	Microbial degradation and alkaline hydrolysis; formation of TCP metabolite	TCP shows higher mobility and microbial toxicity	Remediation must address both parent compound and metabolites	(Racke et al. 1996; Fenner et al. 2013)
<b>Transport mechanisms</b>	Runoff and sediment-bound transport; erosion-driven dispersal	Contamination of adjacent water bodies and sediments	Links field-scale contamination to landscape-scale ecological risk	(Mackay et al. 2014; Stehle and Schulz 2015)
<b>Physicochemical behavior</b>	Low water solubility; high K <sub>oc</sub> ; strong sorption to soil organic matter and clay fractions	Limited vertical mobility but prolonged surface persistence	Increases long-term exposure of soil biota; slows natural recovery	(Racke 1993; Singh et al. 2003)
<b>Soil microbial communities</b>	Reduced soil microbial counts; enzyme inhibition	Reduced microbial diversity, biomass, and enzymatic activity	Decline in nutrient cycling and soil fertility; delayed ecological recovery	(Cycoń et al. 2017; Karpun et al. 2021)
<b>Soil fauna (earthworms, arthropods)</b>	Inhibition of acetylcholinesterase leading to neurodegeneration	Reduced survival, reproduction, and bioturbation activity	Loss of soil (structure regulation and organic matter turnover	(Giesy et al. 1999; Wang et al. 2012)
<b>Plant–soil interactions</b>	Rhizosphere disruption; indirect phytotoxicity	Reduced root growth, nutrient uptake, and plant vigor	Weakens crop productivity and resilience of agroecosystems	(Geissen et al. 2015; Kumar et al. 2018)
<b>Agroecosystem-level effects</b>	Chronic exposure and repeated applications	Reduced biodiversity, impaired	Reinforces land degradation and dependency on external inputs	(Geissen et al. 2015; Stehle and

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2015)

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## ii. Ecological Effects on Soil Microbial Communities and Ecosystems

Soil quality depends heavily on the indigenous microbial communities that drive vital biogeochemical cycles. Applying chlorpyrifos has been shown to dramatically change the microbial diversity of the soil. Chlorpyrifos has been shown in numerous studies to alter microbial biomass, diversity, and functional activity, mainly by membrane toxicity and enzyme inhibition (Singh and Walker 2006; Cycoň et al. 2017). Shortly after application, reductions in microbial biomass carbon and nitrogen have been documented, along with decreases in important enzymatic activities such as urease, phosphatase, and dehydrogenase that are crucial for nutrient cycling (Tejada et al. 2015).

Even though some microbial communities can break down or adapt to chlorpyrifos, this adaptation frequently leads to a change in community structure rather than complete functional recovery. Reduced microbial evenness and resilience may result from the proliferation of bacteria that break down chlorpyrifos, such as *Pseudomonas*, *Enterobacter*, and *Bacillus* species, whereas sensitive taxa drop (Singh et al. 2004). A decline in microbial diversity, in turn, compromises soil fertility and thereby exerts long-term detrimental effects on crop yields and ecosystem health (Kumar et al. 2021).

## iii. Toxicological Effects on Non-Target Organisms

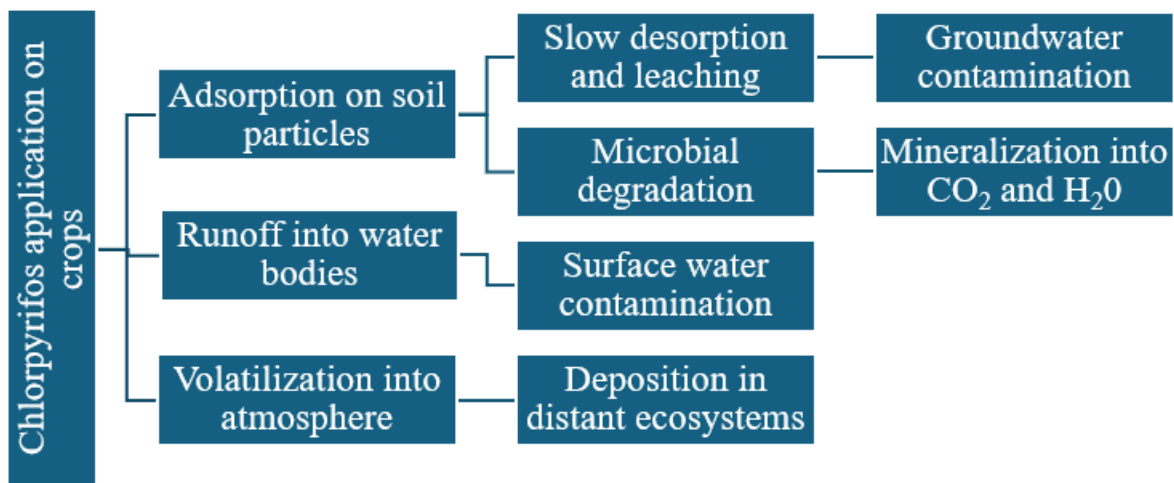
Chlorpyrifos exposure is highly poisonous to a wide range of non-target organisms, especially soil invertebrates like earthworms, collembolans, and helpful arthropods. When exposed to environmentally relevant quantities of chlorpyrifos, earthworms—which are frequently used as bioindicators of soil health—show decreased survival, growth, and reproduction (Wang et al. 2012). These consequences jeopardize soil structural stability, bioturbation, and the breakdown of organic materials.

