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Comparative Review of Marine Plastic (HDPE) and Terrestrial Plastic (LDPE): Reusability, Microbiological, and Chemical Perspectives

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Abstract

The environmental crisis of plastic pollution is largely fueled by the persistence of polymers like high-density polyethylene (HDPE) in aquatic regions and low-density polyethylene (LDPE) in land-based habitats. Their resistance to natural decay and high rate of infiltration into the biosphere present significant ecological hazards. This comparative analysis evaluates the mechanisms of chemical and microbial decomposition alongside material reusability. Findings indicate that HDPE offers superior structural resilience, characterized by high thermal stability during pyrolysis (488-492°C) and robust recyclability through up to ten extrusion cycles. In contrast, LDPE is more susceptible to biological breakdown demonstrating a mass reduction of 36.4% when exposed to fungal communities yet it lacks the mechanical endurance of its high-density counterpart. Analytical data from DSC, FTIR, and SEM confirm that the dense crystalline lattice of HDPE acts as a deterrent to biodegradation, whereas the molecular configuration of LDPE facilitates easier colonization by bacterial and fungal consortia. Future remedial efforts focus on the development of microbial co-cultures and enzyme engineering to optimize degradation rates and support sustainable waste mitigation.

Key Words

HDPE, LDPE, plastic pollution, chemical degradation, microbial biodegradation, reusability, plastisphere, polyolefin recycling

1. Introduction

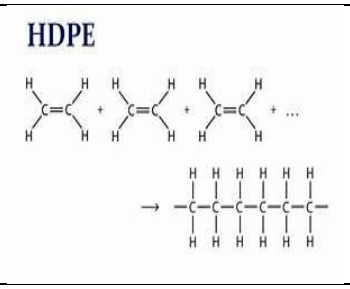
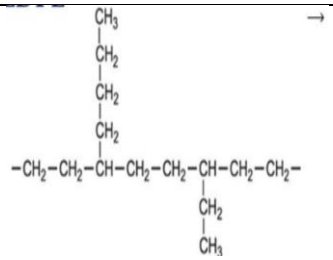
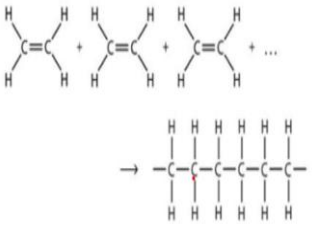
1.1. Overview of Global Plastic Pollution, emphasizing marine and terrestrial environments.

The proliferation of plastic waste has developed into one of the most widespread and rapidly intensifying ecological challenges of the modern era, impacting both land and ocean biomes on a global scale [1][13][50][55][56][99][101]. With global production now exceeding 400 million metric tons per year, only a minimal portion of these durable synthetic polymers is successfully reclaimed. Consequently, between 11 and 23 million metric tons of plastic debris enter aquatic ecosystems annually, the majority of which is transported from land-based sources [2][14][58][59][118]. This pollution manifests in a spectrum of sizes, from macroscopic litter to microplastics and nano-plastics, all of which remain in the environment for decades or even centuries due to their inherent chemical stability [3][15][54][60][106][119][120]. In the ocean, plastic materials represent roughly 80% of all marine debris. They cause profound ecological harm by entangling wildlife, being mistaken for food by marine organisms, destroying sensitive habitats, and introducing toxic chemical additives into the global food web [16][17][18][57][100][104][107]. Projections suggest that if current trends continue without major intervention, the total mass of plastic in the world's oceans may outweigh the total biomass of fish by 2050, underscoring a desperate need for more effective waste management and reduction policies [2][19][62][61].

1.2. Importance of HDPE and LDPE as widely used polymers for shaping environmental fate.

High-density polyethylene (HDPE) is widely used in marine and coastal applications because of its high tensile strength, chemical resistance, and durability against saltwater exposure, ultraviolet radiation, and mechanical impact, making it suitable for structures such as boats, docks, pipelines, and floating installations [20][21][51][73]. In contrast, low-density polyethylene (LDPE) is a softer, more flexible, and lightweight polymer primarily used in terrestrial environments for packaging films, plastic bags, liners, and containers due to its good moisture resistance and ease of processing, although it exhibits lower rigidity, heat resistance, and mechanical strength compared with HDPE [5][22][52][53]. These structural differences between HDPE and LDPE strongly influence their environmental behaviour, degradation pathways, and recycling efficiency in marine and terrestrial ecosystems [15][105].

