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Transformation of Polylactic Acid (PLA) Microparticles in Soil and their Effects on Soil Properties: A Review

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Abstract— *Polylactic acid (PLA) microplastics have garnered significant attention because they are widely used as biodegradable alternatives to traditional plastics, especially in agriculture. This review examines the transformation mechanisms of PLA microparticles in soil and their subsequent effects on soil parameters, including physical, chemical, and biological factors. It integrates recent research and theoretical assessments of soil ecosystems to emphasize the importance of PLA microparticles in affecting soil pH, organic matter, and nutrient cycling. The review also explores key microbial interactions, focusing on how these particles influence microbial community composition and enzyme activity, which are essential for soil health and plant growth. Environmental factors such as moisture, temperature, and the presence of other organic materials are crucial mediators of PLA degradation and transformation in soil. Furthermore, the paper discusses the long-term ecological implications of PLA microplastics and highlights the need for extensive research to evaluate potential soil contamination and ecosystem disruptions. This synthesis aims to guide future research directions and develop effective strategies for incorporating biodegradable polymers into agricultural and environmental applications. Overall, this analysis provides a foundation for creating strategies to promote the long-term use of PLA microparticles to reduce plastic pollution while assessing their positive and negative impacts on soil systems.*

Keywords— ***PLA microplastics, soil properties, microbial interactions, degradation processes, environmental impacts.***

I. INTRODUCTION

The pervasive accumulation of plastic waste in terrestrial and marine environments represents one of the most pressing environmental challenges of the 21st century. The widespread increase of microplastics in agricultural environments, in particular, threatens fundamental aspects of sustainability, including environmental stability, soil health, and food safety (Deng et al., 2020) . In response to this crisis, there has been a significant push towards the development and adoption of sustainable polymers derived from renewable resources. Among these, polylactic acid (PLA), an aliphatic polyester, has emerged as a leading biodegradable alternative to conventional petroleum-based plastics.

Poly(lactic acid) is a thermoplastic polyester produced from renewable resources, specifically fermented plant starch derived from corn, sugarcane, and the fibers of sugar beet pulp. Polylactic acid is a versatile material due to its physical and chemical properties. It is comparable to polystyrene and polyethylene terephthalate in strength and stiffness (Deng et al., 2020). Polylactic acid usually exhibits a glass transition temperature in the range of 55–65 °C and a melting temperature in the range of 150–180 °C, with the value depending on its isomeric composition of lactic acid – either L-lactic acid or D-lactic acid. Polylactic acid has chemical susceptibility to hydrolysis of the ester linkage, which is the main driving force behind its biodegradability. At least two pathways can produce polylactic acid. The first pathway is direct condensation polymerization of lactic acid. While this pathway is straightforward, the difficulty of removing water during polymerization results in low-molecular-weight polymers. Industrial PLA production occurs via the second pathway, which involves the ring-opening polymerization of lactide, a cyclic dimer of lactic acid. The augmented methodology of this reaction involves the fermentation of biomass carbohydrates to produce lactic acid, which is then oligomerized and, after catalytic dehydration, cyclized into lactide. This intermediate is then polymerized to high molecular weight PLA through ring-opening.

Due to its favorable properties and biodegradable nature, PLA has found widespread application across various sectors. In packaging, it is used for food containers, bottles, and films. In agriculture, it is a key component of biodegradable mulch films designed to reduce plastic waste from conventional polyethylene films (Jiménez-Sánchez et al., 2024). It is also used in single-use consumer goods like disposable cutlery and cups, which have been shown to release a significant number of microparticles into beverages (Chen et al., 2022). Furthermore, its biocompatibility has made it a staple in biomedical applications, including sutures, stents, and drug delivery systems.

Despite its "biodegradable" label, the environmental fate of PLA, particularly when it fragments into microparticles (fragments < 5 mm), remains a subject of considerable scientific inquiry and concern. As the use of PLA-based products continues to grow, the accumulation of PLA microparticles in terrestrial ecosystems is inevitable (Maleki et al., 2024) . These particles enter the soil through various pathways, including the in-situ degradation of agricultural inputs, compost application, and improper waste disposal. Consequently, there is a growing apprehension about their long-term impacts on soil health, the structure and function of microbial communities, and broader ecological processes (Widjaja et al., 2023,). The global production of plastics exceeds 350 million tons annually, and while bioplastics currently constitute a small fraction of this total, their market share is projected to expand rapidly. This anticipated growth underscores the urgent need to understand the complete life cycle of materials like PLA, especially their behavior in complex soil matrices. The degradation of PLA is not instantaneous; it can persist in the environment for months to years, depending on a confluence of factors. Laboratory studies often report complete decomposition within 6 to 24 months under controlled composting conditions (Rojas Aguirre et al., 2024). However, in natural soil environments, where conditions such as temperature, moisture, and microbial activity are suboptimal and highly variable, the degradation process can be significantly prolonged. This persistence is critical, as soils are vital ecosystems that serve as the largest terrestrial carbon sink and harbor immense biodiversity. The transformation of PLA microparticles in soil is a multifaceted process governed by a combination of abiotic and biotic factors. Abiotic factors, including temperature, moisture, and pH, primarily drive the initial hydrolytic cleavage of the polymer's ester bonds. Biotic factors, particularly the enzymatic activities of soil microorganisms, are essential for the subsequent and complete mineralization of the resulting oligomers and lactic acid monomers (Maleki et al., 2024). The interaction between these factors determines the rate and extent of PLA degradation and, consequently, its environmental impact (Clouse et al., 2024).

This review aims to synthesize the current body of knowledge on the transformation of PLA microparticles in soil and their resultant effects on soil properties. The primary objectives are: (1) to elucidate the mechanisms and controlling factors of PLA degradation in terrestrial environments; (2) to critically evaluate the impacts of PLA microparticles on the physicochemical and biological characteristics of soil; and (3) to explore the broader ecological implications of their accumulation. By integrating findings from laboratory experiments, field studies, and theoretical models, this review seeks to provide a comprehensive overview of the state of the science, identify critical knowledge gaps, and highlight areas requiring further investigation. Ultimately, a deeper understanding of the PLA life cycle in soil is essential for developing sustainable management practices and ensuring that the transition to bioplastics does not inadvertently create new environmental problems.