Through trophic transfer and exposure through runoff, chlorpyrifos causes serious threats to aquatic organisms, birds, and pollinators in addition to soil fauna. Acetylcholinesterase inhibition, its neurotoxic mechanism of action, causes acute and chronic toxicity in a variety of taxa and contributes to the loss of biodiversity in agroecosystems (Giesy et al. 1999; Stehle and Schulz 2015) Research on *Drosophila melanogaster* has shown that chlorpyrifos exposure induces the generation of reactive oxygen species and reduces the levels of reduced glutathione, effectively leading to oxidative stress and mitochondrial dysfunction (Kumar et al. 2021). These biochemical alterations are considered early triggering events in neurodegeneration and have been linked to

motor dysfunction and overall diminished survival rates in these model organisms. The significance of assessing chlorpyrifos contamination in a broader ecological context, rather than as a soil-only problem, is highlighted by these non-target impacts.

**iv. Effects on Agroecosystem Functioning and Plants**

The presence of chlorpyrifos in soil can negatively impact plant growth and physiology, even though it is not mainly intended as an herbicide. It includes decreased nutrient uptake, root elongation, and seed germination, especially at higher concentrations or under repeated application regimes (Kumar et al. 2018). Plant production and health are further harmed by indirect impacts that are mediated by the disturbance of rhizosphere microbial populations. These combined effects result in decreased soil multifunctionality, impaired ecosystem services, and decreased system resilience at the agroecosystem level. Long-term use of chlorpyrifos has been linked to deteriorating soil biological quality and a greater reliance on external inputs, resulting in feedback loops that exacerbate land degradation (Geissen et al. 2015). Understanding the environmental fate and transport of chlorpyrifos is essential for effective remediation and management strategies. Various factors, including soil properties, climate conditions, and microbial activity, influence the persistence and movement of this pesticide. A simplified overview of the multi-step environmental processes affecting chlorpyrifos after its application on agricultural fields is shown in Figure 1.



**Figure 1: Flowchart depicting the fate and transport pathways of Chlorpyrifos in the environment**

Once applied, chlorpyrifos may be adsorbed by soil particles, degraded through photochemical and chemical processes, or moved into the water column through leaching (Raffa and Chiampo 2021). It is shown that soil pH profoundly influences the degradation rate of chlorpyrifos (Kumar

et al. 2021; Singh et al. 2003). In alkaline soils (pH >6.7), microbial activities responsible for degradation remain effective over extended periods, while in acidic soils, degradation is slower (Singh et al. 2003). Soil pH, organic matter content, and texture are central to the sorption and desorption dynamics of chlorpyrifos, which can limit its bioavailability for microbial degradation (Laura et al. 2013). After field application, chlorpyrifos may be transported via multiple pathways: This compound can migrate from agricultural fields to nearby water bodies during rainfall events, contributing to surface water contamination (Kumar et al. 2021; Syafrudin et al. 2021). Due to its water solubility in certain formulations, chlorpyrifos can leach through soil layers, reaching groundwater and spreading contamination (Singh et al. 2003; Syafrudin et al. 2021). In some cases, chlorpyrifos may volatilize and become part of the atmospheric particulate matter, leading to its deposition in distant ecosystems (Aktar et al. 2009).

