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Review Paper

Biodegradation of LDPE by *Bacillus* and *Pseudomonas* and its effects on Soil Phytotoxicity: A Comprehensive Review

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Abstract

Low density polyethylene (LDPE) is widely applied in agriculture, for example as mulch films, greenhouse covers, and packaging materials. Owing to its high durability, hydrophobic nature, and resistance to natural degradation, LDPE accumulates in soil ecosystems and causes adverse physicochemical and biological impacts. A growing body of evidence shows that LDPE residues and LDPE-derived microplastics can modify soil structure, adsorb agrochemicals and heavy metals, disturb soil microbial communities, and trigger phytotoxic responses in plants. Microbial biodegradation has therefore attracted attention as an eco-friendly approach to alleviate LDPE-induced soil phytotoxicity. Among soil microorganisms, Bacillus and Pseudomonas spp. are especially important because of their metabolic versatility and ability to colonies plastic surfaces. Bacillus spp. support long-term soil remediation by forming endospores and mediating moderate enzymatic oxidation of LDPE, thereby improving soil resilience, whereas Pseudomonas spp. generally achieves higher LDPE degradation rates through strong biofilm formation and diverse oxidative enzyme systems, resulting in more extensive polymer breakdown and lower phytotoxicity.

Keywords: LDPE, Soil phytotoxicity, Microbial biodegradation, *Bacillus, Pseudomonas,* Agricultural soils, Microplastics.

Introduction

Low-density polyethylene (LDPE) is now one of the dominant plastic contaminants in agricultural soils worldwide because it is used extensively in many farming applications[1]. The material's durability, flexibility, and low cost have made it attractive for improving crop yields and water-use efficiency, which has encouraged widespread adoption in mulching, greenhouse covers, and agricultural packaging[2,3]. However, the same physicochemical properties that make LDPE agronomically attractive also contribute to its extreme persistence in terrestrial environments, where it resists natural degradation for a long time[4]. In aquatic ecosystems, plastic waste is subjected to continuous physical abrasion, UV radiation, and hydrodynamic forces[5]. Whereas soil systems provide a relatively stable environment that promotes the retention of LDPE fragments. In agricultural fields, LDPE pieces remain in close contact with soil minerals, microorganisms, and plant roots. This close contact gives rise to complex physicochemical and biological interactions at the soil-plastic interface[6].

Increasing accumulation of LDPE debris in agricultural soils alters soil physical properties such as bulk density, porosity, and aggregation dynamics[7]. LDPE fragments interfere with soil cohesion, resulting in changes in pore size distribution that affect water infiltration and gas exchange; such changes impair soil health and reduce its capacity to support crop production[8].

Beyond physical effects, LDPE contamination also alters soil chemical properties by acting like a vector for organic pollutants, and heavy metals, and these contaminants may be released into the rhizosphere, exposing plant roots to chronic stress and contributing to phytotoxic effects[9]. LDPE additives like antioxidants, stabilizers, and plasticizers may leach into soil during aging, exacerbating chemical toxicity[10].

Plastic surfaces provide novel ecological habitat, referred as the "plastisphere," which selectively enrich microorganisms capable of adhering and utilizing polymer surfaces[11]. Phytotoxic stress leading from LDPE contamination is documented in crop plants, with effects including reduced seed germination, inhibited root elongation, and impaired biomass accumulation[12]. Microplastics have been reported to induce oxidative stress in the several plant species, including increased reactive oxygen species production and lipid peroxidation. These physiological responses suggest that LDPE contamination alters plant cellular homeostasis, affecting crop yield and food security[6].

Bacillus and *Pseudomonas spp.* have been identified as dominant LDPE degraders due to their metabolic versatility and environmental adaptability[13]. These bacteria are ubiquitous in agricultural fields and possess the enzymatic machinery to initiate oxidative and hydrolytic degradation of polyethylene[14]. *Bacillus spp.* are well suited for LDPE degradation because of their ability to form endospores[15]. *Bacillus* strains have demonstrated LDPE weight loss, surface erosion, and chemical modification of polymer chains under laboratory and soil incubation conditions[13]. Several Enzymes produced by *Bacillus* play a role in introducing oxygen-containing functional groups into LDPE, so that increasing its susceptibility to microbial attack[15].