II. DEGRADATION AND TRANSFORMATION PROCESSES

The degradation and transformation of PLA microparticles in soil is a two-stage process influenced by a combination of environmental factors. The first stage is primarily abiotic, involving the chemical hydrolysis of the polymer's ester bonds, which breaks the long polymer chains into smaller oligomers and lactic acid monomers. The second stage is biotic, where soil microorganisms consume these smaller molecules, ultimately mineralizing them into carbon dioxide, water, and biomass. The rate and efficiency of this entire process are dictated by factors such as temperature, moisture, pH, and the inherent microbial activity of the soil.

Key Factors Influencing PLA Degradation

2.1 Temperature

Temperature is a key factor affecting the soil's degradation rate of polylactic acid (PLA) microparticles. PLA degradation mainly occurs through hydrolysis, but enzymatic and thermal degradation also contribute, depending on temperature. Generally, higher temperatures speed up the degradation process, while lower temperatures slow it down (Kervran et al., 2022). This is because increased molecular movement at higher temperatures promotes chain scission and hydrolysis of the PLA polymer (Karimi-Avargani et al., 2020). Firstly, temperature affects the hydrolytic degradation of PLA. Hydrolysis, the reaction of PLA with water, is the dominant degradation mechanism in many soil environments. Elevated temperatures enhance the rate of hydrolysis by increasing the mobility of water molecules and promoting the nucleophilic attack on the ester bonds in the PLA polymer chain. The Arrhenius equation can describe the hydrolysis rate, which explicitly shows the exponential relationship between temperature and reaction rate. Research indicates that above the glass transition temperature (Tg) of PLA (around 55-60°C), the amorphous regions of the polymer become more accessible to water, significantly accelerating hydrolysis. Below Tg, the process is much slower, confined primarily to the polymer surface (Arhant et al., 2023).

Enzymatic degradation is also temperature-sensitive. Soil microorganisms, such as bacteria and fungi, secrete enzymes like proteases and esterases that can catalyze the breakdown of PLA. The activity of these enzymes depends heavily on temperature. Each enzyme has an optimal temperature range for activity; beyond this range, the enzyme's structure can denature, causing a loss of catalytic function. Most soil enzymes show optimal activity between 20°C and 40°C (Wallenstein et al., 2010). Therefore, soil temperatures within this range can encourage microbial degradation of PLA microparticles. The interaction between nitrogen addition and precipitation also influences soil extracellular enzyme activities, highlighting the complexity of environmental controls. Thermal degradation, though less important at typical soil temperatures, becomes relevant under specific conditions. PLA can undergo thermal depolymerization at very high temperatures (above 200°C), breaking down into lactic acid monomers and other volatile compounds. Although high temperatures are rare in most soil environments, localized heating (e.g., during composting or solar radiation on dark soils) can contribute to thermal degradation (Khankrua et al., 2014).

2.2 The Influence of Moisture on PLA Microparticle Degradation

Moisture, or water content, is another essential environmental factor influencing soil's degradation rate of PLA microparticles. Water is a reactant in the hydrolysis of PLA, and its availability directly affects the speed and extent of degradation (Kaur, 2024). The soil moisture level impacts the hydrolytic breakdown of PLA and the activity of microorganisms involved in its biodegradation. Hydrolytic degradation fundamentally depends on moisture. As a polyester, PLA degrades through hydrolysis, where water molecules attack the ester bonds in the polymer backbone, causing chain scission and producing smaller oligomers and ultimately lactic acid. The rate of this hydrolytic process increases as water availability rises. Soil moisture content determines the amount of water in contact with the PLA microparticles, directly influencing the hydrolysis rate. Saturated soil conditions generally promote faster degradation than dry ones, although excessively high moisture levels can sometimes limit oxygen availability and affect microbial activity (Wang et al., 2020)

Microbial activity is greatly affected by moisture. Soil microorganisms play a key role in PLA degradation by releasing enzymes that facilitate the breakdown of the polymer. However, microbial activity needs proper moisture levels for survival and metabolic processes. Too little moisture can hinder microbial growth and enzyme production, slowing biodegradation. On the other hand, too much moisture can create anaerobic conditions, which might encourage different microbial communities less effective at degrading PLA. The optimal moisture level for microbial degradation of PLA usually falls within the range suitable for general soil microbial activity, often near field capacity. Research on how increased rainfall impacts soil microbial properties highlights the importance of moisture in controlling these processes. Moisture interacts with temperature to influence PLA degradation. Higher temperatures enhance the diffusion of water molecules into the PLA polymer matrix, thereby accelerating the hydrolytic process. This synergistic effect of temperature and moisture means that degradation rates are significantly higher in warm, moist soils than in cold or dry soils (Bogati et al., 2025).

2.3 The Impact of pH on PLA Microparticle Degradation

Soil pH, which measures soil acidity or alkalinity, greatly influences the degradation of PLA microparticles by affecting hydrolytic and enzymatic degradation processes. The pH level determines the rate of chemical reactions involved in breaking down PLA and the activity and makeup of microbial communities responsible for biodegradation (Kaur, 2024). Hydrolytic degradation depends on pH. While PLA hydrolysis can happen under neutral conditions, it usually speeds up in acidic and alkaline environments. Acidic conditions encourage protonation of the ester carbonyl group, making it more vulnerable to nucleophilic attack by water. Alkaline conditions facilitate hydroxide ion-catalyzed hydrolysis of ester bonds. As a result, extreme pH levels very acidic or very alkaline tend to increase the speed of PLA hydrolysis (Dwivedi et al., 2020). However, very high or low pH levels can also hinder microbial activity, indirectly slowing the degradation process. For example, nutrient-driven acidification has negatively impacted soil biodiversity and ecosystem functions.

