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The Possibility of Using Polylactic Acid and Polyhydroxyalkanoates to Replace the Normal Plastics in Life

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Abstract. traditional plastics such as polypropylene (PP), polyethylene (PE), and car tire rubber (CTR) have been widely used in our lives, leading to significant microplastic pollution, particularly in major river systems in China like the Yangtze River Basin. These plastics possess highly durable and resistant properties that resist natural degradation, resulting in long-term environmental problems and ecological risks. This study investigates the possibility of replacing conventional plastics with biodegradable alternatives, especially polylactic acid (PLA) and polyhydroxyalkanoates (PHA). By comparing their degradation in water, environmental behavior, mechanical properties, and industrial production processes, the paper analyzes the potential of PLA and PHA to reduce microplastic emissions. The results show that although PLA and PHA exhibit superior biodegradability under specific environmental conditions, their thermal resistance and mechanical limitations hinder their full replacement of conventional plastics in demanding applications such as vehicle tires. However, through polymer blending, plasticization, and nanocomposite reinforcement techniques, significant improvements in heat and abrasion resistance can be achieved, pointing toward a future where biodegradable plastics could play a vital role in mitigating microplastic pollution.

Keywords: Microplastics, biodegradable plastics, Yangtze River Basin, PLA, PHA

1. Introduction

Nowadays, plastics such as PP (polypropylene), PE (polyethylene), and PET (polyethylene terephthalate) are widely distributed in our lives. These plastics possess properties of being lightweight, flexible, heat-resistant, durable, and chemically resistant. This makes these plastics very hard to decompose and widely used in many areas. Consequently, these plastics will pass through different pathways and eventually enter rivers, seas, or oceans, participating in the life cycles of all living organisms, which may cause risks of disease. The Yangtze River is the largest river on the Eurasian continent and is also regarded as the river that exports the most microplastics to the ocean [1,2]. The abundance of microplastics in the study area ranged from 21 to 44,080 $n \cdot m^{-3}$, with an average abundance of 4,483 n·m [3], which is much higher than the average. Therefore, the main problem is that PP, PE, and PET are very hard to decompose in water. Hence, one method to reduce microplastics in the Yangtze River is to replace conventional plastics used in daily life with biodegradable plastics such as PLA and PHA.

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In this work, the aim is to compare the industrial production procedures between conventional and biodegradable plastics, discuss the possibility of replacing conventional plastic products with biodegradable alternatives, and predict the abundance of microplastics in the Yangtze River if biodegradable plastics are adopted.

2. Sources and characteristics of microplastics

2.1. Definition and morphology of microplastics (particles, fibers, fragments)

Microplastics, commonly defined as plastic debris smaller than 5 mm, can appear in various forms such as fibers, fragments, and particles.

2.2. Analysis of main sources

Microplastics originate from various sources in daily life, such as plastic bottles, wastewater discharge containing textile microfiber [4], wear and tear of tires and road markings [5,6], the use shampoo and similar personal care products, and especially the decomposition of plastic waste [7], this results in microplastics flowing in the air and being inhaled into human lungs. However, microplastics are inherently toxic and difficult todegrade [8], affecting organisms' normal growth and development and potentially threatening human health.

2.3. Compositional characteristics of microplastics in the Yangtze River Basin (PP and PE dominate, with fibers accounting for 54.63%)

The Yangtze River has total length of 6,363km and cross 11 provinces in the Mainland of China. The water quality of the Yangtze River directly affects the health of China's population. According to the search by Siqiong Si and colleagues [3]. Their result shows that the main microplastics in Yangtze River are PP (Polypropylene) and PE (Polyethylene), with sizes ranging from 0-1mm, dominated by fibers (54.63%) and fragments (32.43%) [3]. During automobile operation, microplastics produced by tire wear enter water environments through road runoff or rainwater runoff [9]and have become the largest source of microplastics in water bodies [10].

2.4. Vehicle tire wear (global annual emissions: 5.91 million tons)

Kole et al [11]. calculated those per capita emissions of tire wear microplastics reached 0.81 kg, with global releases up to 5.91 million tons per year. Simultaneously, the number of vehicles determines the release amount of tire wear microplastics [12].

3. Environmental and health risks of microplastics

3.1. Release of chemical toxic substances

Marco Capolupo and colleagues identified chemical contents released when car tire rubber (CTR) and PP react with freshwater or sea water [13]. Acetophenone and phenoxyethanol were found in PP particles and leachates (freshwater and seawater). Benzothiazole, 2(3H)-benzothiazolone, and phthalimide were detected in CTR particles and leachates [14].