### **Remediation Strategies for Chlorpyrifos-Contaminated Soils**

Although a variety of remediation approaches have been proposed for chlorpyrifos-contaminated soils, each method presents distinct advantages and limitations in terms of efficiency, environmental compatibility, scalability, and cost. Conventional physical and chemical methods can provide rapid contaminant reduction but are often expensive and environmentally disruptive, particularly when applied to large agricultural landscapes. In contrast, biological approaches such as bioremediation, phytoremediation, and rhizoremediation offer more environmentally sustainable alternatives but may require longer time frames and are influenced by site-specific environmental conditions. Soil amendments such as compost, farmyard manure, and biochar can further enhance microbial activity and improve degradation efficiency. A comparative overview of the major remediation strategies, including their mechanisms, effectiveness, advantages, and limitations, is presented in Table 2. This comparison highlights that no single method is universally applicable, and the effectiveness of each strategy depends strongly on environmental conditions, contamination levels, and site management practices.

**Table 2: Comparative evaluation of remediation strategies for chlorpyrifos-contaminated soils.**

Remediation Strategy	Principle / Mechanism	Effectiveness	Advantages	Limitations	References
Physical remediation	Removal of contaminated soil and replacement with clean material	High (site-specific)	Immediate reduction of contamination; technically simple	High cost; soil structure destruction; disposal issues; not scalable	(Vidali 2001)
Chemical remediation	Chemical transformation of chlorpyrifos into less toxic compounds	Moderate to High (controlled conditions)	Rapid degradation	Risk of secondary pollution; soil chemical imbalance; limited field use	(Racke 1993; Feng et al. 1998)
Bioremediation	Microbial enzymatic breakdown via organophosphate hydrolases	Moderate to High	Eco-friendly; cost-effective; improves soil health	Site-specific performance; sensitive to environmental conditions	(Singh and Walker 2006; Cycoń et al. 2010)
Bioaugmentation	Introduction of specialized chlorpyrifos-degrading microbes	High (laboratory); Variable (field)	Targeted degradation	Poor survival of introduced strains; competition with native microbes	(Singh et al. 2011)
Biostimulation	Enhancement of native microbial activity through nutrients/organic matter	Moderate	Utilizes indigenous microbes; low ecological risk	Slower response; dependent on soil properties	(Cycoń and Piotrowska-Seget 2016a,b)
Phytoremediation	Uptake, transformation, or stabilization by plants	Low to Moderate	Low cost; non-invasive; compatible with farming	Slow process; limited depth; food-chain risk	(Pilon-Smits 2005; Glick 2010)
Rhizoremediation	Plant-microbe interactions enhance degradation in the rhizosphere	Moderate	Synergistic plant-microbe effects	Requires careful plant selection	(Glick 2010)
Organic amendments (FYM, compost, green manure)	Stimulate microbial activity and enzymatic degradation	Moderate	Improves soil fertility; farmer-friendly	Over-application may cause nutrient imbalance	(Kumar et al. 2018)
Biochar-assisted remediation	Adsorption reduces mobility and	Moderate	Long-term stabilization;	Excess adsorption may reduce biodegradation	(Beesley et al. 2011)

	toxicity; improves soil structure		carbon sequestration		
Integrated remediation approaches	A combination of microbes, plants, and amendments	High	Holistic soil restoration; sustainable	Requires site-specific design and monitoring	(Cycoń and Piotrowska-Seget 2016b)

### **Chlorpyrifos Remediation by Traditional Approaches**

Traditional strategies included physical and chemical techniques. Physical remediation techniques like excavation, soil replacement, and containment have been applied primarily in heavily contaminated or localized sites. However, it is economically expensive, disruptive to soil structure, and impractical for large agricultural landscapes (Vidali 2001). Chemical remediation strategies focus on accelerating the degradation or transformation of chlorpyrifos through chemical reactions such as oxidation or hydrolysis. Alkaline hydrolysis and the use of oxidizing agents (e.g., hydrogen peroxide, permanganate) have been shown to enhance chlorpyrifos breakdown under controlled conditions (Racke 1993). However, these methods often alter soil physicochemical properties, may generate toxic intermediate compounds, and can negatively affect soil microbial communities (Racke et al. 1996). Moreover, these methods are often costly, energy-intensive, and disruptive to soil structure, organic matter pools, and microbial communities (Alexander 1999; Brusseau et al. 2019; Feng et al. 1998).