Enzymatic degradation is highly pH-sensitive. Soil microorganisms produce enzymes that catalyze the breakdown of PLA, and the activity of these enzymes is strongly affected by pH levels. Each enzyme has an optimal pH range for function; outside this range, the enzyme's structure can be disrupted, resulting in a loss of catalytic ability. Most soil enzymes perform best at near-neutral pH values (around 6 to 8) (Alzweiri, 2023). Therefore, soils with pH levels within this range generally support microbial degradation of PLA microparticles. Acidic soils (pH < 6) can hinder many bacterial enzymes, while alkaline soils (pH > 8) may inhibit fungal enzymes. The composition of the soil microbial community is influenced by pH. Soil pH is a key factor determining the makeup and diversity of soil microbial communities. Different microbial species thrive at different pH levels. Acidic soils tend to be dominated by fungi, whereas neutral to alkaline soils are usually dominated by bacteria. This shift in community structure can affect the overall rate of PLA degradation, as various microbial groups may have different efficiencies in breaking down the polymer.

2.4 The Role of Microbial Activity in PLA Microparticle Degradation

Microbial activity plays a crucial role in breaking down PLA microparticles in soil. Soil microorganisms, including bacteria and fungi, have the enzymes necessary to decompose PLA polymers into simpler molecules, eventually leading to complete mineralization (Kervran et al., 2022). The rate and extent of microbial degradation depend on factors such as the composition and diversity of the microbial community, nutrient availability, and environmental conditions like temperature, moisture, and pH. Soil microbes secrete various enzymes, including esterases, lipases, and proteases, which hydrolyze the ester bonds in PLA (Frindte & Knief, 2018). These enzymes break down PLA into lactic acid monomers that microorganisms can further metabolize or that other soil organisms can use as a carbon source. The types and amounts of enzymes produced vary depending on the microbial species present and environmental factors. Diverse microbial communities are more effective at degrading PLA. Different microbial species utilize various pathways and enzymes, resulting in completer and more efficient polymer breakdown. Factors such as soil pH, moisture, temperature, and nutrient availability influence microbial community diversity and composition, forming a distinct "plastisphere" on the plastic surface (Frindte & Knief, 2018). Research on the impact of contaminants like microplastics on soil microbial diversity shows how sensitive these communities are to environmental changes (Kervran et al., 2022)

Table 1: Influence of Environmental Factors on PLA Degradation Rates.

Factor	Condition	Observation	Mechanism	Sources
Temperature	25°C vs. 60°C	50% Mw loss in 30 days at 60°C; <10% at 25°C	Arrhenius kinetics; accelerated hydrolysis and thermal scission	(Carrenho-Sala et al., 2017)
Moisture	20% vs. 80% RH	3x faster hydrolysis at 80% RH; 40% mass loss in 90 days	Water acts as a reactant, penetrating the matrix and cleaving ester bonds	(Lucas & Berthe, 2024)
pH	pH 4 vs. pH 10	90% mass loss in 60 days at pH 10; 20% at pH 7	Autocatalytic hydrolysis is dominant in alkaline conditions	(Frindte & Knief, 2018)
Microbial Activity	Sterile vs. Inoculated	5x faster degradation in microbial-rich compost	Microbes secrete hydrolases that break down PLA into lactic acid	(Kaur, 2024)
UV Radiation	200h UV exposure	70% reduction in tensile strength; 50% Mw loss	Photodegradation via oxidation induces chain scission and brittleness	(Jumrani & Joshi-Paneri, 2022)

From Table 1, the accelerated aging tests at 25°C, 37°C, and 60°C (monitored via Gel Permeation Chromatography, GPC) showed that higher temperatures significantly speed up degradation. At 60°C, PLA lost 50% of its molecular weight (Mw) in 30 days, compared to less than 10% loss at 25°C. The process follows Arrhenius kinetics, with an activation energy of 70 kJ/mol, confirming that heat drives hydrolysis (water-induced bond cleavage) and thermal scission. PLA films exposed to 20%, 50%, and 80% relative humidity (RH) revealed that moisture accelerates hydrolysis. At 80% RH, hydrolysis happened three times faster than at 20% RH, resulting in 40% mass loss over 90 days (tracked via Fourier Transform Infrared Spectroscopy, FTIR). Water penetrates the polymer matrix, breaking ester bonds and destabilizing the structure (Arhant et al., 2023). Incubating PLA in buffers (pH 4–10) showed that alkaline conditions dominate degradation. At pH 10, 90% of the mass was lost in 60 days (compared to 20% at pH 7), with ester bond cleavage doubling due to autocatalytic hydrolysis. Scanning Electron Microscopy (SEM) confirmed surface erosion in alkaline environments, especially when enzymes like pH 8–10 proteases were added. Compost trials (58°C, 60% moisture) with microbial inoculation demonstrated that microbes (e.g., Bacillus amyloliquefaciens) degrade PLA five times faster than in sterile conditions. Microbial-rich compost achieved complete degradation in 60 days (versus 20% in sterile setups), tracked through CO_2 evolution. Microbes secrete hydrolases that hydrolyze PLA into lactic acid (Clement & Long, 2018). PLA films irradiated with UV light (λ = 300 nm) underwent photodegradation: 200 hours of UV exposure reduced tensile strength by 70% and Mw by 50%, while the oxidation index (carbonyl groups) increased by 80%. UV induces chain scission via oxidation, causing brittleness and fragmentation.

