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Review

Pesticide Degradation by Soil Bacteria: Mechanisms, Bioremediation Strategies, and Implications for Sustainable Agriculture

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Abstract

Modern agriculture relies on pesticides for pest management and yield improvement; however, pesticide soil persistence creates major environmental and health threats through bioaccumulation, groundwater contamination, and harm to non-target organisms. This comprehensive review synthesizes current research findings on pesticide breakdown by soil bacteria and discusses their mechanisms and implications for sustainable agriculture. The persistence of pesticide classes, including organophosphates, carbamates, pyrethroids, neonicotinoids, triazines, and organochlorines, in soil varies from days to years, based on chemical structure and environmental conditions. Soil bacteria *Pseudomonas*, *Rhodococcus*, *Arthrobacter*, and *Bacillus* break down these compounds using enzymatic pathways, including hydrolysis, oxidation, and nitroreduction, while plasmid-encoded genes and horizontal gene transfer boost soil bacterial efficiency. Pesticide degradation rates are heavily influenced by environmental factors, including pH, temperature, moisture, and organic matter, as optimal conditions enhance microbial activity, whereas stressors like drought act as inhibitors. Bioremediation methods, including natural attenuation, bioaugmentation, and synthetic consortia, offer environmentally friendly solutions, with omics technologies and synthetic biology enabling the development of better degraders. Combining microbial isolation techniques with kinetic assays and metagenomics enables researchers to identify pathways. The use of modified soil bacteria in agriculture adheres to regulatory standards, ensuring safety while addressing scalability issues in developing regions. Bacterial pesticide breakdown reduces residue levels, enhances soil fertility, and supports resilient agroecosystems. Field-scale validation and AI-driven predictive models are essential for optimizing degradation under climate change conditions and demonstrate solutions as an interdisciplinary approach to mitigate pesticide impacts and support sustainable agriculture.

Keywords: soil bacteria; pesticide degradation; bioremediation; soil bacterial enzymes; sustainable agriculture; omics technologies; synthetic biology

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1. Introduction

Modern agriculture depends on pesticides to enhance crop production while managing pests, weeds, and diseases [1,2]. However, their widespread use causes significant environmental and health problems, including soil and water contamination, damage to food chains, non-target organisms, and human health [3,4,5,6]. Persistent pesticides, including organophosphates, carbamates, pyrethroids, and neonicotinoids, accumulate in living organisms and cause long-lasting ecological harm[4,5]. The need for sustainable solutions has positioned degradation by soil bacteria as a natural and eco-friendly approach [7,8,9]. Soil bacteria possess diverse metabolic functions, enabling them to decompose complex pesticide compounds into less toxic substances through enzymatic processes [10,11,12]. This review explores pesticide degradation mechanisms by soil bacteria, their pathways, environmental factors influencing these processes, bioremediation strategies, and their impact on sustainable agriculture. Drawing on recent studies, it highlights the progress in omics technologies and synthetic biology and regulatory challenges [13,14,15,16]. Recent field studies show that soil bacteria play a vital role in breaking down pesticide residues in both tropical and temperate farming systems, helping to support global sustainability efforts[9,16,17].

The urgency of soil bacteria-based remediation is underscored by global reports indicating escalating pesticide usage and associated risks, as evidenced by the UNEP's Global Chemicals Outlook, which calls for innovative solutions for managing contaminants [18]. Research on endocrine-disrupting pesticides reveals their dual threat to reproductive health and biodiversity, positioning bacterial degradation as a critical countermeasure [8]. Isolating degraders from contaminated sites, such as sugarcane farms, demonstrates how indigenous bacteria, like those degrading chlorpyrifos, can be used for targeted bioremediation practices [19].

