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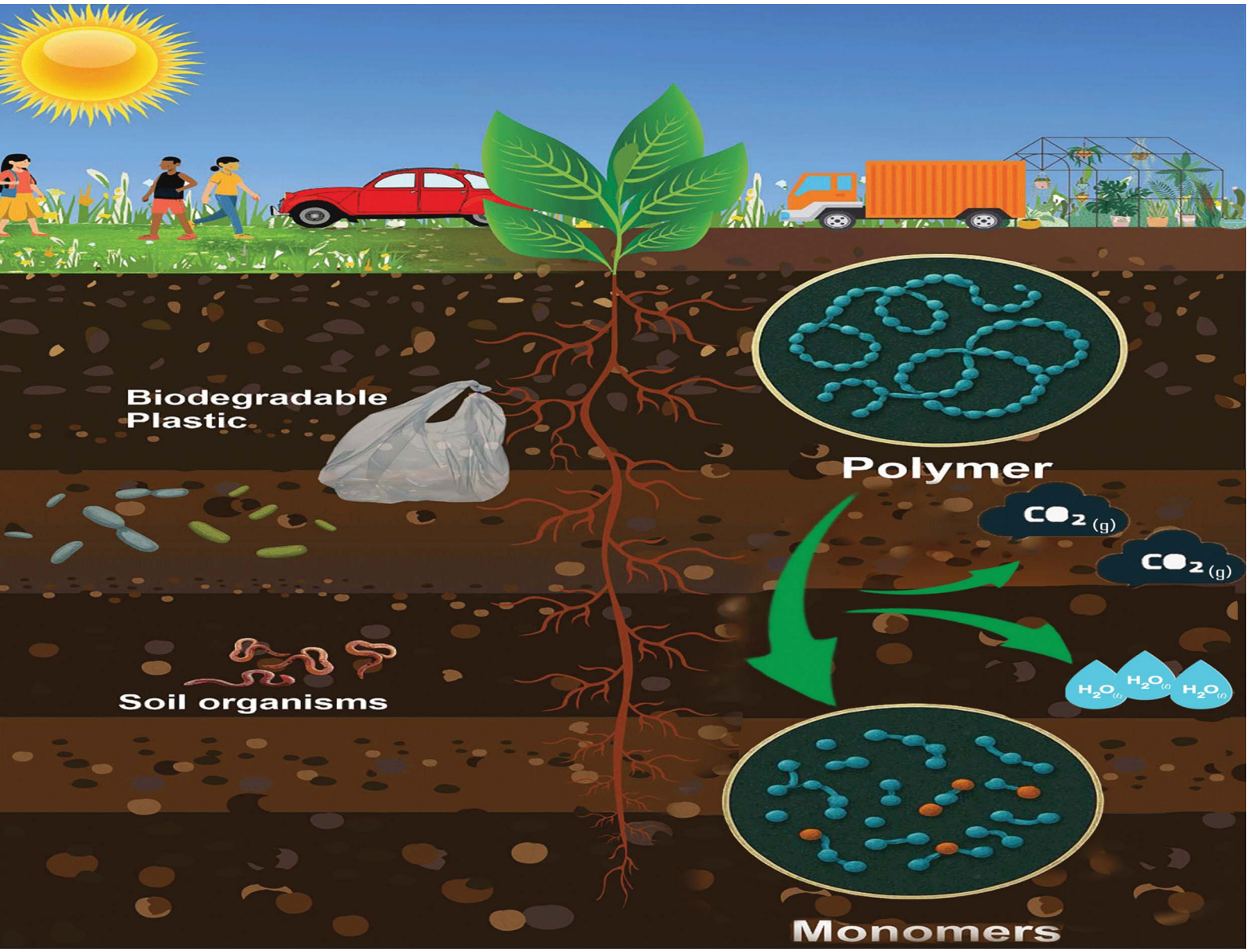

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CRITICAL REVIEW
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Biodegradable plastics in soils: sources, degradation, and effects

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Biodegradable plastics (BPs) are increasingly marketed as sustainable alternatives to conventional plastics, yet their environmental impacts on soil ecosystems remain uncertain. Attention to plastic-related policies, global treaties, and initiatives assessing industrial sustainability are growing, and thus there is an urgent need for scientific data on the life cycle of BPs in soils to determine their viability as a truly sustainable alternative. BPs enter soil through agricultural applications, waste disposal, and landfills, undergoing complex degradation processes influenced by soil properties, environmental conditions, and polymer characteristics. However, the release of degradation by-products, including potential toxins and microplastics, raises concerns about soil health and plant growth. Furthermore, discrepancies in biodegradability claims and the lack of standardized assessment methods hinder the reliable evaluation of BP sustainability. To ensure the environmental viability of BPs, rigorous long-term studies and standardized testing protocols are necessary to validate their degradation, *in situ*, under environmentally relevant soil conditions. Without robust scientific evidence demonstrating the safe and effective degradation of BPs in soils, the expansion of their production and investment in these materials may be limited. This review highlights the urgent necessity for integrated approaches to support effective BP assessment, to bridge scientific research, industrial deployment, and policy frameworks, which are beneficial for mitigating potential unintended environmental consequences and achieving the relevant UN Sustainable Development Goals (SDGs).

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Environmental significance

Biodegradable plastics (BPs) are emerging as a sustainable alternative to petroleum-based plastics, which are non-biodegradable, persist in the environment, and contribute to microplastic pollution. Agriculture, as a major user of BPs, has turned soils into long-term sinks for these materials and their residues. Although marketed as 100% degradable, evidence indicates incomplete degradation and the release of microplastics. In soils, BPs undergo chemical, physical, and biological degradation, producing CO_2, H_2O, and biomass, while intermediate by-products may affect soil fertility and plant growth. This review identifies BP sources in soils, explores their degradation mechanisms, and assesses their impacts on soil properties. We also highlight a methodology for evaluating BP degradation in soils and propose future research directions to address existing knowledge gaps.

1. Introduction

Plastic pollution has significant environmental impacts, potentially jeopardizing human health, and damaging ecosystems essential for species survival. Over 430 million tons of plastic are produced annually, with two-thirds discarded after a single use. If this trend continues, plastic waste is likely to triple by 2060,[1] negatively affecting ecosystems and human health. Even with prompt and coordinated efforts, approximately 710 million metric tons of plastic waste are projected to enter both aquatic and terrestrial environments.[2] Recent studies have highlighted agricultural soils as significant reservoirs of microplastics (MPs).[3] MPs enter soils mainly through compost, sewage sludge, agricultural mulching, littering, and

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atmospheric deposition.[4] Environmental issues related to plastic pollution, particularly MP pollution, have attracted significant attention from scientists, civil society, and policy-makers. MPs are plastic particles ranging from 100 nm to 5 mm in size. These can originate either as primary MPs produced in microscopic sizes or as secondary MPs resulting from the breakdown of larger plastic fragments.[5] In March 2022, over 170 United Nations member states agreed to forge a new global plastic treaty on plastic pollution and to date negotiations are still ongoing. The UN treaty emphasizes the necessity for global scientific and policy communities to collaborate and adopt a life-cycle approach to address the issues from production to disposal.[1] Plastic recycling policies have been adopted by many countries to protect their plastic industries and to prevent, gradually reduce, and eliminate plastic pollution throughout the life cycle by 2040. This demonstrates that conventional plastics have insufficient cyclability, which is essential for establishing a carbon-neutral and eco-friendly society based on a truly circular economy.

Bioplastics constitute an important advancement in sustainable material development. Bioplastics display properties similar to those of conventional plastics while providing additional advantages such as a lower carbon footprint and more diverse waste management prospects such as composting. The use of bioplastics can contribute to reducing the reliance on fossil fuels, lowering greenhouse gas (GHG) emissions, promoting a sustainable and circular economy, and attaining a "Cradle to Cradle" design.[6] However, there has been considerable uncertainty and distrust regarding claims of biodegradability associated with plastic products. This is mainly because of instances where materials marketed as biodegradable failed to degrade as anticipated. Biodegradable plastics (BPs) are a subset of a broader category known as bioplastics. However, the ambiguity regarding the term "bioplastics" is widespread. A prevalent misconception is that materials derived from biomass would biodegrade. However, the utilization of biological feedstock does not ensure complete biodegradability of the final product. For example, bio-based plastics such as polyethylene (PE) are not biodegradable, and BPs such as polycaprolactone (PCL) are not derived from biomass (Havstad, 2020).[7] Plastic materials can originate from bio-based (renewable), fossil (petroleum), or mixed resources. Their end-of-life degradation determines whether these are classified as biodegradable or nonbiodegradable plastics (Fig. 1).

Although the BP manufacturing processes vary, these do not affect the overall biodegradability of the material. The common procedures include producing plastics from a mechanically or chemically processed bio-based polymer (*e.g.*, destructurized starch-based plastics) and chemically synthesizing a polymer from a monomer obtained through the biotechnological conversion of a renewable resource (*e.g.*, using lactic acid from sugar fermentation for polylactic acid (PLA) production). Additionally, biotechnological procedures can be used to produce polymers from renewable resources, such as sugar fermentation

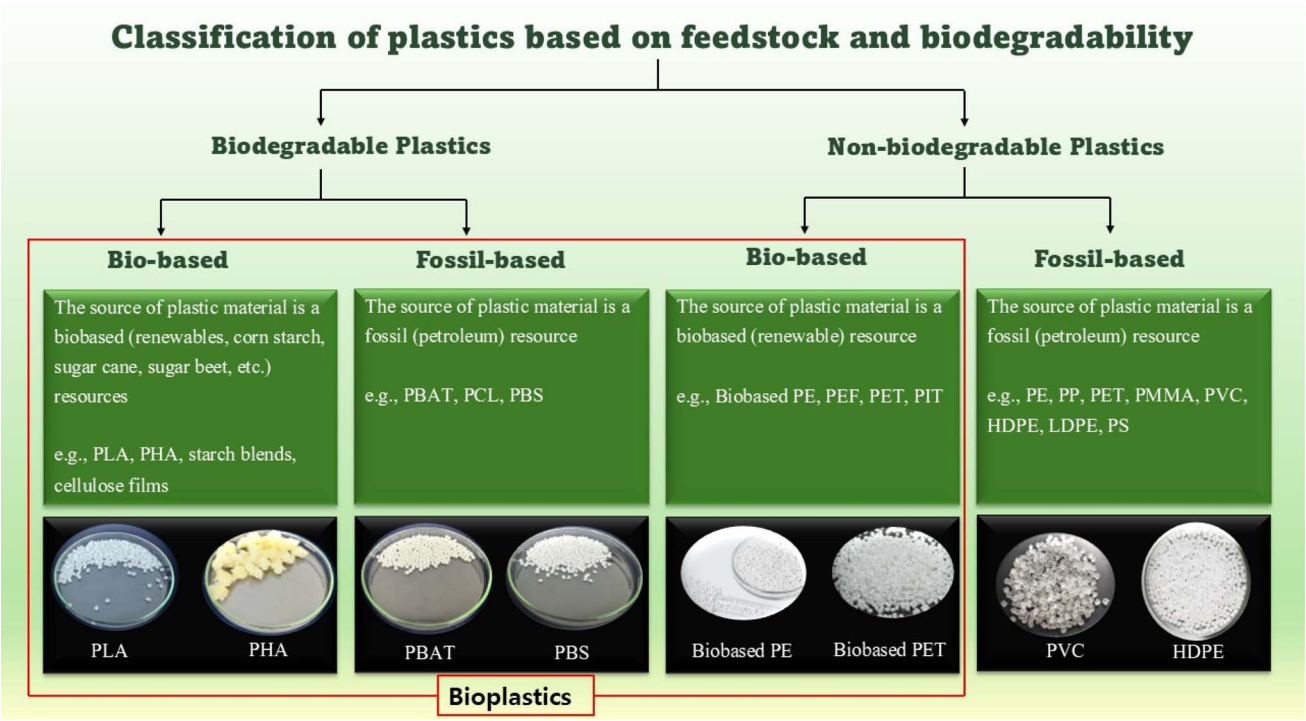

Fig. 1 Plastic types based on their raw material origin and biodegradability.[8,9] (PLA = poly(lactic) acid, PHA = polyhydroxyalkanoates, PBAT = polybutylene adipate terephthalate, PCL = polycaprolactone, PBS = poly(butylene succinate), PE = polyethylene, PEF = polyethylene furanoate, PET = polyethylene terephthalate, PIT = poly(isosorbide terephthalate), PMMA = polymethyl methacrylate, PVC = polyvinyl chloride, HDPE = high-density polyethylene, LDPE = low-density polyethylene, PS = polystyrene).