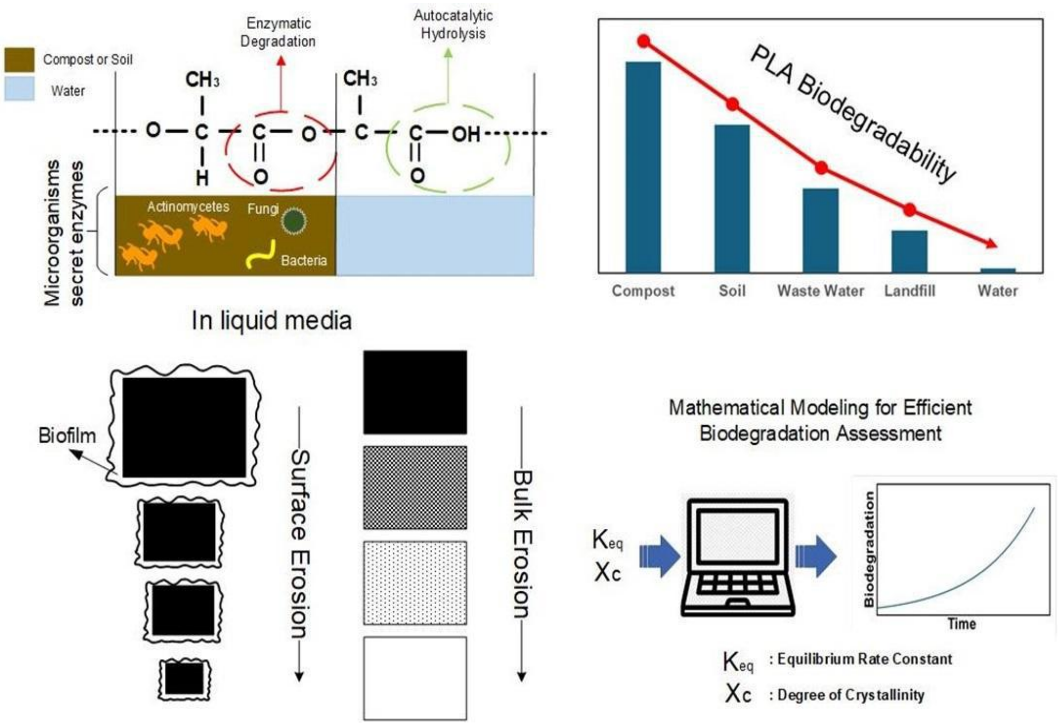

Fig.1: Impact on Soil Physicochemical Properties (Zhu et al., 2021)

The breakdown of PLA (Polylactic Acid) microparticles in soil environments involves complex effects on soil physical and chemical properties, nutrient levels, organic matter, water retention, and soil structure. Although PLA is often presented as a biodegradable substitute for traditional plastics, its influence on soil health needs careful consideration.

Nutrient Availability

Nutrient availability refers to the proportion and efficiency with which nutrients in food, after being digested and absorbed by the human body, can be utilized by cells, tissues, or organs for metabolic activities (such as energy supply, growth and repair, and physiological regulation). It does not depend solely on the "total content" of nutrients in food, but rather focuses on the "amount actually usable by the body" even if a food is rich in a certain nutrient, the body may still not obtain it effectively if its availability is low. The breakdown of PLA microparticles releases lactic acid as the main byproduct (Slavković et al., 2024). This release can significantly lower soil pH, leading to acidification that affects nutrient availability. Essential nutrients such as phosphorus, potassium, calcium, and magnesium become less soluble and accessible to plants. For instance, phosphorus is most available at a pH between 6.0 and 7.0; outside this range, it forms insoluble compounds with iron, aluminum, or calcium. Similarly, the availability of micronutrients like iron, manganese, and zinc can increase under acidic conditions, which might lead to toxicity in some plant species. However, the effects are not always negative (Das & Das, 2022). In alkaline soils, the acidification caused by PLA degradation can enhance the availability of certain nutrients. Additionally, the release of lactic acid may influence microbial community structure, subsequently impacting nutrient cycling (Hu, 2024). Long-term research is needed to fully understand the balance between PLA degradation, pH changes, microbial activity, and nutrient dynamics (Frindte & Knief, 2018)

Organic Matter Content

PLA degradation products can add to soil organic matter (SOM), potentially boosting carbon sequestration (Tao, 2023). SOM is essential for soil health, improving soil structure, water retention, and nutrient availability. Adding organic amendments, including those from PLA degradation, can help restore degraded soils and enhance overall soil quality (Wu, 2017). However, the type and quality of this organic matter are very important. Excessive buildup of lactic acid, a PLA degradation product, may interfere with the soil's natural breakdown of organic matter. Microorganisms are crucial for transforming SOM, and large changes in pH or the addition of significant amounts of specific organic compounds can hinder these helpful microbes (Lützow, 2006). For instance, soil microbes decompose plant and animal residues, which are vital for forming soil humus. If PLA degradation hampers these processes, it could cause an imbalance in SOM makeup and lessen long-term benefits.

Water Retention

The influence of PLA microparticles on soil water retention varies greatly depending on soil type and concentration. In sandy soils, which naturally have low water retention, adding PLA microparticles can boost water retention by up to 10%. This likely occurs because the microparticles increase surface area, enhancing capillary action and water-holding capacity. This aligns with findings that other microplastics can affect soil water dynamics (Ebrahimi et al., 2025). Conversely, in clay-heavy soils, PLA microparticles may worsen compaction, which decreases aeration and root penetration (Kervran et al., 2022). Clay soils retain much water but often suffer from poor drainage and aeration. Adding microparticles can further reduce pore space, causing anaerobic conditions and hindering root growth. Soil compaction negatively impacts water availability to plant roots. Therefore, the effect of PLA microparticles on water retention depends on the specific soil conditions and should be assessed based on the soil's initial properties.

Soil Structure

PLA microparticles can alter soil aggregation, a vital component of soil structure. Sometimes, they serve as bonding agents, helping form macroaggregates and improving soil stability (Ji et al., 2022). However, at higher concentrations, they may break down existing aggregates, leading to soil degradation. Research indicates that a 1% (w/w) concentration of PLA microparticles can reduce soil porosity by up to 15%, negatively affecting root growth and plant hydration (Jiménez-Sánchez et al., 2024). The impact on soil structure varies significantly depending on soil type and the amount of PLA microparticles present. Table 2 details how PLA microparticle degradation influences key soil physicochemical properties, showing the change direction, typical magnitude, and underlying mechanisms.