2. Pesticide Classes and Environmental Persistence

Major pesticide categories are classified by chemical composition and mode of action, including organophosphates (e.g., chlorpyrifos), carbamates (e.g., carbofuran), pyrethroids (e.g., cypermethrin), neonicotinoids (e.g., imidacloprid), triazines (e.g., atrazine), and organochlorines (e.g., DDT, endosulfan) [20,21,22,23,24,25]. Their half-lives vary significantly for soil persistence, as shown in Table 1, with glyphosate exhibiting a short half-life of 3–5 days, while organochlorines persist for 2–15 years. Neurotoxic organophosphates and carbamates inhibit acetylcholinesterase activity, persisting in soils for weeks to months, depending on environmental factors [26,27]. Pyrethroids, synthetic analogs of pyrethrins, possess hydrophobic properties and persist for several months to years in anaerobic soils, causing aquatic toxicity [28,29,30]. Systemic neonicotinoids dissolve easily in water, leading to groundwater contamination and extended exposure risks for pollinators [31,32,33]. The herbicide atrazine, a triazine, exhibits a moderate persistence of 60–100 days and often contaminates surface water bodies [34]. Organochlorines, owing to their stability, persist in the environment, despite restrictions on their use [3]. Pesticide persistence is influenced by soil organic matter content, pH levels, and microbial activity, with some pesticide metabolites becoming resistant to degradation, exacerbating pollution [22,33,35,36,37,38,39]. These residues are widespread, impacting natural environments [25,40].

Phenylpyrazoles and sulfonylureas exhibit rapid degradation under high temperatures but elevated leaching risks, as observed in field studies [41,42,43]. Glyphosate exhibits strong binding to soil particles, but its potential to contaminate groundwater remains a concern, necessitating integrated monitoring [35,36]. Neonicotinoid persistence varies between regions, as shown in Colombian tomato production research, which found higher residue levels in greenhouses than open fields [20]. Table **1** illustrates pesticide classes, their half-lives, and persistence categories, highlighting their environmental behaviors.

Table 1. Pesticide classes and their environmental persistence.

Pesticide class	Representative compounds	Average soil half-life (DT_{50})	Persistence category	Sources
Organophosphates	Chlorpyrifos, Parathion	30-60 days	Moderate	[27,44]
Carbamates	Carbofuran, Aldicarb	10-50 days	Low to Moderate	[23,45]
Pyrethroids	Cypermethrin, Permethrin	30-100 days (up to years in anaerobic conditions)	Moderate to High	[29,30,46]
Neonicotinoids	Imidacloprid, Acetamiprid	40-150 days (dry conditions longer)	Moderate	[31,32,33,47,48]
Triazines	Atrazine, Simazine	60-100 days	Moderate	[34,49]
Organochlorines	DDT, Chlordane	2-15 years	High	[3,12]

Others (e.g., Glyphosate)	Glyphosate	3-5 days (variable)	Low	[35,36]

3. Bacterial Taxa Involved in Pesticide Degradation

Soil bacteria are the primary agents of pesticide breakdown in soil, with various species in contaminated sites exhibiting diverse degradation capabilities [9,10,11]. Table 2 presents key genera, including *Pseudomonas*, which degrades organophosphates and pyrethroids through hydrolytic enzymes [10,50,51,52]. *Rhodococcus* species, such as *R. koreensis*, degrade endosulfan and triazines, producing metabolites like endosulfan diol monosulfate [53,54]. *Arthrobacter* strains, such as *A. aurescens* and *A. sp*. AD26, mineralize s-triazines like atrazine via dechlorination and ring cleavage [52,55].

Table 2. Microbial taxa involved in pesticide degradation.

Bacterial genus/Species	Pesticides Degraded	Mechanism/Notes	Sources
Pseudomonas	Organophosphates, Pyrethroids, DDT, Phenolics	Hydrolysis, Oxidation, genetically modified for phenolics; consortia synergy	[10,50,51,52]
Rhodococcus	Endosulfan, Triazines, Chlorpyrifos	Oxidative enzymes, Monooxygenases Ring Cleavage, Metabolite Formation	[53,54,56,57]
Arthrobacter aurescens TC1	Atrazine, S-Triazines	Specialized hydrolytic pathways, Dechlorination	[52,55,58]
Bacillus	Pyrethroids, Diphenyl Ethers, Carbamates	Esterase Activity, Nitroreduction; ~85% triazoles; consortia enhance rates	[57,59,60,61,62]
Burkholderia	Parathion, Carbofuran, Various Organochlorines	Hydrolases, Oxidases, Broad-Spectrum Degradation; cometabolism with plants	[9,11,63,64]
Flavobacterium	Organophosphates	Hydrolysis	[9,10,11]
Klebsiella	Neonicotinoids, Chlorpyrifos	Esterases	[39,65,66]
Novosphingobium	PAHs, Sulfonylureas, Neonicotinoids	Dioxygenases, Hydrolysis	[67]
Acinetobacter	Neonicotinoids, Diazinon, Organophosphates	Esterases, Hydrolysis; up to 80% diazinon removal in lab settings	[39,65,68]
Streptomyces	DDT,Endosulfan, Diflufenican Carbamates, Organophosphates	Esterases, Cometablolic processes Actinobacterial Degradation	[39,47,69]
Sphingomonas	Neonicotinoids, Sufonylureas	Oxidases, Hydrolysis, genetically modified for carbamates/organophosphates; biofilm enhances stability	[28,70]
Stenotrophomonas	Neonicotinoids, Sufonylureas	Hydrolysis, Cometabolism	[43,71]
Alcaligenes	Organochlorines	Reductive, Dechlorination	[72]
Achromobacter	Triazines	Hydrolysis, Ring Cleavage	[29,73]
Paracoccus	Pyrethroids	Ester Hydrolysis	[43,74]