Table 1. Significance of Marine and Terrestrial Plastic

Feature	HDPE	LDPE	Environmental Implication
Molecular Structure			The linearity of HDPE imparts high rigidity and strength, while LDPE's branching imparts flexibility.[15][23]
Density & Buoyancy	**High Density** (approx. 0.94-0.97gm/cm3).	**Low Density** (approx. 0.91 - 0.94 gm/cm3).	HDPE microplastics can be found in both floating and sinking debris, whereas LDPE microplastics predominantly float**.** [3][16]
Environmental Durability	**High** UV and chemical resistance (often UV-stabilized for outdoor use).	**Lower** UV resistance, susceptible to photo-oxidation and embrittlement.	HDPE's durability makes it highly persistent in the macro form (e.g., pipes, containers).[15][24]
Microplastic Formation	Degradation is complex, often involves initial selective breakdown of the amorphous regions and then fragmentation within its spherulite structure (crystalline/amorphous units).	Degradation is accelerated by UV exposure; branched structure promotes preferential delamination and separation of cross-linked parts, rapidly forming fragments. 	LDPE forms microplastics faster than HDPE, increasing environmental dispersion [15][25]
Primary Use & Leakage Risk	Used for Rigid, Durable Items (bottles, pipes, crates). Longer lifespan, lower immediate littering rate per item.	Used heavily for Flexible, Single-Use Items (plastic bags, cling films). High production volume in agriculture (films) and packaging leads to high leakage rates.	High production and disposal rates of LDPE films lead to higher leakage into terrestrial and aquatic environments [2][22]
Recyclability (#2 vs #4)	Easier to Recycle (Recycling Code #2). Rigid form simplifies sorting and processing.	More Difficult to Recycle (Recycling Code #4). Films are lightweight, often contaminated, and	LDPE recycling challenges increase environmental accumulation compared with HDPE [5][20]

		prone to tangling machinery.	
Life Cycle Emissions	HDPE is a significant contributor to global warming potential (GWP) during granulate production and transportation.	LDPE was found to be a top contributor among common plastics to CO2 equivalent emissions in life-cycle assessments.	The initial production stage is the highest contributor to GWP for both polymers [1][26]

1.3. Objective

Table 2. Objective of Marine and Terrestrial Plastic

Objective Category	HDPE	LDPE
Primary Structural Objective	To provide high rigidity, tensile strength, and structural integrity for load-bearing and shape-retaining applications.	To provide maximum flexibility, ductility, and softness for pliable and conforming applications.
Key Functional Properties	High Strength-to-Density Ratio (Tensile Strength approx 4000 psi); High Resistance to chemicals and heat deformation; Opaque appearance for content protection.	High Elongation and Impact Absorption (Tensile Strength approx 1400 psi); Excellent Heat-Sealing capability; Transparent/Translucent appearance for visibility.
Intended Product Lifespan	Long-Term Use	Short-Term/Single-Use
Recycling Objective	Efficient Mechanical Recycling (Recycling Code #2). The rigid form is easy to sort, clean, and process into new rigid products (e.g., lumber, pipes).	lexible Film and Liner Recycling (Recycling Code #4). Focuses on recovering difficult-to-handle films and wraps for low-grade applications or chemical recycling.
Major Application Examples	Rigid Containers (Milk jugs, detergent bottles), Piping Systems (Water, gas, sewage), Structural Components (Crates, outdoor furniture, geomembranes).	Flexible Films (Plastic bags, shrink wrap, agricultural films), Squeezable Bottles, Protective Liners (Cable insulation, food coatings).