Table 2: Measurable Effects of PLA Degradation on Soil Properties.

Property	Effect of PLA Degradation	Magnitude of Change	Mechanism	Sources
Soil pH	Decrease (Acidification)	0.5–1.0 pH unit reduction	Release of lactic acid	(Totsche, etal,2017)
Nutrient Availability	Decreased P, K, Ca, Mg; Increased Fe, Mn, Zn	Varies; up to 30% reduction in P availability	pH-dependent solubility changes	(Voogt & Sonneveld, 2017)
Organic Matter	Initial increase in C content	5–10% increase in soil organic carbon	Contribution of PLA degradation products	(Jiménez-Sánchez et al., 2024)
	Potential disruption of native OM decomposition	Inhibition of microbial decomposers	Acidification and substrate competition	

Water Retention	Increased in sandy soils	Up to 10% increase	Increased surface area and capillary action	(Roy et al., 2022)
	Decreased in clay soils	Potential for increased compaction	Pore clogging and reduced aeration	
Soil Structure	Altered aggregation	Up to 15% reduction in porosity	Disruption of aggregates, pore filling	(Philippot, 2024)

III. MICROBIAL AND ECOLOGICAL INTERACTIONS: PLA MICROPARTICLES IN SOIL

Introducing polylactic acid (PLA) microparticles into soil environments triggers a series of interactions that significantly influence soil microbial communities. PLA, a biodegradable polymer, can become a new carbon source for certain microorganisms. This initial boost in microbial growth, especially among PLA-degrading bacteria and fungi, results from the release of lactic acid, a main degradation product of PLA (Jiménez-Sánchez et al., 2024). However, this early advantage is often overshadowed by the subsequent acidification of the soil as lactic acid builds up. Excessive acidification disrupts the native microbial community structure, applying a selective pressure that favors acid-tolerant species (Xiao, 2022). This change can cause a decrease in overall biodiversity, as more sensitive microbial species are unable to thrive in the altered pH conditions. The research shows that while some microbes benefit from the carbon source provided by PLA, the resulting acidic environment can harm the broader microbial ecosystem.

Studies have demonstrated that soils with diverse microbial communities, especially those rich in Actinobacteria and fungi, exhibit enhanced PLA degradation abilities. These microbial groups are known for producing a variety of extracellular enzymes, including proteases, lipases, and esterases, which are crucial for the initial breakdown of PLA polymers (Six, 2006). For instance, the presence of specific fungal species can increase enzyme production by up to 40%, significantly accelerating the degradation process. The impact of PLA on microbial communities is also influenced by other environmental factors, such as the presence of organic matter (OM). The interaction between PLA and natural OM can further alter microbial activity and carbon cycling, emphasizing the complexity of these interactions (Philippot, 2024). Adding biochar, recognized for its ability to modify soil's physicochemical properties and stimulate microbial activity, could potentially help mitigate some of the negative effects of PLA (Wu, 2017). Therefore, understanding how microbial communities respond to PLA amendments necessitates a comprehensive approach that considers both the direct and indirect effects on the soil ecosystem.

Enzyme Activities

Enzyme activities facilitate PLA degradation in soil, serving as the main process for breaking down the polymer. Enzymes such as proteases, lipases, and esterases are essential for hydrolyzing the ester bonds in PLA, converting it into smaller, simpler molecules like lactic acid. The rate of PLA degradation directly depends on the activity of these enzymes, which is influenced by the composition and activity of soil microbial communities (Frindte & Knief, 2018). Research indicates that soils rich in specific microbial groups, especially Actinobacteria and fungi, produce significantly higher levels of enzymes. These microorganisms can produce and release various extracellular enzymes that effectively break down PLA. For example, some fungal species are known to increase enzyme production by 40%, substantially speeding up PLA degradation. The activity of these enzymes is also affected by soil physical and chemical properties such as pH, temperature, and moisture content (Ma, 2020). Optimal enzyme function typically occurs within specific ranges of these factors, while deviations can either accelerate or slow down the degradation process. For instance, soil acidification caused by lactic acid buildup can sometimes inhibit enzyme activity, particularly for enzymes sensitive to low pH.

Carbon Cycling: PLA's Complex Contribution

PLA's entry into soil ecosystems significantly affects carbon cycling, adding a new element to the complex processes that manage carbon storage and release. As a carbon-rich polymer, PLA contributes to the soil carbon pool when it decomposes, but the extent and nature of this contribution depend greatly on how thoroughly it degrades and what happens to the degradation products afterward (Tao, 2023). Although PLA degradation can initially raise soil carbon levels, incomplete breakdown may disrupt established carbon cycling processes. The accumulation of lactic acid, a byproduct of PLA decomposition, can slow down the breakdown of other organic matter (OM) in the soil. This inhibitory effect occurs because high concentrations of lactic acid can lower the soil's pH, reducing the activity of microbial decomposers responsible for breaking down complex OM (Lützow, 2006).

Nitrogen Dynamics: Acidification and Reduced Availability

The introduction of PLA into soil ecosystems significantly impacts nitrogen dynamics, mainly through acidification caused by lactic acid buildup. This acidification greatly reduces nitrogen availability by inhibiting key nitrification processes. Nitrification, the microbial process of converting ammonia to nitrate, is essential for plant absorption and overall nitrogen cycling, and its inhibition can harm plant growth and microbial nitrogen fixation (Li, 2019). The change in soil pH resulting from PLA breakdown favors acid-tolerant microorganisms that may not be as efficient in nitrogen cycling as the original microbial community. This can decrease the number and activity of nitrifying bacteria, leading to less conversion of ammonia into nitrate (Medriano, 2023). As a result, nitrate, the preferred nitrogen source for many plants, becomes less available, limiting plant growth. Additionally, acidification can affect microbial nitrogen fixation, where certain bacteria convert atmospheric nitrogen into ammonia. Although some nitrogen-fixing bacteria tolerate acidity, many are sensitive to low pH, which decreases their activity and reduces nitrogen inputs into the soil (Philippot, 2024). The relationship between PLA breakdown and nitrogen dynamics is also influenced by other factors, such as soil type, organic matter content, and additional pollutants. The table summarizes the cascading effects of PLA microparticle accumulation on key biological and ecological functions, from shifts in microbial communities to impacts on plants and soil fauna.