Bacillus species, including *B. subtilis* and *B. sp.* Za, degrade pyrethroids and diphenyl ethers through esterase activity and nitroreduction [57,59,60,61]. *Actinobacteria*, such as *Streptomyces*, participate in the degradation of carbamates, organophosphates, and other pesticides [47]. *Azotobacter* isolates from sugarcane soils remediate chlorpyrifos and other toxic pesticides [16]. These bacterial

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taxa often thrive in pesticide-enriched environments, adapting via horizontal gene transfer and plasmid-encoded degradative genes [15,63,75]. Research in malaria-endemic regions demonstrates simultaneous degradation of DDT and pyrethroids by indigenous bacteria [3,15]. This degradation process is enhanced by fungal-bacterial interactions, but bacteria remain the primary agents for rapid mineralization [9,26]. Recent studies have revealed additional bacterial genera, including *Sphingomonas* and *Alcaligenes*, which can break down neonicotinoids and organochlorines through oxidative and reductive pathways. These findings broaden our understanding of the diversity of pesticide-degrading soil bacteria[28,39,76].

Figure ***1*** illustrates detailed pathways of microbial pesticide degradation.

Genomic analysis of metaldehyde-degraders shows that different strains share similar pathways, suggesting selection pressure drives degradative capabilities [75]. *Rhodococcus* and other endosulfan degradation capabilities of earthworm gut isolates demonstrate their adaptation to specific ecological niches [54]. Recent global perspectives highlight the diversity of microbial degraders, with new isolation techniques identifying strains for recalcitrant compounds [11,26]. Key bacterial genera, their pesticide targets, and degradation processes are presented in Table **2**.

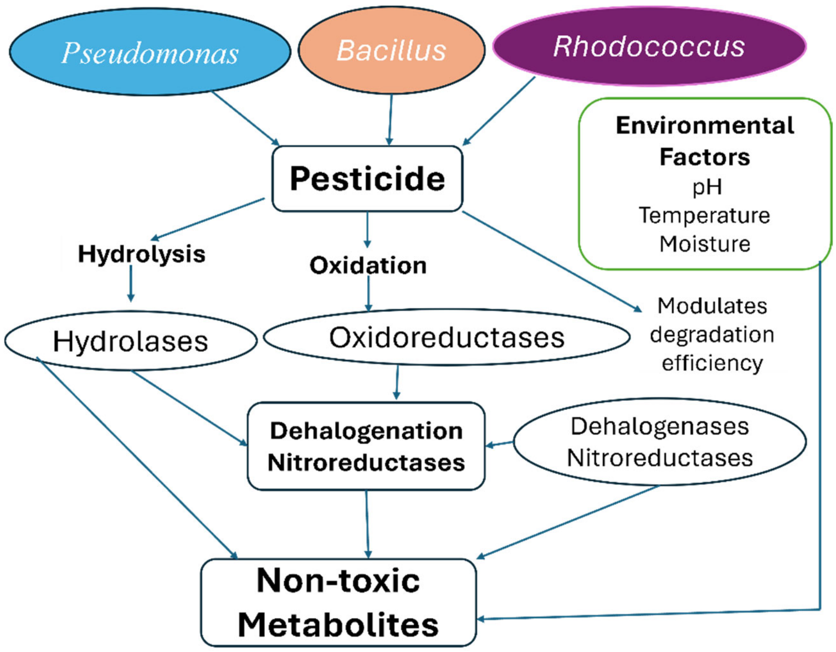

Figure 1. Microbial Pesticide Degradation Pathways.

