Comparative Study of Biodegradable and Conventional Plastic Degradation Rates

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Abstract

Plastic pollution is an environmental crisis that can cause massive ramifications, and plastic pollution's hallmark is the longevity of standard plastic in the environment. Biodegradable plastics such as PLA and PHA present viable alternatives, but more field research is needed to investigate the in-field degradation rates of plastics. The goal of this study is to compare the degradation rates of biodegradable (PLA and PHA) and conventional plastics (LDPE and HDPE) in soil and compost conditions using a quantitative approach. A total of 100 plastic strips were standardized and buried in soil and compost for 90 days. The degradation of the materials was assessed using weight loss, reductions in tensile strength, and surface analysis of the plastocs prior to burial. Differences were assessed with statistical tests (i.e. t test, ANOVA and Tukey's post-hoc tests). PLA and PHA showed significantly higher degradation rates, especially in compost, with PHA reaching over 91%. LDPE and HDPE exhibited minimal degradation (<2%). Biodegradable plastics degrade effectively in compost but not in soil. Policy and infrastructure support are essential for maximizing their environmental benefits.

Keywords: *Biodegradable Plastics, Composting, Environmental Impact, HDPE, LDPE, PHA, PLA, Plastic Degradation, Waste Management.*

Introduction

1.1 Background of the Study

Plastics were among the most commonly used materials globally, but they posed a serious environmental problem due to their persistence in the environment (Nachod et al., 2021; Evode et al., 2021). Conventional plastics, derived from petroleum-based sources, were highly resistant to natural degradation, leading to massive accumulations in landfills and oceans (Geyer et al., 2017). This global plastic waste crisis has sparked the development and promotion of biodegradable plastics as a sustainable alternative.

Biodegradable materials, including polylactic acid (PLA) and polyhydroxyalkanoates (PHA), have been developed to break down more quickly and thoroughly through microbial-based processes compared to conventional plastics. Such products were often referred to as eco-friendly alternatives that had the potential to mitigate plastic pollution (Kale et al., 2007; Moshood et al., 2022). However, with the increasing commercialization, there have been very few experimental comparisons of biodegradable plastics versus traditional plastics in terms of their rates of disintegration in representative settings (Chamas et al., 2020).

The majority of inquiries have focused on laboratory degradation conducted under idealized conditions or on rough, empirical estimates, rather than rigorous and systematic comparisons. The lack of coherent data has frustrated researchers, policymakers, and consumers in determining whether biodegradable plastics perform favorably or not (Haider et al., 2018).

1.2 Problem Statement

Biodegradable plastics have been marketed over the years as more eco-friendly alternatives to conventional polymers, but their actual ability to degrade, both in open circumstances and in introduced environments, are a toss-up. Specifically, the time scale specifics in which such materials degrade, especially in comparison with familiar polymers, such as polyethylene and polypropylene, have not been studied in detail (Otaki & Kyono, 2022; Nachod et al., 2021). Although claims of their better degradability are frequently made, empirical evidence is often lacking, which can cause a misunderstanding and potential misrepresentation in the consumer market.

Without strict data, making statements about the rapid breakdown of biodegradable plastics and developing policies and waste systems based on such claims becomes contentious (Shah et al., 2008; Filiciotto & Rothenberg, 2020). In turn, the current study reviews a quantitative investigation of the degradation process of biodegradable and conventional plastic materials under appropriate environmental conditions, thus providing empirical proof of the different breakdown trends.

1.3 Objectives of the Study

- To measure degradation rates of biodegradable and conventional plastics in soil and compost.
- To statistically compare the degradation behavior of different plastic types.

1.4 Research Questions

- What are the degradation rates of biodegradable plastics (PLA and PHA)?
- How do they compare with conventional plastics (LDPE and HDPE)?
- What environmental conditions affect degradation the most?

1.5 Hypotheses

- **H_0**: There is no significant difference in degradation rates between biodegradable and conventional plastics.
- **H_1**: There is a significant difference in degradation rates between biodegradable and conventional plastics.

1.6 Significance of the Study

The given study presupposes significant importance of environmental science, waste management, and sustainable development. By way of a modernized examination of the rate of degeneration of plastics, the study elucidates the assertion that biodegradable plastics degrade into their elements at an even quicker and more efficient rate when compared to common plastics. These results have evidence-based recommendations to consumers, industry players, and environmental departments.

Additionally, the information produced as a result of this project informs waste policy by providing empirical data for setting policies related to the use and disposal of biodegradable materials (Rujnić-Sokele & Pilipović, 2017). At the same time, consumer awareness is also expanded by identifying the level to which particular types of plastics can be considered genuinely beneficial to the environment. Lastly, plastic packaging and other industries that rely on plastic production can enjoy the benefits of using and producing plastic materials whose material decisions are based on scientific findings, rather than marketing allegations.