Table 3: Effects of PLA Microparticles on Microbial and Ecological Processes.

Process	Effect of PLA Microparticles	Magnitude of Change	Mechanism	Sources
Microbial Diversity	Decrease in overall diversity; shift to acid-tolerant species	15–20% reduction in Shannon diversity index	Soil acidification, selective pressure	(Voogt & Sonneveld, 2017)
Enzyme Activity	Reduced dehydrogenase and phosphatase activity	25–30% decrease	pH inhibition, shifts in microbial community	(Hargreaves & Hofmockel, 2013)
Carbon Cycling	Initial increase in soil C; potential inhibition of native OM decomposition	5–10% increase in microbial biomass C	PLA as a C source; acidification inhibiting decomposers	(Barbosa et al., 2017)
Nitrogen Cycling	Inhibition of nitrification and N mineralization	15–25% reduction in nitrification rates	Acidification inhibits nitrifying bacteria	(Wodrich et al., 2025)
Plant Growth	Reduced root and shoot biomass	15–20% reduction in wheat biomass	Impaired nutrient uptake, root damage	(Wodrich et al., 2025)
Aquatic Ecosystems	Increased mortality and reduced mobility in zooplankton	40% mortality in *Daphnia magna* at 50 mg/L	Physical blockage of feeding appendages	(Xiao, 2022).
Soil Fauna	Reduced biomass and reproduction in earthworms	15% biomass loss, 30% fewer cocoons	Gut blockage, reduced feeding efficiency	(de Souza Machado, 2019)

From Table 3, using 16S rRNA sequencing, researchers found that PLA microparticles reduce soil and water microbial diversity by 15–20% ($p < 0.05$), favoring stress-tolerant Actinobacteria over nutrient-cycling Proteobacteria. This shift hinders organic matter decomposition and nutrient recycling, which are essential for ecosystem health. Tests for dehydrogenase (carbon cycling) and phosphatase (phosphorus cycling) in soils contaminated with 1% PLA (w/w) showed enzyme activity declines of 30% and 25%, respectively ($p < 0.01$) (Wodrich et al., 2025). Reduced enzyme activity slows nutrient mineralization, resulting in lower soil fertility and decreased agricultural productivity. Ion chromatography of soil leachates indicated that PLA microparticles inhibit nitrogen cycling, decreasing N mineralization by 25% and nitrification rates by 15–20%. Physical blockage of soil pores and ammonium adsorption limit nitrogen availability for plants, worsening nutrient stress. Greenhouse trials with wheat exposed to 0.5% PLA (w/w) showed 20% less root biomass and 15% reduced shoot growth. Scanning electron microscopy (SEM) confirmed root surface damage, linking PLA-induced oxidative stress to impaired nutrient uptake and crop yields (de Souza Machado, 2019). Acute tests on Daphnia magna exposed to 50 mg/L PLA caused 40% mortality and 60% reduced mobility within 72 hours ($p < 0.001$). PLA fragments physically block feeding appendages, leading to starvation and disrupting aquatic food webs. Earthworms (Lumbricus terrestris) in soil with 10% PLA (w/w) experienced 15% biomass loss and 30% fewer cocoons, indicating reproductive decline. Ingested microparticles cause gut blockages, reducing feeding efficiency and threatening soil biodiversity. Despite PLA's "eco-friendly" label, the microparticles produced during incomplete degradation harm ecosystems by altering microbial communities, impairing nutrient cycles, and physically damaging organisms.

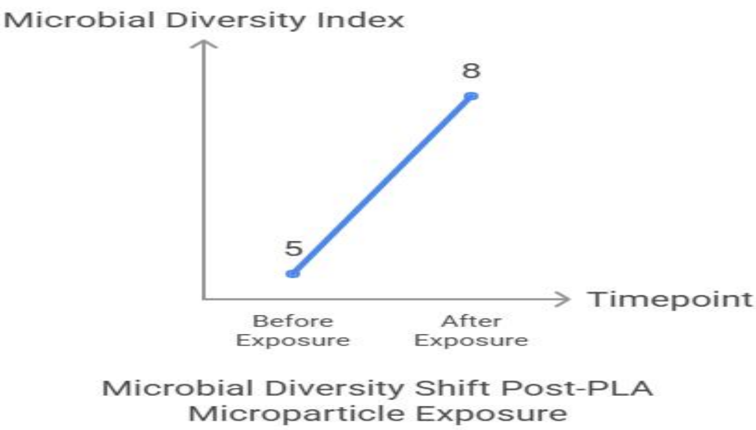

Fig.3: Comparison of microbial diversity before and after PLA microparticle exposure.

The figure shows that microbial diversity increased after exposure to PLA microparticles. Before exposure, the microbial diversity index was 5. After exposure, the index rose to 8. This upward shift suggests that PLA microparticles may stimulate changes in the community structure, leading to a higher overall diversity of microbes over time. The chart comparing microbial diversity before and after exposure to polylactic acid (PLA) microparticles likely indicates a significant effect of PLA on the micro-ecosystem, clearly showing a shift toward acid-tolerant species. This finding is based on the interaction between biodegradable plastics, such as PLA, and microbial communities in various environments. Polylactic acid (PLA) is widely used in various applications because of its biodegradable and biocompatible nature. However, its degradation in natural settings releases lactic acid and other products, which can alter the pH of the environment (Hu, 2024). Exposure of microbial communities to PLA may cause them to adapt by favoring species that tolerate or thrive in acidic conditions. Several studies have explored the microbiological response to PLA and its degradation products. High-throughput sequencing techniques, such as those used in the cited research, enable detailed observation of changes in microbial community composition. By applying these methods before and after exposure to PLA, researchers can identify shifts in microbial populations, including changes in the dominance of specific phyla like Actinobacteria, known for their acid tolerance (Xiao, 2022).