Pseudomonas spp. are highly efficient LDPE degraders due to their biofilm-forming capacity and broad enzymatic repertoire[16]. Biofilm formation on LDPE layers enhances microbial adhesion and facilitates sustained enzyme polymer interactions[17]. The biodegradation of LDPE by *Bacillus* and *Pseudomonas* also changes the toxicity profile of contaminated soils[17]. Microbial degradation products are more biodegradable and less phytotoxic than intact LDPE polymers[14]. Soil phytotoxicity studies have shown more seed germination and root growth in soils treated with LDPE-degrading bacteria compared to untreated plastic-polluted soils[18].

Incomplete LDPE degradation may increase phytotoxicity due to its accumulation of intermediate oxidation products and the integration of *Bacillus* and *Pseudomonas*-based biodegradation approaches with soil management practices hold significant potential for reducing LDPE-induced phytotoxic stress and restoring soil functionality[8].

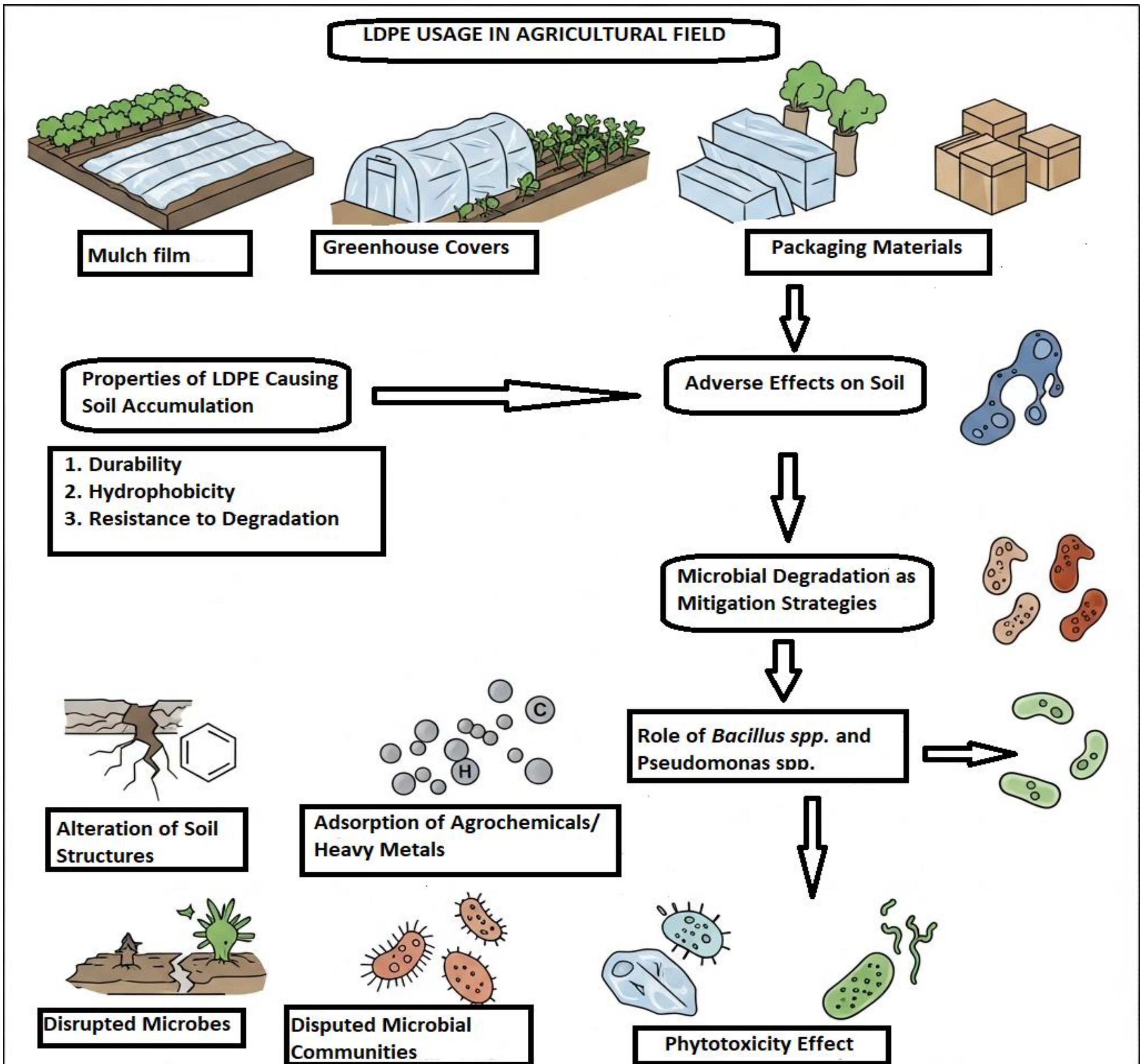

Figure-1: LDPE usage and phytotoxicity effect in agricultural field[2,3].

