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Investigation of the Biodegradability of Bio-Plastics Based on Polypropylene and Starch

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ABSTRACT

To address the environmental crisis caused by plastic accumulation, this study investigated the biodegradation potential of bio-based containers using indigenous microorganisms isolated and purified from plastic-contaminated sources. Two types of polymers were tested: pure polypropylene granules and starch-polypropylene based bioplastic. The biodegradation process was evaluated through visual observation, gravimetric analysis, field emission scanning electron microscope, Fourier transform infrared analysis, and thermogravimetric analysis. Results showed the indigenous bacterial strain Bacillus sp. achieved weight reductions of 4.73% for the granules and 7.1% for the bio-based product after 150 days of incubation. Fourier transform infrared analysis revealed significant surface oxidation, evidenced by the appearance of hydroxyl groups. The disappearance of methyl stretching and methylene asymmetrical stretching peaks indicated microbial carbon consumption. For the bio-based product, starch-related peaks at 713, 871, and 998 cm^{-1} disappeared, confirming the successful degradation of starch components. Thermogravimetric analysis results demonstrated a decrease in thermal stability for both polymer types, with weight loss beginning at 120°C for the granules and 150°C for the bio-based product. These findings highlight the effectiveness of indigenous microorganisms in biodegrading bioplastics, offering a targeted bioremediation approach to reduce persistent plastic waste.

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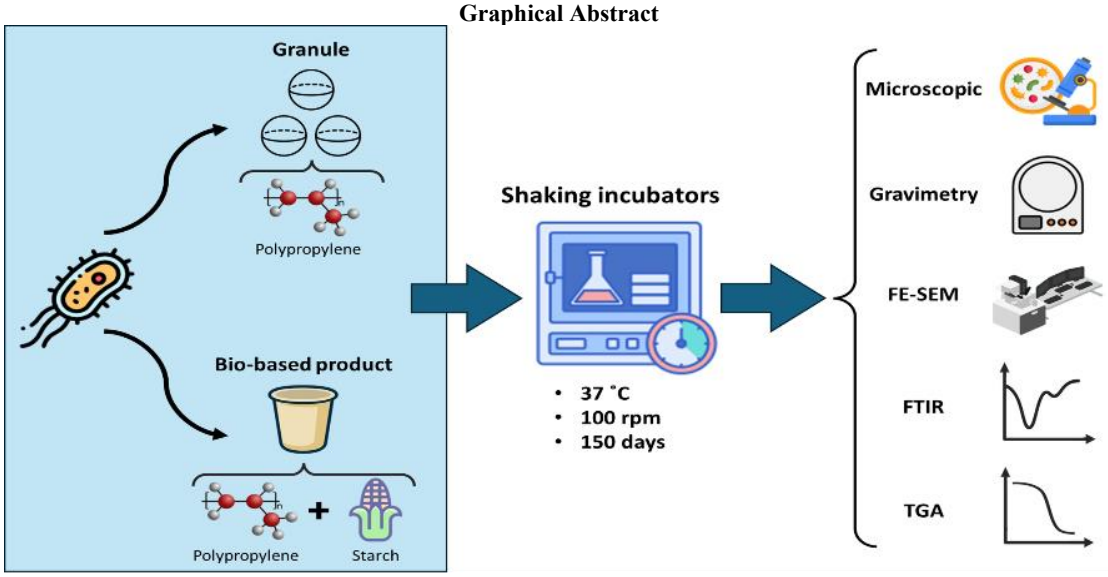
Graphical Abstract



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1. INTRODUCTION

In the era of living in the plastic age, plastic production has significantly increased over recent decades (1). Synthetic plastics are recognized as highly significant materials in all modern societies. This is due to their outstanding characteristics acquired over time, including low cost, durability, and high resistance, which stem from their polymeric structure, making plastics an integral part of all aspects of our daily lives (2, 3). According to official reports, a large portion of waste consists of plastic waste, of which only 19.5% is recycled, 25.5% is incinerated, and the remaining 55% persists in the environment or landfills (4). Furthermore, according to a United Nations report, annual plastic production is expected to reach approximately 800 million tons by 2035 and 1600 million tons by 2050 (5).

More than 50% of plastic waste present in the environment may consist of polyolefins. The degradation of polyolefins in nature is a very slow process, leading to their annual accumulation in the environment (6). Polyethylene (PE) and polypropylene (PP) are considered the most common plastic wastes found (7). One of the factors contributing to the slow degradation of plastics is the weak formation of biofilm or attachment of microorganisms to the surface of polypropylene, which is related to its hydrophobic nature, causing difficulties in their degradation (6). In addition to high hydrophobicity, polypropylene is composed solely of carbon and hydrogen elements and does not provide the necessary nutrients for long-term survival and growth, such as nitrogen, phosphorus, sodium, potassium, trace elements, amino acids, and others (8).

Polypropylene, due to its excellent properties, including exceptional mechanical characteristics, ease of manufacturing, and cost-effectiveness, has been widely used in applications ranging from disposable products to long-lasting durable items. Improvements in the transparency, strength, and durability of polypropylene production have led to a significant increase in its consumption (9). Polypropylene is a cost-effective polymer derived from propylene, one of the derivatives of oil refining. The dense and hydrophobic nature of polypropylene, combined with its high crystallinity, makes it resistant to microbial attack, as it is not easily accessible to enzymes produced by microorganisms. Consequently, polypropylene is considered to have low biodegradability and can persist in the environment for extended periods, contributing to the accumulation of plastic waste (10). This polymer, with a low density of 0.90 to 0.92 g/cm³, possesses a range of superior properties, including ease of processability, desirable hardness and mechanical strength, chemical resistance, and moisture resistance, which enable its use in various industries (11). Only a limited number of microorganisms, such as *Bacillus* sp., *Brevibacillus* sp., *Phanerochaete chrysoporium*, and *Rhodococcus* sp., have been reported to degrade polypropylene (12-14). Experimental studies have shown that plastic degradation by microorganisms begins within a few days to several weeks (12). Microorganisms that grow on plastic polymers initiate the biodegradation process by adhering to the polymer surface and forming a biofilm (15, 16).