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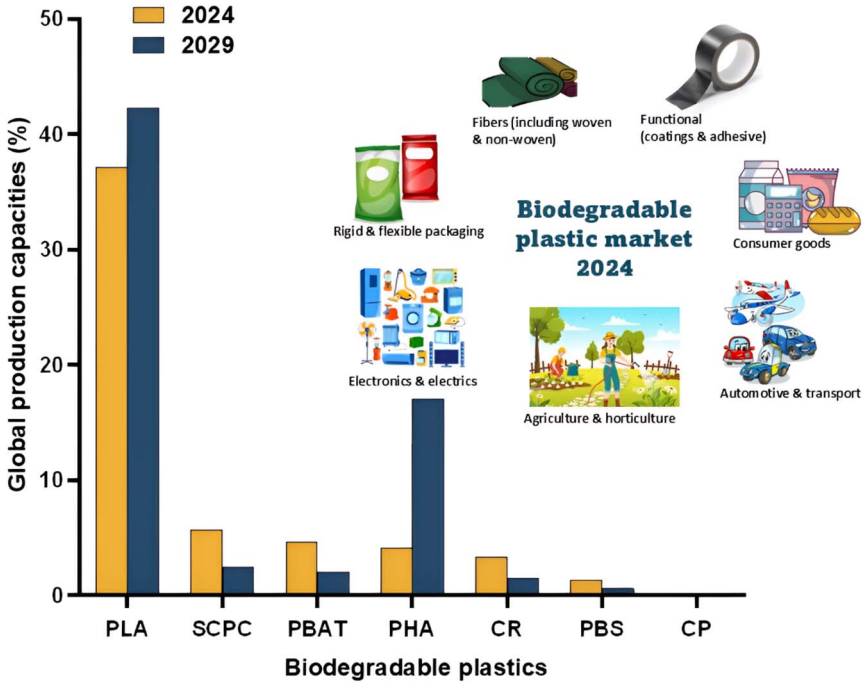

Fig. 2 Global production capacities of biodegradable plastics (biobased) in 2024 and 2029 (%).[15] (PLA = poly(lactic) acid, SCPC = starch-containing polymer compounds, PBAT = polybutylene adipate terephthalate, PHA = polyhydroxyalkanoates, CR = regenerated cellulose films, PBS = poly(butylene succinate), and CP = casein polymers).

by microorganisms to synthesize aliphatic polyesters (*e.g.*, polyhydroxybutyrate (PHB)). Another common method is to chemically synthesize polymers from components obtained *via* petrochemical processes from non-renewable resource (*e.g.*, polyvinyl alcohol (PVA)) polymerization.[10–13]

Currently, the market is dominated by commercially available bio-based BPs such as PLA, PBS (poly(butylene succinate)), its derivative PBSA, polyhydroxyalkanoate (PHA), and polybutylene adipate terephthalate (PBAT),[14] where BPs constitute 0.5% of the total annual plastic production and is >400 million tons. Following a period of stagnation due to the COVID-19 pandemic, global plastic production began to rebound in 2023, driven by rising demand and the development of more advanced applications and products.[15] This growth is also evident in the bioplastics sector, where production capacity is expected to increase significantly, from approximately 2.18 million tonnes in 2023 to around 7.43 million tonnes by 2028. More recent projections indicate an increase from 2.47 million tonnes in 2024 to approximately 5.73 million tonnes by 2029. These trends underscore the continuous expansion of both conventional plastics and bioplastics, fueled by technological advancements and evolving market demands.[9] (Fig. 2).

The agriculture and horticulture sectors have emerged as major drivers of the BP market, leading to higher BP production. These account for 98.6 t (in 1000 tons) of market production in 2023.[9] This increase indicates that large quantities of BPs would ultimately reach soils. Although labeled as "biodegradable," existing research emphasizes the complexities and challenges in achieving complete degradation within desired timeframes (typically between six months to one year) and generates concerns regarding the generation of BP-based MPs (BMPs), which pose additional ecological risks. However, annual sustainability reports of global industries engaged in the development of BPs and related products reveal significant challenges. The current evaluations focus predominantly on marine ecosystems or composting facilities. These do not have comprehensive data on the full biodegradability of these plastics under realistic soil conditions. This presents a severe problem, and industries may inaccurately assert their products' recyclability, compostability, and biodegradability. This can potentially lead to false sustainability claims and the "greenwashing" of these products.

It is our understanding that, with plastic-related regulations and standards still evolving, along with the UN's introduction of new plastic regulations and the recognition of BPs by the United Nations Conference on Trade and Development,[16] there is an urgent need for scientifically validated, research-based information on BPs. This includes their sources, degradation in soils, associated byproducts, and overall impact on soil fertility to ensure the long-term sustainability of BPs in soils. Furthermore, as the Environmental, Social, and Governance (ESG) framework gains traction in assessing industry sustainability, global industries should prioritize the production of more environmentally sustainable products. Considering these global initiatives, stronger collaboration between the scientific and policy communities is essential. Therefore, this review provides a timely and comprehensive analysis of BPs in soils, offering important scientific insights into their lifecycle in soils for various stakeholders, including those involved in product development, policy initiatives and more. Specifically, this

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review discusses BP sources, degradation mechanisms, effects on soil, and associated challenges. The specific objectives of this study were to: (1) provide critical insights into the sources, fate, transport, and impacts of BPs on soil ecosystems, including degradation mechanisms and resultant byproducts; (2) discuss social and political considerations regarding the use and application of BPs to support sustainable development practices, and (3) propose novel research areas that can inform public policies while suggesting new methodologies for analyzing BP degradation in soils.

2. Biodegradable plastics in soils

BPs are frequently used in agriculture activities, including mulch films,[13,17] shielded greenhouse tunnels, soil stabilizers, seed coatings, seedling pot pesticide bottles, and fertilizer bags.[18] BPs, particularly PBAT, PLA, and PBS, are preferred for agricultural mulches because of their high non-recyclability. Notwithstanding its good mechanical and processing properties as well as biodegradability, PBAT has limitations in toughness and photoaging resistance for large scale applications.[19] In contrast, PLA (known for its good mechanical properties, processability, and biodegradability) has become a successful rigid BP widely used in agriculture for mulch, drip irrigation pipes, and shielded greenhouse tunnels.[20,21] With the low thermal stability and processing properties of PHA, recent studies have evaluated its potential in agriculture, primarily as a biocarrier for mulch and slow-release fertilizers.[22] Additionally, polypropylene carbonate has been applied in the field of slow-release fertilizer materials. It exhibits effective slow-release properties and a capacity for water retention.[23]

PLA and PBAT are also extensively utilized in the production of textile fibers. Additionally, BPs play a significant role in the medical field, where they are used for manufacturing medical equipment, personal protective equipment (PPE) including gloves, and blood storage containers. Their biodegradable nature makes them particularly suitable for biomedical applications, avoiding extra treatment for surgical removal. Additionally, these materials are incorporated into cardiovascular devices, burn and wound dressings, drug delivery systems, and dental implants.[24] If not managed properly, waste from the biomedical industry poses a significant risk of accumulating in the environment. This issue became more prominent during the COVID-19 pandemic, which led to a substantial rise in biomedical plastic waste, mainly due to the extensive use of PPE (*i.e.*, masks, gloves, face shields, and sanitizer bottles). The surge in plastic waste has placed immense pressure on existing waste management systems. Improper disposal, particularly in open environments like roadsides, has further contributed to the accumulation of biomedical plastic waste on land, exacerbating environmental concerns.[25]

BPs also enter soils through landfill waste, if they are not disposed of or composed effectively, and then they degrade and release their byproducts into soil ecosystems. Composting is a common practice for managing plastic waste, and when performed effectively, BPs can break down and contribute nutrients to the soil. However, improper composting may result in incomplete degradation, leading to plastic contamination (mainly through the introduction of BMPs) in soils. Littering is another source of BP contamination, as these plastics can accumulate in soils. Once littered, BPs degrade over time, releasing their byproducts into soil ecosystems.[13] When BPs degrade in soils, evidence suggests that BMPs can eventually enter water bodies. Riverine inputs and surface runoff serve as pathways for the transportation of BMPs from terrestrial environments into aquatic systems. Sediments, which act as receptors for various pollutants including metals, organic contaminants, and MPs, carry BMPs along waterways. As a result, these plastics accumulate in water bodies, contributing to their contamination.[26]

3. Biodegradable plastic degradation in soils

The fate of BPs in soils depends on several factors, including their physicochemical properties, soil and environmental conditions, soil management practices, and the duration for which the plastic has been in the soil. In general, BPs can undergo several processes in soils, including fragmentation and mineralization.[27] Degradation is the process by which microorganisms break down plastics into simpler organic compounds. In soils, microorganisms (such as bacteria and fungi) can degrade plastics by secreting enzymes that break down polymer chains into smaller molecules (monomers). These molecules can be broken down further into CO_2, water, and other compounds.[27] The rate and extent of degradation depend on various environmental factors such as the temperature, moisture, and availability of O_2 and nutrients. Fragmentation is another process that occurs when BPs are exposed to soils. This process involves the physical breakdown of plastics into smaller pieces. Compared with petroleum-based plastics, BPs in soils are significantly more reactive. Additionally, their effects on the chemical, physical, and biological properties of soils also differ significantly.[17,27,28] Understanding the degradation processes and the fate of byproducts is essential for assessing the environmental impacts and effectiveness of BPs as sustainable and viable alternatives to fossil-based plastics.

3.1. Factors affecting the biodegradable plastic degradation in soils

The degradation of BPs in soil is primarily affected by BP and soil properties, and environmental factors. Consequently, the ecological safety of plastic materials cannot be assessed by considering individual influencing factors. Rather, these should be evaluated simultaneously.[29]

3.1.1. Environmental factors and soil properties. Soil type can affect the degradation of BPs in soils and their rates. This is because certain soils have higher microbial populations and better nutrient availability for microorganisms which facilitate degradation. César *et al.*[30] observed that the degradation percentage of BPs such as PCL was higher in clayey soils than in sandy soils because of higher microbial proliferation (likely related to the finer soil texture). The maximum mineralization

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percentages of carbon contained in PCL were 72.5% and 60.5% in clayey and sandy soils, respectively, after 120 days of incubation.[30] However, Mazzon *et al.*[31] observed that the highest dose of BPs (commercial mulch film made of Mater-Bi (grade EF04P)) (1%) increased CO_2 emissions, with a greater effect in sandy soil than in loamy soil. Sandy soil exhibited a higher C mineralization capacity, releasing twice the amount of CO_2 compared to loamy soil.

