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Assessing Biodegradation Rates of Biodegradable Plastics Under Diverse Environmental Conditions

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ABSTRACT

This study investigated the biodegradation rates of various biodegradable plastics in soil and aqueous environments, demonstrating that these materials do not always degrade as efficiently as expected due to their strong dependence on environmental conditions. Biodegradation was examined under controlled variations of temperature, pH, salinity, and microbial activity to simulate real-world disposal scenarios, with conditions adjusted weekly to accelerate breakdown and allow for measurable results. Degradation rates were monitored through weekly mass measurements. The results showed significant variation among plastics, with degradation strongly influenced by temperature, pH, microbial activity, and polymer chemical structure. Alkaline conditions (pH 9) combined with higher temperatures were the most effective in accelerating degradation. Polylactic acid (PLA) degraded the fastest, particularly in water-based environments under high heat and alkaline conditions, fragmenting at 70 °C, while Polyhydroxyalkanoates (PHA) exhibited gradual mass loss and required longer exposure to heat to degrade. Polycaprolactones (PCL) showed the least degradation across all conditions. These findings suggest that higher ester bond density within polymer structures may correlate with faster degradation under high heat and alkaline environments. Overall, the study highlights that biodegradable plastics require specific conditions to degrade efficiently and may persist otherwise, contributing to microplastic pollution or methane emissions in landfills, emphasizing the need for improved waste management strategies to maximize their environmental benefits.

INTRODUCTION AND GOALS

Plastic pollution has been a growing environmental crisis for decades, with global production doubling since the beginning of the century, reaching nearly 400 million metric tons per year (Davison, 2024) . Oceans and beaches are overrun with plastic waste, and microplastics have entered water sources, food, and even the human body, posing long-term ecological and health risks. Finding a solution has been challenging, as alternatives to conventional plastics have trade-offs. Recycling helps reduce waste but is limited by material variety and collection issues. Biodegradable plastics are being explored as a promising option to replace conventional plastics and mitigate environmental impact.

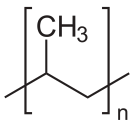
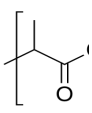
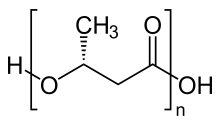
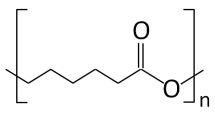
Even more concerning, about 85% of plastic waste ends up in landfills, especially in low-income countries with poor waste management (Davison, 2024). Marine life is at risk, with an estimated 1 million sea creatures projected to die in the next decade(Davison, 2024). Single-use plastics, which make up roughly half of all plastic produced, are particularly harmful. For example, items such as plastic bags are used for minutes but can take decades to break down (Davison, 2024). Public awareness is growing, with three-quarters of people supporting bans on single-use plastics. Without intervention, global plastic waste could reach 1,100 million tons annually by 2050, emphasizing the urgent need for sustainable alternatives and stricter regulations (Davison, 2024).

Currently, a significant gap exists between the supposed biodegradability of these polymers and how they actually degrade in natural environments. While many bioplastics are marketed as eco-friendly solutions, most current research focuses on their degradation within controlled industrial facilities with ideal conditions rather than real-world conditions with 'leakage' scenarios, such as saline marine environments or varying soil pH levels. Additionally, we lack sufficient data on how a polymer's chemical composition, specifically the concentration of ester bonds, reacts to environmental factors to determine how fast it degrades. There is a lack of knowledge on the relationship between these vulnerable molecular points and external stressors, which makes it difficult to predict whether a plastic will truly degrade or simply persist. Without understanding these precise environmental triggers, biodegradable plastics risk becoming an inadequate solution that persists in the environment, contributing to microplastic toxicity rather than actually resolving the plastic crisis.

Biodegradable plastics, very much like traditional ones, offer versatility in terms of conversion to different shapes and forms. They can be formed into packing materials, extruded, and injection-molded using modified conventional machines. These materials can also incorporate various fillers, including wood flour, lime, clay, or waste paper, which can be adjusted in granulation size to alter their appearance and functionality. Additionally, biodegradable plastics can be co-injected with other plastic materials such as low density polyethylene (LDPE), polypropylene (PP), and high density polyethylene (HDPE), creating a thin outer layer. This co-injection process results in materials that are cost-effective, waterproof, and visually similar to traditional plastics, making them more viable for commercial use. Among the most commonly studied biodegradable plastics are PLA, PHA, and PCL.