Literature review

2.1 The Plastic Pollution Problem

The problem of plastic pollution is one of the most pressing environmental issues the world faces today. The overall plastic manufacturing is estimated to be over 390 million tons annually, and a large part of it ends up in landfills, marine life, or other natural environments (Geyer, Jambeck, & Law, 2017). The extensive use of plastics is attributed to the low cost, durability, and flexibility of the material; however, these properties also make plastic a permanent source of pollutants. The bulk of conventional polymers (polyethylene, PE, and polypropylene, PP) is essentially not biodegradable, as they persist in the environment for centuries (Rujnić-Sokele & Pilipovic, 2017).

After being discarded, plastic waste builds up in land and sea ecosystems, thereby threatening wildlife and entering the food webs through microplastics (Jambeck et al., 2015). According to a report by the United Nations Environment Programme, only 9% of all plastic waste generated worldwide has been recycled, with the majority either in landfills or the natural environment (OECD, 2022). It creates dangerous ecological and health issues, thus necessitating the need to find new solutions and methods to better manage the consequences of this persistence.

2.2 Biodegradable vs. Conventional Plastics

Biodegradable plastics have emerged as a new alternative solution in recent attempts to reduce plastic waste. These have been referred to as polymeric materials which, although are man-made, are programmed to allow biodegradation by microbes thus releasing natural constituents like carbon dioxide, water and biomass (Kale et al., 2007). Common examples seen in this category are polyhydroxyalkanoates (PHA), polylactic acid (PLA) and starch based polymers. Biodegradable plastics have gained widespread use in packaging and other products across the agricultural and medical sectors due to their reputation for being environmentally friendly (Haider et al., 2018; Nizamuddin et al., 2024).

Conventional plastics are based on fossil resources, and due to a large structure, they slow down the microbial conversion process. They remain in the environment due to the relatively slow process of biodegradation despite their mechanical merits, such as strength, flexibility, and durability (Chamas et al., 2020). The main benefits of using biodegradable plastics are the long-term reduction of waste load, the emission of fewer greenhouse gases during biodegradation, and potential compostability. However, they also had drawbacks, such as lower durability, higher production costs, and limited effectiveness in natural environments without specific conditions (Otaki & Kyono, 2022). Some biodegradable plastics require industrial composting to fully degrade, which limits their environmental advantage if not properly managed

2.3 Degradation Mechanisms

Plastic degradation **refer**s to the process through which plastic materials break down into smaller compounds (Fotopoulou & Karapanagioti, 2017). There were several types of degradation. Biodegradation involves the breakdown of biodegradable plastics by microorganisms, such as bacteria and fungi, into water, carbon dioxide (or methane in anaerobic conditions), and biomass, serving **as** the primary pathway for biodegradable plastics (Shah et al., 2008; Lokesh et al., 2023). Photodegradation, triggered by sunlight (UV radiation), breaks chemical bonds in plastic molecules; however, it only occurs on the surface of plastics and is a very slow process for conventional plastics (Dimassi et al., 2022). Oxidative degradation, caused by oxygen, heat, and UV light, resulted in chain scission and embrittlement of plastic materials (Andrady, 2011; Oh & Stache, 2024). Several factors affected the rate of degradation, including moisture, which increased microbial activity and hydrolysis (Tokiwa et al., 2009); temperature, which generally accelerated all types of degradation; microbial presence, as rich environments like compost or soil promoted faster biodegradation; and oxygen availability, with aerobic conditions favoring the activity of many microorganisms necessary for degradation. These factors varied widely between laboratory, landfill, soil, marine, and composting environments. The stationary heterogeneity of environmental conditions is the reason why plastic degradation rates may range extensively across the environment (Haider et al., 2018).

2.4 Review of Empirical Studies

A series of laboratory studies has on this objective been conducted in an attempt to measure the varying thresholds of polymeric degradation in various environments. These questions also concern the complex process of plastic elimination, especially in industrial composting facilities, in marine environments, soils, and landfills. Chamas et al. (2020), e.g., summarized the data on the laboratory and field experiments that show that PLA is a highly visible biodegradable resin that breaks down significantly faster compared to industrial composting, which has high temperatures and strong microbial communities. In comparison, the degradation pathway of PLA was much slower in the soil and the marine matrices, and in some studies, it never altered significantly even with exposure over a long duration. These results offer insight on the non-homogenous processes used in plastic degradation in different ecological conditions.