LDPE Characteristics Relevant to Soil Phytotoxicity

Physico-chemical properties of LDPE and their implications in soil: LDPE is a synthetic thermoplastic formed from long, branched chains of ethylene units that create a largely hydrocarbon backbone. This backbone imparts high chemical stability and resistance to degradation[1]. The dense network of carbon–carbon (C–C) and carbon–hydrogen (C–H) bonds makes LDPE non-polar and strongly hydrophobic, limiting its interaction with water and most soil enzymes[4].Reduced surface wet ability hinders microbial attachment and the accessibility of extracellular enzymes to the polymer surface, thereby slowing biodegradation processes in soil[17].

Structurally, LDPE contains both amorphous and crystalline regions[14]. The tightly packed crystalline domains are particularly resistant to chemical oxidation and enzymatic penetration[15]. As a result, microbial degradation is largely confined to the more disordered amorphous regions, and overall breakdown of the material is typically slow and incomplete[13].

High molecular weight of LDPE shows to its recalcitrance[1]. In terrestrial environments, LDPE undergoes only limited abiotic fragmentation because soils generally experience lower ultraviolet radiation and mechanical stress than exposed aquatic or coastal habitats[5]. Furthermore, LDPE fragments can act as physical obstacles to root growth, especially for fine roots and root hairs that are crucial for nutrient and water uptake[12].

By altering the continuity of soil pores and restricting gas diffusion, LDPE can also create localised zones with reduced oxygen availability[8]. Taken together, these properties show that LDPE functions not merely as a passive contaminant but as an active modifier of soil structure, aeration, and microbial community organization[5].

LDPE as a source of phytotoxic stress in agricultural soils: Although LDPE is often described as chemically inert, its prolonged residence and progressive ageing in agricultural soils enable it to contribute indirectly and significantly to phytotoxic stress[4]. One major mechanism involves the strong sorption of pesticides, herbicides, and heavy metals onto LDPE surfaces, particularly as the plastic fragments and its surface area increases[9]. This sorption enhances the persistence of these contaminants and allows their gradual release into the rhizosphere, thereby extending the period during which plant roots are exposed to potentially toxic compounds[18].

Another important pathway arises from the wide variety of additives blended into LDPE during manufacturing, including stabilizers, plasticizers, antioxidants, and processing aids[10]. As LDPE weathers, these additives can migrate out of the polymer and leach into surrounding soil. Several studies have demonstrated that leachates from polyethylene materials can inhibit seed germination and impair early seedling development due to additive toxicity[9].

Environmental weathering and partial biodegradation of LDPE generate microplastic particles[5]. These small fragments readily infiltrate the soil matrix, where they can come into direct contact with root surfaces and the rhizosphere microbiome[6].

The physiological consequences of oxidative stress include reduced photosynthetic efficiency, impaired nutrient uptake, and disruption of hormonal signaling pathways essential for root and shoot development[8]. Experimental studies consistently report decreased seed germination rates and inhibited root elongation in plants grown in LDPE-contaminated soils, indicating that both physical interference and chemical toxicity contribute to adverse growth outcomes[12]. Collectively, the adsorption of contaminants, release of additives, and formation of microplastics position LDPE as an active driver of phytotoxic stress rather than an inert soil contaminant[8].

Role of *Bacillus* in LDPE Biodegradation

Soil adaptation and survival of *Bacillus* spp.: *Bacillus spp.* are distributed in the agricultural soils because of adaptation nature to harsh environmental conditions like temperature, moisture, and nutrient availability[19]. *Bacillus spp.* are capable to form endospores, which leads long-term persistence in extreme soil environments, including soils contaminated with plastic particles[20]. Endospore formation allows *Bacillus* to remain dormant during harsh conditions and resume metabolic activity once environmental conditions become suitable for growth and interaction with LDPE particles[21].