[5][15][20][21][22]

2. Chemical and Physical Properties

Table 3. chemical and physical properties of Marine and Terrestrial Plastic

Chemical properties			Physical properties		
	HDPE	LDPE		HDPE	LDPE
General Chemical Resistance	Excellent	Good	Molecular Structure	Linear with minimal branching. Allows for tight molecular packing (high crystallinity).	Highly branched chains. Prevents tight molecular packing (low crystallinity, 50-60%).
Environmental Stress Cracking Resistance (ESCR)	Excellent	Poor / Lower	Density	High Density (approx. 0.94-0.97gm/cm3).	Low Density (approx. 0.91 - 0.94 gm/cm3).
Water Absorption / Permeability	Extremely Low	Extremely Low	Stiffness / Flexibility	Stiff and Rigid	Low
Gas Permeability O2$CO_2 etc.)	Lower	Higher	Tensile Strength	approx. 4000 psi	Approx. 1400 psi
UV Resistance (Photo-oxidation)	Good/High	Poor/Low	Melting Point	Higher approx. 120□C - 135□C.	Lower approx. 105□C - 115□C.

[5][6][15][20][21][22][23][24][25][27]

3. Analytical Ways

3.1. Chemical Degradation Pathway

Due to its robust crystalline structure, high-density polyethylene (HDPE) displays greater thermal endurance during decomposition than low-density polyethylene (LDPE). This leads to higher pyrolysis thresholds and a stronger defense against molecular chain breakage in HDPE. Conversely, LDPE is susceptible to earlier degradation, typically manifesting as initial cross-linking followed by chain scission during recycling and extrusion stages [4][5][27][78][79][80]. In the presence of heat and oxygen, HDPE undergoes significant chain fragmentation that drastically reduces its molecular mass, necessitating the use of stabilizing additives. LDPE, however, generally experiences a sequence of initial cross-linking followed by oxidative breakdown, resulting in the formation of carbonyl groups and a subsequent decrease in stability following treatment [23][24][28][81][82]. The process of photo-oxidative breakdown occurs more gradually in HDPE because its dense crystalline regions act as a barrier to radical propagation and oxygen permeation. In contrast, LDPE is more prone to rapid oxidation, characterized by the emergence of hydroperoxides and higher carbonyl indices as measured via FTIR spectroscopy [15][25][29][83][108]. Similarly, when subjected to mechanical forces or extrusion, HDPE undergoes substantial chain scission and rapid depletion of stabilizers. LDPE tends toward cross-linking with relatively minor fluctuations in molar mass, emphasizing how differences in molecular configuration influence the relative recyclability of these two polymers [4][30][31][121][122]. In summary, the superior thermal and oxidative resistance of HDPE compared to LDPE is primarily driven by its higher degree of crystallinity. These structural variations ultimately dictate the environmental durability and recycling potential of each material [15][24][109][110].

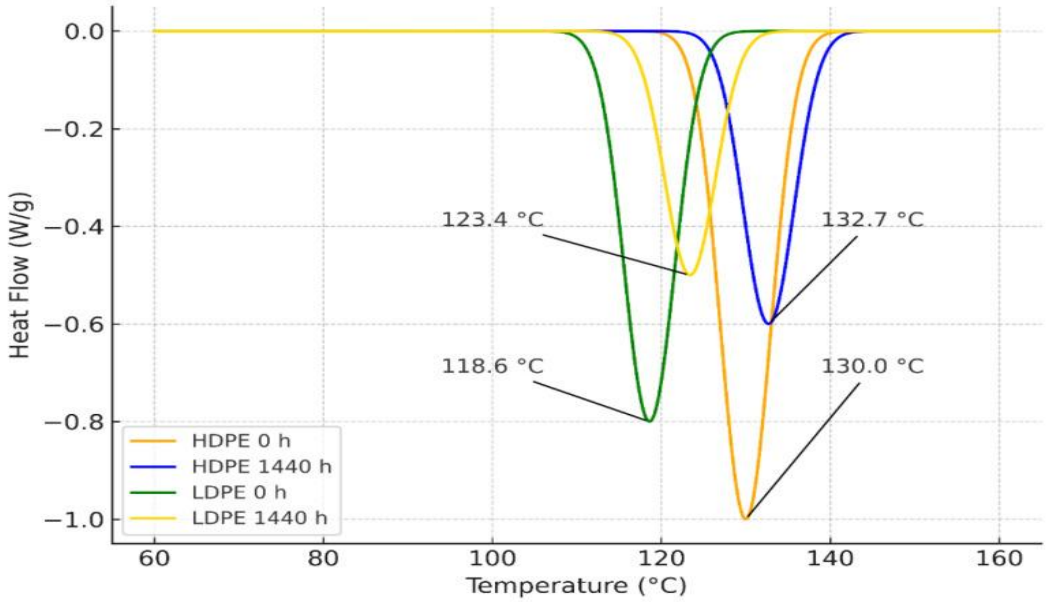
Differential Scanning Calorimetry (DSC) parameters of HDPE and LDPE films after 0, 288, 864, and 1440 h of weathering.