Furthermore, it was observed that soil texture influenced enzymatic activities, with loamy soil showing higher values due to stronger enzyme adsorption onto clay particles.[31] Also, soil texture can influence the degradation of BPs, due to their impacts on microbial activity and soil moisture retention. Loamy soils, which have a balanced mixture of sand, silt, and clay, typically exhibit higher microbial activity and better moisture retention compared to sandy soils. This enhanced microbial presence and sustained moisture create favorable conditions for the breakdown of BPs. In contrast, sandy soils, with larger particle sizes and lower water-holding capacity, may support reduced microbial activity, potentially leading to slower degradation rates of these materials.[32]

Chen *et al.*[33] demonstrated that incorporating clay minerals like kaolinite and montmorillonite into artificial soil increased CO_2–C emissions from MPs, including PE, polypropylene, polystyrene, and polyvinyl chloride. This enhancement is due to clay minerals serving as microbial habitats and providing a larger surface area for microbial colonization. Ding *et al.*[34] further supported this mechanism, reporting that kaolinite, in particular, accelerated MP oxidation and led to the production of reactive oxygen species (*e.g.*, $^{\bullet}OH$ and $O_2^{\bullet-}$). The negatively charged surfaces of clay minerals may also play a role in stabilizing MP radical cations, preventing their recombination with hydrated electrons, and promoting $^{\bullet}OH$ radical formation in oxygen-rich environments.[34]

The soil moisture content is essential for determining the rate and extent of plastic degradation. Adequate moisture promotes conditions favorable for microbial activity, which is essential for BP degradation.[27] Optimal moisture levels promote microbial growth, enzymatic activity, and nutrient availability, that could accelerate plastic degradation. PLA-based films demonstrated increased weight loss when exposed to wet conditions, showing significant degradation after a year. Under wet conditions, the percentages of weight loss were 86.4 ± 2.8 for clay soil and 89.4 ± 1.8 for loam soil. Conversely, under dry conditions, the weight loss percentages were 69.3 ± 10.6 for clay soil and 84.9 ± 2.3 for loam soil.[32] Excessively dry or waterlogged soils can hinder microbial activity. Insufficient moisture limits the microbial breakdown of plastics, whereas waterlogged conditions impede aerobic degradation owing to restricted O_2 availability. Generally, anaerobic metabolic pathways are less efficient than aerobic respiration, and yield lower degradation rates.[35] Identifying preferable soil moisture conditions is essential for optimizing plastic degradation *via* providing adequate moisture for microbial activity without saturation. Moisture can enhance BP degradation and promote sustainable plastic waste management in soils.[32]

Temperature is another critical factor governing the degradation of BPs in soils, primarily because it regulates microbial activity, enzyme secretion, and abiotic hydrolysis processes. Studies have shown that under industrial composting conditions, BP degradation rates are significantly high due to elevated temperatures (>58 °C) and the extensive growth of thermophilic microorganisms capable of breaking down plastic polymers. However, such high-temperature and moisture conditions are not feasible in natural environmental settings, leading to much slower degradation rates in soils, particularly in cooler climates.[36] Generally, the degradation rate of BPs increases with increasing temperatures due to enhanced microbial metabolism. However, the extent of this effect depends on the type of BP and the temperature tolerance of the microbial communities involved.[37]

Laboratory degradation tests in soils are typically conducted at stable temperatures between 25 and 28 °C, but the average temperatures in many temperate regions are lower. This suggests that real-world degradation rates may be significantly slower than those observed in laboratory studies. A study by Huo *et al.*[38] highlights the strong influence of temperature variations within the mesophilic range (20–40 °C) on the degradation of PBAT and starch-based BPs. The study found that mesophilic microorganisms, which thrive at moderate temperatures (30–40 °C), exhibit optimal enzyme secretion, particularly hydrolytic enzymes such as lipases and cutinases. These enzymes accelerate the breakdown of ester bonds in PBAT, generating hydrolysis products such as terephthalic acid, 1,4-butanediol, and adipic acid. Similarly, Sintim *et al.*[39] observed that mulch films derived from PLA/PHA degraded more rapidly during summer than winter, emphasizing the role of temperature in enhancing microbial degradation. Fig. 3 schematically illustrates the variability of BP degradation in soils depending on temperature (Dissanayake *et al.*, 2024).[40]

Despite these observations, laboratory experiments often do not fully capture real-world temperature fluctuations. In controlled environments, stable temperatures create optimal conditions for microbial activity and enzymatic hydrolysis, leading to consistent and predictable degradation rates. Laboratory tests typically maintain uniform temperatures (20–40 °C), providing valuable insights into biodegradation mechanisms. However, natural field conditions are far more variable daily and seasonal temperature fluctuations significantly influence microbial metabolism, often slowing degradation compared to laboratory predictions. Even in warmer climates, laboratory tests tend to underestimate actual degradation timelines, highlighting temperature as a key factor contributing to discrepancies between controlled studies and real-world observations.[36] Understanding these temperature-dependent differences is important for improving the accuracy of biodegradation assessments in environmental settings.

The degradation of BPs in soils is largely governed by the biological activity of soil macroorganisms, such as earthworms and insects, and a diverse range of microorganisms, including bacteria and fungi. These organisms play a major role in breaking down BPs into simpler compounds, eventually converting them into CO_2, water, and biomass under favorable

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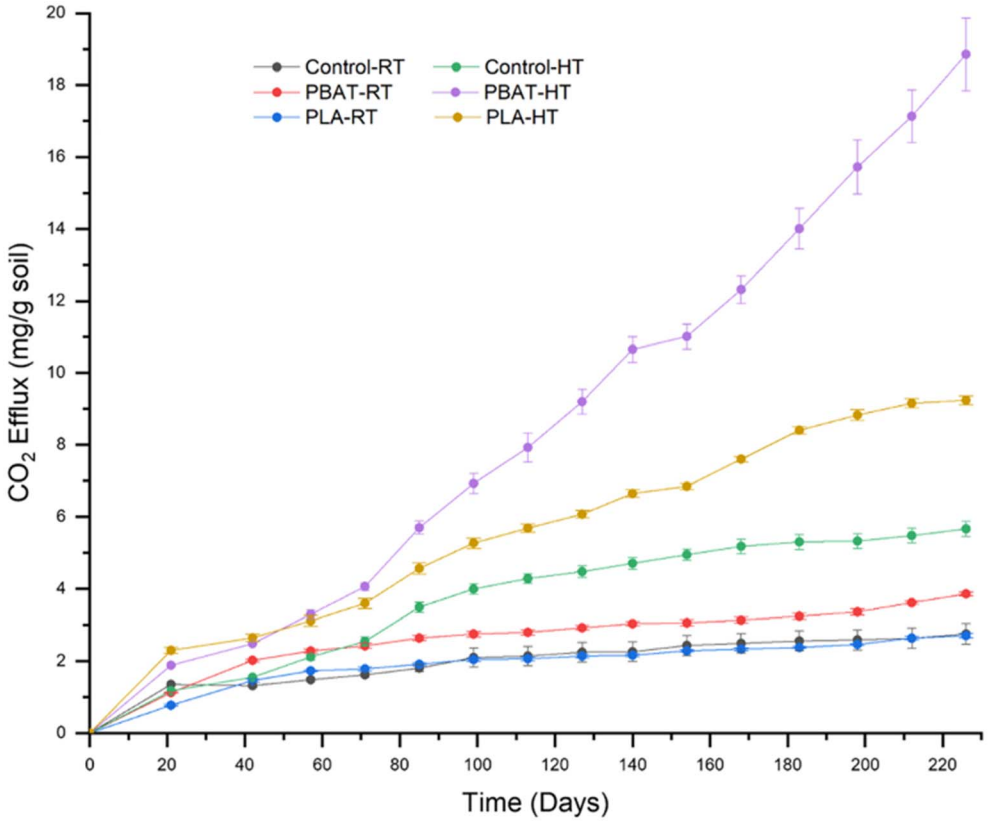

Fig. 3 Cumulative CO_2 efflux during incubation experiments. PBAT and PLA = poly(butylene adipate-*co*-terephthalate) = poly(lactic acid). RT and HT = room temperature (25 °C) and high temperature (58 °C), respectively. Figure adapted and reprinted from ref. 40.

environmental conditions. Typically, environments rich in microorganisms, particularly those with high temperatures and humidity levels, exhibit accelerated degradation rates.[41]

Microorganisms, particularly plastic-degrading bacteria and fungi, colonize BP surfaces and form biofilms that secrete specialized enzymes. These enzymes facilitate the breakdown of plastic polymers into smaller fragments, such as oligomers, dimers, and monomers, through a series of distinct stages including biodeterioration, depolymerization, assimilation, and mineralization. The microbial biomass present in the soil plays a critical role in the degradation of various BPs, such as PBS, PBS–starch blends, and PLA. Over extended periods, ranging from 28 days to two years, higher microbial biomass levels have been directly linked to increased degradation rates, highlighting the strong relationship between soil microbial activity and BP breakdown.[41]

Certain microbial groups exhibit unique contributions to BP degradation. For instance, nitrogen-fixing bacteria have been shown to facilitate the microbial degradation of polybutylene succinate-*co*-adipate (PBSA). Their activity promotes fungal proliferation, which enhances the production of enzymes involved in plastic degradation and influences fungal community interactions essential for breaking down plastics.[28] The presence of these microorganisms accelerates enzymatic activity, leading to more efficient BP degradation.

Beyond microorganisms, soil macroorganisms such as earthworms also play a significant role in BP degradation. Earthworms interact with biodegradable mulch films buried in the soil for six to twelve months, ingesting these films and promoting degradation through processes like bioturbation and vermicomposting. These activities enhance BP fragmentation and increase microbial exposure to the degraded material, further accelerating decomposition.[42]

O_2 availability also plays an important role in the degradation of BPs in soils. Aerobic degradation occurs in the presence of O_2. It is typically the preferred pathway for degradation because it is more efficient and yields higher degradation rates. Under aerobic conditions, microorganisms utilize O_2 to break down BPs into CO_2, water, and biomass through enzymatic reactions. Microorganisms in anaerobic environments may adopt alternative metabolic pathways such as fermentation or methanogenesis. These result in the production of CH_4 and other organic compounds. These pathways are generally less effective in breaking down BPs than aerobic degradation, potentially resulting in prolonged persistence of plastic materials in soils. For example, considering the O_2 content, BP degradation decelerates under anaerobic conditions within the soil profile compared with the soil surfaces,[43] suggesting that the O_2 availability directly influences the extent of BP degradation in soils. Factors such as soil porosity, moisture content, and microbial activity can

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affect the O_2 diffusion and availability within soils and thereby, the degradation kinetics of BPs. In environments where O_2 is abundant, aerobic degradation processes are dominant.

Additionally, UV light exposure can induce the photodegradation of BPs. This reduces their molecular weight, potentially influencing microbial activity on BPs. These plastics are particularly vulnerable to degradation initiated by natural light, particularly in the near-UV band ranging from 290 to 400 nm. Photons in this range carry energy that can induce unstable states in polymer macromolecules and even cleave carbon–carbon bonds.[44] The photodegradation of BPs generally involves Norrish reactions, which include the stages of photoionization and chain scission, as well as crosslinking reactions or oxidative processes. Furthermore, photodegradation can cause a decrease in the molecular weight and mechanical properties of BPs.[44]

Temporal factors also influence the dynamics of soil BP degradation. Degradation typically occurs gradually over extended periods. The duration of exposure to soil conditions significantly influences the degradation rate and extent. Over time, BPs undergo physical, chemical, and biological transformations in soil ecosystems. Microorganisms colonize plastic surfaces and produce extracellular enzymes that break down polymer chains into smaller molecules. These molecules are assimilated by microorganisms as carbon and energy sources.