4. Enzymatic and Genetic Mechanisms of Degradation

Soil bacteria degrade pesticides through enzymatic reactions that cleave chemical bonds via oxidation and hydrolysis [10,22,23,77]. Table 3 outlines key enzyme classes and their roles in pesticide degradation. Phosphotriesterases in *Pseudomonas* cleave P-O bonds in organophosphates, yielding non-toxic alcohols and acids [10,78,79]. Carbamate degradation occurs through carboxylesterases and amidases, with microbial genomes conserving motifs that enable ring [23,45,77]. Pyrethroids undergo initial ester hydrolysis by carboxylesterases before being oxidized into carboxylic acids [29,46,56]. Neonicotinoids are metabolized via nitroreduction and demethylation by *Rhodococcus* and *Bacillus* using nitroreductases [39,80,81]. Genetic mechanisms include plasmid-borne operons (e.g., opd for organophosphates) and chromosomal genes (e.g., atz for atrazine degradation in *Pseudomonas* and *Arthrobacter*) [52,55].

Metagenomic analyses reveal that CRISPR-Cas systems enable microbes to adapt to environmental conditions [82]. Pesticide degradation via cometabolism occurs when pesticides serve as carbon sources, with 3,5,6-trichloro-2-pyridinol from chlorpyrifos undergoing further

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mineralization [15]. Synthetic biology clarifies these mechanisms through gene knockouts, showing esterases' pivotal role in multi-pesticide degradation [77,83]. Laccase-assisted systems can degrade recalcitrant pesticides [84]. Studies have identified cytochrome P450 monooxygenases in Sphingomonas and Alcaligenes, which enable the oxidative breakdown of neonicotinoids and organochlorines, respectively, thereby expanding the enzymatic toolkit available for bioremediation [29,85,86]. Carbamate degradation exhibits evolutionary conservation across microbes via hydrolysis and oxidation, central to detoxification [23]. Organophosphate-degrading enzymes extend beyond remediation, serving as medical countermeasures for poisoning [87]. Studies of pyrethroid catalysis demonstrate how microbial adaptation enhances degradation efficiency [46].

Table 3. Enzymatic mechanisms of pesticide degradation.

Enzyme class	Pesticide type	Mechanism	Bacterial examples	Sources
Phosphotriesterases / Organophosphorus hydrolases (PTE/OPH)	Organophosphates (e.g., chlorpyrifos, diazinon, methyl parathion)	Hydrolysis of P-O bonds	*Pseudomonas Roseomonas, Sphingobium, Bacillus, Arthrobacter*	[10,78,79,88,89]
Carboxylesterases / Esterases	Carbamates, Pyrethroids	Ester hydrolysis, Ring opening	*Bacillus, Pseudomonas, Rhodococcus, Acinetobacter, Stenotrophomonas*	[21,29,46,56]
Nitroreductases	Neonicotinoids, Diphenyl ethers, Nitroaromatic	Nitroreduction, Demethylation, Nitroreduction	*Bacillus, Rhodococcus Arthrobacter, Enterobacter, Klebsiella*	[39,80,81]
Cytochrome P450 Monooxygenases/ Other Monooxygenases	Neonicotinoids, Organochlorines, Pyrethroids, Fungicides	Oxidative degradation (hydroxylation, dealkylation, N-oxidation)	*Sphingomonas, Alcaligenes, Pseudomonas, Bacillus, Streptomyces*	[90,91,92,93]
Amidases/Hydrolases	Carbamates, Triazines	Amide bond cleavage	*Arthrobacter, Pseudomonas, Burkholderia, Variovorax, Paenarthrobacter*	[23,45,52,94]
Oxidases (e.g., Laccases, Peroxidases, Multicopper oxidases)	Recalcitrant Pesticides, Aromatics, Dyes	Oxidation of aromatic rings, radical-mediated reactions	*Pseudomonas, Ochrobactrum, Bacillus, Azospirillum, Streptomyces*	[83,84,95,96,97]

5. Environmental Factors Affecting Degradation

Pesticide degradation rates in soil ecosystems are controlled by abiotic and biotic factors [5,20,49], as shown in Table **4**. Pyrethroid persistence increases in acidic conditions, but organophosphate hydrolysis accelerates in neutral pH [35,49,98]. An optimal temperature range of 25–30°C and field capacity moisture levels enhance enzyme kinetics [99,100]. Organic matter content binds pesticides, reducing bioavailability but promoting microbial adaptation [37,98,101]. Drought and climate change exacerbate persistence by altering microbial communities and increasing pesticide application rates [100,102]. Biochar amendments limit mobility and enhance microbial colonization but can inhibit degradation if over-applied [98,103]. Heavy metals and co-contaminants compete for enzymatic sites, slowing degradation [104].