Table 1

Structure and melting points of polymers selected in this study

Properties	PP	PLA	PHA	PCL
Chemical Structure				
Melting Point	160°C	175°C	180°C	60°C

Molecular Weight Range(Daltons)	200,000 to 600,000	80,000 to 380,000	50,000 to 1,000,000	80,000 to 150,000

As seen from table 1, there is an inherent difference in the chemical structures of the various biodegradable polymers versus a polyolefin like polypropylene. It is this difference in the form of an ester bond, in the chemical structure that lends materials like PLA, PHA and PCL to be more degradable versus PP.

PHA bioplastics are typically biodegradable in marine environments, with bottles lasting 1.5–3.5 years and thin films degrading in 0.1–0.2 years (Boyandin et al., 2019). PLA degrades faster under industrial or heat-induced conditions, showing noticeable breakdown within the first nine days (Hussain et al., 2024). PCL degrades more slowly, over months to years, depending on factors such as molecular weight, crystallinity, morphology, and environment, and shows optimal degradation in soil, aided by certain bacteria and fungi (Ilyas, 2022).

Despite these benefits, biodegradable plastics can still pose environmental risks. In landfills, they decompose gradually and release methane, a gas 23 times more potent than CO_2 (Biodegradation, explained, 2023). Innovations such as embedding polyester-degrading enzymes in PLA have accelerated its breakdown under heat and moisture, allowing complete degradation within weeks without leaving microplastic residues (Sanders, 2021). These advancements improve the real-world feasibility of biodegradable plastics but highlight the need for proper disposal and environmental conditions for effective degradation.

This study aims to determine the following: Which type of biodegradable plastic (PLA, PHA or PCL) has the most efficient biodegradation rates under controlled soil and aqueous environments, and which conditions, considering pH, moisture, temperature, and microbial factors, are best suited to increase degradation rates? All the results are compared against the control PP material.

Ultimately, the findings from this study may contribute to future research and innovation in the field of sustainable plastic design and waste management.

METHODS

To begin the experiment, 3D plastic bars were printed with dimensions of 6.4 cm by 1.3 cm by 0.3 cm (ASTM E23 standard for molding izod bars), producing 32 bars of each type of plastic. All the parts were printed with a constant line width setting of 0.4. Once printing was completed, soil conditions were prepared by filling 16 ceramic pots with 1½ cups of potting soil each. Each environment was unique with no replicates. Four 3D-printed bars, each corresponding to a specific polymer type, served as the replicates within each environment. These bars were analyzed every four weeks to monitor for weight changes.

Table 2
3D Printing parameters for various plastics

Parameters	PLA	PHA	PP	PCL
Layer Height mm	0.2	0.28	0.2	0.2
Initial Layer Height mm	0.24	0.28	0.3	0.2
Infill Density	100	50	100	100
Temperature C	205	190	230	200
Build Plate Temperature C	60	20	100	40
Fan Cooling	100	100	20	100

One of the significant challenges in plastic waste management is leakage. This is waste that ends up either in soil, rivers, water runways and eventually the oceans, due to lack of improper disposal by consumers or inadequate waste management practices. Hence it is critical to ensure that plastic waste in these environments naturally degrades away since it is not easily possible to collect it anymore into the organized waste management system. Thus, the experiments were designed to test plastic degradation in different soil and water conditions to replicate real life conditions. This specific variety of environments, spanning pH 4 to 9 and including saline conditions, was selected to address the data gap regarding how these materials behave when they leak into unmanaged natural systems rather than controlled industrial facilities. The water conditions were broadly split into saline and natural water conditions to mimic ocean and river type environments. Whilst pH of natural water systems ranges between 6 to 9 depending on mineral elements they are exposed to, the pH range of oceanic water is tighter and ranges between 7.5 and 8.5 typically. Our experiments in the aqueous conditions spanned the range of 4 to 9. The acidic end of pH 4 mimics a more accelerated degradation condition.

The pH range of most soils vary from 4 to 9 once again depending on the minerals present in the soil and the amount of rainfall it receives. A range of pH 4 to 8 for the soil samples was selected. In the wet soil setup, extra water was added, while the dry soil remained unchanged. The acidic soil was created by mixing vinegar with water before adding it, and the basic soil was made by dissolving baking soda in water.

It is recognized that ultraviolet (uv) rays present in natural sunlight cause slow degradation of plastics but it was not introduced as a variable in our studies due to the challenge of managing a combination of uv and high temperature studies in the same setup.

Lastly, the temperature of land can vary between -20 to 43°C depending on the season and location of the land mass. The ocean temperature range is narrower and can vary between 0°C and above 30°C once again, based on location and season. To keep the length of the study to a reasonable time period, the temperature for the experiments was started at room temperature and then increased in steps to 70°C to partly mimic real life conditions and partly to accelerate the degradation rates.