	Polyethylene Type	Exposure Time (h)	Condition/Series	Tm (°C)	Tonset (°C)	ΔHf (J/g)	Xc (%)
T01	HDPE (high-density)	0	Initial control	130.0 ± 1.5	128.0 ± 1.0	3.20 ± 0.50	1.09 ± 0.17
T02	HDPE (high-density)	288	≈12 days	129.8 ± 1.2	128.5 ± 1.1	3.05 ± 0.90	1.04 ± 0.31
T03	HDPE (high-density)	864	≈36 days	137.5 ± 2.5	136.9 ± 2.8	0.15 ± 0.08	0.05 ± 0.03
T04	HDPE (high-density)	1440	≈60 days	132.7 ± 2.1	131.1 ± 2.6	1.40 ± 0.55	0.48 ± 0.19
T05	LDPE (low-density)	0	Initial control	118.6 ± 2.1	116.9 ± 2.0	1.40 ± 0.80	0.48 ± 0.27
T06	LDPE (low-density)	288	≈12 days	123.7 ± 0.9	122.3 ± 1.0	1.55 ± 0.75	0.53 ± 0.25
T07	LDPE (low-density)	864	≈36 days	125.4 ± 1.6	123.6 ± 1.7	2.35 ± 0.95	0.80 ± 0.32
T08	LDPE (low-density)	1440	≈60 days	123.4 ± 0.8	122.0 ± 0.7	1.15 ± 0.65	0.39 ± 0.22

Fig.1 Differential Scanning Calorimetry (DSC) parameters of HDPE and LDPE films

Representative DSC thermograms of HDPE and LDPE plastic films used for banana (*Musa paradisiaca*) preservation at 0 h and 1440 h of weathering under storage conditions.

Fig.2 Representative DSC thermograms of HDPE and LDPE plastic films used for banana (Musa paradisiaca) preservation



3.2. Microbial degradation mechanism

3.2.1. Biofilm Formation (Plastisphere)

HDPE supports a higher initial microbial diversity that remains stable over time, with Proteobacteria and Actinobacteria as the predominant phyla. This stability may contribute to a more consistent degradation process [32][33][34][90][91][97]. In contrast, LDPE starts with lower microbial diversity, which increases significantly over time. It shows strong fungal adhesion, particularly from genera such as Alternaria and Trametes, which may enhance its degradation potential [35][36][37][98][102][103].

3.2.2. Key Microbes

Several bacterial and fungal strains capable of degrading polyethylene have been identified. For HDPE, Microbacterium barkeri SH20 has demonstrated measurable degradation ability, while fungi such as Aspergillus terreus contribute to polymer deterioration through oxidative enzyme secretion [8][9][64][65][66]. LDPE degradation is frequently driven by fungal isolates, including Aspergillus oryzae, and mixed microbial consortia involving Alternaria, Trametes, and bacterial species such as Bacillus cereus, which can result in significant polymer weight loss during incubation [7][35][38][67][68][69].