Bioplastics are among the most innovative materials, considered to be bio-based and biodegradable (17). According to the definition of bioplastics, a polymer is classified as a bioplastic if it is either bio-based, biodegradable, or possesses both characteristics. Therefore, the use of the prefix "bio" does not necessarily imply that a plastic is biodegradable, which may lead to confusion (18). The global market size for bioplastics is expanding daily and is projected to reach US$ 20 billion by 2026. Asia remains the primary hub for production, supplying 46% of the total bioplastics produced worldwide, followed by Europe with 26%, North America with 17%, and South America with 10% (19). Bioplastics can be synthesized from natural organic materials such as polysaccharides, proteins, and lipids, but starch-based bioplastics are considered the most promising type due to their abundance in nature (20). Starch is regarded as one of the most promising biopolymers for producing edible films, and its cost-effectiveness enhances its appeal. Starch-based bioplastics exhibit mechanical properties and transparency comparable to traditional plastics (21). Starch-based bioplastics offer several advantages, including biodegradability and ease of processability, such as those derived from potato starch, corn starch, wheat starch, jackfruit seed starch, and cassava plant starch (17). Starch is a natural polymer extracted from plants and, due to its inherent properties and low cost, can be utilized for producing biodegradable plastics (22).

The biodegradation process of plastics refers to a process in which microbes or microbial communities are used to degrade plastics (23). In this process, the conversion of organic compounds into biogas and residual biomass occurs as a result of microbial activity, with microorganisms utilizing the plastic as a carbon source (24-28). The biodegradation of polymers is a slow process influenced by multiple factors. Some factors are related to the polymer itself, such as its composition, structural arrangement, carbon content, chain mobility, crystallinity, molecular weight, and the presence of plasticizers or additives. Other factors depend on environmental conditions, such as the efficiency of degradation by microorganisms and the optimal activity of enzymes. These conditions can be affected by variables such as humidity, temperature, pH, nutrients, electron acceptors/donors, salinity, oxygen, sunlight, water, copolymers, and the composition of the environment which are the key factors influencing the efficiency of the biodegradation process. By optimizing

these conditions, the efficiency and rate of biodegradation can be enhanced, ideally leading to the mineralization of persistent pollutants (29-33). Microbial growth and enzyme activity are key to biological degradation and are shaped by environmental conditions. Accordingly, Ghobadi Nejad et al. (34) reported that optimizing temperature and pH enhanced bacterial growth and enzyme production.

One of the studies in this field was conducted by Wichithem et al., where a strain of the bacterium *Streptomyces ardesiacus* NBI0111 was isolated from plastic-contaminated soil in Thailand. This strain was selected based on its ability to grow on a Bushnell-Haas medium containing 1% polypropylene. The study was conducted in two phases: laboratory and natural. In the laboratory phase, sterilized 1×1 cm polypropylene pieces were added to the culture medium, and after 90 days of incubation, a 17.52% weight reduction of the plastic was observed. FESEM images confirmed the presence of cracks, surface roughness, and surface degradation. FTIR and GC-MS analyses showed a reduction in the intensity of characteristic peaks and the formation of new O-H bonds, indicating degradation of the polymeric structure. This study demonstrated that indigenous strains, through growth, surface colonization, and enzyme secretion, are capable of degrading resistant polymers such as PP (35). In another study by Lu et al., researchers investigated the role of deep-sea bacteria of the genus *Pseudoalteromonas* in degrading polypropylene and polystyrene. These bacteria were initially enriched with plastic pieces over one year at a depth of 4700 meters in the western Pacific Ocean and then cultured in the laboratory at 15°C. Two strains, *Pseudoalteromonas lipolytica* and *P. tetraodonis*, were able to reduce the weight of polypropylene films by 2.3% and 1.8%, respectively, after 80 days (36).

In recent decades, numerous efforts have been made to develop biodegradable materials. One promising approach is the combination of synthetic polymers, such as polypropylene, with bio-based compounds like starch to enhance their biodegradability. Starch, as a natural, biocompatible, and cost-effective material, can act as a dispersed phase in the polypropylene matrix, creating conditions favorable for microbial activity. However, these modified composites still exhibit relative resistance to degradation and require further investigation to assess their degradation performance by indigenous microorganisms. Given the limited information available regarding the precise performance of these microorganisms in the biodegradation of bioplastic composites, the present study was designed to evaluate the ability of indigenous microbial species to degrade disposable containers made from a combination of polypropylene and starch. The significance of this study lies in its potential to provide a biocompatible solution for managing plastic waste, contribute to the development of indigenous technologies in the field of biorecycling, and take a step toward reducing the environmental hazards caused by plastics.

2. MATERIALS AND METHODS

In this study, two different types of polymer samples were used to investigate biodegradability. One type of sample consists of pure polypropylene granules, referred to in this study as "granules." The granule samples, with an initial weight of 0.15 g, were isolated and examined. The other type is a composite of polypropylene and starch. These samples were divided into sheet-like pieces in the form of 1×1 cm squares. The initial mass of each square piece was measured as 0.04 g, and in this study, these samples are referred to as the "bio-based product."

Bacterial sampling was conducted at the site of a factory producing plant-based containers made from polypropylene and starch, which are the samples examined in this experiment. This factory, named "Kimia Samaneh Sabz Co. (with the Amelon brand)," specializes in the production of bio-based disposable containers based on polypropylene and starch. To study indigenous bacteria, two general culture media, Nutrient Agar and Nutrient Broth, and mineral salt medium (MSM) were used. The MSM culture medium is a type of medium containing inorganic compounds (mineral salts) necessary for microbial growth but lacking organic carbon sources. This is to ensure that the bacteria utilize the carbon from the structure of the material targeted for degradation instead of the carbon present in the culture medium. The components of the specialized culture medium are presented in Table 1. After performing the preparation and enrichment stages for potential bacteria, adapting the bacteria to the environment containing polymer samples, and acclimating the microorganisms to the specialized culture medium, suitable indigenous bacteria were isolated and purified. Following the

TABLE 1. Components of Mineral Salts Medium Culture medium

Component	Concentration [g. L^{-1}]
NH_4NO_3	1
K_2HPO_4	1
KCl	0.15
$CaCl_2.2H_2O$	0.1
$MgSO_4.7H_2O$	0.2
Yeast extract	0.1
$FeSO_4.7H_2O$	0.001
$ZnSO_4.7H_2O$	0.001
$MnSO_4·7H_2O$	0.001

isolation and purification of the bacteria, the polymer samples were added to erlenmeyer flasks containing the bacteria and the MSM culture medium, and they were incubated for 150 days in a shaker incubator at 37˚C and 100 rpm.