Prior pesticide use influences microbial diversity, enhancing resilience as degraders are more prevalent after repeated exposure [63,99]. Studies of tropical and greenhouse soils reveal that high humidity accelerates degradation but heightens leaching risks [20,41]. Heavy metals, such as copper

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and zinc, can inhibit soil bacterial degradation by altering enzyme active sites or reducing microbial diversity, necessitating strategies like biochar amendment to mitigate these effects [105][106,107]. Table **4** summarizes these factors and their impacts on degradation efficiency. Biochar critically influences pesticide fate by altering soil properties, with balanced application recommended to optimize microbial activity [98]. Climate change-driven increases in pesticide use necessitate adaptive measures to maintain degradation efficiency [102]. Historical pesticide use has shaped soil microbiomes, influencing their degradation capacity [99].

6. Bioremediation Strategies

Bioremediation leverages soil bacteria to detoxify pesticide-contaminated sites, offering cost-effective alternatives to chemical methods [7,13,108,109,110]. Table **5** outlines bioremediation strategies for pesticide degradation.

6.1. Natural Attenuation

Natural attenuation relies on native microbial populations to break down pesticides through a cost-effective but slow process, independent of human intervention [13,108,110,111]. Attenuation of chlorpyrifos and endosulfan involves hydrolysis and oxidation, accelerated by microbial adaptation in periurban environments [111]. This process is slow, limited by natural factors and pesticide stability [77]. It is effective for low pesticide pollution, but its slow pace and incomplete mineralization pose challenges [22,112]. Success depends on diverse soil bacterial populations with specific pesticide degradation capabilities, whose abundance varies between soil types and geographic locations [83]. Sites with prior pesticide treatment harbor soil bacterial populations that degrade contaminants at accelerated rates through soil bacterial priming [14].

Table 4. Environmental factors affecting pesticide degradation.

Environmental Factor	Effect on Degradation	Optimal Range	Negative Impact Examples	Source
pH	Influences sorption and enzyme activity	Neutral (6-7)	Acidic soils slow pyrethroid breakdown	[35,49,98]
Temperature	Affects enzyme kinetics and microbial metabolism	25-30°C	Low temps (<10°C) reduce rates	[99,102]
Moisture	Enhances microbial growth and substrate diffusion	Field capacity (60-80%)	Drought inhibits activity	[82,76]
Organic Matter	Increases sequestration but aids adaptation	High content	Low OM reduces bioavailability	[37,98,101]
Aeration/Oxygen	Promotes aerobic degradation	Well-aerated soils	Anaerobic conditions prolong persistence	[29,30,35]

Reviews confirm natural attenuation is effective in agricultural fields with diverse taxonomic species [108,110]. Optimized soil conditions, including higher organic matter content and pH adjustments, enhance the activity of indigenous microorganisms, particularly for organophosphate degradation [60,101]. Biochar addition enhances natural pesticide attenuation by creating improved environments for microorganisms and increasing pesticide bioavailability to microbial action [113]. In Brazilian soils, natural attenuation combined with other remediation techniques achieves better performance [112]. Variable microbial responses necessitate site-specific assessments to ensure effective results [11].

6.2. Bioaugmentation

Bioaugmentation accelerates pesticide degradation in contaminated soils by introducing specific microbial strains or consortia [31,114]. *Bacillus sp.* degrades chlorpyrifos in contaminated soil systems, and kinetic experiments verify first-order degradation [60]. *Bacillus* and *Sphingomonas* consortia exhibit successful degradation of pyrethroids and neonicotinoids [14,56]. *Rhodococcus pyridinivorans* Y6 efficiently degrades multiple pyrethroids [57]. Strain survival and competition are mitigated with carrier materials [113,114]. Advanced delivery systems, encasing microorganisms in biodegradable carriers, enhance performance in challenging soil conditions [15,115]. Combining biochar or compost with biological methods yields synergistic effects, enhancing bacterial survival, pesticide bioavailability, and activity [116]. Bioaugmentation, combined with these methods, enhances degradation speed and microbial retention, making it suitable for large-scale remediation [101].