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3.2. Toxic effects

Acetophenone is slightly soluble in water but highly flammable, posing fire hazards. Most vapors are heavier than air. Runoff to sewers may create fire or explosion risks. Toxicity from inhalation or ingestion is low, but it may cause slight narcotic effects and eye/skin irritation [15]. Phenoxyethanol, used in cosmetics, has incompletely elucidated effects on organisms [16].

Benzothiazole and 2(3H)-benzothiazolone are combustible and slightly soluble. Decomposition produces toxic fumes (hydrogen cyanide, nitrogen oxides, sulfur oxides). Inhalation causes coughing; skin/eye contact leads to irritation [17]. Phthalimide is combustible and not soluble in water. But it will give off irritating or toxic fume (or gases) in a fire. Phthalimide is combustible and insoluble, releasing toxic fumes when burned. It causes skin/eye irritation, respiratory issues, allergic reactions, and potential cancer risk [18].

4. Degradation challenges of conventional plastics

4.1. Degradation mechanisms and limitations of PP

PP degrades via photo-oxidative fracture under UV irradiation, but only the surface layer degrades; the interior remains stable. High temperatures (>60℃) accelerate chain breakage but are rarely achieved naturally [19]. Figure 1 shows degradation rates: The rate of degradation for PP in sunlight is the fastest which has 105μm/year and under biological has 20μm/year, so to decompose under the condition of sunlight, a 1m piece of PP require 9523810 years to be fully degradation.

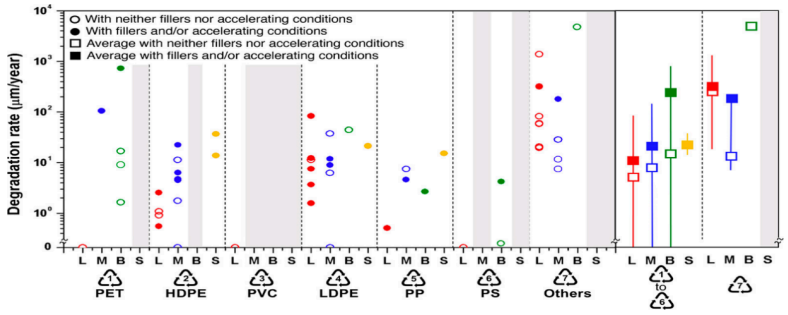


Figure 1. (Specific surface degradation rates for various plastics, in μm year–1) [20]

4.2. Degradation difficulty of tire rubber (CTR) (requires>200°cor strong oxidizing conditions)

CTR degrades only at high temperatures ($>200^{\circ}C$) or under strong oxidation—conditions unattainable naturally [21]. Thus, CTR waste requires chemical recovery (e.g., pyrolysis) rather than natural degradation.

4.3. Comparison of degradation rates

As shown, PP and CTR are harmful upon water contact and resist natural degradation. Since they dominate microplastics in the Yangtze River and tires, replacing non-biodegradable PP/CTR products with rapidly degradable alternatives (e.g., PLA/PHA) could reduce pollution.

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5. Alternatives to degradable plastics

5.1. Degradation characteristics of PLA and PHA

PLA (polylactic acid), a biodegradable polyester, degrades via hydrolysis of ester bonds into lactic acid. Stages: 1) Water diffusion fractures amorphous regions; 2) Crystalline regions gradually decompose [22]. Degradation rates depend on: 1. Molecular weight: Low MW degrades faster (terminal carboxyl groups catalyze hydrolysis). 2. Crystallinity: Higher crystallinity resists moisture penetration. 3. Environmental pH: Alkaline conditions accelerate hydrolysis. 4. Composite effects: Hydrophilic fillers accelerate degradation; hydrophobic fillers slow it [22]. When PLA has the condition of low molecular weight (Mn=40kDa), noncrystalline and 37℃ it has a half-life of 4-8 weeks. Under the condition of high molecular weight (Mn=150kDa), semi-crystalline and 25℃ it has a half-life 12-18 months which is has a big different. But the under the condition of pH12 and 60℃ it has half-life of less than one week, which is much shorter than other two experiments.

PHA (Polyhydroxyalkanoates) is synthesized by microorganisms, and its degradation highly relies on the activity of environmental microorganisms. Thus, it is essential to clarify the degradation rules in different environments [23]. The benefit of PHAs compared to other bio-plastics is their complete biodegradability. Under aerobic conditions (e.g., soil and marine), it can degrade into carbon dioxide and water, under anaerobic conditions (e.g., sediments and landfills), it can degrade into carbon dioxide and methane [23]. The prediction of PHAs degradation pathway is presented in Figure 2. The rate of PHAs degradation can be determined by several factors like: temperature, oxygen, salinity and PHAs properties, such as monomeric composition and crystallinity [24,25].