These traditional methods tend to evaluate success solely through reductions in contaminant concentration, overlooking functional indicators such as microbial activity, nutrient cycling, and soil aggregation. This narrow viewpoint has led to a growing understanding that, especially in intensively managed agroecosystems, pollution reduction is not enough to provide sustainable land restoration. As a result, biological and nature-based remediation strategies that concurrently focus on ecological restoration and pollution removal have received more attention.

### **Biological Approaches: Bioremediation, Phytoremediation, and Rhizoremediation**

Bioremediation, phytoremediation, and rhizoremediation are examples of biological remediation techniques that have become environmentally acceptable substitutes for dealing with pesticide contamination in soils. These methods improve the ecological health of the soil by using the metabolic capacities of plants and microbes to break down, change, or stabilize pollutants. Plants are used in phytoremediation techniques to help stabilize or change contaminants in soils and sediments (Srivastava and Bharti 2023). Plant roots can indirectly promote pesticide breakdown by generating root exudates that increase microbial activity and improve soil structure, even though plants seldom absorb large amounts of chlorpyrifos directly (Pilon-Smits 2005). Therefore,

the rhizosphere functions as a biologically active zone where interactions between microbes and plants speed up the breakdown of contaminants.

Chlorpyrifos-degrading microorganisms, both native and foreign, have been shown in numerous studies to greatly improve pesticide dissipation in soil conditions. Strong degrading capabilities have been proven by bacterial genera like *Pseudomonas*, *Bacillus*, and *Enterobacter*, which are commonly employed in bioremediation investigations (Singh and Walker 2006; Cycoń et al. 2017). Through enzymatic hydrolysis and metabolic transformation pathways, these microbes break down chlorpyrifos into less hazardous intermediates or mineralized products.

**Table 3: Key microbial strains/consortium and their roles in the bioremediation of Chlorpyrifos (CPF) and its derivative 3,5,6-trichloro-2-pyridinol (TCP).**

Microbial Strain/consortium	Key Function	Degradation Efficiency	References
<i>Pseudomonas putida</i>	CPF degradation	Produces organophosphorus hydrolases; high tolerance to CPF; effective in liquid and soil systems	(Liu et al. 2016; Kumar et al. 2020)
<i>Pseudomonas aeruginosa</i>	Degradation and plant growth promotion	Promote plant growth via enhanced nutrient solubilisation	(Singh et al. 2004; Verma et al. 2022; Yadav et al. 2024)
Mixed bacterial isolates ( <i>Pseudomonas</i> , <i>Bacillus</i> , <i>Alcaligenes</i> , <i>Brevundimonas</i> ) consortia	Degradation by a multi-genera consortium	Consortia showed up to ~92 % CPF degradation; consortia outperform individual isolates.	(Wepukhulu et al. 2024; Singh and Srivastava 2025)
<i>Klebsiella pneumoniae</i>	Degradation in both liquid and soil	Significant degradation between 25-100 ppm	(Mary John, and Rebello 2014)
Bacterial consortium ECO-M ( <i>Agrobacterium tumefaciens</i> ECO1, <i>Cellulosimicrobium funkei</i> ECO2, <i>Shinella zoogloeoides</i> ECO3, <i>Bacillus aryabhatai</i> ECO4)	Multi-strain CPF degrading consortium	At an initial 50 mg L <sup>-1</sup> CPF, degraded 100 % within ~6 days; also degraded TCP and produced intermediate 2-hydroxypyridine (GC-MS verified)	(Uniyal et al. 2021)
<i>Aspergillus terreus</i> (ERM C-1)	Fungal-assisted degradation	Synergistic effect when combined with bacteria	(Fierro et al. 2009)

<i>Xanthomonas sp.</i> and <i>Rhizobium sp.</i>	Dual degradation of CPF and TCP	Effective in metabolizing and reducing toxicity	(Rayu et al. 2017)
<i>Cupriavidus nantongensis</i> (X1 <sup>T</sup> )	Efficient CPF and TCP degradation	Degrades CPF rapidly and can simultaneously metabolize chlorpyrifos and its hydrolysis product TCP with high activity.	(Shi et al. 2018; Yang et al. 2019)
<i>Bacillus cereus/ Bacillus subtilis</i>	Fast CPF degradation	Spore-forming; resilient under field conditions; produces esterases and phosphatases.	(Farhan et al. 2021; Zhang et al. 2021; Kumar et al. 2023)

By transforming the pesticide and its main metabolite, 3,5,6-trichloro-2-pyridinol, into less dangerous substances, microbial strains and consortia are especially crucial to the detoxification of chlorpyrifos. Table 3 summarizes a number of important microbial strains and consortia involved in the breakdown of chlorpyrifos.