For the water-based conditions, multiple containers were prepared. The saline water condition was created by mixing salt into water. The neutral water condition contained only water, while the acidic condition had vinegar mixed in. The basic water condition was prepared using baking soda dissolved in water. After setting up these environments, plastic bars were placed in each soil pot and water container, ensuring they were either buried or submerged. The soil samples were kept under a light source to simulate sunlight initially before later being moved to incubators for further observation.

After setting up these environments, the soil conditions were set up in a similar way, taking the required amounts for each condition and adding it to each pot. Plastic bars were then placed in each soil pot and water container, ensuring they were either buried or submerged. The soil samples were kept under a light source to simulate sunlight initially before later being moved to incubators for further observation.

At week five, bacteria were introduced into all conditions except the dry soil to study their role in plastic degradation. A common over the counter bacterial source (VSL#3) was used for this study. VSL#3 was chosen because it contains a mixture of probiotic bacteria widely used by humans and known to effectively improve the balance of microorganisms in the gut, making it a useful starting point for testing whether similar beneficial microbes could function in soil environments. However, probiotic bacteria are adapted to the controlled conditions of the human body and may not survive or perform as well in soil or water where environmental conditions, nutrient availability, and competition with native microbes vary significantly. Additionally, there are hundreds of bacterial strains in nature, many of which may influence degradation rates differently, meaning other bacteria could potentially be better suited for soil and aqueous environments. By week ten, the temperature in the incubators was raised to speed up the process. The temperature was increased again the following week, and by week twelve, certain plastic samples were placed in a separate incubator at a more suitable temperature for their breakdown.

Each week, the plastic bars were removed, dried, cleaned and weighed to track any changes in mass. After drying, each bar was weighed to record any changes in mass using a digital 200 gram pocket scale weighing scale with a scale precision of +_0.01g. The pH levels of the soil and water conditions were also checked to ensure stability. After measurements, the water and soil conditions were refreshed to maintain consistency, and bacteria were replenished where needed. Since the incubators were set at high temperatures, water was occasionally added to prevent excessive drying. The dry soil condition remained untouched throughout the experiment.

Table 3

Details of various conditions to study degradation of plastics over extended time periods

Condition	Week 0 (Setup)	Week 5 (1 tbsp Bacteria Added)	Week 10	Week 11	Week 12	Each week up to Week 16	Every other week (up to week 22)	Target pH
Wet potting soil	140 ml water	Yes						Neutral (pH 6)
Dry potting soil (dry)	No water added	No						None
Potting soil with vinegar (pH 4)	60 ml vinegar + 60 ml water	Yes						Acidic (pH 4)
Potting soil with baking soda (pH 9)	60 ml baking soda + 30 ml water	Yes						Alkaline (pH 8)
Saline water	60 ml salt + 125 ml water	Yes						Neutral (pH 7)
Aqueous water (neutral)	125 ml water	Yes					Weigh bars, add ingredients to maintain appropriate conditions	Neutral (pH 7)
			Temp. increased to 42°C	Temp increased to 60°C, PCL excluded	Temp increased to 70°C, PCL moved to 42°C	Weigh bars, add ingredients to maintain appropriate conditions		
Aqueous water with vinegar (pH 4)	60 ml vinegar + 60 ml water	Yes						Acidic (pH 4)
Aqueous water + baking soda (pH 9)	60 ml baking soda + 500 ml water	Yes						Alkaline (pH 8)

Within the polyolefinic materials, polypropylene (PP) is broadly used in a variety of single use and durable applications ranging from containers to medical supplies to automotive bumpers. The annual production volume in 2022 was 87 million tons globally. In this experiment, the control group is characterized by the polypropylene plastic (PP) in the dry soil condition, as unlike the other conditions, it

did not receive any modifications like water, vinegar, saline, or bacteria and represents a non-biodegradable plastic. This made it possible to observe the degradation of the plastic bars in the absence of any external influences, providing a baseline for comparison. The independent variables include the environmental conditions, temperature, pH levels, and bacterial level, as they weren't impacted, and were the leading factors that contributed to the outcomes of the degradation rates. Additionally, the dependent variable in this study was the degradation rates of the biodegradable plastics in their conditions, since it is the main factor that is influenced.

RESULTS

Figures 1 through 4 show the results of the studies for the different plastics under varying conditions in aqueous and soil environments. It should be noted that the mass of all the samples are normalized to the initial weights to represent the data in a consistent manner across the entire duration of the study. The error bars represent one standard deviation on either side of the average of the measurements.