3.1.2. Biodegradable plastic properties. The chemical structure and crystallinity of BPs can affect their susceptibility to degradation, with certain plastics being more resistant to microbial attack than others. During degradation, preferential attacks tend to occur in the amorphous regions of these materials.[45] However, the crosslinked structures within these materials can impede water penetration and microbial growth, slowing down their degradation. Specifically, polyesters that contain side chains, such as PCL, exhibit accelerated degradation rates while certain types of BPs such as PLA have shown persistent behavior in soils over extended periods. BPs with lower structural complexity or molecular weight are more susceptible to microbial degradation, and enzymatic hydrolysis degradation is accelerated with a decrease in BP crystallinity.[44] Poly(*p*-dioxanone) (PPDO) demonstrated the highest potential for weight loss in soils (56.8 ± 4.8%), while the weight loss ranged from 1.1% to 8.0% for PLA and from 0.8% to 6.8% for PBAT. This disparity can be attributed to the unique ether bond of PPDO and the degradation mechanisms by diverse microorganisms present in the biofilms. The microbiota associated with PPDO is significantly distinct and enriched with *Chloroflexi* and *Firmicutes*, which play key roles in carbon cycling and organic matter degradation.[44] It has been also reported that the degradation rate of PBS–starch was higher than those of PLA and PBS after 28 days. In particular, powdered PBS–starch (a combination of PBS and starch) was degraded by 24%.[41]

BP blends are being produced to enhance mechanical properties while maintaining degradability and striving for improved performance and environmental sustainability. Thus, the degradation degrees are as follows: pure BPs > BP blends > claimed "BP" ≈ non-BP (PE).[44] The degradation performance of both the PLA blend (with PE) and PBAT blend (with PLA) was inferior to that of their respective pure BPs. These differences can be attributed to the enhanced mechanical properties resulting from the blending. These improved properties hinder the polymers from fragmenting or cracking into smaller pieces. Previous studies have indicated that the plastic surface hydrophobicity of BP blends (*i.e.*, a PLA blend with PE) can undergo alterations complicating the degree of degradation.[44] MD40, marketed as a "BP" exhibited minimal indications of degradation compared with nonbiodegradable PE. This is because MD40 is composed of 40% mineral-doped PE plastic, which implies that it may pose a higher challenge to degradation than regular PE.[44]

The size and shape of plastic can influence its surface area and thereby, the rate of microbial colonization and enzyme activity. As reported, larger contact surface area of plastic blends results in a higher degradation rate.[38,46] A comparison of the sizes of biodegradable mulch films at 1% and 2% (w/w) content levels revealed that macro-sized pieces exhibited higher porosity than micro-sized particles in soils.[47] Over a period of 140 days at 28 °C under dark conditions with a moisture level of 14.6%, rapid degradation was observed in smaller-sized BP pellets (50–75 μm) compared with larger-sized pellets. This phenomenon can be attributed to the larger surface areas of materials with smaller particle sizes loaded with more microorganisms.[48] During a 10–12 month burial at a depth of 15 cm, the PHA BPs including PHB and poly(3-hydroxybutyrate-*co*-3-hydroxyvalerate) (PHBV) (both in pellet and film forms) underwent degradation where films exhibited faster degradation than pellets. Notably, microorganisms attached more readily to the surfaces of PHA films. This indicates a potential correlation between surface properties and microbial activity during degradation.

The concentrations of BPs in soils play a significant role in the degradation process, influencing microbial activity and soil respiration. It has been observed that the highest dose of BPs (1%) caused a noticeable increase in CO_2 emissions from the soil, particularly in sandy soil, highlighting the effect of plastic concentration on microbial respiration.[31] The increased CO_2 release can be attributed to both the microbial degradation of the BPs and a potential priming effect. When high doses of carbon-rich materials like BPs are added to soil, they can stimulate microbial activity, often leading to an acceleration of microbial biomass turnover or changes in the mineralization of soil organic matter (SOM), a phenomenon known as the priming effect.[31] This priming effect is particularly pronounced when the added BP is nitrogen-poor, as microorganisms may rely on native SOM to meet their nitrogen needs, further accelerating CO_2 emissions. Mazzon *et al.*[31] presented that the highest BP dose supplied a large amount of carbon but lacked nitrogen, leading to increased soil respiration due to both the degradation of BPs and enhanced microbial activity from the priming effect. In contrast, lower doses of BPs did not significantly affect CO_2 emissions, as they did not induce sufficient changes in microbial dynamics or nutrient balance to trigger the priming effect. Overall, the concentration of BPs directly influences their degradation rate in soils, with higher

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concentrations stimulating greater microbial activity and carbon cycling. The stoichiometric imbalance caused by adding a nitrogen-poor plastic material to soil ecosystems determines how effectively the microbial community degrades plastic. Thus, plastic concentration is a crucial factor in BP degradation, influencing microbial dynamics, nutrient cycling, and overall carbon turnover in soils.[31]

Another factor influencing BP degradation in soil is the presence of various additives, including plasticizers, fillers, oxidants, colorants, and stabilizers. These additives serve specific functions, shaping the mechanical properties, longevity, and environmental impacts of BPs.[49,50] Plasticizers, used to enhance flexibility, may inadvertently hinder microbial degradation by forming protective barriers around polymer chains or leaching into soil, potentially affecting soil health.[51] Fillers, incorporated to improve mechanical strength, can either promote or obstruct degradation based on their composition. Organic fillers such as starch enhance microbial activity, whereas inorganic fillers like clay may limit microbial access to the polymer matrix. Oxidants facilitate degradation by breaking polymer chains into small fragments, accelerating the decomposition process. Colorants, commonly added for aesthetics or UV protection, may contain toxic compounds that disrupt soil microbial communities or alter the thermal properties of plastics, affecting degradation kinetics. Other additives, such as stabilizers, antioxidants, pro-oxidants, and surfactants, further influence the breakdown process by prolonging plastic lifespan, preventing oxidation, or promoting surface interactions.[28,51,52]

Surface charge can also play an important role in determining the behavior and fate of BPs, MPs, NPs, and BMPs in soil environments. Plastics are generally positively charged in soils; however, environmental weathering introduces carbonyl functional groups, leading to an overall negative surface charge on the particles.[53] These changes in surface charge significantly influence interactions between plastics and environmental contaminants. For instance, positively charged NPs have been shown to exert a stronger impact on plant roots than negatively charged ones. Sun *et al.*[54] found that while positively charged NPs accumulated at lower levels in root tips, they induced higher levels of reactive oxygen species, ultimately inhibiting plant growth and seedling development more severely than negatively charged, sulfonic-acid-modified NPs. In contrast, negatively charged NPs were predominantly transported through the apoplast and xylem, suggesting differences in uptake pathways and potential ecological effects. Both positively and negatively charged MPs exhibit strong attachment to soil particles, primarily due to electrostatic interactions and physical trapping. The extent of this attachment is closely related to the soil's zeta potential and is influenced by several factors including pH and ionic strength. These interactions ultimately affect the degradation, mobility, bioavailability, and potential risks associated with MPs, NPs, and BMPs in terrestrial ecosystems.

3.1.3. Soil management practices. Intensive tillage practices can accelerate plastic degradation by enhancing microbial activity and facilitating improved O_2 penetration. Tillage may cause plastic fragmentation *via* breaking down mulch films into pieces. Nevertheless, the degradation rate is subject to changes based on plastic type and environmental conditions, and therefore effective management of mulch films is necessary to ensure adequate aeration and microbial activity and thereby promote degradation.[39] Incorporating crop rotation and cover crops into soils can enhance soil health and microbial diversity, and potentially enhance plastic degradation. Additionally, adding organic additives such as compost or manure can augment microbial activity. This would provide additional carbon and nitrogen sources to facilitate plastic degradation. Soil compaction poses a challenge to degradation processes by inhibiting microbial activity and reducing O_2 diffusion. The implementation of appropriate soil management practices to alleviate compaction can promote plastic degradation. Therefore, adopting sustainable soil management practices is essential for optimizing the degradation of BPs in soil ecosystems.

3.1.4. Global environmental change (GEC) factors. The degradation of BPs in soils may be influenced by global environmental change (GEC) factors, including increasing temperatures, shifts in precipitation patterns, and the timing, frequency and severity of disturbances such as fires, floods, storms, droughts, and hurricanes. For instance, extreme rainfall events can increase river discharges, significantly amplifying plastic transport in aquatic systems, potentially by over a hundred-fold.[55] GEC-induced warming may accelerate microbial activity, enhancing enzymatic reactions that break down BPs. However, excessively high temperatures can also cause soil desiccation, reducing microbial activity and ultimately slowing degradation. Similarly, changes in precipitation and runoff impact soil moisture levels, which are critical for microbial-driven degradation. While sufficient moisture supports microbial activity, excessive waterlogging due to poor drainage can limit O_2 diffusion, thereby impeding degradation rates. Disturbances such as wildfires may further alter the soil structure and disrupt microbial populations, hindering subsequent BP degradation. Additionally, GEC-related factors like acid rain and shifts in soil composition can influence enzyme activity and nutrient availability, indirectly affecting degradation rates.[55]

3.2. Pathways of biodegradable plastic degradation in soils

3.2.1. Physical pathways of biodegradable plastic degradation in soils. Plastics degrade physically and break down into smaller pieces owing to factors such as UV light, weathering, temperature fluctuations, and mechanical stress. This can be considered as a gradual fragmentation process wherein larger plastic particles are broken down into smaller fragments. Liao and Chen[44] observed small fragments of plastics, oligomers, and monomers in the environment before the complete degradation of BPs. The crystalline square fragments they observed were likely formed by the initial degradation of the amorphous fraction of PPDO, which eventually resulted in a slower degradation of the crystalline parts of these materials.[44] The fragments disintegrated further into smaller particles and occasionally, this reached a point where these became invisible

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to the naked eye. Disintegration occurs primarily because of weathering or microbial activity. Small plastic particles can be dispersed throughout the soil matrix owing to various factors such as wind, water flow, or animal activities. Small plastic particles can be ingested by microorganisms such as bacteria and fungi and soil macroorganisms. In general, the physical pathways can be more rapid than the chemical pathways of degradation and can result in the production of small plastic particles that can persist in the environment for a long time.

3.2.2. Chemical pathways of biodegradable plastic degradation in soils. The chemical pathways of BP degradation in soils involve a series of reactions that break down the polymer chains of plastics into simpler molecules such as oligomers and monomers and eventually, into CO_2, water, and biomass that are interlinked with biological pathways. The chemical pathways of BP degradation that involve several stepwise processes are complex and can vary depending on the type of plastic and the environmental conditions in the soil.

Enzymatic hydrolysis is the first step in this process. Microorganisms in soils produce enzymes such as lipases, esterases, and proteases. These can hydrolyze esters or other chemical bonds in the polymer chains of plastic and thus, break these down into smaller oligomers. As an example, for PLA, hydrolysis occurs in the presence of moisture at temperatures above 30 °C releasing smaller oligomers and monomers. This process begins in the amorphous regions of the polymer and causes an increase in the number of carboxylic acid chain ends.[27] In the second step, oligomer degradation occurs. Here, oligomers are broken down further by microorganisms through enzymatic reactions such as dehydrogenation and decarboxylation. These cleave the carbon–carbon and carbon–oxygen bonds in oligomers. In the monomer formation step, oligomers are broken down into monomers such as lactic acid, glycolic acid, or 3-hydroxybutyrate. These can be utilized by microorganisms as a source of energy and carbon. The monomers are degraded further through a process called mineralization and involves the complete oxidation of carbon to CO_2 and the release of water and other organic compounds. This process is performed by microorganisms that use O_2 as an electron acceptor.[27]

3.2.3. Biological pathways of biodegradable plastic degradation in soils. BP degradation in soils is a complex, multi-step biological process facilitated primarily by microbial activity and enzymatic reactions. This degradation process begins with the colonization of plastic surfaces by microorganisms, including bacteria and fungi. These microorganisms form a microbial film on the polymer surface, marking the initiation of the degradation process.[56] Once the microbial film is established, the polymer undergoes enzymatic depolymerization. The microorganisms involved, particularly film-degrading bacteria and fungi, secrete extracellular hydrolases that break down the polymer chains into smaller monomers and oligomers.[57] These breakdown products are then assimilated by microorganisms, which use them for energy production, leading to the release of CO_2 and the formation of biomass.[58] It has been shown that fungal and bacterial communities, particularly those from the ascomycete phylum, are important in the degradation of BPs in soils.[59] Fungi are attracted to plastic surfaces, forming grooves and cavities on the plastic, which suggests an interactive process with bacteria and actinomycetes. This microbial consortium is critical to the breakdown of materials like PHBV films in soils.[59]

Enzymatic processes play a critical role in breaking down specific types of bioplastics. For instance, polysaccharide-based