Field experiments in Brazil demonstrate its global applicability [115]. Studies in Argentine horticultural soils show bioaugmentation is an effective approach to reduce endosulfan residues [111]. Genetically modified *Bacillus* strains effectively reduce organochlorine residues [72]. Cyclodextrin-based technologies enhance herbicide removal in contaminated soil systems [117].

6.3. Synthetic Microbial Consortia

Engineered soil bacterial communities, comprising *Pseudomonas, Bacillus*, *Streptomyces*, and *Sphingomonas*, demonstrate enhanced pesticide degradation efficiency over individual strains [39,77,118]. These consortia achieve synergistic degradation by combining multiple strains [107,117,118,119]. These consortia enhance degradation through complementary hydrolytic, oxidative, and reductive enzymatic activities [57,119]. Quorum sensing regulates esterases expression in *Bacillus subtilis*, ensuring synchronized metabolic processes [61]. Advanced genetic tools, such as CRISPR-Cas9, enable optimization of consortia performance by enhancing metabolic output and stability under variable soil conditions [120,121]. These consortia improve efficiency and offer applications in soil fertility recovery [118,122,123].

Bioinformatics and machine learning predict strain interactions, enabling effective bioremediation [122,124]. Pesticide-tolerant consortia effectively remediate multi-contaminated sites [123]. Modular consortia designed for neonicotinoids and triazines include built-in stress tolerance to withstand heavy metals and extreme pH [14,116,123]. Novel *Pseudomonas* and *Streptomyces* consortia exhibit enhanced degradation capabilities for field-based pesticide residue removal [3,22]. Studies of complex consortium development show combined strains achieve complete mineralization through synergistic reactions [119]. Quorum sensing circuits and synthetic regulatory elements ensure stable function in contaminated soils [61,125,126]. Their application to soil fertility enhancement demonstrates broader agricultural benefits, though deployment requires detailed ecological and regulatory considerations [118].

6.4. Field-Scale Applications

Field-scale bioremediation represents a critical step in translating laboratory innovations into practical strategies for managing pesticide contamination in agricultural systems. Common approaches include the use of biomixtures and biobeds, soil amendments with biochar or compost, phytoremediation, and application of adapted microbial consortia[127,128,129,130]. Biomixtures and biobed systems consistently demonstrate effective pesticide dissipation under field and pilot conditions, often exceeding 50% removal and, in optimized designs, achieving near-complete dissipation within approximately 30–90 days. However, degradation rates remain highly dependent on pesticide formulation, biomixture maturity (pre-incubation period), hydraulic load, and climatic conditions [131,132,133,134]. Evidence from Mediterranean and temperate regions highlights that composition, moisture content, and pre-incubation strongly determine the dissipation efficiency of pesticides such as chlorpyrifos and triazine herbicides [129,135,136].

Formulation strategies that enhance pesticide bioavailability (e.g., inclusion complexes) or combine adsorption capacity (via biochar) with active degraders tend to accelerate degradation rates and improve microbial persistence. Nonetheless, the effectiveness of biochar remains strongly dependent on feedstock type, pyrolysis conditions, and environmental context [137,138,139,140]. Regional field studies further corroborate these outcomes: European and Brazilian biobed systems have shown high removal efficiencies for organophosphates, triazines, and glyphosate, while tropical systems employing alternative biomixture substrates such as banana stems, pine litter, or vermicompost can also sustain rapid degradation when properly aged and [128,134,141,142].

Advances in synthetic biology have enabled the development of engineered strains and designer microbial consortia, such as multi-enzyme *Pseudomonas putida* constructs, which exhibit strong capacity for degrading mixed pesticide residues at laboratory and pilot scales. However, their environmental application remains limited due to biosafety concerns and regulatory constraints [50,128,143,144]. Integrating biochar or compost amendments with microbial inocula or plant-assisted systems shows promise in enhancing microbial survival, modifying pesticide sorption and bioavailability, and accelerating dissipation, though outcomes remain site-specific and require systematic optimization and monitoring[140,141,145,146] To achieve scalable, environmentally safe, and socially acceptable applications, standardized field monitoring protocols, ecological risk assessments, and active engagement with regulatory bodies and stakeholders are essential[115,127,133,134].