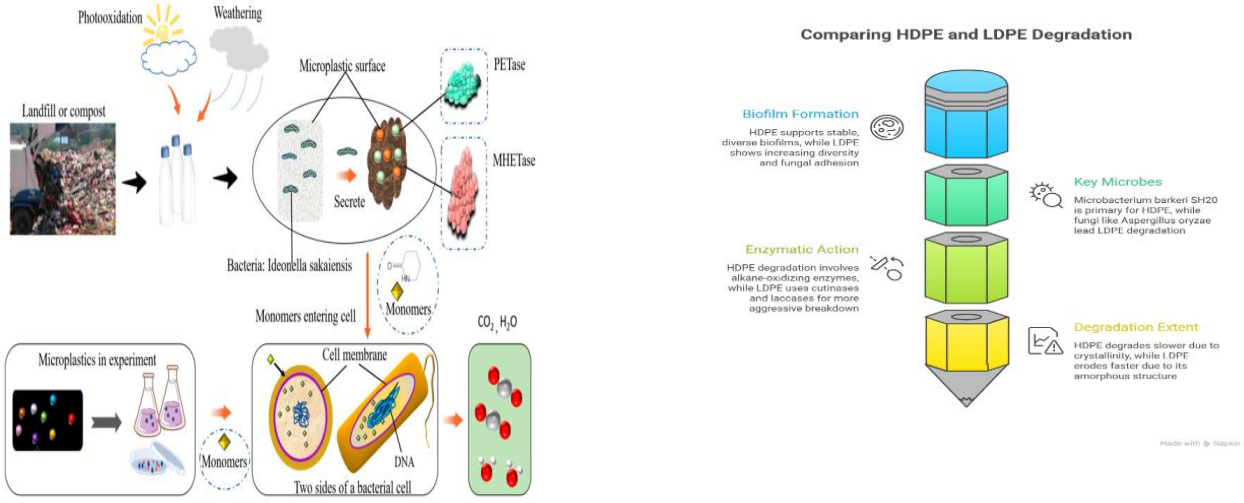
3.2.3. Enzymatic Action

Microbial degradation of HDPE involves oxidative enzymes such as alkane monooxygenases that introduce functional groups into polymer chains, leading to measurable changes in FTIR spectra and gradual polymer breakdown [9][12][70][71][72]. In LDPE, enzymes such as cutinases, laccases, and peroxidases accelerate oxidation, resulting in increased carbonyl formation and enhanced chain cleavage, especially after thermal or photo-oxidative pretreatment [39][40][41][84][85][86].

3.2.4. Degradation Extent

Although HDPE undergoes measurable microbial degradation, its high crystallinity limits enzymatic penetration and slows overall weight loss compared with LDPE [15][24][92][93]. LDPE's amorphous structure allows easier microbial attachment and enzymatic attack, resulting in greater mass loss during bacterial or fungal treatment [7][42][43][94][95][96]. These structural differences explain the faster erosion of LDPE and the slower, more resistant degradation behaviour observed in HDPE.

Fig.3 Microbial degradation mechanism



3.3. Reusability Assessment

HDPE generally maintains better reusability across multiple recycling cycles than LDPE, owing to its higher initial mechanical strength and slower degradation, though both undergo chain scission and require stabilisers.

Table 4. Comparative Reusability Assessment Mechanisms

Mechanism/Aspect	HDPE Characteristics bohrium^{+2}	LDPE Characteristics bohrium^{+2}
Multiple Extrusion Cycles	Chain scission dominant; limited viscosity changes at high shear, but increasing crossover frequency indicates branching competition; up to 4-10 cycles viable with stabilizers.	Initial cross-linking then scission; odd n-alkane increases; substantial degradation after 1-2 cycles, up to 100 cycles tested, but with major property loss.
Mechanical Properties Retention	Tensile strength retained better; ESCR improved via two-step extrusion with peroxides/antioxidants; negligible shear viscosity shiftin processing.	~30% higher static tensile strength in recycled vs virgin, but 56% reduced elongation/breaking displacement; cyclic fatigue viable to 80% max load.
Oxidation Stability (OIT)	Enhanced OIT/ESCR with two-step extrusion (DCP first, antioxidants second); higher stabilizer need.	Lower OIT; prone to thermo-oxidative instability in blends post-extrusion.
Quality Markers for Reuse	Decrease in even n-alkanes; use short-chain alkanes (<C30) as recycling indicators.	Increase in odd n-alkanes; limits multi-loop reuse without virgin blending.