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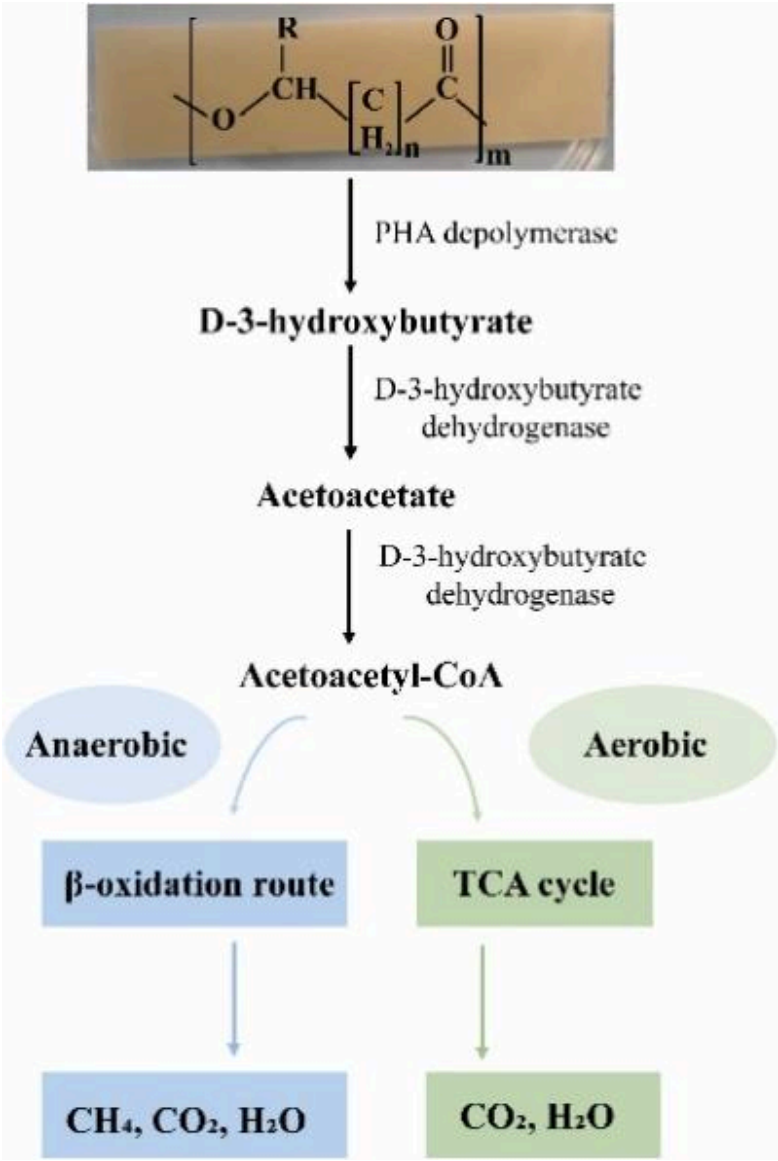


Figure 2. A simplified representation of extracellular PHA degradation under anaerobic and aerobic conditions [23]

Volova et al. compared the PHBV degradation rate using natural seawater at different temperatures (4°C, 25°C, and 40°C), and demonstrated that a high temperature (40°C) increased degradation efficiency [26]. Requiring weeks to months for full decomposition.

5.2. Industrial production cost and feasibility analysis

5.2.1. Industrial production procedure of PLA and PHA

Based on the research of Pan Xiang et al [27], the industrial production of polylactic acid (PLA) is achieved through an integrated process of biological fermentation and catalytic polymerization: Firstly, biomass raw materials such as corn or sugarcane bagasse are enzymatically hydrolyzed to generate glucose, which is then fermented by Lactobacillus species to produce L-lactic acid with high optical purity; subsequently, the lactic acid monomers undergo dehydration and cyclization at

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high temperatures (130–180°C) in the presence of tin octoate catalysts, and the resulting key intermediate, cyclic lactide, is distilled and purified, with its purity directly affecting the performance of the final polymer; then, high-purity lactide undergoes metal-catalyzed ring-opening polymerization in a vacuum inert atmosphere, and the molecular weight of PLA (>100 kDa) is controlled by adjusting the temperature and catalyst concentration; finally, closed-loop production is achieved through blending modification (such as adding PDLA to enhance heat resistance) or recycling unreacted monomers, significantly optimizing material performance and cost.