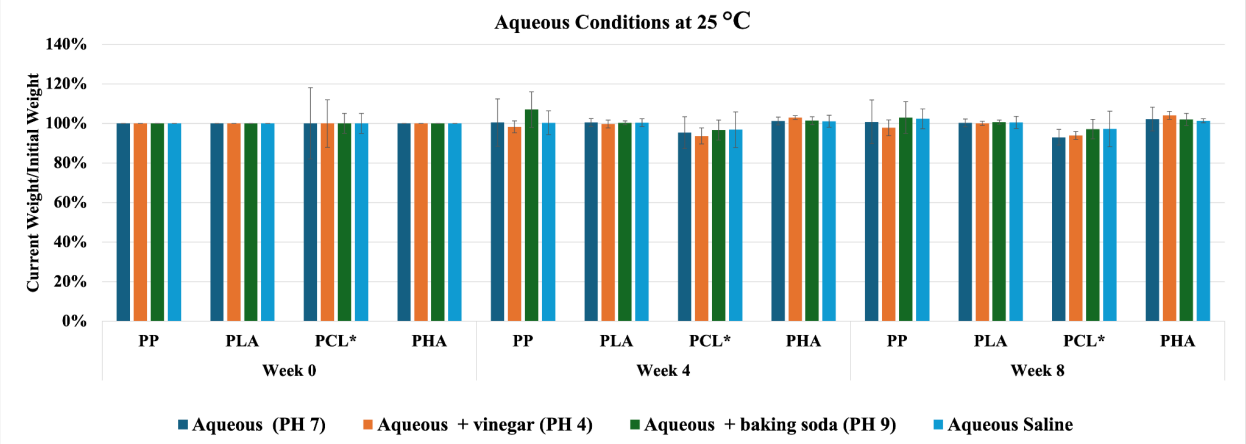


Figure 1

Effects of different aqueous conditions on material degradation over the first 8 weeks

Figure 1 shows the degradation of the polymers in the aqueous environment for the first 8 weeks under varying pH, salinity condition and introduction of bacteria at week 5. As can be noted, there is no significant change at ambient temperature conditions throughout the first 8 weeks.

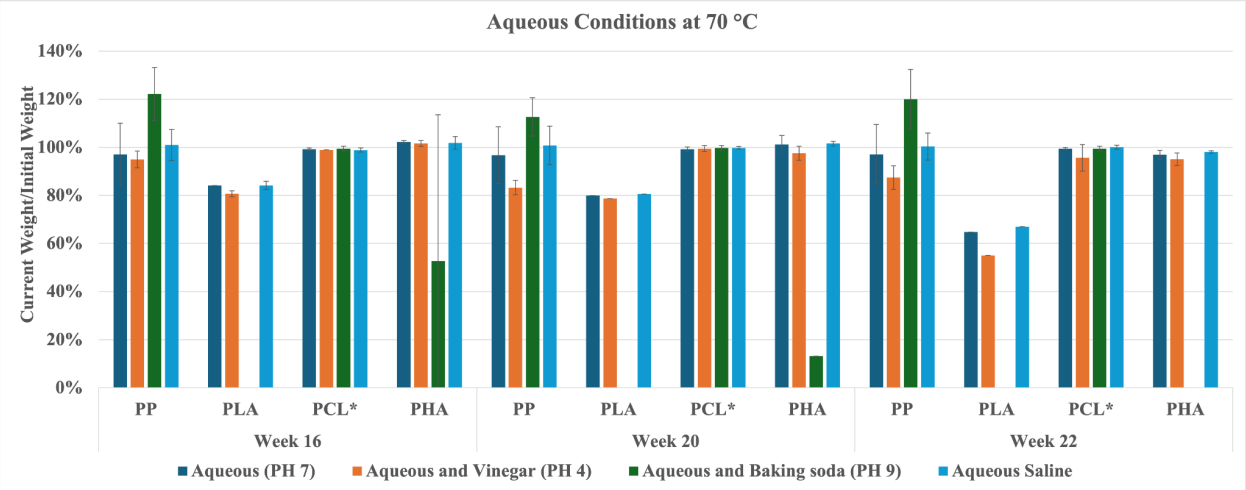


Figure 2

Effects of different aqueous conditions on material degradation from weeks 16 to 22, in response to pH and moisture.

Figure 2 shows some significant changes observed in weeks 8 through 22. The most significant change during this time period was in the increase of temperature in stages. Once the temperature was raised to 70 C in week 14, the acceleration was evident in materials such as PLA and PHA, especially in alkaline conditions.