Table 5. Bioremediation strategies for pesticide degradation.

Strategy	Description	Mechanism	Advantages	Limitation	Examples	Sources
Natural Attenuation	Relies on indigenous microbes for passive degradation	Hydrolysis and oxidation by native enzymes	Cost-effective, minimal ecological disruption	Slow rates, incomplete mineralization (varies with soil conditions)	*Chlorpyrifos* and *endosulfan* attenuation	[13,108,110,111,112]
Bioaugmentation	Introduces specific degraders to accelerate processes, using isolates or carrier materials	Esterase-mediated hydrolysis, nitroreduction	Targets specific contaminants, accelerates degradation	Strain survival, competition with natives, cost of inoculation	*Bacillus* sp. for *chlorpyrifos*, *Rhodococcus pyridinivorans* Y6 for pyrethroids	[57,60,114,115]
Synthetic Microbial Consortia	Engineered combinations of strains for synergistic degradation, regulated by	Complementary enzymatic pathways (e.g., esterases, oxidases) via quorum sensing	Synergistic efficiency, adaptable to multi-contaminants	Complex engineering, regulatory hurdles (e.g., safety assessments)	*Pseudomonas* and *Bacillus* consortia	[15,77,82,117,118,122,123]

	quorum sensing					
Field-Scale Applications	Large-scale deployment of consortia and amendments	Enhanced degradation with biochar and consortia	Scalable, high efficiency	Requires monitoring, site-specific	Biobeds for chlorpyrifos; biochar for atrazine & Chlorpyrifos	[147][132][148]

7. Methodology

This review systematically synthesizes knowledge on microbial pesticide breakdown. Information was collected from peer-reviewed databases, including PubMed, Scopus, and Web of Science, for publications from 1995 to 2025. Search terms included "pesticide degradation," "soil bacteria," "bioremediation," "microbial enzymes," "omics technologies," and "sustainable agriculture." The review selected scientific articles on microbial taxa, enzymatic and genetic mechanisms, environmental factors, bioremediation methods, and sustainable agricultural applications. It prioritized English peer-reviewed articles, reviews, and book chapters from high-impact journals, particularly recent developments post-2019. It examined pesticide classes, microbial degradation mechanisms, bioremediation approaches, and their regulatory and sustainability aspects. Incorporating 119 references from primary research, reviews, and policy reports, it provides a comprehensive, expert-level overview.

8. Advances in Omics Technologies and Synthetic Biology

Omics technologies have revolutionized pesticide degradation research by integrating metagenomics, transcriptomics, and proteomics to reveal soil bacterial catabolic pathways, discover new genes, enzymes, and regulatory systems [14,73,149,150,151]. Metagenomics identifies degradation genes in bacteria metabolizing chlorpyrifos and unculturable microorganisms, expanding bioremediation capabilities [14,15]. Proteomics reveals neonicotinoid degradation is enhanced by esterase and laccase activity, while transcriptomics shows how environmental stressors influence pathway regulation [152]. Integrating omics with machine learning facilitates prediction and optimization of degradation pathways, revealing complex soil bacterial community interactions and synergistic effects in contaminated sites [48,73,80,124,150,153]. Metabolomics tracks intermediary metabolites to address pathway limitations, aiding the development of efficient synthetic consortia [14].

Synthetic biology enhances bioremediation through genetic modifications of *Pseudomonas putida* KT2440, enabling degradation of multiple pesticides via CRISPR-Cas and *E. coli* strains engineered with multiple degradation genes for enhanced pollutant removal [50,82,87,116,121,152,154,155]. Epigenomics elucidates regulatory processes controlling degradation gene expression, maximizing microbial function, and AI-based models predict engineered ecosystem outcomes, enabling precise bioremediation [48,156]. *Bacillus* cells expressing nitroreductase accelerate herbicide degradation, and microalgae-bacteria combinations facilitate large-scale pollutant management [81,121]. Integrated omics and machine learning position microbial bioremediation as a cornerstone for sustainable environmental management [14,153]

9. Regulatory and Practical Considerations

Regulatory frameworks emphasize safety standards for genetically modified microbes [157,158]. Approving GMOs encounters challenges worldwide due to varying regulatory systems, complicating GMO authorization and ecological protection [15,159]. The Global Chemicals Outlook advocates innovative approaches, but risk evaluation is required for outdoor releases [18]. Ecological modelling-based risk assessment frameworks enhance GMO bioremediation evaluations, facilitating regulatory approvals [15,158,159].