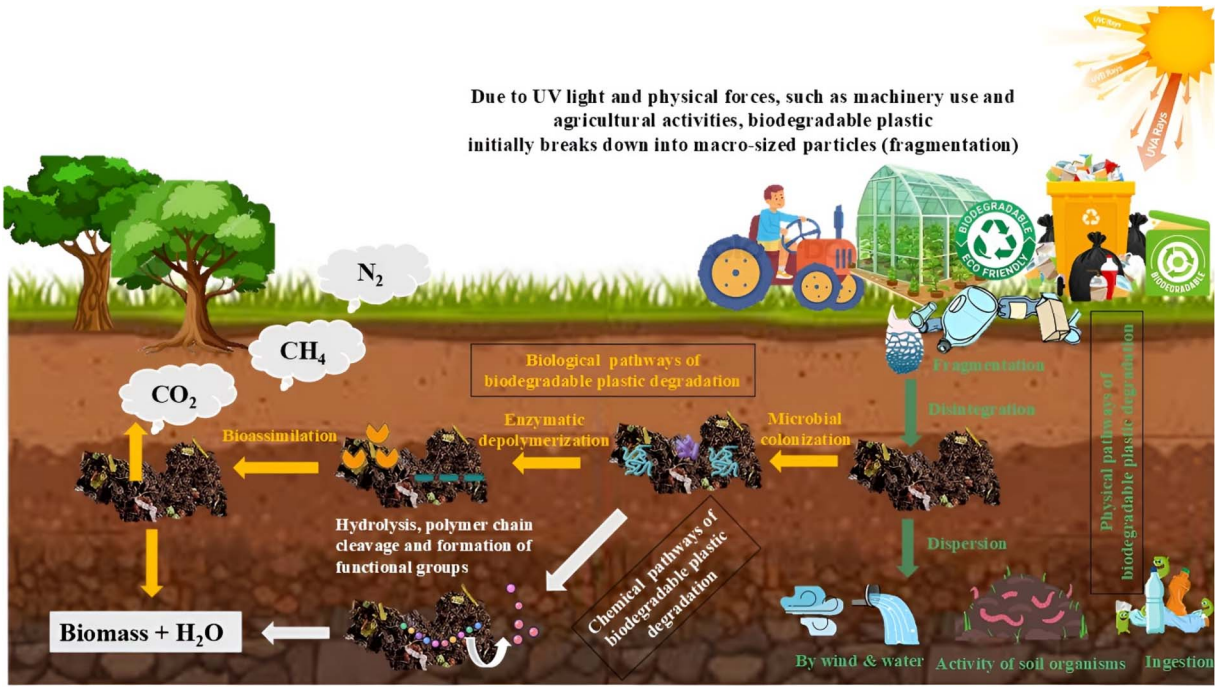

Fig. 4 Degradation pathways of biodegradable plastics in soil.

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bioplastics, such as starch and cellulose, undergo enzymatic hydrolysis facilitated by amylases and cellulases. These enzymes cleave ester bonds and release carboxylic acids and alcohols as byproducts.[60] The degradation is driven by a catalytic triad mechanism involving serine, histidine, and aspartate amino acids, where serine and histidine interact to form nucleophilic alcohol groups that facilitate ester bond cleavage. For other types of BPs, such as PBS and PCL, the enzymatic breakdown is mediated by lipases and cutinases. Lipases attack ester bonds in PBS through hydrolysis, forming water-soluble intermediates like 4-hydroxy butylene succinates, which are then mineralized.[61,62]

It is important to acknowledge that the degradation of BPs in soils involves multiple pathways including biological, physical, and chemical processes that are not mutually exclusive. Therefore, achieving the complete degradation of BPs in soils generally entails a combination of these pathways working collaboratively. Fig. 4 illustrates the degradation pathways of BPs in soils. It outlines the various processes involved, including the biological, physical, and chemical pathways (Fig. 4).

4. By-products and waste generated by degradation of biodegradable plastics

Studies indicate that the degradation of BPs does not pose significant harmful effects.[14] However, there remains limited knowledge regarding the chemical safety of BPs. Specifically, the composition of chemical compounds used in these materials and the potential toxicity of their leachates in both ecosystems and human health are poorly understood. Research suggests that BPs often contain similar additives to conventional plastics and may exhibit comparable levels of toxicity.[51] During the degradation of BPs in soils, various by-products and waste can be generated depending on the specific plastic and degradation processes involved. CO_2 and water are common by-products of degradation because microorganisms oxidize the carbon in plastics to CO_2. Organic acids such as acetic acid, propionic acid, and butyric acid, and volatile organic compounds such as ethanol, methanol, and acetone can be generated during the degradation of BPs.[63] CH_4 can be produced during anaerobic degradation of certain BPs under O_2 deficit conditions.[64]

Plastic manufacturing intentionally incorporates various compounds including additives such as plasticizers, antioxidants, and stabilizers (which enhance their functionality), as well as solvents and catalysts that facilitate their production.[50] So, there is a possibility that these compounds may be released in soil environments upon the degradation of BPs. Because most of these compounds are not covalently bonded to polymers, these can potentially migrate to surrounding air, solids (*e.g.*, packaged goods or soil), or liquids (*e.g.*, beverages) *via* chemical migration.

Organic additives commonly found in plastics include bisphenols, phthalates, brominated flame retardants, organotin compounds, alkylphenols, formaldehyde, antimicrobials, and azo colorants.[65] Many of these substances are recognized or suspected endocrine-disrupting chemicals (EDCs), suggesting that they interfere with hormonal regulation and potentially lead to various adverse health effects.[66] In addition to organic additives, trace metals are frequently used as inorganic additives in plastics.[67] Trace metals such as lead, mercury, and cadmium accumulate in soils at varying rates, depending on plastic types and environmental conditions and can also be toxic to soil organisms and inhibit plant growth, homeostasis, and reproduction.[29] Certain oligomers and monomers generated during BP degradation are toxic. For example, terephthalic acid (a monomer contained in PBAT) functions as an EDC that can damage the endocrine system of organisms. The migration and potential health risks associated with non-intentionally added substances (NIAS) including oligomers formed during polymerization and monomers that are not covalently bonded to the polymer, have long been acknowledged.[17] Additionally, other substances are present, both intentionally (*e.g.*, unreacted monomers) and unintentionally (NIAS, side or breakdown products).

Regarding BP degradation, most scientific attention has been focused on the formation of BMPs. If BPs are not degraded completely in soil, there is a possibility of residual plastic fragments or MPs being left behind. These can persist in the environment and cause long-term environmental problems.[29] The application of film coatings containing fungicides and/or insecticides on agricultural seeds has gained approval as a method for improving seed germination and overall seedling health. Consequently, fragments of the coating can detach and enter the soil in varying amounts. Previous studies have indicated that these detached seed-coat fragments typically have dimensions less than 5 mm. This makes these comparable to MPs in size and appearance.[18] The environmental impacts of the MPs and NPs generated from BPs are likely to be similar to those of petroleum-based plastic derived MPs and NPs.

MPs also act as vectors of various toxic substances. They have a strong affinity for pollutants such as polycyclic aromatic hydrocarbons (PAHs), pesticides, heavy metals, and antibiotics, which are commonly found in agricultural soils.[68] When MPs undergo oxidation in soil, their ability to bind pesticides increases, potentially altering the chemical behavior and bioavailability of these toxic compounds in unpredictable ways. Consequently, MPs not only serve as pollutants themselves but also enhance the mobility and persistence of hazardous contaminants, further compromising crop quality and posing risks to food security and human health.[68]

Evidence has shown the presence of MPs in the human body, which can enter through multiple pathways, including contaminated food, inhalation, drinking water, and even skin absorption.[69] Given these risks, it is crucial to expand research efforts beyond MPs alone and investigate other byproducts and waste generated during the degradation of BPs. Understanding their potential migration from soils to the human body is of utmost importance, especially considering the unknown risks of bioaccumulation and biomagnification within the food chain. Without comprehensive studies, the long-term

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implications of these contaminants for human health remain uncertain, emphasizing the urgency for further research in this field.

5. Impact of degradation of biodegradable plastics

5.1. Impacts on soil properties

5.1.1. Soil chemical properties and ecosystem processes. The degradation of certain BPs can release organic acids such as terephthalic acid and adipic acid,[70] leading to a decrease in soil pH. Alternatively, degradation can release alkaline compounds, which may increase soil pH. These pH variations can influence soil nutrient availability, microbial activity, and plant growth. In their study on the degradation of PLA and polyethylene terephthalate (PET) plastics in compost soil using rhizosphere microorganisms, Janczak *et al.*[71] observed that the introduction of PLA led to a decrease in soil pH and an increase in soil redox potential. This effect may be attributed to ongoing degradation processes, which produce lactic acid. PLA is also known to absorb moisture, leading to the hydrolysis of its ester linkages and the release of smaller oligomers and monomers capable of affecting soil pH.[27] Furthermore, the degradation of PBAT involves the breakdown of adipate ester groups, a process that becomes more pronounced at higher temperatures. This degradation results in the formation of vinyl esters and acids, including terephthalic acid and adipic acid,[70] ultimately leading to a reduction in soil pH.

The degradation of BPs can release essential nutrients such as carbon, nitrogen, and phosphorus, making them available for uptake by soil microorganisms and plants. However, studies have shown that microplastics, including BMPs, can negatively impact soil nitrogen dynamics by disrupting both soil carbon and nitrogen cycles.[72,73] PBAT–MPs may also have a stronger inhibitory effect on the nitrification of ammonium nitrogen (NH_4^+–N) compared to PE–MPs. Both types of MPs contribute to reductions in total nitrogen and available potassium in soils while increasing the available phosphorus.[74] Additionally, the presence of PLA–MPs has been observed to promote the accumulation of NH_4^+–N. Specifically, NH_4^+–N concentrations increased by 185.8% and 156.8% in soils containing 0.5% and 1.5% (w/w) PLA MPs, respectively.[75]

BP degradation in soils contributes to the formation of SOM as microbial activity breaks down plastics and incorporates them into SOM. This process can improve the soil structure, water-holding capacity, and nutrient retention. The addition of PLA–MPs significantly increased soil total organic carbon and dissolved organic carbon (DOC) ($p < 0.05$).[75] Additionally, BPs can serve as carbon sources for soil microorganisms, potentially influencing microbial composition, activity, and function in the long term. Chen *et al.*[37] observed a higher rate of NH_4^+ transformation in PLA MP-treated soils compared to pure soils, suggesting that PLA–MPs function as a carbon source in soil ecosystems. A study by Zhou *et al.*[76] examined the biochemical transformations induced by BP amendments in a plant–soil system. They found significant increases in microbial biomass carbon and DOC with PHBV, a common BP. These increases are likely the result of microbial assimilation of BPs. The study also demonstrated nitrogen immobilization, as evidenced by decreased dissolved organic nitrogen (DON) and increased microbial biomass nitrogen. Sanz-Lázaro *et al.*[77] also observed substantial increases in the carbon : nitrogen ratio and changes in nitrogen cycling induced by PLA compared to conventional plastics.

As discussed, certain BPs may contain heavy metals that can be released during degradation, making them bioavailable for plant uptake and potentially toxic to soil microorganisms. The mechanisms involved in the sorption of MPs, including BMPs, are primarily attributed to hydrophobic interactions, electrostatic forces, π–π interactions, hydrogen bonding, and other effects.[78] However, few field investigations and experimental studies have verified the sorption behaviors and mechanisms of MPs and BMPs. BMPs exhibit higher affinities for chemical substances than MPs. For example, PBAT–MPs show the highest affinity for phenanthrene in aqueous solutions of PBAT, PE, and PS MPs due to the low crystallinity of PBAT.[79] Similar observations have been made regarding the adsorption of oxytetracycline (OTC) onto PLA–BMPs under different environmental conditions.[80] It was shown that biofilm-formed PLA–BMPs had a significantly stronger affinity for OTC due to their increased surface area, the generation of oxygen-containing functional groups, and enhanced hydrogen bonding, among other interactions with biofilms. Moreover, OTC desorption behavior was more pronounced for biofilm-formed PLA–BMPs.[80]

5.1.2. Soil physical properties. Degradation of BPs can contribute to the formation of soil aggregates and alter the soil structure. Additionally, BPs impact the distribution of aggregates in soils. The random dispersion of BP fragments and BMPs within soils can create impermeable barriers, obstruct soil pores, and alter the direction of water flow, potentially modifying the soil structure.[81] However, the use of BP mulch films has been shown to have a positive impact on the overall stability of soil aggregates compared to soils without mulch which resulted in a 9–16% higher aggregate stability compared to reference plots without mulch.[82] However, aggregate stability reduced over time in all treatments due to ongoing soil disturbance caused by continuous cultivation.