Additionally, polymer samples were placed in Erlenmeyer flasks without bacteria to serve as control samples, allowing consideration of physical changes unrelated to bacterial activity, such as sample collisions with the flask walls, sample-to-sample collisions, and temperature effects. After 150 days, the samples were removed from the flasks. The samples were then placed in an oven at 80˚C for 24 hours to eliminate moisture and ensure complete drying. To thoroughly investigate the changes in the samples and the performance of the bacteria, macroscopic observations and various analyses, including gravimetric analysis, FESEM, FTIR, and TGA, were conducted on the granule and bio-based product samples. For FESEM analysis, after coating the samples with gold and placing them under high vacuum conditions at ambient temperature, imaging was performed at 1000x magnification and a 50 µm scale. For FTIR analysis, the samples were analyzed in the wavenumber range of 600 to 4000 cm^{-1}. TGA analysis was performed on both the granule and bio-based product sheet samples, subjected to heating at a rate of 20˚C per minute, with the temperature ranging from 40˚C to 800˚C.

3. RESULTS AND DISCUSSION

After performing the isolation and purification stages of the sample collected from the site, it was observed that only one bacterial strain was present in the initial sample. Following Gram staining, it was determined that this bacterium is a Gram-positive *bacillus*, with its microscopic image visible in Figure 1 and its characteristics presented in Table 2.

Bacterial biodegradation of bioplastics based on polypropylene and starch involves distinct mechanisms due to their differing chemical structures, where starch-based bioplastics are generally more readily biodegraded by bacteria, while PP requires specific microbial adaptations and often pretreatment to enhance degradation. For polypropylene (PP), initial oxidation occurs as bacteria such as *Bacillus cereus*, *Bacillus pasteurii*, and *Gordonia spp.* initiate PP degradation by oxidizing the polymer surface, introducing carbonyl, hydroxyl, and ester groups, with this often being the rate-limiting step as PP's hydrophobic, high-molecular-weight structure resists enzymatic attack (37-42). Enzymes are natural, green catalysts produced from sources such as fungi and bacteria, enabling more sustainable and cost-effective processes (43). Enzymatic action involves key enzymes including hydrolases, alkane hydroxylases, alcohol dehydrogenases, and cytochrome P450s, which break down oxidized PP into smaller oligomers (40, 44-46). Biofilm formation happens as bacteria form biofilms on PP surfaces, facilitating localized enzyme secretion and further polymer breakdown (37, 40, 41). Biofragmentation and mineralization follow as the fragmented oligomers are assimilated and mineralized to CO_2 and H_2O via microbial metabolic pathways (37, 44, 45). For starch-based bioplastics, rapid hydrolysis takes place as starch's hydrophilic and amorphous structure allows bacterial amylases and glycoside hydrolases to quickly hydrolyze glycosidic bonds, producing sugars that are readily metabolized (40, 47, 48). Sequential degradation occurs in blends (e.g., starch with PBAT or PLA), where starch is degraded first, followed by slower breakdown of the synthetic component (48, 49). Environmental factors such as temperature, moisture, and microbial diversity significantly influence degradation rates, with thermophilic conditions accelerating the process (48-50). In conclusion, bacterial biodegradation of starch-based bioplastics is efficient due to accessible hydrolytic pathways, while pure PP degradation is slower, requiring initial oxidation and specialized enzymes, and blending starch with PP or other polymers can enhance overall biodegradability, but the synthetic fraction remains the bottleneck, with environmental conditions and microbial

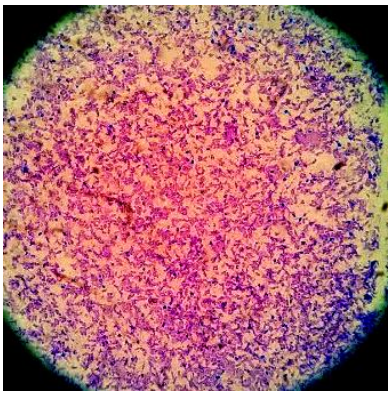

Figure 1. Microscopic image of purified indigenous bacteria

TABLE 2. Scientific classification of purified indigenous bacteria

Classification	***Bacillus* sp.**
Domain	*Bacteria*
Phylum	*Bacillota*
Class	*Bacilli*
Order	*Bacillales*
Family	*Bacillaceae*
Genus	*Bacillus*
Species	*Bacillus* sp.

community composition being critical for optimizing degradation.

3. 1. Macroscopic One of the initial indications of biodegradation of the samples by bacteria was the observation of microbial growth in the culture medium containing the polymer samples and bacteria, indicating that the microorganisms utilized the granules and the bio-based product as a carbon source. In this study, after the designated time intervals, the appearance of the samples visibly changed. Examinations revealed that due to the formation of a biofilm on and around the surface of the sample particles, these samples had settled at the bottom of the Erlenmeyer flasks. Notably, in the control samples, i.e., in the absence of bacteria, no sedimentation or biofilm formation was observed; thus, the presence of bacteria was a significant factor in the observed changes and biodegradation of the samples in this experiment. Another macroscopic observation was the high turbidity in the flasks containing bacteria compared to the control flasks. This turbidity can be attributed to two factors. The first is that the samples underwent degradation, and small fragments detached from them caused turbidity in the liquid medium. The second factor indicates bacterial growth and an increase in their population, which stems from their access to the necessary nutritional resources. Given the absence of carbon in the culture medium, this suggests that the bacteria utilized the carbon present in the polymeric bonds of the samples, leading to their degradation.