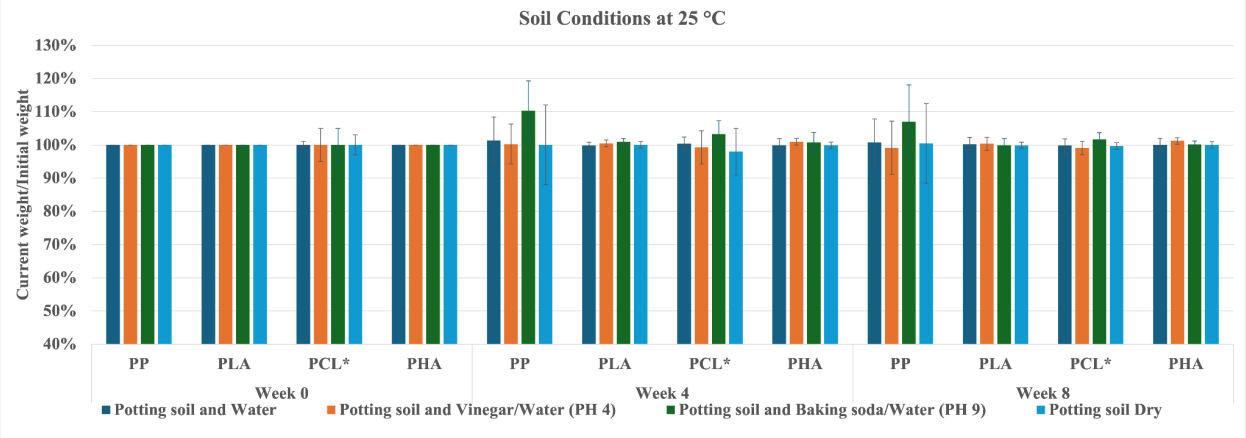


Figure 3

Effects of different soil conditions on material degradation over the first 8 weeks, in response to pH and moisture.

Similar to the aqueous conditions, Figure 3 shows the degradation of the polymers in the soil environment for the first 8 weeks under varying pH, moisture levels and introduction of bacteria at week 5. As can be observed, there is no significant change at ambient temperature conditions throughout the first 8 weeks.

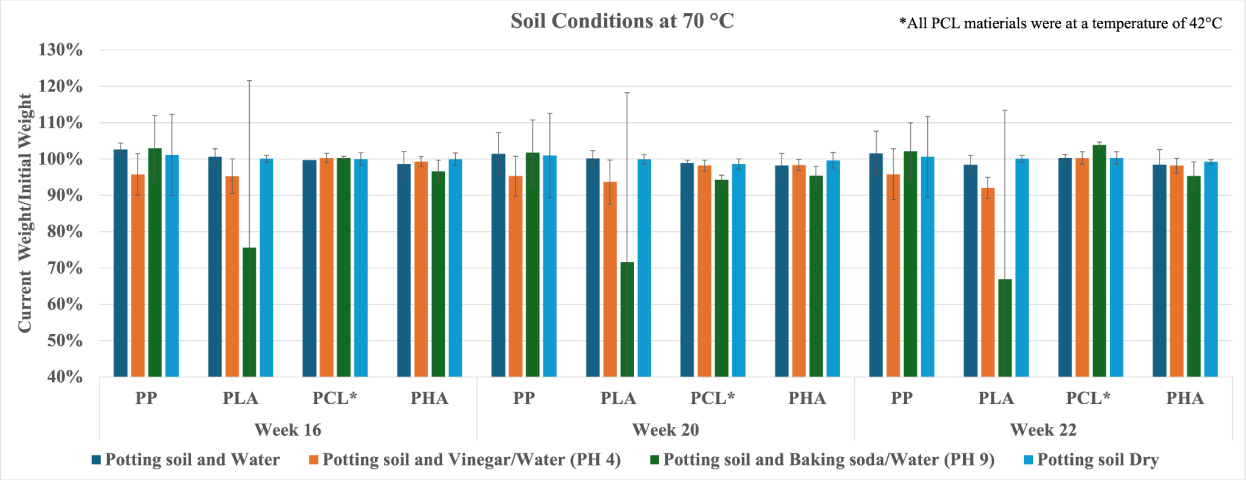


Figure 4

Effects of different soil conditions on material degradation over weeks 16 to 22, in response to pH and moisture.

In Figure 4, some significant changes are observed in weeks 8 through 22 although the changes in the soil environment are lesser than that observed in aqueous conditions. The most significant change during this time period was in the increase of temperature in stages. Once the temperature was raised to 70 C in week 14, the acceleration was evident in materials such as PLA, especially in alkaline conditions.

Since PCL melts at 55 C, it could not be subjected to the 60 C environment in weeks 11 and 12. Starting week 13, a fresh set of PCL bars were subjected to degradation at 42 C.