Resilience of *Bacillus spp.* enhance their association with LDPE particles in soil, increasing the likelihood of surface colonization and biofilm development[22]. The interaction is critical for initiating the slow and progressive biodegradation of LDPE in soil systems[23].

Enzymes involved in LDPE degradation: The biodegradation efficiency of *Bacillus spp.* is more attributed to their diverse extracellular enzyme capable of catalyzing oxidative and hydrolytic reactions[24]. Lipases play a role in initiating polymer surface modification by hydrolyzing ester-like linkages formed during LDPE oxidation[25]. Esterase enzyme produced by *Bacillus* enhance polymer depolymerization by cleaving low-molecular-weight oxidation products into metabolizable fragments[26].

Alkane monooxygenase are involved in LDPE biodegradation, as they introduce molecular oxygen into long hydrocarbon chains through terminal or subterminal oxidation[27]. The presence of oxygen atoms into LDPE chains results in formation of C=O and –OH functional groups, that increase polymer hydrophilicity and susceptibility to the microbial attack[28]. The chemical modifications are detected using Fourier transform infrared spectroscopy, where an increased carbonyl index serves likean indicator of LDPE biodegradation[29].

Impact of *Bacillus*-mediated LDPE degradation on soil phytotoxicity: Soil bioassays conducted using *Vigna radiata* and *Triticum aestivum* have improved seed germination percentages in soils treated with *Bacillus*-degraded LDPE compared to untreated plastic residues soils. Enhanced germination is imputed to reduction in physical and chemical interactions with intact LDPE particles[30]. Biochemical analyses show significantly lower levels of oxidative stress markers, like malondialdehyde and reactive oxygen species, in the plant exposed to biodegraded LDPE as compared to untreated controls[30]. These findings suggest that *Bacillus*-mediated LDPE biodegradation also mitigates LDPE-induced phytotoxic stress, supporting the ecological relevance of *Bacillus spp.* in soil plastic remediation[21].Several studies have been shown that *Bacillus spp.* possess the capacity to reduce weight of polyethylene, as indicated in the Table-1.

Table-1: LDPE degradation by *Bacillus spp.*

Bacillus spp.	Weight Loss Capacity	Ref.
Bacillus safensis, *B. cereus,* *Bacillus siamensis*	18.6 %, 6.33±0.2%, 8.46 ± 0.3%	31
Bacillus paralicheniformis G1	34%	32
Bacillus sp. strain YP1	10.7%	33
Bacillus amyloliquefaciens, *Bacillus safensis*	18 %, 18.6 %	34
Bacillus subtilis (H-248))	1.68%	35
B. subtilis ATCC6051, *B. licheniformis ATCC14580*	3.49%, 2.83%	36

Role of *Pseudomonas* in LDPE Biodegradation

Soil adaptation and survival of *Pseudomonas spp*.: *Pseudomonas spp.* are well known for forming robust biofilms, a trait that is crucial for effective LDPE degradation in soil environments[17]. Biofilm formation enables *Pseudomonas* to compactly adhere to hydrophobic LDPE surfaces, overcoming the inherent resistance of the polymer to microbial colonization[37]. The extracellular polymeric substances produced within *Pseudomonas* biofilms enhance adhesion, protect cells from environmental stress[38].

Enzymes involved in LDPE degradation: The biodegradation potential of *Pseudomonas spp.* is attributed to their diverse oxidative enzyme systems which enable transformation of recalcitrant hydrocarbons[27]. Oxygenase, monooxygenases and dioxygenases, play a role in initiating LDPE degradation by molecular oxygen insertion into inert carbon–carbon bonds[39]. Peroxidases contribute LDPE oxidation by generating reactive radicals that disrupt polymer crystallinity and enhance chain scission[40]. These enzymes convert LDPE into shorter-chain hydrocarbons and fatty acid-like compounds that can enter central metabolic pathways[39].

Impact of *Pseudomonas* -mediated LDPE degradation on soil phytotoxicity: Plant bioassays conducted using agricultural crops shows soils treated with *Pseudomonas*-degraded LDPE support improved plant growth compared to untreated LDPE residues soils[18]. Morphological improvements, plants grown in *Pseudomonas*-treated soils exhibit higher chlorophyll content, suggesting improved photosynthetic efficiency and nutrient uptake. Reduced inhibition index values in germination and seedling growth assays indicate that microbial degradation lowers the overall toxicity of LDPE-polluted soils[18]. Several studies have recognized that *Pseudomonas spp*. possess the ability to degrade polyethylene, as resulting in a measurable reduction in its weight, as presented in Table-2.