3. 2. Gravimetric One of the methods used to assess the extent of polymer degradation is to examine the weight changes of the samples compared to the initial samples. For this purpose, the weight of the granule and bio-based product samples, from which the biofilm had been removed and moisture eliminated, was measured using a balance. The dry weight of the samples and the percentage of weight reduction for each sample over the 150-day period are presented in Table 3. According to Table 3, the results indicate that the samples placed in the control environment, as expected, exhibited the least weight reduction, highlighting the significance of the presence of bacteria and their role in biodegradation. The slight weight reduction in the control environment may be attributed to physical factors such as abrasion of the samples against each other or against the flask walls, leading to the detachment of a small portion of the sample surface and consequently a reduction in their weight.

In contrast, the greatest weight reduction was observed in the bio-based product, which, from the perspective of gravimetric analysis, indicates higher biodegradability of this sample. This difference can be attributed to the presence of starch in the composition of the bio-based product, which increases the hydrophilicity of the sample, thereby enhancing its degradation.

TABLE 3. Gravimetric analysis results

Sample	Condition	Weight (g)	Weight loss (%)
Granule	Sample	0.15000	N/A
	Control	0.14950	0.31
	Indigenous bacteria	0.14440	4.73
Bio-based product	Sample	0.04000	N/A
	Control	0.03991	0.22
	Indigenous bacteria	0.03716	7.10

3. 3. Field Emission Scanning Electron Microscope (FESEM) In Figures 2 and 3, images of the surface of the granule and bio-based product samples, respectively, are presented. Each figure depicts the sample in the initial environment, control environment, and under biological degradation by the indigenous bacterial strain. Upon examination of the control samples, it is observed that in the control environment, which lacks bacteria, very minor changes, including the formation of some irregularities and small cavities in the polymer structure, have occurred. These changes may be due to the abrasion of samples against each other or their collision with the flask walls.

Figures 2.a.3 and 3.b.3 indicate that the samples subjected to biological degradation exhibit more significant surface structural changes compared to the initial and control samples, demonstrating an effective biodegradation process. Specifically, more and larger cavities are observed in the biologically degraded samples compared to the control and initial samples. When comparing the different types of samples, it can be claimed that the granule samples underwent less degradation than the bio-based product samples. This observation can be attributed to the presence of starch in the composition of the bio-based product samples compared to the granules. A similar phenomenon was also reported in a previous study by Wang et al., and Jeon et al. observed comparable results, noting that the PP microplastics treated with *Lysinibacillus* sp. showed similar outcomes (23, 51). Also, in the study by Anggiani et al., which investigated the degradation of polypropylene in contact with a bacterial consortium, it was observed that the control sample had minor surface changes, but cracks and holes were observed in the samples exposed to the bacterial consortium (52).

3. 4. Fourier Transform Infrared Spectroscopy (FTIR) The FTIR spectra for the initial granule samples, control samples, and those exposed to indigenous bacteria reveal key structural changes due to the influence of different environments. As shown in Figure 4, in the initial granule sample, characteristic peaks at 808 cm^{-1} (C-C stretching), 971 cm^{-1} (CH_3 rocking vibration), 1159 cm^{-1} (C-H wagging vibration),

1374 cm^{-1} and 1454 cm^{-1} (CH_3 symmetrical bending vibration), 2838 cm^{-1} and 2871 cm^{-1} (CH_3 stretching), 2913 cm^{-1}, and 2950 cm^{-1} (CH_2 asymmetrical stretching) indicate the primary structure of polypropylene. These findings are consistent with those reported in several other studies, , which also identify these peaks as characteristic of polypropylene structures (53). When comparing the control sample to the initial sample, slight

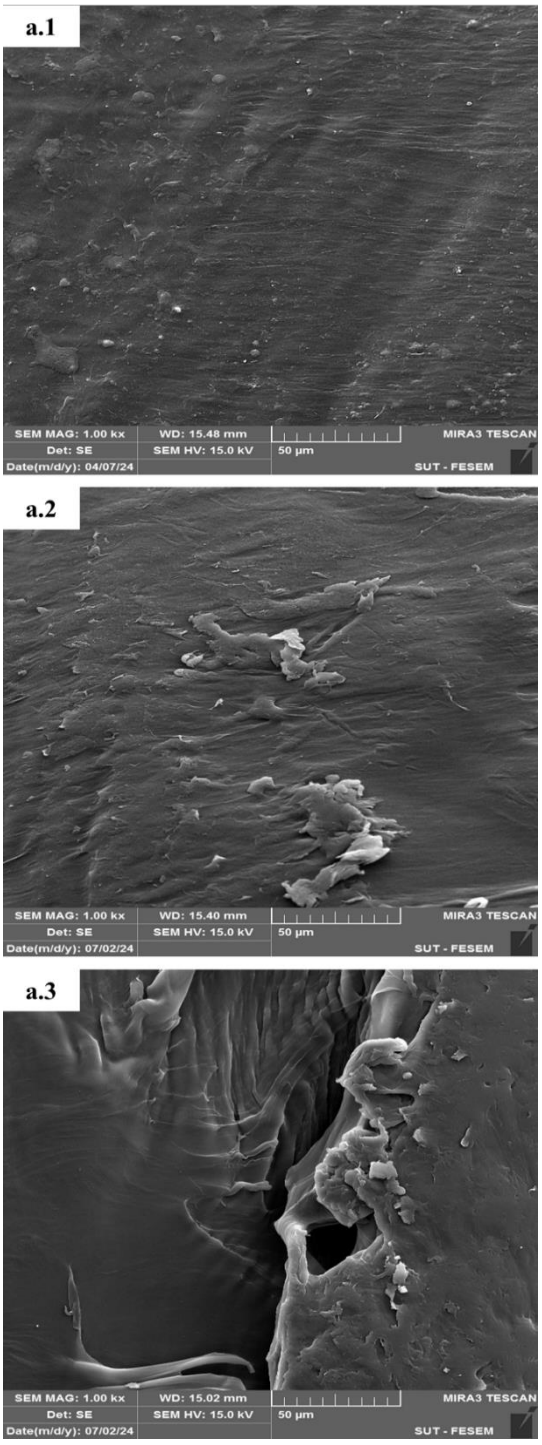

Figure 2. Field emission scanning electron microscope images of the granule at 1000x magnification: a.1, a.2, and a.3 sequentially represent the initial, control, and subjected to biodegradation by indigenous bacteria samples