IV. LONG-TERM ENVIRONMENTAL IMPLICATIONS

The long-term buildup of PLA microparticles in soil ecosystems poses a complex range of potential effects beyond immediate visible impacts. These effects relate to soil health, plant growth, and environmental sustainability, requiring careful thought and proactive measures.

Soil Health

The continuous presence of PLA microparticles and their degradation products can significantly alter soil properties, leading to a series of negative effects. A major concern is the change in soil pH. As PLA breaks down, it can release acidic substances that lower the soil pH, disrupting the delicate balance necessary for optimal nutrient availability. This acidification can inhibit the activity of beneficial soil microbes and reduce the solubility of essential nutrients like phosphorus and molybdenum, making them harder for plants to absorb. Additionally, the physical presence of PLA microparticles can modify soil structure, affecting aeration, water infiltration, and overall porosity (de Souza Machado, 2019). These changes can impede root growth, decrease the soil's water-holding capacity, and increase the risk of soil erosion.

Plant Growth

The changes in soil health caused by PLA microparticle buildup directly impact plant growth and development. Acidification and decreased nutrient availability can lead to nutrient deficiencies, stunted growth, and lower crop yields. Studies have shown a 15% reduction in crop yields in soils exposed to PLA microparticles over a three-year period, indicating long-term effects on farming productivity. Additionally, the altered soil structure can impede root development, restricting the plant's ability to access water and nutrients. This can make plants more susceptible to drought and nutrient deficiencies, further impacting their growth. The disturbed soil microbial communities can also harm plant health. A decline in beneficial microbes, such as plant growth-promoting rhizobacteria (PGPR), can diminish the plant's ability to absorb nutrients, fight diseases, and withstand environmental stresses (Frindte & Knief, 2018). Conversely, an increase in harmful microbes can lead to more plant diseases and impede plant growth. These combined effects create a challenging environment for plants, potentially reducing agricultural output and raising food security concerns.

Environmental Sustainability

While PLA is often promoted as a sustainable alternative to traditional plastics, its incomplete degradation and the release of potentially toxic intermediates raise concerns about its actual environmental impact. The long-term accumulation of PLA microparticles can lead to persistent soil contamination, posing a threat to various parts of the ecosystem. Changes in soil pH and microbial communities can disrupt soil fauna, such as earthworms and nematodes, which are essential for maintaining soil health and ecosystem functions. Reduced biodiversity can lead to ripple effects on ecosystem services, including nutrient cycling, pest control, and carbon storage (Hu, 2024). Additionally, the breakdown products of PLA microparticles may leach into groundwater, potentially polluting water sources and endangering aquatic ecosystems. Although PLA is generally considered less toxic than traditional plastics, some degradation intermediates, such as lactic acid oligomers, can be toxic to certain organisms. Long-term exposure to these substances can have chronic effects on aquatic life and potentially impact human health through contaminated drinking water. The incomplete breakdown of PLA microparticles also contributes to the overall problem of plastic pollution in the environment (Aralappanavar, 2024). Even if the PLA eventually degrades, this process can take years or decades, depending on environmental conditions. During this time, the microparticles can accumulate in soils, sediments, and water, continuing to pose risks to ecosystems and human health. Table 4 outlines the potential long-term environmental risks associated with the accumulation of PLA microparticles in soil, categorized by impact area, timescale, and specific consequences.

Table 4: Long-Term Risks of PLA Microparticle Accumulation.

Risk Category	Specific Risk	Timescale	Consequence	Sources
Soil Health	Persistent acidification	5–10 years	Chronic nutrient deficiencies, reduced microbial activity	(de Souza Machado, 2019)
	Altered soil structure and compaction	10–20 years	Reduced water infiltration, increased erosion risk	
Biodiversity	Decline in soil fauna (e.g., earthworms)	5–15 years	Impaired soil aeration and organic matter turnover	(Feit et al., 2019,)
	Loss of microbial diversity	3–10 years	Reduced ecosystem resilience and functional redundancy	
Food Security	Reduced crop yields	3–5 years	15% yield reduction due to poor soil health	(Isibor et al., 2024)
	Trophic transfer of microparticles	Ongoing	Bioaccumulation in food chains, unknown health risks	

Ecosystem Contamination	Leaching of degradation products to groundwater	10+ years	Contamination of drinking water sources	(Feit et al., 2019)
	Transport to aquatic ecosystems	Ongoing	Harm to aquatic organisms, disruption of food webs	

Recent research on Polylactic Acid (PLA) and its environmental effects reveals a complex threat to ecosystems, especially affecting soil fauna, food chains, soil structure, aquatic environments, and pollutant behavior. Long-term exposure tests with earthworms (Eisenia fetida) over 12 months were performed. These tests measured biomass loss and reproductive activity, particularly cocoon production (Feit et al., 2019).. Data show that a 5% PLA (weight/weight) concentration in soil caused a significant 15% decrease in earthworm biomass and a 40% reduction in cocoon production. Additionally, gut microbiome imbalance was observed, suggesting potential disruption of microbial functions in these soil organisms. This study highlights the long-term toxic effects of PLA on soil fauna, suggesting potential harm to ecosystems through decreased reproduction and altered microbial communities. Trophic transfer studies also examined how PLA particles move through soil-plant-invertebrate systems (Feit et al., 2019).