Fig.4 Comparative Reusability Assessment of HDPE and LDPE

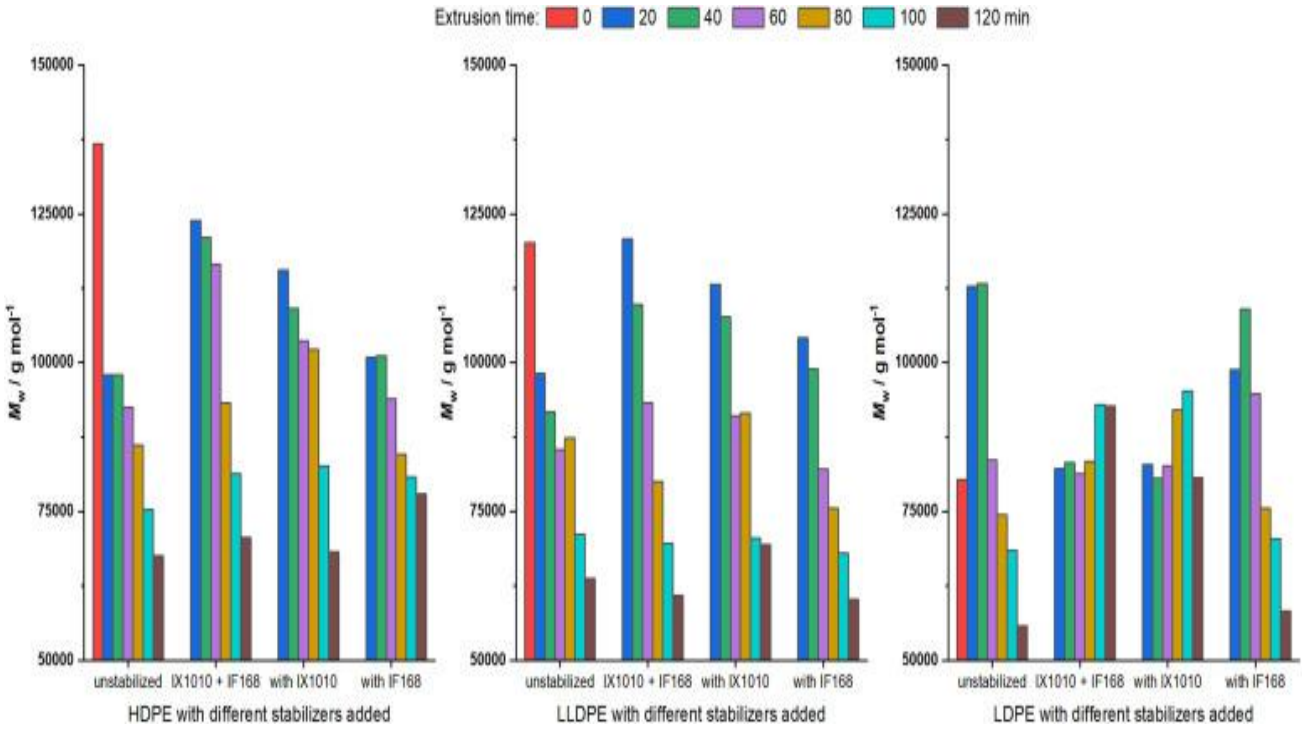
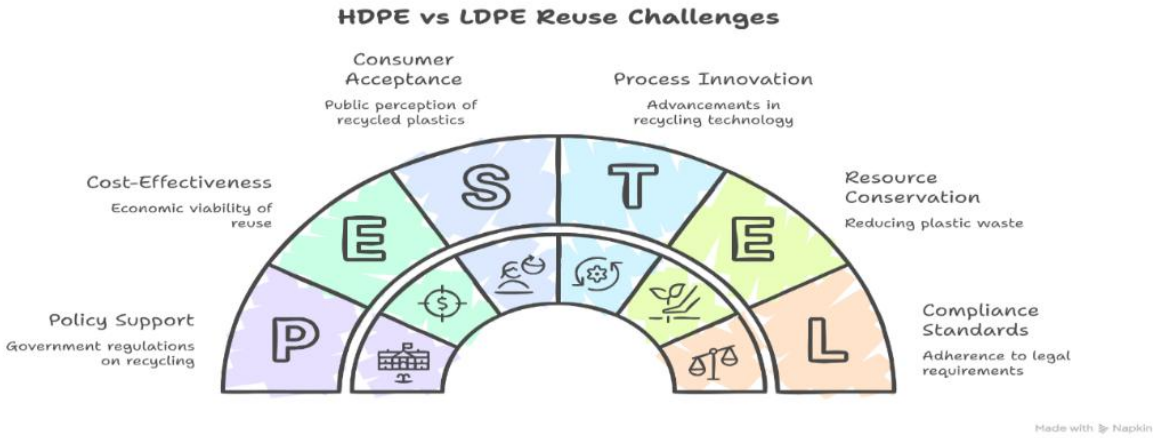