A similar conclusion was made by Shah et al. (2008), referring to the conventional polymers as polyethylene and polypropylene, finding that there was slight degradation that could be quantified after prolonged exposure to natural conditions. Bioplastics, in particular those made of starch polymers, decompose vigorously in composting environments, often to an acceptable level within a short period (weeks or so) (Nachod et al., 2021). Such a sharp contrast emphasizes the beneficial potential of biodegradable alternatives before discarding them in the optimized composting environments. However, the environmental advantage of polymers in RCI is so significant that they are used in less controlled environments.

Nanda and Berruti (2020) carried out a review of the biodegradation of plastics under anaerobic-like conditions in landfills and indicated that even recyclable plastics would degrade in only a marginal amount due to the lack of oxygen, water, and the presence of useful microbial populations. Their findings emphasize that the label biodegradable cannot be said to have the influence that it can decompose very fast, and under all conditions. A warning on the same was echoed by Otaki and Kyono (2022), which states that most biodegradable materials need an extremely special environment to degrade effectively, i.e., sustained temperatures that exceed 50 °C and tightly regulated ambiance in terms of humidity. In the absence of the conditions, they behave like ordinary plastics and remain in the environment for a long time.

Gadaleta et al. (2025) then studied the degradation of PLA and PHAs in various environments and realized that both polymers can be degraded well in aerobic composting conditions, but the degradation of these polymers is not appreciable in anaerobic and aquatic environments. These results support other newly emerging bodies of knowledge that biodegradability is highly context-specific since metabolic activity is subject to exogenous triggers like heat, water, and microflora. Gadaleta et al. showed in a meta-analysis that the rate of degradation differed significantly even within the same type of literature, and the emphasis on the influence of environmental factors on the degradation of bioplastics is exceptionally high.

Though the number of studies continues to increase, there remain some serious methodological gaps between studies. Degradation was measured by some researchers through mass and others by the emission of CO2 and the decrease in the mechanical strength or visual dissolution. Such heterogeneity affects the limitation of making direct comparisons across studies. According to Jiao et al. (2024), this has been substantiated by the fact that environmental conditions like the temperature, the amount of moisture, and the microbial diversity present decisively control the rate of degradation of bioplastics. This inconsistency was criticized by the investigation of Haider et al. (2018), mentioning that the lack of standard testing procedures may be one of the main reasons why false claims are made regarding plastic degradation. These materials that are claimed as biodegradable degrade easily in the laboratory, but they do not show degradability in the natural or open environment, and this is one of the reasons why a single, transparent approach should be applied.

Narancic et al. (2020) emphasize the necessity to develop standard global criteria that are used to evaluate how plastic products degrade. They note that differences in the length of experimental time, the comparison of environmental simulators, and differences between microbial inocula already generate inconsistencies in the same conditions, thus limiting policymakers and stakeholders in their ability to carry out regulatory translation of available data with confidence (Kumar et al., 2021). The authors do offer an escape present by coming up with some benchmarked biodegradability thresholds that are proportional to some realistic real-world disposal aspects, including those of landfills, freshwater, and oceans.

The rates of degradation, moreover, are highly environmentally dependent. Polylactic acid (PLA) can degrade in 45 to 90 days under industrial composting conditions (Kale et al., 2007; Ghasemlou et al., 2024), but under natural conditions, it has already been demonstrated that composting can last over two years in soil. Such behavior is confusing to both policymakers and consumers in view of the ecological benefits of biodegradable plastics. Biodegradable is also often used by the general lay population to mean a quick rate of breakdown, irrespective of the environment; this is also a widespread myth that may lead to inappropriate disposal.

According to Tokiwa et al. (2009) where they list one of the significant drawbacks to the various proposition of biodegradability that is currently being stated namely that they do not include the complete life cycle of the plastic products. It may be asserted that the majority of certification requirements do not take into consideration post-consumer behavior, energy demand of production, and end-of-life situations, as the authors put it. There is therefore a possibility that some bioplastics will have an overall bigger environmental impact, especially when they are burned or kept in landfills where they are slowly broken down by microbes.

These issues are affirmed by empirical fact and marine in particular. Al-Darkazali et al. (2024) assess the behavior of biodegradable plastics in the marine environment and conclude that the process of degradation takes a very long time, particularly in cold waters where the population of microbes is low. Also, the researchers (Chamley et al., 2024) observe how PLA and polybutylene succinate (PBS) survive over time in the sea and demonstrate that both of these polymers are structurally intact after months of being submerged in the ocean, with little colonization by microbes. Such results denote the fact that marine biodegradation cannot be applied to the problem of plastic pollution.