DISCUSSION

The study used multiple two-factor ANOVA tests to evaluate how different factors, such as pH, temperature, and polymer type, influenced the rate of degradation across various conditions. Three 2 factor ANOVA tests were conducted to validate the following - i) Effect of polymer type, pH and associated interactions on polymer weight loss (Refer to Tables 5a and 5b) ii) Effect of polymer type, temperature and associated interactions on polymer weight loss (Refer to Tables 6a and 6b) iii) Effect of polymer type, environment and associated interactions on polymer weight loss (Refer to Tables 6a and 6b)

Table 5a:

Data set of normalized mass retention ratios of PP, PLA, PCL, and PHA measured in aqueous conditions with different pH levels (pH 4, 7, and 9) after 22 weeks at 70°C, with four bars for each condition.

Material	pH 7	pH 4	pH 9
PP	1.086957	0.861635	1.320755
	0.968944	0.911950	1.257862
	0.913043	0.911950	1.176101
	0.937888	0.855346	1.150943
PLA	0.649351	0.550162	0.000000
	0.649351	0.550162	0.000000
	0.649351	0.550162	0.000000
	0.649351	0.550162	0.000000
PCL	0.502732	0.293729	0.471503
	0.306667	0.380952	0.469697
	0.425926	0.484211	0.494681
	0.433333	0.478947	0.301639
PHA	0.972028	0.972028	0.000000
	0.986014	0.965035	0.000000
	0.979021	0.951049	0.000000
	0.986014	0.968531	0.000000

Table 5b:

ANOVA table for dataset represented in Table 5a

Source of Variation	SS	df	MS	F	P-value
Materials	3.080475	3	1.026825	343.7658	2.37E-28
pH Level	1.074303	2	0.537151	179.8303	1.47E-19
Interaction	2.677801	6	0.446300	149.4147	4.56E-27
Within (Error)	0.107532	36	0.002987		
Total	6.940111	47			

Table 5b shows that both material type and pH level had a statistically significant effect on mass retention ($p < 0.0001$ for both). The F-values for materials ($F = 343.8$) and pH level ($F = 179.8$) show that neither factor alone explains the variation in degradation, since both independently contributed to differences in mass loss during the 22-week study. The interaction effect was also statistically significant ($F = 149.4$, $p < 0.0001$), meaning the impact of pH on mass retention varied across polymer types. For example, PLA and PHA saw major mass degradation under pH 9 conditions, while PP remained relatively stable across all tested pH levels. PCL showed moderate degradation, with less variation across pH levels compared to PLA and PHA.

Table 6a:

Dataset for normalized mass retention ratios of PP, PLA, PCL, and PHA measured in aqueous conditions at pH 9 with different temperature levels comparing 12 weeks at 25°C and 22 weeks at 70°C except for PCL at 42°C, with four bars for each condition.

Material	Room Temp (25°C)	High Temp (70°C)
PP	1.093168	1.086957
	0.981366	0.968944
	0.937888	0.913043
	0.968944	0.937888
PLA	1.006494	0.649351
	0.996753	0.649351
	1.003247	0.649351
	1.006494	0.649351
PCL	0.967213	0.502732
	1.000000	0.306667
	0.856481	0.425926
	0.861905	0.433333
PHA	1.003497	0.972028
	1.013986	0.986014
	1.006993	0.979021
	1.017483	0.986014

Table 6b:

ANOVA table for dataset represented in Table 6a

Source of Variation	SS	df	MS	F	P-value
Materials	0.571520	3	0.190507	67.4768	3.12E-12
pH Level	0.410858	1	0.410858	145.5243	6.91E-12
Interaction	0.350594	3	0.116865	41.3931	3.54E-09
Within (Error)	0.067759	24	0.002823		
Total	1.400732	31			

Table 6b statistically confirms what was previously observed in Figures 1 and 2: increasing the temperature from 25°C to 70°C caused a major increase in mass loss across all materials ($F = 145.5$, $p < 0.0001$). This aligns with the study's controlled temperature increases, which were intended to mimic and accelerate natural degradation conditions. The significant interaction effect ($F = 41.4$) is important because it shows that the polymers reacted in different ways to the temperature increase. For example, PCL, which has a relatively low melting point of about 55°C, could not be tested at the highest temperature and instead had to be tested at 42°C, while PLA broke apart much more rapidly at higher temperatures. These differences show that how a material responds to heat depends strongly on its polymer structure.

Table 7a:

Dataset for normalized mass retention ratios of PP, PLA, PCL, and PHA measured in alkaline conditions at week 22 comparing aqueous environments to potting soil environments.