The effectiveness of microbial degradation varies greatly among microbial consortia and strains. Through enzyme-mediated hydrolysis, certain organisms like *Pseudomonas putida*, *Bacillus* species, and *Klebsiella pneumoniae* can break down chlorpyrifos. However, because of the synergistic metabolic interactions between several species, microbial consortia frequently show better degradation efficiency. For instance, the engineered ECO-M consortium completely degraded 50 mg L<sup>-1</sup> chlorpyrifos in six days while concurrently metabolizing the toxic intermediate TCP, whereas mixed bacterial consortia have shown degradation efficiencies of up to roughly 92% (Uniyal et al. 2021; Wepukhulu et al. 2024; Singh and Srivastava 2025).

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Similar to this, bacterial species such as *Pseudomonas*, *Bacillus*, *Cupriavidus*, and *Klebsiella* can metabolize TCP, the principal hydrolysis product of chlorpyrifos, and break it down via organophosphorus-degrading enzymes (Racke 1993; Singh and Walker 2006; Li et al. 2010; Yang et al. 2019). By increasing the bioavailability of pesticides and secreting extracellular enzymes

that speed up breakdown processes, fungi, especially *Aspergillus* and *Trichoderma*, further aid in the decomposition of chlorpyrifos (Vidali 2001; Singh and Walker 2006).

Crucially, compared to individual strains, microbial consortia and rhizosphere-associated microbial communities frequently show higher operational stability in field settings. These communities assist the sustainable repair of soils contaminated with chlorpyrifos by integrating complementary metabolic pathways, improving soil microbial recovery, and lowering residual toxicity (Johnsen et al. 2001; Dar et al. 2019; Gómez-Sagasti et al. 2018).

Soil supplements are an essential component of chlorpyrifos cleanup, in addition to microbiological methods. Pesticide breakdown is accelerated by organic amendments such as compost, green manure, and farmyard manure because they increase microbial biomass and enzymatic activity (Kumar et al. 2018). Because they can adsorb chlorpyrifos, lowering its mobility and bioavailability while enhancing soil structure and water retention, carbon-rich compounds like biochar have also drawn more attention. However, too much sorption by biochar can restrict microbial access to chlorpyrifos, which could impede biodegradation. In order to balance immobilization and degradation processes, amendment-assisted remediation must be carefully optimized (Beesley et al. 2011).

High chlorpyrifos breakdown efficiency under controlled conditions are often reported in laboratory investigations, it is still difficult to translate these findings to field settings. Degradation efficiency in natural systems is frequently lowered by environmental unpredictability, soil heterogeneity, microbial competition, varying moisture levels, and nutrient constraints. For instance, under ideal laboratory settings, degradation efficiencies over 90% have been observed (Uniyal et al. 2021; Wepukhulu et al. 2024), while ecological limitations frequently result in poorer field-scale performance (Singh et al. 2011). Therefore, strong microbial strains, efficient microbial consortia, and favorable environmental conditions that encourage continuous degrading activity are necessary for successful field-scale restoration.

### **Integrated and Sustainable Remediation Approaches**

In order to simultaneously remove toxins and restore soil ecological processes, integrated remediation techniques that incorporate phytoremediation, microbial degradation, and soil amendments are becoming more and more supported by recent research. Integrated remediation approaches that combine microbial degradation, plant–microbe interactions, and soil amendments are increasingly considered the most sustainable option for restoring contaminated soils (Cycoń and Piotrowska-Seget 2016a). As summarized in Table 2, integrated systems generally outperform single remediation strategies by simultaneously promoting contaminant degradation and soil ecological recovery. Cutting-edge advancements in chlorpyrifos remediation are represented by emerging hybrid remediation technologies, such as enzyme-assisted degradation, nano-enabled

delivery systems, and controlled-release microbial formulations (Dar et al. 2019; Fenner et al. 2013; Wang et al. 2021). Through increased contaminant bioavailability, focused catalytic activity, and defense against microbial or enzymatic agents, these strategies seek to improve degradation efficiency (Kumar et al. 2020; Yang et al. 2019).