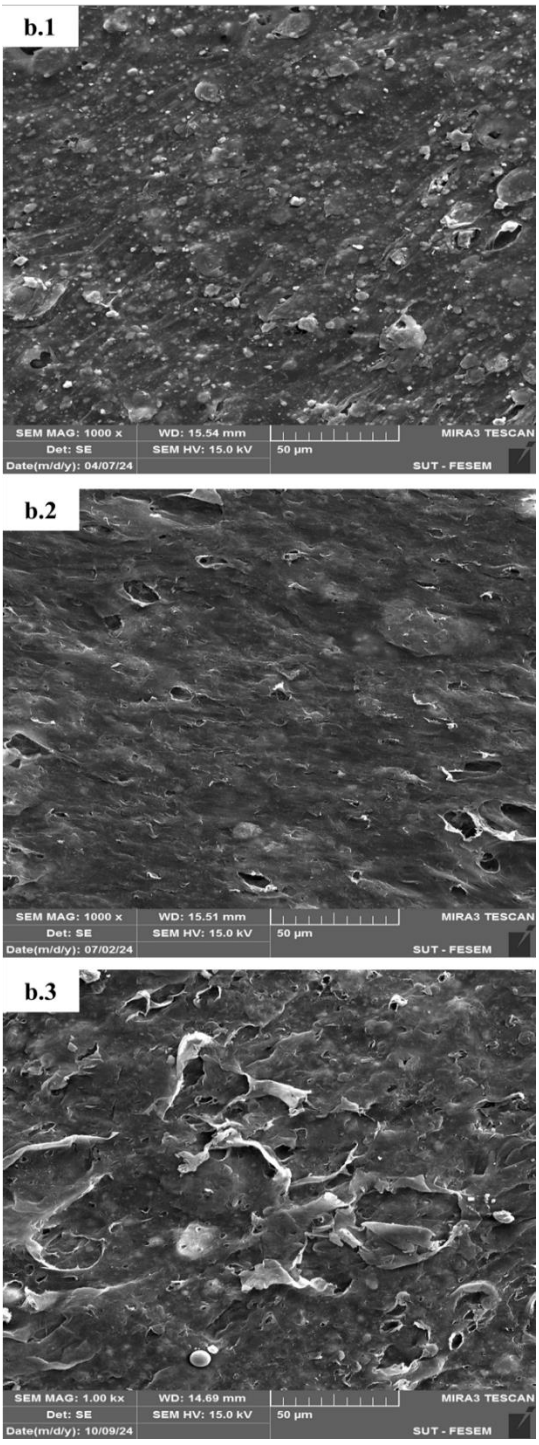

Figure 3. Field emission scanning electron microscope images of the bio-based product at 1000x magnification: b.1, b.2, and b.3 sequentially represent the initial, control, and subjected to biodegradation by indigenous bacteria samples

shifts and changes in peak positions are observed, suggesting that the control environment did not cause significant structural degradation in polypropylene. In the environment with indigenous bacteria, new intense peaks at 3425, 3521, 3637, and 3729 cm^{-1} emerged, indicating the presence of the hydroxyl (OH) functional group, which signifies strong oxidation of the samples and the progression of oxidative processes. This pattern aligns with previous studies, which also observed OH group formation at similar wavenumbers (35). These changes also report a shift in the sample surface from hydrophobic to hydrophilic, facilitating greater biofilm formation and, consequently, enhancing the biodegradability of the sample. Additionally, the previous peaks at 2834 to 2954 cm^{-1}, which represent CH_3 stretching and CH_2 asymmetrical stretching, disappeared, indicating bacterial activity and likely the consumption of carbon from these functional groups. Furthermore, the peaks at 1374 cm^{-1} (CH_2 methylene bending vibration) and 1454 cm^{-1} (CH_3 methyl bending vibration) were significantly weakened and disappeared after exposure to bacteria (54, 55). The observed changes indicated a progressive establishment and firm adherence of the microbial population onto the surface of the PP plastic, signifying increased colonization and biofilm formation. This trend, wherein the plastic-degrading community becomes more prominent over time, corroborates the findings reported by previous studies (56).

As shown in Figure 5, for the bio-based product samples, including those placed in control and indigenous environments, the control group exhibits no significant changes in peak intensity, as expected in a bacteria-free environment. Peaks around 713 cm^{-1} (CH out-of-plane vibration in starch), 871 cm^{-1} (CH rocking vibration), 998 cm^{-1} (C-O-C and OH bending in starch), 1157 cm^{-1} (C-H wagging vibration), and 1411 cm^{-1} (CH bending in starch or CH_3 symmetrical bending vibration) remain stable, indicating that the structure of the bio-based product is preserved in the absence of bacteria. The C-H stretching peaks at 2842, 2915, and 2950 cm^{-1}, corresponding to CH_3 stretching, CH_2 asymmetrical stretching, and CH_3 asymmetrical stretching in polypropylene, respectively, remain unchanged, confirming the material's stability. However, in the indigenous environment, most peaks related to starch have disappeared, indicating partial or complete consumption of this material during the process. The disappearance of functional groups at peaks 2842, 2915, and 2950 cm^{-1}, corresponding to CH_3 stretching, CH_2 asymmetrical stretching, and CH_3 asymmetrical stretching, respectively, suggests their consumption by bacteria (54, 55). Additionally, peaks at 3417, 3517, 3633, and 3722 cm^{-1} indicate the formation of hydroxyl (OH) groups, with peak intensity reflecting high oxidation in these environments and the transition of the sample surface from hydrophobic to hydrophilic (57). Regarding the FTIR peak in the range of 2850 to 3000 cm^{-1}, which corresponds to aliphatic CH stretching, it was observed that this peak disappeared after the samples were exposed to bacteria. This is consistent with findings from other investigations, where similar peak formation was observed after degradation. The biodegradation of starch-based nanocomposites showed comparable FTIR peaks, especially in the OH groups, indicating microbial activity. In these studies, the observed peaks are as follows: 1455 cm^{-1} due to the symmetric bending of CH_3, 2919 and 2953 cm^{-1} due to the asymmetric stretching of CH_2 and CH_3, and a broad band between 3000 and 3600 cm^{-1} due to OH groups linked by hydrogen bonding (58-60).