BP degradation can also positively impact soil water-holding capacity by increasing soil organic matter and improving the soil structure. Qi *et al.*[83] observed that the presence of macro-sized BP fragments at 1% and 2% levels increased soil field capacity. Additionally, alterations in porosity, saturated hydraulic conductivity, and soil water repellency were observed in the presence of these fragments. The random dispersion of MPs in soils also created water-resistant barriers, hindering soil pore function and altering the water flow direction. Jiang *et al.*[84] observed that residual MP fragments altered various soil properties such as soil water content, bulk density, hydraulic conductivity, and porosity, which affected soil water distribution near plant roots.

BP degradation can reduce soil bulk density as the formation of soil aggregates increases soil porosity. Furthermore, BPs can alter soil aeration by reducing soil compaction and improving

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the soil structure. This, in turn, facilitates better gas exchange between the soil and the atmosphere. Qi *et al.*[83] compared the impact of macro-sized BP fragments at 1% and 2% levels on porosity, observing that macro-sized fragments resulted in higher porosity compared to micro-sized particles.

5.1.3. Soil biological properties. Degradation of BPs in soils can stimulate microbial activity. Microorganisms, such as bacteria and fungi, break down plastics and consume them as a carbon and energy source. This can increase microbial abundance and diversity in soils. Evidence suggests that the presence of PLA contributes to an increase in the overall abundance of microorganisms in the soil, from 5.4 to 5.7 cfu ml^{-1} (colony-forming units) for bacteria and from 3.0 to 3.2 cfu ml^{-1} for fungi. However, in the case of PET, the number of bacteria decreased to approximately 0.3 cfu ml^{-1}.[71] Zhou *et al.*[76] examined the effects of adding polyhydroxyalkanoates (PHAs) on the soil microbial community structure, growth, and exoenzyme kinetics in the soil plastisphere (the interface between soil and microplastics), rhizosphere, and bulk soil.[85] Using the common PHA biopolymer poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV), they observed that the microbial community utilized PHBV as a carbon source.

The degradation of BPs can thus enhance soil biodiversity as microbial populations increase.[32] According to Zhou *et al.*[76] the introduction of bioavailable carbon (*via* the degradation products of PHBV) resulted in a two-fold increase in enzyme activities in hotspots compared to bulk soils. This increased microbial activity was anticipated, considering that poly-3-hydroxybutyrate is a common compound produced by diverse groups of microorganisms, particularly in response to nitrogen deficiency and cold stress. The addition of PHBV affected the activities of carbon- and nitrogen-degrading enzymes, with activity differences between hotspots and bulk soil being 2–10 times greater when PHBV was introduced. This indicated its direct influence on carbon and nitrogen cycling.[76] According to the authors, the higher maximum velocity (V_{max}) of β-glucosidase in the soil plastisphere, compared to the rhizosphere, can be attributed to the faster growth of biomass following PHBV additions. This correlation is supported by the positive relationship observed between active microbial biomass and the V_{max} of β-glucosidase ($R^2 = 0.7$). Additionally, the increase in β-glucosidase activity suggests that PHBV stimulates the breakdown of other common soil polymers, such as cellulose. Furthermore, PHBV can be broken down by depolymerases, releasing hydroxybutyric acid monomers that serve as fuel for the production of energetically expensive exoenzymes, such as leucine aminopeptidase.[76] These exoenzymes are capable of degrading soil organic matter to acquire nitrogen for microbial growth, indicating a positive priming effect.

Although the alteration of soil properties by BP degradation has been discussed separately, soil should be considered as a complex ecosystem. While plastic degradation may directly alter one soil property, it can also indirectly affect others. Therefore, we emphasize that when conducting soil research, ecosystem complexity should be considered. Investigators should consider the overall variations in soil properties following degradation and their potential impacts on crop growth. Table 1 summarizes the mechanisms by which BPs and their degradation affect soil properties.

5.2. Effects of BP degradation on crop growth

The impact of BP degradation on crop growth is a multifaceted issue that requires a comprehensive examination within the context of the broader soil ecosystem. As BPs degrade in soils, they release diverse byproducts and breakdown components, which influence soil health and, consequently, plant growth. These effects manifest through changes in the soil structure, nutrient availability, water retention capacity, microbial activity, and various soil processes. Depending on the specific BP type and environmental conditions, these alterations can either promote or inhibit crop growth.

One of the major concerns regarding BP degradation is its influence on soil physical properties, which directly affect plant growth. The physical presence of degraded plastic residues in soil can alter root penetration, soil aeration, and moisture distribution, critical factors in determining crop productivity.[66,106–108] The formation of BMPs from BP breakdown may lead to soil compaction, reduced porosity, and restricted root development, ultimately impeding nutrient absorption and water uptake. Furthermore, weathered BP fragments can create barriers in soil pores, affecting water infiltration and retention, which may further impact plant growth and yield.

Beyond physical modifications, BP degradation also releases chemical compounds that may interact with plant physiological processes. While some degradation byproducts may act as growth stimulants, others could inhibit seed germination, root elongation, or nutrient uptake. Yang and Gao[108] found that MPs derived from PBAT-based biodegradable mulch films altered nitrogen metabolism and photosynthesis in rice plants. Exposure to these MPs downregulated genes responsible for nitrogen transportation and phenylpropanoid biosynthesis in rice roots, leading to oxidative stress in both roots and shoots. Similarly, Liu *et al.*[106] demonstrated that 2% PBAT-derived MPs had a more pronounced inhibitory effect on *Arabidopsis thaliana*'s growth and photosynthetic system compared to PE–MPs after 14 and 28 days.

Further evidence suggests that biodegradable mulch film residues can significantly hinder plant growth. Serrano-Ruiz *et al.*[109] reported that fragments of polyhydroxybutyrate-based (PHB) biodegradable mulch films reduced tomato and lettuce growth by 90% and 95%, respectively. Additionally, both pristine and field-weathered BP fragments delayed lettuce development, with weathered fragments exhibiting more severe effects than unweathered ones. These findings suggest that the impact of BP degradation on plants is influenced not only by their physical presence but also by their chemical composition and environmental changes.

Another pressing concern is the potential uptake of MPs by plants, which raises food security and safety issues. While most research has focused on MP contamination in soil and its effects on microbial communities, recent studies indicate that MPs and plastic nanoparticles (<100 nm) can be absorbed by plant roots and translocated to aboveground tissues.[68] This has been corroborated by the detection of MPs in commonly

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Table 1 Mechanisms of impact of biodegradable plastics on soil properties

Soil property	Mechanisms of impact of biodegradable plastics on soil properties	References
Total organic carbon (TOC)	The degradation of BPs in soil can alter TOC concentration in soil. That is, the polymeric units of BPs, BMPs, and MPs are approximately 80% carbon and thus their introduction into soil can increase its storage of organic carbon	86
	Rapid production of BPs may lead to the accumulation of these materials in soil ecosystems. This accumulation may disrupt soil biogeochemical cycles, particularly the carbon and nitrogen cycles acting as an exogenous carbon input	87
C : N ratio	BPs affect soil carbon cycling due to their high carbon content, resulting in increased ranges of C : N ratios, which may adversely affect the soil nitrogen and carbon cycles	87
Dissolved organic carbon (DOC)	BPs are more readily degraded by soil microbes, leading to the release of BP-derived DOC into soil. Additionally, soil water molecules may attack the ester bonds of BPs (*e.g.*, PLA), facilitating the leaching of soluble low-molecular-weight oligomers into soil. Both these forms of BP degradation can contribute to the alteration of DOC concentrations in soil	76, 88 and 89
	Microorganisms colonize the surfaces of BPs and produce enzymes that initiate the breakdown of polymers into smaller molecules, including DOC and other organic residues which serve as nutrients thus assimilated by microorganisms.	76
	The concentrations of DOC in soil are altered by direct impacts on the carbon and nitrogen cycles resulting from the degradation of BPs in soil	
Biomass C	When BPs degrade in soils, microorganisms metabolize the resulting degradation products and thus, incorporate some of the products' C into their biomass. Therefore, the biomass C concentration in microorganisms may increase due to their assimilation	76
	The microorganism activity stimulated by the presence of BPs can lead to an increase in the decomposition of organic matter in soils, thereby releasing additional carbon into soil and further contributing to changes in biomass carbon concentrations	
Dissolved organic nitrogen (DON)	Microorganisms that colonize and degrade BPs may also utilize nitrogen-containing compounds released during the degradation process as a source of nitrogen for their growth and metabolism. Thus, some of the DON in soil may be assimilated by these microorganisms, leading to a decrease in DON concentrations	76
	The degradation of BPs can alter soil properties, such as pH, water content, and O_2 availability. These alterations can influence the chemical and biological processes that control nitrogen cycling in soils, potentially leading to alterations in the forms and concentrations of DON	
	The presence of BPs in soil increases the availability of carbon and other nutrients, which can increase microbial activity. This may lead to increased nitrogen mineralization, whereby organic nitrogen compounds are converted into inorganic nitrogen compounds (such as NH_4^+ ions), that are subsequently taken up by plants or immobilized by microbes, potentially reducing DON concentrations in soil	
NO_3^-–N and NH_4^+–N content	BPs, especially MPs derived from the breakdown of PBAT may influence soil nitrogen dynamics, potentially affecting the nitrification process	90
N losses	BPs may alter the soil structure and porosity, leading to increases in the abundances of denitrifying bacteria and thus increases in nitrogen loss	91
pH	When BPs are broken down into macro-sized particles and micro-sized particles (*i.e.*, MPs) that infiltrate soil, these particles' large surface area enable them to effect cation exchange processes, leading to changes in soil pH	66
	The presence of MPs may indirectly influence soil pH by modifying the structure and function of soil microbial communities. Specifically, changes in microbial dynamics can have cascading effects on soil processes that may lead to shifts in soil pH	

Table 1 (*Contd.*)

Soil property	Mechanisms of impact of biodegradable plastics on soil properties	References
Trace elements mobility in soils	Compared with petroleum-based plastic (*i.e.*, PE) MPs, BMPs (*i.e.*, PBAT) are smaller and have rougher surfaces and different cracking patterns and functional groups, which can lead to their higher sorption capacities for heavy metals, such as copper. This can result in alterations in the mobility and availability of heavy metals in soil containing BMPs	90
Microbial community richness and diversity	The disintegration and formation of biofilms were found to be more pronounced on BMPs than on petroleum-based MPs, which could result in greater alterations in microbial community structures in soils	66 and 83
	The distinct chemical compositions and surface characteristics of BPs can favor the proliferation of different microorganism species in soil, resulting in variations in their abundance in soils	
	Alterations in soil physicochemical properties resulting from the degradation of BPs may indirectly impact their microbial activities and community structures	92
	Increases in the concentrations of available carbon due to the release of BP degradation by-products into soils result in the growth of soil microorganisms. Moreover, as BPs are exogenous carbon sources, they provide selective niches for soil microorganisms	76 and 93
	Degradation of BPs in soil could affect airflow in soils and contribute to the high abundance of ammonia-oxidizing archaea-like organisms, which are involved in nitrification	94
	BPs can stimulate nutrient turnover, thereby increasing bacterial growth over time	95
	The presence of BP mulch films can create favorable microclimatic conditions and optimized soil water storage, thereby increasing bacterial diversity	96
Soil enzymes	Changes in enzyme activities in soil are largely induced by changes in the physicochemical properties of soil that occur because of BP degradation	94 and 97
Impacts on animals and plants	Degradation of BPs in soil can cause changes in the physiochemical and biological properties of soil that negatively affect plant health	98
	Degradation of BPs in soil can increase the intracellular concentrations of reactive oxygen species and impair membrane integrity or functioning of organisms	99 and 100
	Particulate-induced toxicity of PLA–MPs in organisms such as zebrafish (*Danio rerio*) and a species of water flea (*Daphnia magna*) may be due to the release of additives, monomers, and toxic intermediates during the relatively rapid degradation of BPs	51 and 101
	Changes in surface properties (*e.g.*, increases in hydrophilicity) or the introduction of oxygen-containing surface groups during the degradation of PLA-like MPs may lead to oxidative damage in organisms such as *Danio rerio*. Thus, the ecotoxicity of MPs can increase during their degradation	100
	Products and secondary metabolites formed during the degradation of BPs may inhibit seed germination and plant growth, and adversely affect root health	102 and 103
	Reductions in shoot and root growth, and fruit biomass of common bean-like crops are attributable to BP-induced alterations in rhizosphere bacterial communities	104
	Compared with normal degradation of BPs, accelerated degradation of BPs can lead to greater alterations in the soil structure and stability and greater biological effects, all of which can affect soil flora and fauna	105