The synthesis of PHA through microbial fermentation can be classified into three steps: 1. Raw material pretreatment: Waste oils, molasses or syngas are hydrolyzed/gasified to convert into fermentable carbon sources [28]. 2. Strain fermentation: Under nitrogen-limited conditions, Cupriavidus necator (a Gram-negative soil bacterium of the class Betaproteobacteria) and other strains convert the carbon sources into intracellular PHA particles (accumulating up to 80% of the cell dry weight) [29]. 3. Extraction and purification: After cell wall disruption (by chemical or enzymatic methods), PHA is extracted with solvents (such as chloroform), and then precipitated and dried to obtain the final product [30].

5.2.2. Possibility to replace CTR for vehicle tire

The mechanical properties of PLA are insufficient. Its elongation at break (<10%) is far lower than that of CTR (>300%), and it exhibits significant low-temperature brittleness (tending to crack at temperatures below -20°C), thus failing to meet the high elasticity and impact resistance requirements of tires [27]. Regarding heat resistance, PLA's glass transition temperature (Tg) is only 55–60°C. However, during driving, tire tread temperatures can reach 70–100°C, causing PLA to soften and deform [31]. Additionally, PLA has a low coefficient of friction (0.2–0.3 in a dry state), which results in insufficient wet grip. Its wear rate is also 3 to 5 times higher than that of CTR [32].

So, I suggest at present, the mechanical and thermal properties of polylactic acid (PLA) fail to meet the tire safety standards (e.g., ECE R30). As such, relevant research remains confined to the conceptual stage.

So does PHA, the mechanical properties are insufficient. The elongation at break (3-15%) is less than 1/20 of that of CTR, and the wet friction coefficient (≤0.25) and wear resistance are far inferior to those of traditional rubber [28,30].

So, as well as PHA, I also suggest it is impossible to replace CTR in manufacturing automobile tires.

5.2.3. Cost compare to CTR

Natural rubber, a key raw material for CTR, saw its price rise by 27.1% between January and October 2024, increasing from $1.55/kg to $2.13/kg [33]. By comparison, the average price of PLA in China during 2024 was $2.5025/kg [34]. The price outlook in China of PHA during Q1 2025 (Jan-March) US$ 3373/MT which is equal to $3.373/kg [35]. These cost figures indicate that CTR remains less expensive than both PLA and PHA. However, despite PLA and PHA exhibiting inferior mechanical properties compared to CTR, their adoption in tire manufacturing is driven by environmental considerations rather than cost or performance equivalence.

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5.3. How to improve PLA and PHA to let it able to replace CTR

The major problem of Pla and PHA can't replace CTR is their physical or mechanic properties. 1. Elasticity and toughness 2. Thermal resistance and abrasion resistance.

PLA can undergo the "stereo-complexation" technology, so the molecular chains of L-PLA and D-PLA are oriented and arranged, therefore to increasing the elongation at break from less than 10% to 50-100% (But it still less than one-fifth of CTR >300%, so require further optimization) [36]. PHA can increase its elongation at break to 400%-600% by adding 20-25 wt% (wt is weight percent) plasticize, which is Citrate esters (ATBC) [37].

To increase the thermal resistance and abrasion resistance for PLA we can use annealing processes or adding blend heat-resistant polymers (e.g., PBS), fibers (plant-based or inorganic fibers), or nanoparticles (e.g., CNTs, MMTs) to introduce rigid structures, so the HDT (Heat deflection temperature) can increase to 108 °C[38]. For PHA, we can increase the thermal resistance by adding 0.1wt% graphene nanoplatelets (GNP) or silver nanoparticles (AgNP) to the surface coating of PHA this will leads to the increasing of vicat softening temperature (VST) by 7-8 °C and also the glass transition temperature (Tg) is concurrently increased. On mechanical properties, the Young's modulus will increase by 10% and stiffness strength increase by 2%.

6. Conclusion and outlook

To sum up, replacing widely used plastics such as PP, PE, and CTR with biodegradable options like PLA and PHA offers a viable yet complex route for addressing the issue of microplastic pollution—particularly in sensitive regions such as the Yangtze River Basin. Despite the environmentally friendly nature and biodegradability of PLA and PHA, their current shortcomings in terms of mechanical strength and thermal stability limit their use in demanding applications like vehicle tires. Even so, emerging techniques—ranging from stereo-complex structuring to the incorporation of nanoparticles and plasticizers—have shown encouraging progress in enhancing their performance. Moving forward, it will be essential for research efforts to prioritize improving material characteristics, lowering production costs, and tailoring materials to fit specific use cases. With continuous development, shifting to biodegradable plastics is not just a technical possibility, but an important step toward reducing environmental harm and building a cleaner future.

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