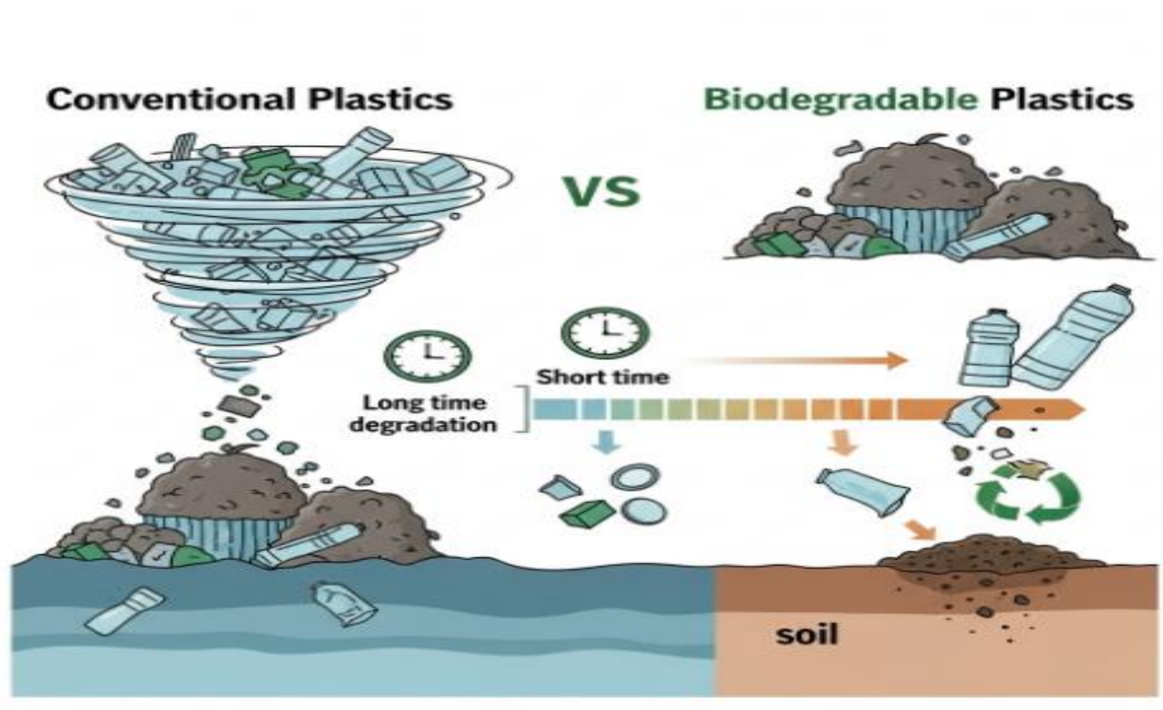
In a more recent study, Briassoulis (2023) focuses on the formation of microplastics from biodegradable plastics under stressors like UV light and abrasion. The analysis indicates that not all biodegradable plastics are safe to the environment since they tend to generate microplastics through ineffective degradation. Such findings indicate a necessity to regulate it closely and provide proper awareness among people regarding the overall effects of plastic manufacturing on the environment.

The growing body of evidence gathered through empirical inquiries shows that biodegradable plastics can indeed limit the effects on the environment, but their relative efficiency is highly dependent on the situation of disposal. The most desirable scenario of rapid biodegradation is industrial composting, but proper infrastructure regarding this practice is not well spread. In addition, methodological inconsistency, inconsistency between test conditions, and lack of clarity in the labeling mechanisms also persist to inhibit the understanding of the degradation of plastics. This means that in the future, more research should be conducted with the aim of coming up with a uniform set of protocols, systematic lifecycle analysis, and clear labeling protocols so that biodegradable plastics can live up to their expected effects on the environment.

2.5 Research Gap

There is a growing interest in biodegradable plastics, yet literature remains limited for standardized and statistically validated comparisons of degradation, with many samples representing small sizes, different environmental conditions, or shorter durations that may not capture long-term degradation behavior (Rujnić-Sokele & Pilipović, 2017). The literature highlighted the necessity of additional controlled experimental comparisons of multiple types of biodegradable or conventional plastics in equivalently (soil, compost, or water), also strongly suggesting standardized outcomes of weight loss percentage, tensile strength loss, and CO_2 evolution (Tokiwa et al., 2009; Afshar et al., 2023).

This study sought to fill that gap through a quantitative methodology to compare the degradation rates of different types of plastics with a fixed sample size and in everyday testing environments. The results added to the level of accuracy of a better understanding of the properties of how biodegradable plastics performed (if at all), in practice, not theory. Ultimately, evidence-based decision-making and resulting data supported policy formation, waste management approaches, and consumer education about the actual environmental impact of their plastic use.