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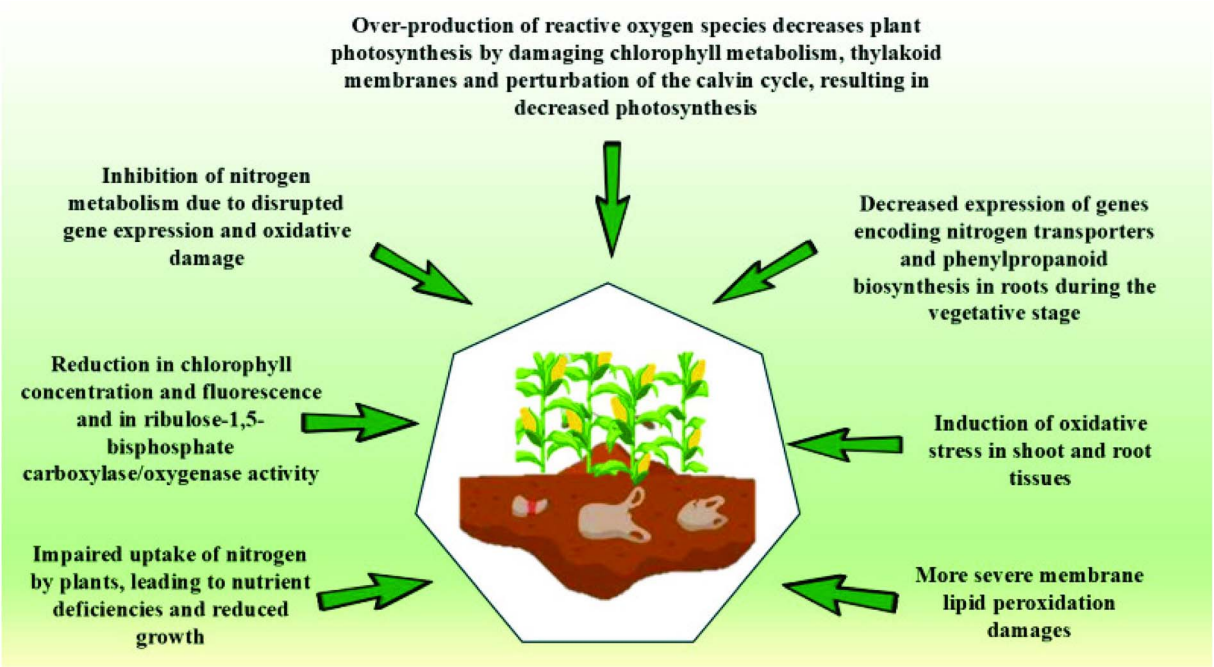

Fig. 5 Potential impacts of biodegradable plastic degradation processes on crop growth.

consumed fruits and vegetables such as apples, pears, broccoli, lettuce, and carrots from local markets.[110] MPs follow similar absorption and translocation pathways as carbon nanomaterials, infiltrating plant tissues through root uptake, seed penetration, and capillary action. The accumulation of MPs in edible crops increases the risk of human exposure through dietary consumption, emphasizing the need for further studies on the potential health implications of BP degradation products entering the food chain.

Given these complexities, it is essential to consider the degradation of BPs not as an isolated event but as part of a dynamic soil–plant system (Fig. 5). While BP mulch films and other BPs offer potential benefits for sustainable agriculture, their long-term effects on soil health and crop productivity remain an area of active research and interest. Investigations should aim to understand how BP degradation products influence plant–soil interactions over time and whether mitigation strategies can minimize negative impacts while maximizing the benefits of biodegradable materials in agricultural applications.

6. Analysis of biodegradable plastic degradation in soils

The assessment of BPs in terms of their degradation is critical for ensuring their sustainability and credibility. Accredited agencies play an important role in evaluating these materials, adhering to international standards to ensure reproducibility and reliability of results. However, the assessment methods may vary across different nations and regulatory bodies, reflecting regional differences in climate, soil productivity, and acidity. Globally, several standardization frameworks guide the evaluation of BP degradation. In Europe, EN standards regulate biodegradability testing, while the ASTM standards apply in the United States, AS standards in Australia, NFT standards in France, and ISO standards internationally. Compliance with these standards is verified by certification marks such as Germany's DIN CERTCO, Belgium's OK Compost, and the European Union's Seedling logo, which indicate adherence to specific biodegradability requirements.

BPs undergo degradation in both terrestrial and marine environments, each requiring distinct evaluation methods. Terrestrial biodegradability is assessed using standards such as ISO 14855, EN 13432, ASTM D6400, EN 14995, and ISO 17088, which outline protocols for measuring degradation under controlled composting conditions. Among these, ISO 14855 is widely emphasized for its ability to replicate anaerobic composting environments, measuring CO_2 evolution to assess the breakdown of organic compounds.

For an analysis under ISO 14855 to be considered valid, the following four criteria must be met:

(1) Stable CO_2 emissions throughout the testing period.

(2) Biodegradability exceeding 70% within 45 days.

(3) Minimal variability (<20%) in biodegradability among different test materials.

(4) CO_2 emissions between 50 and 150 mg g^{-1} of volatile solids over a 10 day period.

In contrast, the evaluation of marine biodegradability remains less standardized and universally accepted. Standards such as ASTM D6691, ASTM D7473, and ISO 16221 guide the assessment of BP degradation in marine ecosystems. However, due to the variability in oceanic conditions, such as

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temperature fluctuations, microbial diversity, and water movement, marine degradation results are often inconsistent and more challenging to validate compared to terrestrial environments.

To quantify the extent of BP degradation in soils, researchers employ a variety of analytical methods. The mass-balance method, which calculates the percentage of mass reduction before and after degradation, is a widely used approach. This method involves weight loss measurements using an analytical balance, a simple yet effective technique, though it poses challenges in extrapolation and upscaling. To complement mass-balance analysis, scientists employ advanced analytical techniques to gain deeper insights into BP degradation mechanisms. Respirometric methods are widely used to indirectly measure microbial respiration rates by monitoring CO_2 emissions, providing valuable data on biodegradation kinetics.[111] Fourier Transform Infrared Spectroscopy (FTIR) helps identify changes in chemical bonds, offering insights into the breakdown of polymer structures, while Nuclear Magnetic Resonance (NMR) spectroscopy provides molecular-level information on the chemical transformations occurring during degradation.[27] Additionally, mechanical property assessments evaluate variations in tensile strength, elasticity, flexibility, and surface morphology, revealing structural changes in BPs over time. Among these techniques, respirometry plays a particularly important role by precisely measuring CO_2 evolution as an indicator of microbial activity. This method typically employs sensors and computerized control programs to ensure accurate data collection and analysis, enhancing the reliability of biodegradability assessments.[111]

By integrating multiple analytical approaches, researchers can achieve a comprehensive understanding of BP degradation in soils, underlying mechanisms, and effects on its mechanical and chemical properties. This knowledge is essential for refining biodegradability assessment protocols and guiding the development of sustainable BP materials that minimize environmental impacts.

7. Laboratory-based certification protocols for biodegradable plastics

Global industries generally label their BP-based products as "100% biodegradable", "marine biodegradable", or "soil biodegradable" without providing valid scientific data to support these assertions. It is important to analyze BP degradation in real soil environments rather than under controlled industrial conditions with high temperatures and overly abundant microbial communities. Real soil conditions in natural environments differ significantly from controlled settings and soils are the primary reservoir of waste including BPs.

Therefore, we proposed a laboratory-based certification protocol for BPs to ensure their degradation and sustainability in soil environments (Fig. 6). This certification should be conducted in accredited laboratories by universally acknowledged methods to ensure consistency across tests. Products claiming 100% biodegradability should be assessed under actual soil conditions to validate their claims. The current standard methodologies for assessing plastic degradation in soil, such as ASTM D5988-18 (ref. 112) and ISO 17556:2019,[113] involve quantifying CO_2 production and monitoring O_2 consumption over time. These

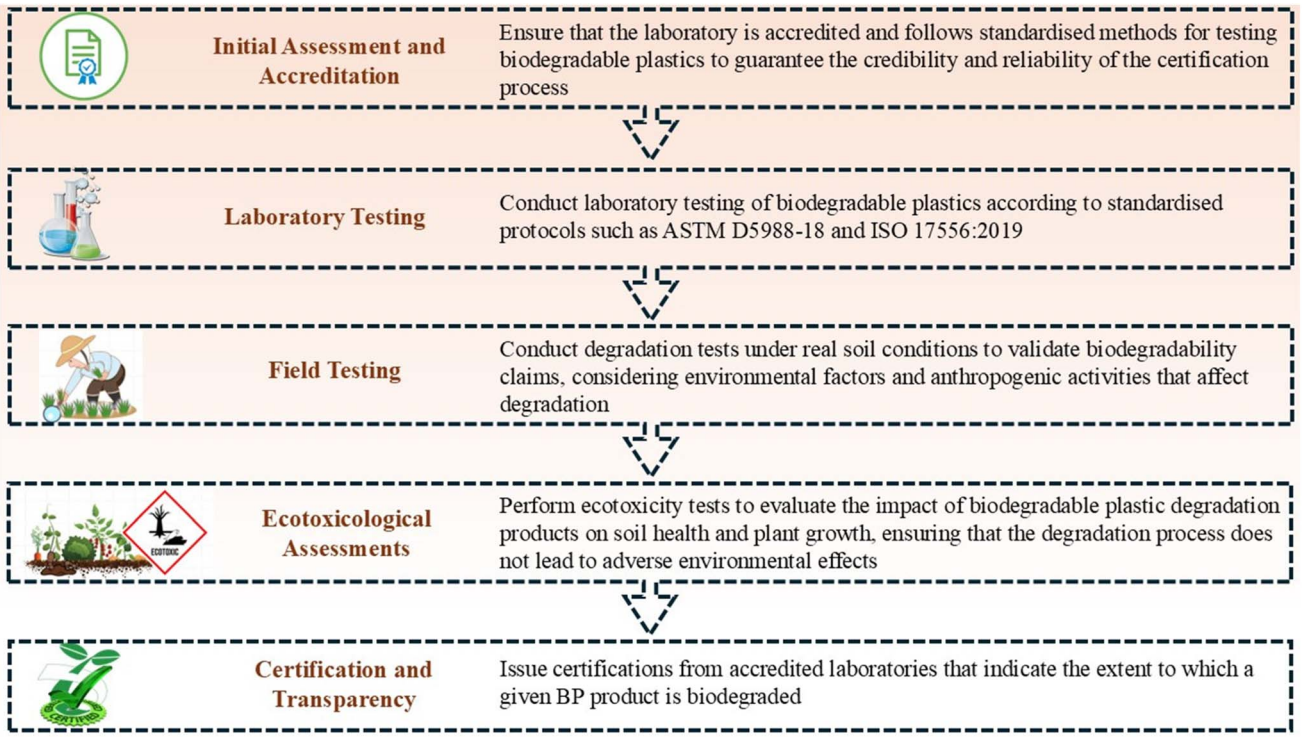

Fig. 6 Comprehensive laboratory-based certification protocol for biodegradable plastics.