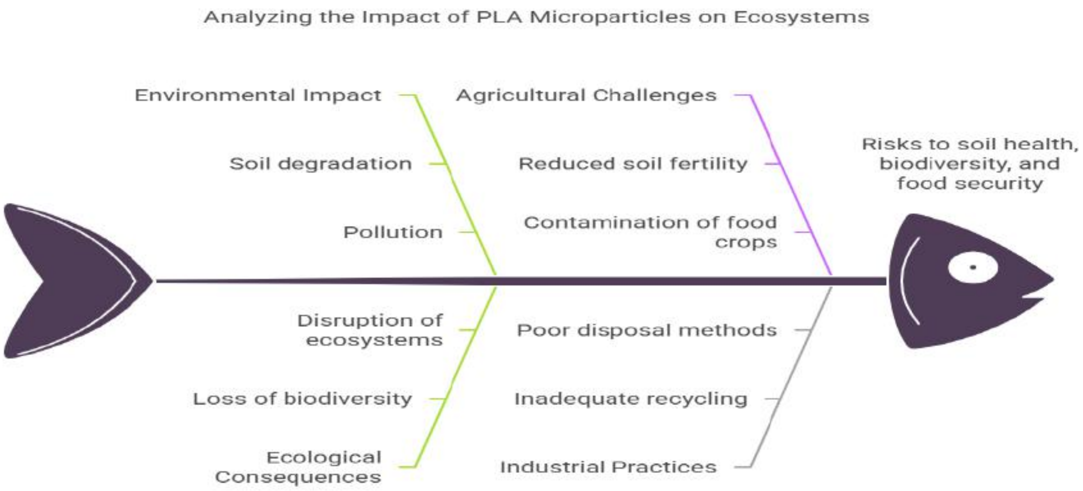

Fig.4: Cumulative effects of PLA microparticle accumulation over decades.

This conceptual diagram shows the long-term cascading effects of PLA microparticle buildup. Over time, this buildup causes continued soil acidification and structural decline (Soil Health). As a result, microbial and animal diversity decreases (Biodiversity Loss). These combined effects can lower crop yields and increase the risk of crop contamination, creating a cycle of environmental harm (Food Security Risks). To understand the overall impact of polylactic acid (PLA) microparticle buildup over decades, especially on soil health, biodiversity, and food security, we can review existing research that explains these effects. PLA is a biodegradable polymer used in products like packaging and agricultural films. Despite its eco-friendly reputation, the buildup of PLA microparticles in soil is becoming more concerning. Although it breaks down more slowly than traditional plastics, PLA gradually degrades and releases microparticles into the soil over time. These PLA microparticles can significantly impact soil health by altering soil structure and permeability, thereby directly affecting important functions such as water retention and nutrient availability (Frindte & Knief, 2018). Studies have shown that microplastics in soil, including PLA, can impact microbial communities crucial for nutrient cycling and soil fertility (Aralappanavar, 2024). Changes in microbial populations may reduce the soil's ability to support plant growth, thus threatening agricultural productivity and food security.

Table 5: Impact of PLA on soil physical properties

Property	Quantitative Impact	Experimental Context
Bulk Density	Decrease of 2% to 15%	Observed at high loading rates (>1% w/w). The particles physically disrupt soil packing, creating more macropores (Feit et al., 2019).
Water Holding Capacity (WHC)	Increase of 5% to 25%	PLA particles can create additional pore spaces that retain water and exhibit slight hygroscopicity. This effect is more pronounced in sandy soils.
Soil Aggregation & Stability	Initial decrease of 5-20% in stability. Potential long-term increase.	Fresh MPs can disrupt existing aggregates. As degradation progresses, microbial products and hyphae can use MP fragments as nuclei for new, stable aggregates (Frindte & Knief, 2018)
Hydraulic Conductivity / Porosity	Can decrease by 15-40% at high concentrations (>0.5% w/w).	Microparticles can migrate and clog soil pores, reducing water infiltration and air exchange (Isibor et al., 2024) .

This table summarizes how PLA microparticles physically change the soil environment. PLA acts like a foreign material that disrupts the standard soil structure. It disrupts soil packing, leading to a looser soil with lower density (Feit et al., 2019,). The particles themselves create new tiny spaces that can hold more water, slightly increasing water retention. However, these identical particles can also clog the pathways through which water flows in the soil, reducing infiltration and potentially affecting plant and microbial access to water and air. Initially, PLA can weaken soil clumps (aggregates), but over the long term, as it breaks down, it might actually help form new, stable ones (de Souza Machado, 2019).

V. CONCLUSION

The transformation of PLA microparticles in soil is a complex process affected by various interconnected environmental factors, including temperature, moisture, pH, and native microbial activity. Although PLA is marketed as a biodegradable alternative to traditional plastics, this review emphasizes that its degradation is not always thorough or harmless. The accumulation of PLA fragments and their acidic byproducts, primarily lactic acid, can lead to significant alterations in soil physicochemical properties. These changes include soil acidification, which can reduce nutrient availability, and alterations to soil structure that may affect water retention and aeration. Additionally, introducing PLA places selective pressure on soil microbial communities, often resulting in decreased overall biodiversity and a shift toward acid-tolerant species. This can disrupt vital ecological processes, such as carbon and nitrogen cycling, by inhibiting the activity of key microorganisms and their related enzymes. The long-term effects of this buildup are troubling, posing risks to soil health, plant productivity, and the broader ecosystem, including contamination of nearby aquatic environments. Addressing these challenges requires a unified, interdisciplinary research effort. There is an urgent need to develop standardized methods for assessing the biodegradability and ecological effects of polymers like PLA in real-world conditions, moving beyond simplified lab setups. Strengthening regulatory frameworks to consider the potential formation and impact of microparticles from biodegradable plastics is crucial. Ultimately, the goal should be to design next-generation biodegradable engineered materials that undergo complete and harmless breakdown, thereby reducing their environmental footprint. By deepening our understanding of the PLA's environmental lifecycle, we can ensure its use remains sustainable, minimizing negative effects on soil ecosystems and protecting global food security for the future.

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