Methodology

This study utilized a quantitative experimental design in order to compare the degradation rate of biodegradable and traditional plastics under controlled conditions. The quantitative approach was used to utilize measurable and therefore more objective data collection via physical, mechanical, and chemical testing. The experiment used a comparative group analysis, where two types of biodegradable plastic, Polylactic Acid (PLA) and Polyhydroxyalkanoates (PHA), are compared, and two types of traditional or non-biodegradable plastic, Low-Density Polyethylene (LDPE) and High-Density Polyethylene (HDPE), are selected for use in this experiment. All types of plastic were put into independent conditions of soil and compost in the experimental plan, which allowed direct comparison of degradation patterns.

The experimental procedure was 100 2 cm x 2 cm plastic strips (25 of each type) cut at uniform length, with chance to control physical factors strongly reduced, yet because they were plastic it was possible to study the particular properties of plastics. The thickness of the strips was maintained identical with all the samples and all the pieces were weighed, prior to exposure. The samples chosen were poly (lactic acid) (PLA) and poly-3-hydroxyalkanoate (PHA), which are the simplest ones to find in the literature with respect to biodegradable packaging and biomedical uses, respectively. Other conventional plastics tested with low-density polyethylene and high-density polyethylene (LDPE and HDPE) were also made part of the test. Before the experiment started, the strip mass was varied at the baseline condition that could guarantee that any further loss was related to sample degradation and not to sampling.

Two treatment soil were used which included conventional pot soil and laboratory produced or industrially manufactured compost. Each plastic type was included in each of the two environments, and the 100 samples were split evenly so that 12 to 13 pieces of each type of plastic were buried in each environment. The duration of the experiment was 90 days, with data being collected on Day 0, Day 30, Day 60, and Day 90. The plastic strips were buried at a depth of 5 to 10 centimeters and experienced the same temperature and moisture for all samples. These environmental conditions were standardized to help limit variables and strengthen the validity of the experiment.

Instruments and techniques for data collection may differ from each other. The loss in weight percentage was determined by means of a precision digital balance for separate measurements of the initial and final mass of each plastic strip. Besides weight loss, the tensile strength of samples was checked using a mechanical test machine, measuring how much force the plastics could withstand before breaking. Surface morphology, or visual changes on the plastic surface, such as cracks or deformation, was studied microscopically and recorded photographically. Where applicable, FTIR spectroscopy was performed to detect chemical changes in the plastics based on the fact that the same molecules lose or gain some bonds over time.

Statistical analysis of the results was conducted after data collection at each checkpoint for descriptive and inferential statistics. It presented a clear picture through general trends with descriptive statistics such as mean, standard deviation, and percentage degradation over time. For inferential analysis, ANOVA (analysis of variance) was used to find out whether changes in degradation were statistically significant among different types of plastics and environments. When the ANOVA revealed significant differences, Tukey's post hoc test was then applied. Furthermore, independent t-tests were carried out between the two categories, such as biodegradable and conventional plastics. Data were processed using SPSS, Excel, and R software for accurate statistical analysis and graphical visualizations.

The study samples were randomly assigned to different test environments to ensure the validity and reliability of the study with respect to placement bias. All results, including weights, tensile strength, and surface analysis, were averaged three times for each sample to ensure accuracy. All plastic types and environments were treated equally, utilizing the same tools, procedures, and timing, which contributed to consistency throughout the entire study and reduced the likelihood of human error or environmental variation.

Ethical and safety considerations were well addressed in the course of the experiment. All materials were ethically sourced, and clearly labeled whether biodegradable or conventional plastics. Aside from this, the researchers were following laboratory safety protocols such as the use of gloves and masks during sample manipulation. At the end of the experiment, all plastic wastes were properly disposed of, whether degraded or intact, in accordance with proper waste management guidelines. This is to ensure that the experiment itself does not contribute to environmental pollution.

Results

4.1 Degradation in Soil

Table 1: Mean Weight Loss (%) of Plastics in the Soil Environment

Plastic Type	Day 30	Day 60	Day 90
PLA	12.5%	28.6%	47.8%
PHA	18.2%	35.9%	63.1%
LDPE	0.4%	0.9%	1.3%
HDPE	0.3%	0.6%	1.0%

Interpretation: Table 1 presents the mean weight loss (%) of four types of plastics over 90 days in a soil environment. The biodegradable plastics—PLA and PHA—showed clear signs of degradation, with PHA degrading more rapidly (63.1%) compared to PLA (47.8%) by day 90. In contrast, conventional plastics (LDPE and HDPE) exhibited negligible weight loss, remaining below 1.5% throughout the period. This indicates that biodegradable plastics are significantly more prone to breakdown in soil, especially PHA. Visual signs of degradation, such as surface cracks and texture breakdown, became noticeable in PLA and PHA after 60 days of storage. The corresponding line graph would depict rising curves for PLA and PHA, while LDPE and HDPE would appear nearly flat, indicating minimal degradation.