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methods include burying the BP samples in closed vessels with prepared soil to create conditions conducive to microbial growth. However, variation in testing procedures has yielded a wide range of reported degradation values for similar biomaterials. This challenges the establishment of unique degradation values for each material. Furthermore, these standards may not include all variables influencing plastic degradation.[111]

To address these challenges, a synergistic approach utilizing various methodologies is necessary, and establishing an international standard that complements the existing ISO and ASTM standards is imperative. This would ensure a more accurate characterization of the biodegradability of each BP entering the market. This, in turn, can support informed decisions regarding disposal techniques to ensure complete and safe degradation. To further verify the test results, degradation tests should be conducted under field conditions. In real soil environments, the numerous environmental and soil management factors are not controlled as in laboratory settings. Factors such as soil erosion, water flow, drought, and human activities including machinery use, plowing, and soil tillage can directly impact the disintegration and degradation of BPs in soils. Unlike laboratory conditions, where optimal parameters such as moisture (*e.g.*, 60% of water holding capacity) and temperature (*e.g.*, 25 °C) are maintained consistently throughout the testing period, real environmental conditions are in constant flux, highly variable, and unpredictable. Soil ecosystems are subject to extreme weather events such as droughts and floods which may further complicate degradation processes. Moreover, soil properties vary significantly across sites. This adds to the complexity of understanding soil characteristics that are mostly conducive to BP degradation. Given these challenges, conducting degradation experiments under both laboratory and field conditions is recommended to obtain a comprehensive understanding of the degradation process and its environmental implications.

For BPs to serve as viable alternatives to petroleum-based plastics, it is important to ensure their complete degradability without causing hazardous ecotoxicological effects. As BPs break down, they release various elements into soils that can hinder or promote plant growth. This highlights the importance of robust ecotoxicological assessments. Seed germination and plant growth bioassays are commonly used only to assess plant ecotoxicity. In these tests, biopolymers are buried in soil at high concentrations and left to degrade naturally. Soil samples are collected periodically and tested for ecotoxicity using bioassays. Control samples, both exposed and unexposed to biopolymers are included. A substance generally recognized as safe (GRAS), such as cellulose, is used as a benchmark. The overall objective is to identify the significant differences between the test and control samples to ensure that degradation did not result in adverse ecotoxic effects. This rigorous assessment helped determine the safety and environmental impact of BP degradation and associated products.[114]

The degradation test under real field conditions should focus on the following:

(1) Variation in soil physical, chemical, and biological properties.

(2) Variation in mechanical properties of BPs/products.

(3) Toxicity test results associated with secondary products released during degradation.

These test results provide a comprehensive understanding of the effects of BP degradation in soils. This ensures that degradation and associated products do not adversely affect soil properties, soil health, crop growth, and overall food security. Based on research data (laboratory- and field-based) obtained from accredited laboratories, a certification can be issued for the respective BP or product to indicate the degree of degradation achieved (*e.g.*, "60% degradation" or "75% degradation"). Thus, this is essential to prevent stating misleading information such as "100% degradation" unless it can be fully verified and substantiated. The certification report should also include quality assurance details including the analysis conditions such as soil properties, experimental conditions, and test duration. This information should be made available to all parties interested in utilizing these products. The test results should also be accessible to these parties. This ensures complete transparency and informs consumers regarding product sustainability. Importantly, these test results can be included in the annual sustainability reports released by industries.

8. Knowledge gaps related to biodegradable plastics in soils and future research directions

While BPs are gaining increasing attention as a sustainable alternative to conventional plastics, significant knowledge gaps remain regarding their degradation in soils. One critical area of uncertainty is how soil properties are affected by BP degradation. Current research primarily focuses on BP degradation in controlled environments, such as compost and marine settings, but the environmental impacts of BP degradation in soils, where conditions are more variable, remain understudied. Soil ecosystems are complex, and factors such as the microbial community structure, soil texture, and moisture levels have not been adequately studied in relation to BP degradation. This highlights the urgent need for more comprehensive research that extends beyond laboratory models to include *in situ* field experiments. Field-based studies should be prioritized to validate laboratory results and provide a better understanding of how BPs degrade under environmentally relevant soil conditions.

Another significant knowledge gap is the lack of understanding regarding which soil properties are most conducive to the complete degradation of BPs. For example, it remains uncertain whether sandy soils or soils with high organic content are more favorable for BP degradation. Similarly, the optimal soil pH for BP degradation is still not well understood. Future studies should focus on how soil characteristics, such as soil texture and moisture content influence BP degradation.

Additionally, research should explore how the surface properties of BP fragments, including micro- and nanoscale particles, affect their behavior in soils. These particles may act as contaminant carriers, influencing the environmental

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behavior of BP degradation products. It is essential to utilize environmentally relevant conditions to assess the real-world impacts of BP fragments on soil ecosystems.[54] Field studies should be conducted at various sites with different soil properties (*e.g.*, pH and organic content) to validate laboratory findings on BP degradation. BP samples can be buried at different soil depths and monitored over time for the degradation rate, microbial community shifts, and environmental factors like moisture and temperature. Then the soils can be collected periodically to assess changes in chemical properties and BP degradation.

Another area that requires attention is the environmental impact of BP degradation. Large-scale BP-producing industries are important in global production, yet their expansion raises concerns. Despite claims of 100% biodegradability, many BP products are composites, combining BPs with petrochemical-based plastics. This raises questions about the transparency of industry claims, and the potential for greenwashing, where products are marketed as environmentally friendly without meeting stringent environmental standards. Thus, future research should focus on scrutinizing the transparency and accuracy of industry claims, establishing clear guidelines for BP labeling, and investigating the true biodegradability of these products under various environmental conditions. The development of more stringent certification protocols is necessary to ensure that BP products meet regulatory guidelines.

Moreover, a significant gap in the current body of research is the absence of standardized methods for identifying and quantifying BP degradation in soils. Most current methods were designed for controlled laboratory conditions and cannot be directly applied to the diverse array of environments found in soils. It is essential to develop and validate methods that can accurately assess BP degradation in natural soil environments. This includes developing protocols to measure not just polymer breakdown but also the resulting biomass, an often-neglected aspect of biodegradation. Incorporating these protocols will help in understanding the fate of carbon during the degradation process, allowing for accurate carbon balance assessments. Recent studies, such as that by Trapp *et al.*[115] have highlighted the importance of accounting for microbial biomass incorporation in degradation tests to prevent underestimating the persistence of chemicals in the environment. They evaluated the microbial turnover to biomass (MTB) approach for estimating biogenic non-extractable residues (bioNER) in degradation tests.

Furthermore, there is a pressing need for research into the impacts of climate change on BP degradation in soils. Climate change alters soil properties and microbial activity, potentially affecting the degradation rates and environmental impacts of BPs. For instance, increased temperatures or changing moisture levels could accelerate or hinder BP degradation, influencing GHG emissions and carbon footprints. Future studies should include climate change scenarios to assess the long-term degradation of BPs and their potential to contribute to or mitigate climate change.

For instance, Posen *et al.*[116] developed a Life-Cycle Assessment (LCA) model featuring five pathways for plastic production in the United States, including both petroleum and renewable energy sources for biobased plastic production. Their findings indicate that corn-based bioplastics, manufactured using conventional energy, reduce GHG emission by 16 Mt CO_2e per year. This reduction could potentially reach 38 Mt CO_2e per year with the utilization of low-carbon energy during production. Based on MRIO-based assessment by Jin *et al.*[117] an 18.4 Mt CO_2e emission reduction from the use of biobased plastics was suggested, aligning closely with the reported estimate of 16 Mt CO_2e. Another study employing the LCA methodology indicates that substituting a significant portion of petroleum-based plastics with biobased alternatives could lead to emission reductions, ranging between 241 and 316 Mt CO_2e per year.[118] Transitioning to a 20% bioplastic adoption rate could result in a reduction of 77 Mt of GHG emissions. Notably, while completely replacing petroleum-based plastics with bioplastics could yield a reduction of 369 Mt in GHG emissions, it may also lead to increased land use and job creation. However, expanding the cultivation areas for bioplastics may inadvertently lead to additional carbon emissions.[117] Overall, the transition from traditional plastics to bioplastics appears to offer environmental benefits in terms of reduced GHG emission, albeit with associated increases in land use and job opportunities. However, careful consideration of the potential impacts on land use and carbon emissions is necessary, particularly with regards to the expansion of cultivation areas for bioplastic production.

In terms of waste management, the presence of BP products that are not purely biodegradable but are composed of a mixture of petrochemical plastics presents significant challenges. Research must focus on developing strategies to manage these mixed BP products, as they complicate recycling and waste disposal efforts. Laboratory trials and field-scale studies are essential to better understand the fate, occurrence, distribution, and release pathways of these mixed BP products.[13] A comprehensive certification protocol for BPs, as proposed in this study (Fig. 6), could be valuable in ensuring that BP products undergo proper testing before entering the market. Additionally, to promote responsible and informed decision-making, there is a need for a standardized method to analyze BP degradation in soils, which industries could adopt before releasing BP-based products. Further research aimed at identifying effective strategies for handling and disposing of these mixed BP products is strongly encouraged.

In addition, ecotoxicological studies on BP and BMPs in soil ecosystems are currently limited. Much of the existing research has focused on common materials like PLA and PBAT, with limited attention given to a broader range of BP types and their ecological impacts. Future research should explore the potential biotoxicity of BMPs, investigating how they interact with soil microorganisms and their potential to release harmful chemicals during degradation. This research should extend beyond single-particle toxicity studies to encompass the impacts of weathering processes and co-exposure of other environmental pollutants. Such studies will help determine whether BMPs pose stronger ecological threats than traditional petrochemical-based MPs. For example, to evaluate the ecological risks of BP degradation, experiments can be designed to expose soil organisms (*i.e.*, earthworms and nematodes) to soils

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undergoing BP degradation. Toxicity will be assessed by measuring the survival, growth, and reproduction rates of the organisms, along with changes in microbial diversity. Additionally, the potential leaching of harmful substances from BP materials and their bioaccumulation in soil organisms can be studied.

Furthermore, expanding the range of polymer types, sizes, and species in these studies is essential. Not all BPs behave similarly, and it is important to assess whether specific BP types are viable substitutes for conventional plastics. Studies should consider the full life cycle of BPs, examining not only their degradation but also their potential long-term environmental effects and the socio-economic implications of their widespread adoption. The surface charge of BP particles can be modified through chemical treatments to assess its impact on their mobility and interactions with contaminants. Column leaching experiments are proposed to track the movement of BP particles through soil columns, while sorption tests will measure how these particles interact with various contaminants. These studies are essential for understanding the behavior of BP particles in soil environments and their potential role as vectors for contaminant transport.

Addressing these knowledge gaps will be critical for ensuring the sustainable development of biodegradable plastics in soil and agricultural environments. Standardizing testing methods, understanding long-term environmental impacts, and conducting LCA are key to guiding future research and policy-making in this field. Additionally, public education efforts should be ramped up to correct misconceptions about the environmental friendliness of BPs and prevent improper waste disposal. By addressing these challenges and ensuring transparency in BP production and labeling, we can ensure the responsible development and use of BPs.

Data availability

All data used during the study appear in the submitted article.

Author contributions

Piumi Amasha Withana: writing – original draft, writing – review & editing, validation, methodology, investigation. Xiangzhou Yuan: writing – review & editing. Darvin Im: writing – review & editing, writing – original draft. Yujin Choi: writing – review & editing, writing – original draft. Michael S. Bank: writing – review & editing, writing – original draft. Carol Sze Ki Lin: writing – review & editing. Sung Yeon Hwang: writing – review & editing, writing – original draft, methodology, supervision. Yong Sik Ok: writing – review & editing, writing – original draft, validation, supervision, methodology, investigation.

Conflicts of interest

There are no conflicts of interest to declare.

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