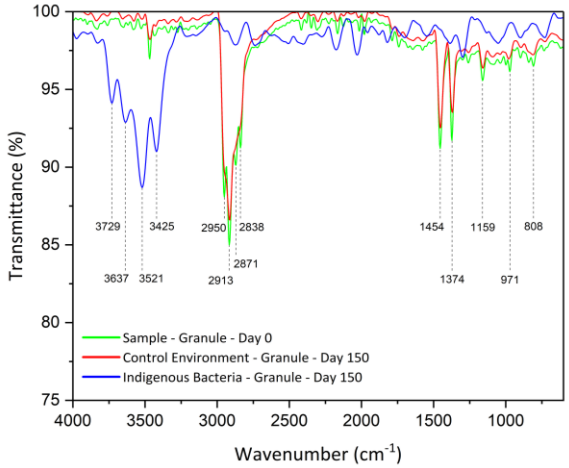

Figure 4. Fourier transform infrared analysis for the granule sample in initial, control, and indigenous bacterial biodegradation conditions

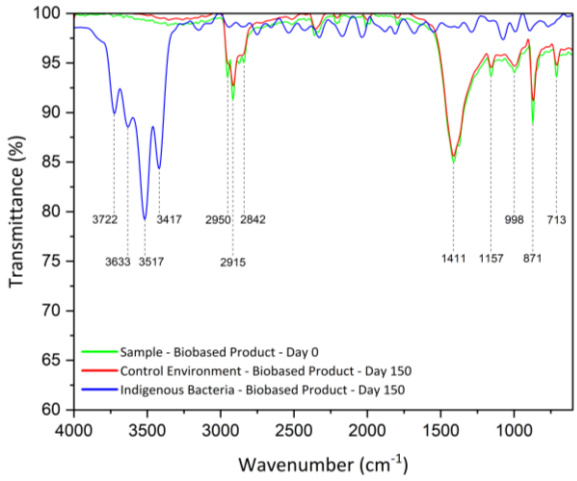

Figure 5. Fourier transform infrared analysis for the bio-based product sample in initial, control, and indigenous bacterial biodegradation conditions

3. 5. Thermogravimetric Analysis (TGA) TGA data for the granule sample reveal a clear difference in thermal stability between the control and indigenous bacterial environments. As shown in Figure 6, in the control environment, the granule sample exhibits excellent thermal stability, with negligible weight loss up to approximately 355°C. This indicates that the polymer maintains its structure in the absence of bacterial influence, retaining over 98% of its original weight up to this temperature. In the indigenous environment, the granule sample begins to lose weight at a lower temperature, suggesting that exposure to bacteria weakens the polymer structure. In the bacterial environment, the onset of thermal degradation is observed at approximately 120°C, earlier than in the control sample. At 460°C, the sample exposed to indigenous bacteria loses nearly all its weight, highlighting the impact of bacterial degradation on the polymer's thermal stability. It is likely that indigenous bacteria initiate hydrolysis or oxidation processes that destabilize the polymer chains, leading to earlier and more severe thermal degradation.

As depicted in Figure 7, in the control environment, the bio-based product remains stable up to approximately 280°C, where less than 3% weight loss is observed. The main degradation stage begins at 300°C, and by 800°C, approximately 70% of the material has degraded. In the indigenous environment, the bio-based product shows earlier degradation compared to the control sample, with weight loss starting at approximately 150°C. At 450°C, about 35% of the polymer has degraded, indicating that exposure to bacteria triggers the onset of polymer degradation, and by 800°C, approximately 80% of its weight is lost. A similar pattern of results was reported by Shiwei et al. (36).

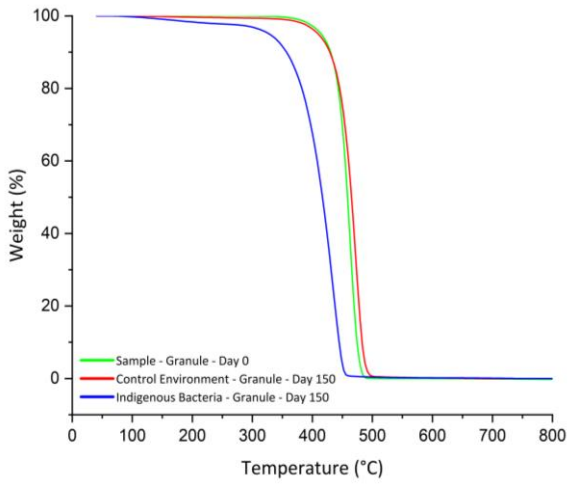

Figure 6. Thermogravimetric analysis for the granule sample in initial, control, and indigenous bacterial biodegradation conditions

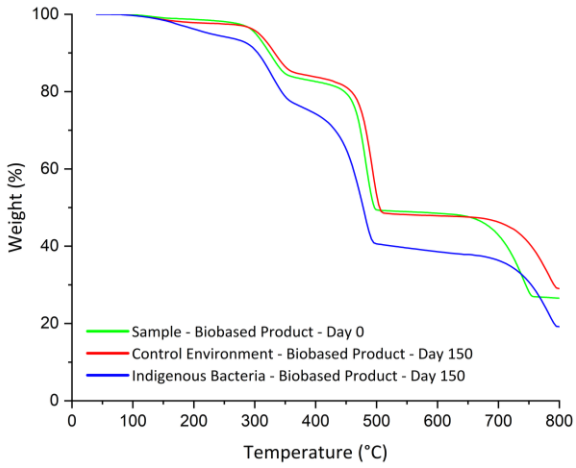

Figure 7. Thermogravimetric analysis for the bio-based product sample in initial, control, and indigenous bacterial biodegradation conditions

To compare the TGA analysis results from the previous studies, this evaluation can be approached from two distinct perspectives. From the first perspective, the analysis of each sample can be examined over time and under the influence of biological degradation. In this regard, the TGA analysis obtained exhibit complete concordance with the investigations by Jain et al. (61) and Pires et al. (62), wherein samples subjected to biological degradation display significantly weaker structural integrity and initiate weight loss at lower temperatures than the initial and control samples. This pattern continues throughout the analysis, and consequently, samples in contact with bacteria, achieve complete weight loss at lower temperatures relative to the initial and control samples. From another perspective, studies indicates that the weight loss profile for pure polypropylene proceeds uniformly (61, 62). In contrast, for bioplastic based on polypropylene and starch, the weight loss profile is non-uniform, featuring alterations during the degradation process. This variability arises because the bioplastic is not constituted from a single pure substance but rather from multiple components (polypropylene and starch), which commence thermal decomposition and weight loss at different temperatures and exhibit differential responses to thermal variations. These findings are fully consistent with the experimental results of the present study, and similar trends are observed with previous studies for the two different samples tested (53).