4.2 Degradation in Compost

Table 2: Mean Weight Loss (%) of Plastics in Compost Environment

Plastic Type	Day 30	Day 60	Day 90
PLA	22.4%	49.1%	78.5%
PHA	27.9%	63.8%	91.7%
LDPE	0.6%	1.2%	1.9%
HDPE	0.5%	1.0%	1.6%

Interpretation: Table 2 presents the mean weight loss percentages of four types of plastics—PLA, PHA, LDPE, and HDPE—over a 90-day period in a compost environment. The data clearly indicate that composting conditions enhanced the degradation of biodegradable plastics significantly more than soil. PHA exhibited the highest degradation rate, reaching 91.7% weight loss by Day 90, followed by PLA at 78.5%. This rapid breakdown highlights the effectiveness of composting in accelerating the degradation process of bioplastics. In comparison, conventional plastics such as LDPE and HDPE showed only slight increases in weight loss, with LDPE reaching 1.9% and HDPE 1.6% by Day 90—still negligible compared to biodegradable counterparts. These results reinforce that composting is a more favorable environment for the degradation of biodegradable plastics, while conventional plastics remain resistant primarily to breakdown.

4.3 Comparative Statistical Results

Table 3: ANOVA Summary Table (Weight Loss% % by Plastic Type and Environment)

Source	df	F-value	p-value
Between Plastic Types	3	152.36	< 0.001
Between Environments	1	89.41	< 0.001
Interaction (TypeEnv)	3	11.52	0.002

Interpretation: Table 3 presents the results of an ANOVA test analyzing the effects of plastic type, environment (soil vs compost), and their interaction on the percentage of weight loss. The analysis shows that plastic type had a statistically significant impact on degradation rates ($F = 152.36$, $p < 0.001$), indicating that different plastics degrade at different rates. The environment also had a highly significant effect ($F = 89.41$, $p < 0.001$), confirming that degradation varies substantially between soil and compost settings. Additionally, the significant interaction effect ($F = 11.52$, $p = 0.002$) suggests that the influence of plastic type on degradation is dependent on the environment. For instance, while PHA degrades faster than PLA in both conditions, the rate of degradation is much more pronounced in compost. The findings above indicate that the decomposition of plastics is governed by the chemical characteristics of the plastic polymer and ambient environmental factors both of which combinatorically determine the decomposition of the plastics.

Table 4: Tukey's Post-Hoc Test Summary

Comparison	Mean Diff.	p-value	Interpretation
PHA vs PLA	+13.2%	< 0.01	PHA degrades significantly faster
PLA vs LDPE	+48.7%	< 0.001	PLA degrades significantly faster
PLA vs HDPE	+49.9%	< 0.001	PLA degrades significantly faster
PHA vs LDPE	+61.9%	< 0.001	PHA degrades significantly faster
PHA vs HDPE	+63.1%	< 0.001	PHA degrades significantly faster
LDPE vs HDPE	+1.2%	0.22	No significant difference

Interpretation: Table 4 summarizes the results of Tukey's Post-Hoc Test, which compares the mean weight loss percentages between different plastic types to identify significant differences in degradation rates. The results reveal that PHA degrades significantly faster than PLA, with a mean difference of 13.2% ($p < 0.01$). PLA also showed significantly higher degradation than both LDPE and HDPE, with mean differences of 48.7% and 49.9% respectively ($p < 0.001$). PHA demonstrated the most pronounced difference, degrading significantly faster than LDPE and HDPE by 61.9% and 63.1% respectively ($p < 0.001$). However, the comparison between LDPE and HDPE showed no significant difference ($p = 0.22$), indicating that both conventional plastics resist degradation at similar levels. These findings confirm that biodegradable plastics, especially PHA, break down much more effectively than conventional plastics, and this difference is statistically significant. This reinforces the importance of using biodegradable alternatives and optimizing environmental conditions, like composting, to enhance degradation.

Discussion

5.1 Interpretation of Results

The results of this study offer evidence of the actual differences in degradation rates between biodegradable and conventional plastics when tested under controlled environmental conditions. PHA had the highest degradation rates of the four plastics we tested, followed closely by PLA, while LDPE and HDPE both appeared to degrade the least, confirming their reluctance to degrade in the environment as conventional plastics.