Table-2: LDPE degradation by *Pseudomonas spp.*

Pseudomonas *spp*.	Weight Loss Capacity	Ref.
Pseudomonas aeruginosa	50.5%	41
Pseudomonas aeruginosa, *Pseudomonas aeruginosa PAO,* *Pseudomonas putida,* *Pseudomonas siringae*	11%, 20%, 9%, 11.3%	16
Pseudomonas aeruginosa	6.25 %	42
Pseudomonas citronellolis	13.07–18.58%	43
Pseudomonas sp. AKS2	5 %	44
Pseudomonas aeruginosa	1.15 ± 0.1 %	31
Pseudomonas sp.	24.22±0.01	45
Pseudomonas aeruginosa (OP007126)	62%	18
Pseudomonas sp. AKS2	5±1 %	37

Comparative Analysis of *Bacillus* and *Pseudomonas* in LDPE Biodegradation and Phytotoxicity Mitigation

Microbial degradation of LDPE in soil is influenced by bacterial strategies i.e. enzymatic competence, and ecological adaptability for *Bacillus* and *Pseudomonas*[46].

Survival and persistence in Soil: *Bacillus spp* .exhibit high survival in soil because of their ability to form endospores, that confer resistance to desiccation, temperature fluctuations, and nutrient limitation, which have ability to survive over extended time periods and ensuring prolonged interaction with LDPE fragments even under unfavorable environmental conditions[19,21]. While, *Pseudomonas spp.*, demonstrates high and comparatively lower survival, relying primarily on metabolic versatility and rapid growth[47].

Biofilm formation and surface colonization: Biofilm formation is polymer biodegradation efficiency, as it governs microbial adherent and enzyme–substrate contact [38]. *Pseudomonas spp.* is recognized for their strong biofilm-forming capacity on hydrophobic surfaces, including LDPE, facilitated by extracellular polymeric substance production[17]. By comparison, *Bacillus spp.* forms moderate biofilms which result in less extensive surface coverage and reduced polymer–enzyme interaction[48].

Enzyme diversity and oxidative potential: The enzymatic repertoire of *Pseudomonas spp.* is diverse, oxygenase, dehydrogenases, peroxidases, and alkane hydroxylases which enable efficient oxidation of long-chain hydrocarbons such as LDPE[39]. The high enzyme diversity allows *Pseudomonas* to initiate and sustain multi-step LDPE degradation pathways[27]. While *Bacillus spp.* possess a more moderate range of enzymes, including lipases, esterases, and monooxygenases, that effective in initiating LDPE oxidation[49]. Many studies shown that various microorganisms exhibit the capability to induce and secrete extracellular enzymes involved in LDPE degradation, as presented in the Table-3.

Table-3: Potential of different organisms to activate Enzymes during LDPE degradation.

Organisms	Activated enzyme during degradation	Ref.
Escherichia coli	Lipase	24
Pseudomonas aeruginosa (LipA)	Lipase	
Bacillus subtilis (LipA)	Lipase	
Bacillus licheniformis	Lipase	
Bacillus subtilis	Cellulase	25
Bacillus spp.	Amylase	
A. globiformis	Carboxyl esterase	26
Pseudomonas marginata	Carboxyl esterase	
Rhodococcus ruber	Carboxyl esterase	
Acinetobacter spp.	Dioxygenase	27
Methylomicrobium spp.	Monooxygenase	

LDPE weight loss and degradation Rate: Quantitative degradation studies indicate that *Pseudomonas spp.* achieve higher LDPE weight loss than *Bacillus spp.* under favorable conditions[16]. *Pseudomonas aeruginosa* has been reported up to 15% weight loss, while *Bacillus subtilis* induces 8–12% weight loss over same incubation periods[17,49]. This reflects the superior oxidative metabolism and surface colonization efficiency of *Pseudomonas*[46].

Impact on microplastic formation: *Pseudomonas*-mediated degradation results in oxidation of fragments into lower-molecular-weight compounds, reducing microplastic persistence[5]. Whereas, *Bacillus* degradation leads to partial fragmentation with comparatively slower mineralization[40].