4. CONCLUSION

Analyses of bio-based product and granule samples showed high similarity between control and initial conditions, while samples in the control environment

differed from those exposed to indigenous bacteria, indicating no structural change in the control environment and bacterial degradation in the presence of bacteria. This study investigated the biodegradability of pure polypropylene and starch-polypropylene based bioplastic samples using control and indigenous bacterial environments. Samples were collected from a factory producing bio-based disposable containers, and a *Bacillus* sp. strain capable of degrading polypropylene was isolated. Over 150 days, bio-based product, due to their starch content, exhibited better performance in biological degradation, decomposing faster and reducing environmental pollution compared to pure polypropylene, thereby contributing to mitigating plastic accumulation in ecosystems, lowering the carbon footprint associated with persistent plastic waste, and supporting broader sustainability goals by decreasing reliance on non-degradable materials in everyday applications. FESEM analysis revealed more cracks, pits, and erosions on bio-based product surfaces than on granules, with bacterial environments showing significantly more severe surface changes than the control, which remained largely unchanged. FTIR analysis indicated reduced methyl bond peak intensity and hydroxyl bond formation in bacterially degraded samples, suggesting oxidation. TGA analysis showed lower thermal stability in bacteria-exposed samples, confirming structural degradation. These results highlight the potential for industrial scaling of microbial biodegradation processes, such as through the integration of bacterial consortia in bioreactors for efficient large-scale treatment of plastic waste in manufacturing and waste management facilities, potentially enabling cost-effective implementation in recycling plants and promoting circular economy practices. Future studies could explore *Bacillus* sp. metabolic pathways for polymer degradation and the impact of environmental factors like pH and temperature on degradation efficiency.

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Ethics Approval and Consent to Participate

This article does not involve any studies with human participants or animals performed by any of the authors. Therefore, ethics approval and consent to participate are not applicable.

Competing Interests

The author declares that there are no known financial or organizational conflicts of interest that could have influenced the work reported in this paper.

Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this manuscript, the author used ChatGPT exclusively for minor language editing and stylistic refinement to improve clarity and readability. The author carefully reviewed, revised, and approved the final content and takes full responsibility for the accuracy, integrity, and originality of the work.

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REFERENCES

1. Silva AL, Prata JC, Walker TR, Campos D, Duarte AC, Soares AM, Barcelo D, Rocha-Santos T. Rethinking and optimising plastic waste management under COVID-19 pandemic: Policy solutions based on redesign and reduction of single-use plastics and personal protective equipment. Science of the Total Environment, 2020;742:140565. https://doi.org/10.1016/j.scitotenv.2020.140565.
2. Ali SS, Elsamahy T, Koutra E, Kornaros M, El-Sheekh M, Abdelkarim EA, Zhu D, Sun J. Degradation of conventional plastic wastes in the environment: A review on current status of knowledge and future perspectives of disposal. Science of the Total Environment, 2021;771:144719. https://doi.org/10.1016/j.scitotenv.2020.144719.
3. Ru J, Huo Y, Yang Y. Microbial degradation and valorization of plastic wastes. Frontiers in Microbiology, 2020;11:442. https://doi.org/10.3389/fmicb.2020.00442.