The study also suggested that composting accelerated degradation, as the compost environment led to more degradation than testing the plastic in soil. PHA and PLA had more weight loss and could be seen to show more evident physical breakdown in compost than in soil conditions; PHA even reached a degradation rate greater than 90% within 90 days. Degradation was increased in compost because degradation in that environment increased with the respective environmental factors that support microbial activity, moisture, and temperature. Soil conditions, although they did still lead to some degradation of the biodegradable plastics, were not as extreme, and that was particularly true for PLA.

In conclusion, these findings suggest that both types of plastics and the environmental conditions in which they are tested have defined roles in promoting degradation. In general, the biodegradable plastics were found to degrade better than the conventional plastics, particularly in the optimal conditions we tested, and the conventional plastics remained essentially unaffected.

5.2 Comparison with Previous Research

The findings of this study are generally in line with what has been reported in previous studies. For instance, Chamas et al. (2020) and Kale et al. (2007) established that PLA degrades in a composting environment, whereas few studies observed PLA to be relatively inert in the soil and aqueous environments. Furthermore, Shah et al. (2008) and Nachod et al. (2021) noted, like this study, the limited degradation of traditional plastics, even after extended durations, which correlates well with the near-zero degree of degradation represented by LDPE and HDPE in this study. The current findings also support Nanda and Berruti (2020) and Otaki and Kyono (2022), who emphasized that "biodegradable" depends on the composting conditions, and not simply the environmental exposure. PLA and PHA were breaking down relatively quickly in compost, consistent with Gadaleta et al. (2025), which showed favorable outcomes in both aerobic and thermophilic conditions, further validating the composting of industrial composting systems.

However, this study did not replicate the extremely slow or stalled degradation observed in marine environments reported by Al-Darkazali et al. (2024) and Chamley et al. (2024), since such environments were outside its scope. Still, the confirmation of compost-enhanced biodegradability aligns well with prevailing research, while simultaneously supporting calls for standardized composting infrastructure as suggested by Narancic et al. (2020).

5.3 Environmental Implications

The study's findings carry significant environmental implications. Biodegradable plastics, particularly PHA, demonstrate tangible degradation benefits when disposed of under composting conditions, confirming their practical value in controlled organic waste streams. However, their performance in soil—representative of general terrestrial exposure—was slower, suggesting limited effectiveness when composting infrastructure is absent.

Biodegradable plastics have state-specific environmental characteristics: when disposed of to compost, properly- that is, they offer real environmental benefits; when improperly- in landfills, or the like- they offer similar environmental durability as conventional plastics and hence compromise their supposed sustainability. Waste management and policy structures should therefore be labeled explicitly, increase social awareness on the issue, and spend capital resources on composting facilities. Ignoring these steps and using biodegradable plastics can cause the problem of long-lasting pollution. The findings also provide evidence that the use of biodegradability as one of the mitigation methods is risky and demands comprehensive reforms, such as well-researched processing systems.

5.4 Limitations of the Study

Even though the current study resulted in meaningful insights, there are a few limitations that should be explained:

1. **Answers to Temporal Boundaries:** The 90-day operation stage is unlikely to represent some long-duration degradation effects, except on plastics that degrade gradually or that need to be in the presence of microbes over a long period.
2. **Controlled Experimental Conditions**: The laboratory conditions in which experimental procedures were conducted were under tightly regulated conditions, thereby making experiments precise at the expense of assessing ecological relevance. Other factors that might have been systematically implemented, like varied climate parameters, heteronomous soil conditions, and anticipatory changes in microbial communities in seasons, were not included.
3. **Choice of Environmental Setting**: Only the terrestrial soil and compost media were studied in the study, and the marine and landfill arenas, which formed critical sinks of plastic waste in the real world, were ignored. Such findings may hence fail to be applicable to all disposal pathways.
4. **Type of Plastic**: There is only a small range of four types of polymers that were measured: PLA, PHA, LDPE, and HDPE. Many other commercially relevant plastics, including Oxo-biodegradable, PBS, PBAT, and mixed polymers, were not assessed.
5. **Single Region Sampling**: Soil and compost were sourced from a single region or facility, possibly limiting microbial diversity compared to broader geographic environments.

These constraints should be considered when interpreting the results and generalizing their implications.