Ecological role and agricultural applicability: *Bacillus spp.* is well suited for long-term soil applications due to their endospore forming ability and compatibility with biofertilizer formulations[21]. while, *Pseudomonas spp.* are more effective for LDPE degradation and phytotoxicity reduction[17,47].

Soil Microbial and Ecological Impacts

Enrichment of plastic-degrading microbiota: The accumulation of LDPE in soils exerts strong pressure on microbial communities, leading to enrichment of plastic-degrading microbiota[11]. Soil microcosm studies have demonstrated increases in populations of hydrocarbon-degrading bacteria, members of *Proteobacteria* and *Firmicutes*, in LDPE-contaminated soils[50]. The enrichment process is enhanced by biofilm formation on LDPE surfaces, that creates microhabitats which support microbial consortia[51]. The plastisphere-associated communities differ from soil microbiota in taxonomic composition and metabolic function[52]. The LDPE presence transforms soil from a heterogeneous microbial environment into a polymer-influenced niche[53]. Several studies have reported that microbial consortia demonstrate greater potential for low-density polyethylene (LDPE) degradation compared to individual strains, as cooperative metabolic activities as presented in Table-4.

Table-4: Microbial consortia degrade LDPE.

Microbial Consortia	Weight Loss Capacity	Ref.
Aspergillus nomius, *Streptomyces spp.*	4.9%, 5.2%	54
A. clavatus strain JASK1	35 %	13
A. niger, *A. flavus*, *Streptomyces spp.*, *A. glaucuswas*, *Penicillium spp.*, *A. fumigatus*	26.17%, 16.45%, 46.7%, 28.8%, 6.58%, 4.65%.	23

Alteration of microbial diversity indices: The introduction and biodegradation of LDPE significantly alter soil microbial diversity[55]. Many studies report an initial decline in microbial richness due to physical obstruction and chemical stress imposed by plastic additives and sorbed pollutants[56]. This reduction in diversity reflects the exclusion of plastic-sensitive taxa and the dominance of stress-tolerant microorganisms[56].

Due to biodegradation progress, microbial diversity partially recovers due to the availability of degradation intermediates sources and recovery is characterized by increased functional diversity, even when taxonomic diversity remains changed relative to uncontaminated soils[50,57]. Some analyses reveal that enrichment of genes associated with hydrocarbon metabolism, oxidative stress response, and membrane transport in LDPEsoils[58]. The shifts suggest that LDPE biodegradation restructures microbial communities toward functionally specialized assemblages[53].

Potential for horizontal gene transfer (HGT) of degradation traits: The physical association of microorganisms within LDPE-associated biofilms creates favorable conditions for horizontal gene transfer of plastic degradation traits[59]. Biofilms enhance cell-to-cell interaction and increase the stability of extracellular DNA, conjugation, and transduction mechanisms[60]. Genes encoding different enzyme pathways have been identified on plasmids and mobile genetic elements in plastic-colonizing bacteria[61].

The ecological implications of HGT extend beyond polymer degradation, because mobile genetic elements can also carry genes affecting antibiotic resistance, virulence, and nutrient cycling. These processes raise important concerns about unintended ecological consequences in agricultural soils, where shifts in microbial interactions can strongly influence plant health and nutrient cycling[59]. This raises concerns about unintended ecological consequences, in agricultural soils where microbial interactions influence plant health and nutrient cycling[57]. HGT-driven dissemination of degradation traits enhances LDPE biodegradation efficiency; it necessitates ecological risk assessment[53].

Implications for Soil Ecosystem Functioning: The enrichment of plastic-degrading microbiota and differ microbial diversity collectively influence key soil ecosystem processes, like carbon cycling, enzyme activity, and nutrient availability[55]. Enhanced microbial respiration associated with LDPE biodegradation may increase soil carbon turnover rates[57]. Shifts in microbial community structure can affect plant–microbe interactions, potentially modifying rhizosphere dynamics and plant nutrient uptake[11]. LDPE biodegradation reshapes soil microbial ecology in ways that have both beneficial and long-term consequences for soil health and sustainability[52].