However, concerns about ecological safety, long-term environmental effects, and field-scale performance have prevented these technologies from being widely adopted (Geissen et al. 2015; Karpun et al. 2021; Stehle and Schulz 2015). In order to ensure compatibility with long-term soil health objectives, the integration of advanced remediation technologies into restoration-oriented frameworks necessitates careful evaluation based on sustainability indicators and ecological risk assessment (Gómez-Sagasti et al. 2018; Brusseau et al. 2019).

### **Scaling up from Remediation at the Field Level to Landscape Restoration**

The realization that chlorpyrifos pollution is entrenched in interconnected agricultural landscapes rather than isolated fields is a defining characteristic of the "remediation renaissance." Therefore, landscape-level strategies like vegetative buffer strips, artificial wetlands, and diverse cropping systems are examples of integrative solutions that go beyond plot-scale interventions. These characteristics improve biodiversity and the supply of ecosystem services while lowering the off-site transport of chlorpyrifos through runoff and erosion (Stehle and Schulz 2015; Geissen et al. 2015).

Integrative techniques support more general sustainability objectives, such as food security, biodiversity conservation, and climate resilience, by coordinating remediation with agroecology and soil restoration concepts. Crucially, multifunctional measures, including soil biological activity, carbon sequestration, and hydrological management, replace residue reduction alone as success metrics. A paradigm shift from merely technological pollution control to ecologically aware restoration solutions is necessary for the effective rehabilitation of chlorpyrifos-contaminated land, according to the collective evidence. By encouraging long-term ecological recovery, integrated systems that incorporate microbial degradation, soil supplements, and landscape management often outperform traditional remediation techniques.

### **Socioeconomic Viability and Policy Implications**

The large-scale adoption of integrated remediation strategies depends not only on technical efficiency but also on cost-effectiveness, farmer acceptance, and policy incentives. Biological approaches such as compost amendment, crop rotation, and biochar application are comparatively low-cost and compatible with smallholder systems, particularly in tropical regions. However, advanced nano-enabled or enzyme-assisted systems may remain economically prohibitive without governmental subsidies. Policy integration with soil health missions, sustainable agriculture

schemes, and ecosystem restoration programs (e.g., UN Decade on Ecosystem Restoration) could facilitate implementation. Incentivizing farmer adoption through carbon credits, soil health certification programs, and residue monitoring frameworks may accelerate transition toward restoration-based remediation.

## **CONCLUSION**

The environmental behavior, ecological effects, fate and transport dynamics, and remediation techniques related to soils polluted by chlorpyrifos are summarized in this paper. Evidence suggests that full ecological recovery may not always follow decreases in chlorpyrifos concentrations because soil microbial populations and nutrient cycling systems may still be compromised even after chemical dissipation. When remediation tactics are critically examined, it is evident that integrated biological and restoration-oriented approaches have replaced traditional physical and chemical treatments. Microbial degradation, phytoremediation, and amendment-assisted remediation are examples of biological remediation strategies that have the ability to simultaneously lower pollutant levels and restore soil ecological services such as organic carbon storage, enzymatic activities, and microbial activity. The necessity to transition from plot-scale cleanup to landscape-level restoration solutions is further highlighted by the interrelated fate and transport pathways of chlorpyrifos across agricultural landscapes. In order to reduce contaminant dissemination and promote ecosystem recovery, strategies like vegetative buffers, diverse cropping systems, and soil conservation techniques are crucial.

However, there are still a number of unanswered questions, especially in the areas of long-term field validation, interactions between various pesticide residues, and the socioeconomic viability of restoration-based remediation techniques in smallholder agricultural systems. Interdisciplinary methods that incorporate soil science, microbial ecology, agronomy, and environmental policy will be necessary to address these issues.

Overall, this review emphasizes the need for a paradigm shift in chlorpyrifos management—from narrow pollution control toward comprehensive ecological restoration frameworks. Chlorpyrifos-contaminated land can be transformed from a legacy of chemical dependency into a route toward resilient and sustainable agricultural landscapes by coordinating remediation techniques with soil health restoration and ecosystem service recovery.

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### **Authors' contributions**

Both authors contributed to the study conception and design. The first draft of the manuscript was written by Sanyam and concept was given by Rajani Srivastava, supervisor of his work. All authors read and approved the final manuscript.

### **Conflicts of Interest**

The authors declare no competing interests.

### **Data Availability Statement**

The authors declare that the data supporting the findings of this study are available within the manuscript.

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