High bioremediation costs limit widespread use in developing countries, due to scale [160,161]. Scaling laboratory solutions to field applications is challenging due to environmental variability, such as temperature fluctuations and soil composition, which reduce efficacy [77,162]. Implementing bioremediation technologies involving GMOs requires public acceptance and stakeholder engagement [14]. Standardized safety protocols and technology transfer are being developed to establish global bioremediation standards and protect freshwater ecosystems [163]. Emerging policy frameworks support sustainable agriculture by promoting pesticide reduction and ecosystem restoration to ensure long-term environmental health [2,18]. Standardized assays help address barriers to scalability and monitoring [24,164].

10. Implications for Sustainable Agriculture

Degradation by soil bacteria supports sustainable intensification by reducing pesticide concentrations in soils and enhancing soil health [165,166,167,168]. It reduces chemical contamination, enhances soil quality, biodiversity, and mitigates risks to health and ecosystems [4,9,11,166]. Bioremediation restores soil fertility and microbial diversity, facilitating nutrient cycling [109,118,149]. By restoring soil bacterial ecosystems, bioremediation fosters fertile conditions for sustainable crop cultivation within global climate-smart agricultural programs [2]. Bio-pesticides complement degradation strategies [7,159]. Integrating bioremediation with organic farming and integrated pest management facilitates a shift to sustainability by reducing chemical pesticide dependency [112,167]. Integrated pest management (IPM) combined with bioremediation reduces pesticide inputs by leveraging natural bacterial degradation processes, promoting sustainable crop production and ecosystem resilience [169][170].

Climate-resilient microbes reduce the need for increased pesticide use [102]. Microbial bioremediation enhances climate resilience by improving soil carbon storage and reducing greenhouse gas emissions from pesticide production and application [14,40]. This approach reduces cleanup costs and improves yields [160,166]. Eco-friendly farming practices in Brazil and India demonstrate global applicability [115,149]. Bioremediation supports pollinator health, enabling essential ecosystem services for sustainable agriculture [39,110]. Bacteria are critical to sustainable agriculture [167]. Recent studies confirm microbial consortia successfully restore polluted agricultural land, contributing to global ecological restoration and food security [2,116].

11. Conclusions

Soil bacteria transform harmful pesticides into harmless substances via their metabolic capabilities, offering a transformative approach to pollution. Pesticide degradation involves complex enzymatic and genetic processes, executed by *Pseudomonas* and *Streptomyces*, among other taxa. These pathways reduce environmental persistence and health risks. Bioremediation, combined with synthetic biology and multi-omics technologies, enhances effectiveness, enabling large-scale, real-world deployment. Deploying soil bacterial solutions in sustainable agricultural systems demands regulatory frameworks that evolve to ensure safety standards. These approaches reduce pesticide impacts, enhance soil health, and support resilient agroecosystems, contributing to global sustainability goals. Furthermore, ongoing research should focus on developing more robust microbial strains through genetic engineering to handle a wider range of pesticides under varying environmental conditions. Collaboration between scientists, policymakers, and farmers is crucial to implement these technologies effectively. By integrating bacterial degradation into agricultural practices, we can significantly decrease reliance on chemical pesticides, promoting biodiversity and reducing the carbon footprint of farming. Additionally, the use of AI and predictive modeling can optimize bioremediation strategies, making them more efficient and cost-effective. Ultimately, this

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interdisciplinary strategy not only addresses current environmental challenges but also paves the way for a more sustainable and resilient future in agriculture, ensuring food security for generations to come.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CRISPR-Cas9	Clustered Regularly Interspaced Short Palindromic Repeats and CRISPR-associated Protein 9
DDT:	Dichlorodiphenyltrichloroethane
DT_{50}:	Disappearance Time 50, or half-life
FAO:	Food and Agriculture Organization
GMOs:	Genetically Modified Organisms
AI:	Artificial Intelligence
SDGs:	Sustainable Development Goals
PTE/OPH	Phosphotriesterases/Organophosphorus Hydrolases
UNEP:	United Nations Environment Programme

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