Material	Aqueous (Water)	Potting Soil
PP	1.320755	1.000000
	1.257862	1.006250
	1.176101	1.093750
	1.150943	1.081250

PLA	0.000000	0.583062
	0.000000	0.811075
	0.000000	0.794788
	0.000000	0.508143
PCL	0.471503	0.455959
	0.469697	0.300341
	0.494681	0.472826
	0.301639	0.465969
PHA	0.000000	0.968531
	0.000000	0.975524
	0.000000	0.965035
	0.000000	0.944056

Table 7b:

ANOVA table for dataset represented in Table 7a

Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**
Materials	3.195245	3	1.065082	183.3969	1.44E-17
pH Level	1.045233	1	1.045233	179.9792	1.69E-13
Interaction	1.785702	3	0.595234	102.4936	8.76E-14
Within (Error)	0.139381	24	0.005808		
Total	6.165561	31			

Table 7b confirms that the type of environment has a statistically strong effect on mass retention ($F = 179.98$, $p < 0.0001$), which aligns with previous observations that aqueous conditions led to higher overall degradation rates compared to soil conditions across the study period. The strong interaction effect ($F = 102.5$) shows how differently each polymer behaved in the two environments. PLA and PHA lost almost all their mass in water at pH 9 but kept much more mass in soil, while PCL showed relatively little difference between the environments. This matches previous studies cited, which suggest that PCL is especially suited for degradation by soil microbes.

The results of this experiment align with findings in existing literature that suggest biodegradable plastics degrade at different rates depending on environmental conditions. PLA showed the highest degradation, averaging approximately 40–50% over the 22-week timeframe, with the most significant breakdown occurring in aqueous conditions at pH 9 under high heat. PCL degraded by approximately 30–40%, PHA by 20–30%, and PP exhibited the least degradation at 5–10%, as it served as the control and is a nonbiodegradable plastic. As shown in Figures 2 and 4, PLA exhibited the highest degradation rate in later weeks when exposed to elevated temperatures of 70°C and a pH of 9 in the baking soda condition, particularly in aqueous environments. PHA, which was expected to degrade efficiently in aqueous environments, showed significant degradation only after extended exposure, particularly after 22 weeks in baking soda and water-based conditions. This reinforces previous findings that PHA biodegrades in marine environments but often requires extended periods, ranging from months to years, to fully break down (Othman et al., 2022).

One major factor contributing to these observed differences is the chemical structure of the polymers, specifically the ratio of ester functional groups to carbon atoms within the polymer backbone. Ester bonds are chemically more prone to degradation than carbon–carbon bonds and serve as primary sites for degradation. Table 5 summarizes the ester-to-carbon ratios of the biodegradable plastics studied and their corresponding likelihood of degradation based on experimental observations.

Table 8:

Ester-to-Carbon Ratio and Degradation Behavior of Polymers

Polymer Type	Ratio of Ester Groups : Carbon Atoms	Relative Ratio	Observed Likeliness of Degradation
PLA	1 ester/ 3 Carbon atoms	High	High
PHA	1 ester/ 4 Carbon atoms	Moderate	Moderate
PCL	1 ester/ 6 Carbon atoms	Low	Low

As shown in Table 8, a higher ester-to-carbon ratio corresponds to a higher likelihood of degradation. PLA, which has the highest density of ester bonds, degraded the fastest across nearly all tested conditions. In contrast, PCL, with the lowest ester bond density, exhibited the slowest degradation, while PHA displayed intermediate behavior. This trend is consistent with the experimental results observed in both soil and aqueous environments.

Ester bonds act as structural weak points within polymer chains because they are more prone to chemical cleavage when exposed to external environmental factors such as heat, water, pH variation, and microbial activity. When these ester linkages are broken, the polymer chains undergo scission, resulting in reduced molecular weight, fragmentation, and eventual mass loss. Polymers with a higher concentration of ester bonds, such as PLA, contain more vulnerable sites along the backbone, making them more susceptible to

degradation. This explains why PLA degraded rapidly in this study, especially under high-temperature and alkaline conditions, where ester bond cleavage is accelerated.

The effectiveness of alkaline conditions compared to acidic conditions observed in this study can be explained by the chemical mechanisms of ester hydrolysis. In alkaline environments, such as the pH 9 baking soda condition, ester bonds are readily attacked by hydroxide ions (OH^-) through base-catalyzed hydrolysis. The hydroxide ion acts as a strong nucleophile, attacking the carbonyl carbon of the ester group, which leads to irreversible cleavage of the ester bond and permanent breakdown of the polymer chain. This process significantly accelerates degradation.

In contrast, acidic environments, such as the vinegar condition (pH 4), promote acid-catalyzed ester hydrolysis, where hydrogen ions (H^+) protonate the ester group and make it more reactive. However, this reaction proceeds more slowly and is reversible, requiring longer exposure times and higher temperatures to produce substantial degradation. As a result, alkaline conditions were consistently more effective at accelerating degradation than acidic conditions in this study.