Future Prospects for LDPE Biodegradation and Phytotoxicity Mitigation

Genetically enhanced *Bacillus* and *Pseudomonas spp.:* Advances in microbial genetics and synthetic biology offer opportunities to enhance the LDPE biodegradation capacity of *Bacillus* and *Pseudomonasspp*[62].Genetic modification strategies targeting oxidative enzymeshave the potential to accelerate polymer chain scission[63]. Genetically Engineered strains with upregulated stress-response and biofilm-associated genes may exhibit improved survival and colonization efficiency on low density polyethylene surfaces in soil[64].

The introduction of modified pathways enabling complete mineralization of LDPE-derived intermediates could reduce the accumulation of partially oxidized[65]. The environmental release of GMO requires biosafety assessment to minimize ecological risks and unintended gene dissemination[66].

Development of Microbial Consortia: Microbial consortia representalternative to single-strain applications by combining metabolic capabilities across different taxa[67]. *Bacillus*, *Pseudomonas*, and other hydrocarbon-degrading bacteria can be enhanced degradation efficiency through metabolic cooperation and cross-feeding of intermediates[68]. Such interactions enable sequential oxidation and assimilation of LDPE-derived compounds, reducing metabolite accumulation and ecological stress[69].

Consortia-based systems are more resilient to environmental fluctuations[70]. The deliberate of synthetic consortia using systems biology approaches may allow control over degradation pathways and ecological outcomes[71].

Integration with phytoremediation

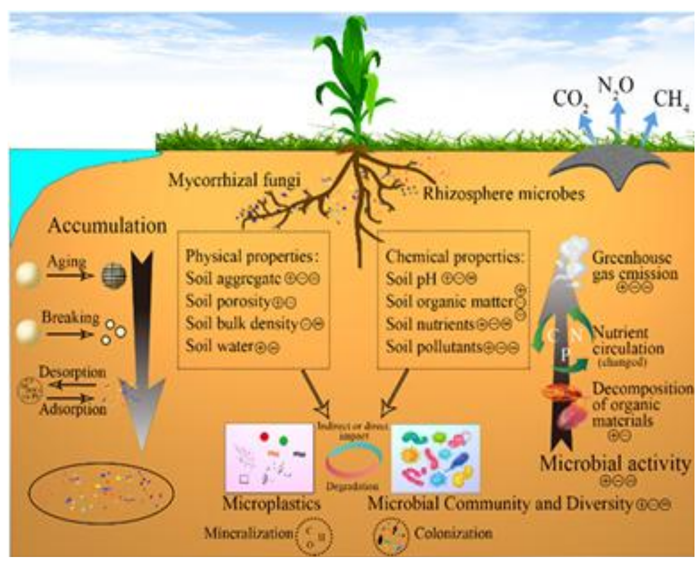

Figure-2: Potential of micro plastics on soil properties: Physical, Chemical and Microbial[72]

The integration offers a holistic approach to restoring plastic-contaminated agricultural soils[73]. Plant roots provide exudates that stimulate microbial activity, so enhancing the growth and enzymatic performance in the rhizosphere[74]. Certain plant species with long root systems and high rhizodeposition rates may promote microbial colonization and polymer breakdown[75]. The combined application of plant–microbe systems can create positive feedback loops, improving soil structure and fertility[74].

Agricultural applications: Agricultural application strategies are essential to maximize LDPE biodegradation benefits and minimizing ecological risks[76]. LDPE-degrading bacteria as bioinoculants or biofertilizers could enable specified delivery and sustained activity in plastic-polluted soils[77]. Encapsulation techniques and carrier-based formulations may enhance microbial survival and functional stability[78].Regulatory frameworks governing microbial inoculants must be strengthened to ensure environmental safety[76]. Integrating microbial LDPE biodegradation into sustainable agricultural practices could contribute plastic waste management and soil health restoration[62].

Conclusion

Bacillus and *Pseudomonas* species mitigate LDPE-induced soil phytotoxicity by oxidizing LDPE into less harmful metabolite[79]. *Pseudomonas spp.* demonstrate higher LDPE degradation efficiency due to strong biofilm formation and diverse oxidative enzyme systems while, *Bacillusspp.* contribute soil resilience through ability to survive harsh environmental conditions via endospore formationin the agricultural soils[80]. The roles of these bacteria highlight the importance of degradation efficiency and ecological stability in plastic-contaminated soils[81]. Plant response studies provide insights into the ecological safety by linking microbial activity to germination, growth, and physiological performance[82].

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