Fig.5 Reusability Challenges of HDPE v/s LDPE



4. Future Discussion

Overcoming current limitations in polyethylene degradation requires integrated bioremediation strategies, including the engineering of LDPE-degrading enzymes such as cutinases and laccases derived from microbial consortia, which have demonstrated significant polymer mass loss and reduced degradation half-life [10][39][40][87][88]. For HDPE, optimization of plastisphere microbial communities through metagenomic approaches may enhance alkane-oxidase activity and improve degradation of highly crystalline polymer regions that resist mono-culture treatment [11][32][33][89][111].

Hybrid strategies combining photo-oxidative pretreatment with fungal–bacterial co-cultures have shown accelerated degradation rates under optimized environmental conditions, indicating the importance of synergistic chemical–microbial approaches [35][44][45][112][113]. Integration of advanced recycling indicators such as n-alkane profiling for HDPE multi-cycle reuse, together with enzymatic upcycling of LDPE films, represents a promising circular-economy strategy, although challenges remain in scaling field applications and assessing long-term ecotoxicological impacts of degradation by-products [4][30][46][114][115].

Emerging technologies such as insect gut microbiomes capable of degrading polyethene and synthetic biology approaches for enzyme pathway reconstruction offer scalable remediation solutions [47][48][49][116][117]. Global collaboration and source-reduction policies are essential, as modeling studies suggest that microbial interventions combined with improved waste management could significantly reduce microplastic accumulation in high-leakage environments by mid-century [1][2][13][63].

5. Conclusion

HDPE and LDPE are representative polyolefins that exhibit strong environmental persistence; however, HDPE's higher rigidity and crystallinity allow better mechanical recyclability and environmental stress crack resistance after extrusion, while simultaneously limiting microbial colonization and biodegradation [4][6][9]. In contrast, LDPE's flexible and amorphous structure enhances microbial attachment and biofilm-mediated degradation, resulting in greater weight loss under fungal and bacterial treatment [7][8][35]. Chemical degradation studies also demonstrate that HDPE shows greater oxidation resistance and slower photo-oxidative chain scission compared with LDPE, reflecting different environmental fates and persistence patterns in marine and terrestrial systems [15][24][74][75].

Integrated microbial–chemical remediation strategies are increasingly proposed as effective solutions, with microbial co-cultures and enzyme engineering significantly enhancing polyethylene degradation efficiency

and reducing polymer half-life [10][11][12][76][77]. Such approaches, combined with improved recycling technologies and circular-economy policies, are urgently needed to address the continuing influx of millions of tons of plastic waste into aquatic environments each year and to promote long-term ecosystem sustainability [1][2][13].

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