The world is actively seeking sustainable and effective solutions for plastic waste disposal. While biodegradable plastics are often assumed to break down rapidly after disposal, research consistently shows that their degradation is highly dependent on external conditions (Grace, 2023). By showing that bio-based polymers fail to meet their expected degradation rates without specific conditions like high heat and alkaline-induced hydrolysis, this experiment helps address a critical gap in understanding. It reinforces that most of these materials still require a long time to break down even when placed in controlled conditions specifically designed to accelerate their degradation. Additionally, as observed in Figure 1, PCL exhibited degradation between weeks 2 and 4 but then plateaued and showed minimal further degradation under temperatures below 42°C, demonstrating its durability and resistance to environmental factors.

Several limitations may have influenced the results of this experiment. Notably, this study did not account for molecular weight or melting point, both of which play critical roles in polymer degradation behavior. PCL, for example, has a relatively low melting point (approximately 55°C) compared to the other plastics and therefore could not be subjected to higher temperatures for accelerated degradation. Additionally, polymers with higher molecular weights typically degrade more slowly due to increased chain entanglement and reduced mobility.

These findings also raise concerns regarding the long-term environmental impact of biodegradable plastics. While PHA's persistence can be beneficial for shelf life and storage, improper disposal may result in environmental accumulation rather than effective degradation. Studies have shown that biodegradable plastics can still generate microplastics or release methane during decomposition in landfills (Mushood, 2022). The increasing presence of microplastics in the food chain further emphasizes potential risks to human health. Although materials such as PLA show promise for reducing plastic waste, their real-world effectiveness remains limited by the specific conditions required for degradation.

This research highlights the need for further studies focused on optimizing biodegradable plastics for faster degradation without compromising performance. Future research should examine how molecular

weight, melting point, and crystallinity interact with ester bond density to influence degradation rates. Improved disposal strategies, such as advanced composting facilities and specialized recycling systems, are also essential to ensure that biodegradable plastics achieve their intended environmental benefits. Overall, while biodegradable plastics represent a promising alternative to conventional plastics, their success depends on balancing durability, degradation mechanisms, and proper waste management practices.

CONCLUSION

The results align with previous studies done showing that the degradation of biodegradable plastics depends on factors like temperature, pH, and bacteria. Research shows that PHA breaks down well in water, PLA requires high heat to degrade, and PCL is best suited for soil. Our experiment supported these findings, though PHA did not degrade as quickly as expected, showed breakdown after long periods of exposure to high heat, while PLA showed immediate results and began degrading quickly once exposed to sufficient heat, and PCL exhibited degradation mostly in soil environments. The differences in degradation rates observed in this study can be attributed to variations in polymer chemical structure, particularly the density of ester bonds, with higher ester-to-carbon ratios corresponding to faster degradation under heat and alkaline conditions

The results answer our original research questions as outlined below:

PLA exhibited the highest degradation rate in aqueous conditions, particularly when exposed to higher temperatures and pH of 9 (addition of baking soda), while PHA degraded the fastest in aqueous environments, especially in acidic and saline conditions. Since our environments were purposefully accelerated to imitate real-life conditions, the presence of bacteria and increased temperature significantly impacted degradation across all plastics. While the addition of probiotic bacteria increased degradation rates in this study, the same level of microbial activity is not guaranteed to occur in natural environments. Since bacteria similar to those in VSL#3 are more used to more controlled conditions, they may not function the same way in soil or water. As a result, the environmental benefits of biodegradable plastics can depend on whether suitable degrading microbes are present in different climates and ecosystems. This shows that biodegradable plastics are not a universal solution and need the right conditions to break down efficiently. By pinpointing these environmental triggers, this study bridges the gap between theoretical biodegradability and practical environmental impact, suggesting that the effectiveness of sustainable plastic alternatives may strongly depend on the specific infrastructure and ecosystem of their end-of-life disposal.

Addressing the plastic waste crisis requires a multifaceted approach, with several key efforts implemented in parallel. Research into the design of chemical structures that are more easily degradable by soil bacteria can enhance the effectiveness of biodegradable plastics. Additionally, education programs focused on teaching communities proper disposal techniques are essential for minimizing plastic pollution at the source. Investment in waste management infrastructure, particularly in collection and recycling systems,

can improve plastic recovery and reduce environmental contamination. Furthermore, increasing the use of reusable materials can significantly decrease reliance on single-use plastics, promoting long-term sustainability and reducing overall waste generation.

Our research is likely to be incorporated in the development of more sustainable use of biodegradable plastics for use in a variety of industries, particularly those relying on single-use plastics, such as packaging, food service, and medical applications. By identifying the environmental conditions that best promote biodegradation, manufacturers can modify the production and disposal methods of biodegradable plastics to improve their eco-friendliness and reduce their long-term environmental impact. Additionally, this research can contribute to guidelines for waste management practices and help determine which types of biodegradable plastics should be used in specific environments for the best degradation results.

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