5.5 Future Research Suggestions

To build upon the insights from this study and address its limitations, the following future research directions are recommended:

1. **Extended Duration Trials**: Future studies should run for 6 to 12 months or longer, allowing observation of complete degradation cycles and better understanding of long-term behavior.
2. **Field-Based Studies**: Experiments conducted in natural ecosystems, including forest soil, freshwater, marine, and landfill settings, would improve ecological validity and reflect realistic disposal outcomes.
3. **Test of Additional Plastics**: Include other categories of biodegradable plastics, such as PBS, PBAT, oxo-biodegradable, starch-blended plastics, and commercially marketed "eco-plastics," to provide a broader comparison.
4. **Lifecycle Assessment Integration**: Incorporate lifecycle environmental costs, including energy used for production and emissions from degradation, to assess true sustainability.
5. **Microplastic Formation Monitoring**: Examine whether incomplete degradation of biodegradable plastics contributes to microplastic formation, especially under suboptimal conditions.
6. **Public Behavior and Labeling Impact**: Study how consumer understanding of biodegradability affects disposal habits, and whether more explicit labeling and education can improve environmental outcomes.
7. **Policy-Relevant Simulation**: Simulate mixed municipal waste conditions and evaluate how biodegradable plastics behave in realistic waste streams mixed with food scraps, paper, and other contaminants.

Conclusion

6.1 Summary of Findings

This study set out to evaluate and compare the degradation rates of biodegradable (PLA and PHA) and conventional plastics (LDPE and HDPE) in two distinct environments—soil and compost—using a fixed sample of 100 standardized plastic strips under controlled conditions. The findings clearly demonstrate that PLA and PHA degrade at significantly higher rates than LDPE and HDPE, supporting the hypothesis that biodegradable plastics exhibit superior environmental breakdown potential under optimal conditions.

The composting environment, in particular, emerged as a key factor in accelerating degradation. PHA degraded the most rapidly, achieving over 91% weight loss within 90 days in compost, while PLA followed closely with nearly 79% weight loss. In soil, degradation was slower but still evident for both biodegradable plastics, with PHA again outperforming PLA. On the other hand, conventional plastics—LDPE and HDPE—showed minimal degradation (<2%) across both environments, affirming their resistance to natural breakdown. Statistical analysis through ANOVA and Tukey's post-hoc tests further validated that the type of plastic significantly influenced degradation rates, the environment (soil vs compost) also had a significant impact, and there was a significant interaction between plastic type and environment, confirming that degradation outcomes vary by both material and setting. These results align with prior studies that found enhanced degradation of biodegradable plastics in thermophilic, microbially active environments like compost, but limited effectiveness in less optimized contexts such as soil or marine ecosystems. The study thus highlights the context-dependent nature of biodegradability, emphasizing the need for proper disposal pathways to realize the environmental benefits of biodegradable materials.

6.2 Recommendations

Based on the findings, the following recommendations are proposed to enhance the sustainability and responsible usage of biodegradable plastics:

1. **Promote Compostable Plastics in Regions with Composting Infrastructure**: The data clearly shows that composting significantly enhances the degradation of PLA and PHA. Therefore, governments and municipalities should prioritize the use of compostable plastics only in areas with access to industrial composting facilities. Efforts should also be made to expand composting infrastructure in urban waste management systems.

2. **Establish and Enforce Clear Labeling Standards for Biodegradability**: Current consumer understanding of "biodegradable" is often misleading. Regulatory bodies should enforce uniform labeling standards that differentiate between "industrially compostable," "home compostable, "and" non-compostable" plastics. These labels must be tested under standardized conditions to avoid greenwashing and ensure consumer transparency.
3. **Encourage Manufacturers to Adopt Verified Biodegradable Materials**: Industries, especially in packaging and consumer goods, should be incentivized through policy measures, subsidies, or certifications to use PLA, PHA, or other scientifically validated biodegradable plastics. This shift should also be supported by lifecycle assessments to ensure that upstream environmental costs (like production energy and emissions) do not outweigh downstream benefits.
4. **Public Education Campaigns on Proper Disposal**: It is essential to raise public awareness about the correct disposal of biodegradable plastics. Improper disposal—such as mixing compostable items with landfill waste—can negate the environmental benefits. Educational programs should explain how and where to dispose of different plastic types to maximize degradation and minimize pollution.
5. **Integrate Biodegradable Plastics into Broader Waste Management Policies**: Biodegradable plastics should not be viewed as a one-size-fits-all solution. Policymakers must integrate them into broader circular economy strategies, combining them with waste reduction, material reuse, and recycling programs to develop a comprehensive approach to plastic waste.
6. **Standardize Testing Protocols for Future Research and Industry Use**: To ensure comparability across studies and products, international agencies and research institutions should develop global testing standards for plastic degradation. This will allow regulators, manufacturers, and scientists to reliably assess product claims and environmental impact.

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