4. Osman AI, Nasr M, Aniagor CO, Farghali M, Huang MM, Chin BL, Sun Z, Lock SS, Lopez-Maldonado EA, Yiin CL, Chinyelu CE. Synergistic technologies for a circular economy: upcycling waste plastics and biomass. Frontiers of Chemical Science and Engineering, 2025;19(1):2-15. https://doi.org/10.1007/s11705-024-2507-0.
5. Ali SS, Elsamahy T, Al-Tohamy R, Zhu D, Mahmoud YA, Koutra E, Metwally MA, Kornaros M, Sun J. Plastic wastes biodegradation: mechanisms, challenges and future prospects. Science of the Total Environment, 2021;780:146590. https://doi.org/10.1016/j.scitotenv.2021.146590.
6. Jeyakumar D, Chirsteen J, Doble M. Synergistic effects of pretreatment and blending on fungi mediated biodegradation of polypropylenes. Bioresource Technology, 2013;148:78-85. https://doi.org/10.1016/j.biortech.2013.08.074.
7. Pabortsava K, Lampitt RS. High concentrations of plastic hidden beneath the surface of the Atlantic Ocean. Nature Communications, 2020;11(1):4073. https://doi.org/10.1038/s41467-020-17932-9.
8. Yang SS, Ding MQ, He L, Zhang CH, Li QX, Xing DF, Cao GL, Zhao L, Ding J, Ren NQ, Wu WM. Biodegradation of polypropylene by yellow mealworms (Tenebrio molitor) and superworms (Zophobas atratus) via gut-microbe-dependent depolymerization. Science of the Total Environment, 2021;756:144087. https://doi.org/10.1016/j.scitotenv.2020.144087.
9. Jeon HJ, Kim MN. Isolation of mesophilic bacterium for biodegradation of polypropylene. International Biodeterioration and Biodegradation, 2016;115:244-49. https://doi.org/10.1016/j.ibiod.2016.08.025.
10. Bautista-Zamudio PA, Florez-Restrepo MA, Lopez-Legarda X, Monroy-Giraldo LC, Segura-Sanchez F. Biodegradation of plastics by white-rot fungi: A review. Science of the Total Environment, 2023;858:165950. https://doi.org/10.1016/j.scitotenv.2023.165950.
11. Wang S, Muiruri JK, Soo XY, Liu S, Thitsartarn W, Tan BH, Suwardi A, Li Z, Zhu Q, Loh XJ. Bio-polypropylene and polypropylene-based biocomposites: solutions for a sustainable future. Chemistry–An Asian Journal, 2023;18(2):e202200972. https://doi.org/10.1002/asia.202200972.
12. Auta HS, Emenike CU, Jayanthi B, Fauziah SH. Growth kinetics and biodeterioration of polypropylene microplastics by Bacillus sp. and Rhodococcus sp. isolated from mangrove sediment. Marine Pollution Bulletin, 2018;127:15-21. https://doi.org/10.1016/j.marpolbul.2017.11.036.
13. Skariyachan S, Patil AA, Shankar A, Manjunath M, Bachappanavar N, Kiran S. Enhanced polymer degradation of polyethylene and polypropylene by novel thermophilic consortia of Brevibacillus spp. and Aneurinibacillus sp. Polymer Degradation and Stability, 2018;149:52-68. https://doi.org/10.1016/j.polymdegradstab.2018.01.018.
14. Shimpi N, Borane M, Mishra S, Kadam M, Sonawane SS. Biodegradation of isotactic polypropylene/poly(lactic acid) and iPP/PLA/nano calcium carbonates using Phanerochaete chrysosporium. Advances in Polymer Technology, 2018;37(2):522-30. https://doi.org/10.1002/adv.21691.
15. Eich A, Mildenberger T, Laforsch C, Weber M. Biofilm and diatom succession on polyethylene and biodegradable plastic bags in two marine habitats. PLoS One, 2015;10(9):e0137201. https://doi.org/10.1371/journal.pone.0137201.
16. Sekhar VC, Nampoothiri KM, Mohan AJ, Nair NR, Bhaskar T, Pandey A. Microbial degradation of high impact polystyrene, an e-plastic with decabromodiphenyl oxide and antimony trioxide. Journal of Hazardous Materials, 2016;318:347-54. https://doi.org/10.1016/j.jhazmat.2016.07.008.
17. Anugrahwidya R, Armynah B, Tahir D. Bioplastics starch-based with additional fiber and nanoparticle: characteristics and biodegradation performance. Journal of Polymers and the Environment, 2021;29:3459-76. https://doi.org/10.1007/s10924-021-02152-z.
18. Lavagnolo MC, Poli V, Zampini AM, Grossule V. Biodegradability of bioplastics in different aquatic environments: a systematic review. Journal of Environmental Sciences, 2024;134:169-81. https://doi.org/10.1016/j.jes.2023.06.013.
19. Nanda S, Patra BR, Patel R, Bakos J, Dalai AK. Innovations in applications and prospects of bioplastics and biopolymers: a review. Environmental Chemistry Letters, 2022;20:379-95. https://doi.org/10.1007/s10311-021-01334-4.
20. Shafqat A, Tahir A, Mahmood A, Tabinda AB, Yasar A, Pugazhendhi A. Environmental significance of carbon footprints of starch-based bioplastics. Biocatalysis and Agricultural Biotechnology, 2020;27:101540. https://doi.org/10.1016/j.bcab.2020.101540.
21. Shahabi-Ghahfarrokhi I, Goudarzi V, Babaei-Ghazvini A. Production of starch-based biopolymer by green photochemical reaction for food packaging applications. International Journal of Biological Macromolecules, 2019;122:201-09. https://doi.org/10.1016/j.ijbiomac.2018.10.154.
22. Wahyuningtyas N, Suryanto H. Analysis of biodegradation of bioplastics made of cassava starch. Journal of Mechanical Engineering Science and Technology, 2017;1(1):24-31. https://doi.org/10.17977/um016v1i12017p024.
23. Jeon JM, Park SJ, Choi TR, Park JH, Yang YH, Yoon JJ. Biodegradation of polyethylene and polypropylene by Lysinibacillus species JJY0216. Polymer Degradation and Stability, 2021;191:109662. https://doi.org/10.1016/j.polymdegradstab.2021.109662.
24. Ali SS, Al-Tohamy R, Manni A, Luz FC, Elsamahy T, Sun J. Enhanced digestion of bio-pretreated sawdust using a novel bacterial consortium. Fuel, 2019;254:115597. https://doi.org/10.1016/j.fuel.2019.06.012.
25. Ali SS, Nessem AA, Sun J, Li X. Effects of water hyacinth pretreated digestate on Lupinus termis seedlings under salinity stress. Journal of Environmental Chemical Engineering, 2019;7(3):103159. https://doi.org/10.1016/j.jece.2019.103159.
26. Shah AA, Hasan F, Hameed A, Ahmed S. Biological degradation of plastics: a comprehensive review. Biotechnology Advances, 2008;26:246-65. https://doi.org/10.1016/j.biotechadv.2007.12.005.
27. Ali SS, Sun J. Effective thermal pretreatment of water hyacinth for enhancement of biomethanation. Journal of Environmental Chemical Engineering, 2019;7(1):102853. https://doi.org/10.1016/j.jece.2018.102853.
28. Magnin A, Pollet E, Phalip V, Averous L. Evaluation of biological degradation of polyurethanes. Biotechnology Advances, 2020;39:107457. https://doi.org/10.1016/j.biotechadv.2019.107457.
29. Priya A, Dutta K, Daverey A. Biotechnological and molecular insight into plastic degradation by microbial communities. Journal of Chemical Technology and Biotechnology, 2022;97:381-90. https://doi.org/10.1002/jctb.6675.
30. Siracusa V. Microbial degradation of synthetic biopolymers waste. Polymers, 2019;11(6):1066. https://doi.org/10.3390/polym11061066.
31. Li S, Yang Y, Yang S, Zheng H, Zheng Y, Nagarajan D, Varjani S, Chang JS. Recent advances in biodegradation of microplastics. Chemosphere, 2023;331:138776. https://doi.org/10.1016/j.chemosphere.2023.138776.
32. Stoleru E, Hitruc EG, Vasile C, Oprica L. Biodegradation of poly(lactic acid)/chitosan stratified composites by Phanerochaete chrysosporium. Polymer Degradation and Stability, 2017;143:118-29. https://doi.org/10.1016/j.polymdegradstab.2017.06.023.

33. Samadi A, Sharifi H, Ghobadi Nejad Z, Hasan-Zadeh A, Yaghmaei S. Biodegradation of 4-chlorobenzoic acid by Lysinibacillus macrolides DSM54T. International Journal of Environmental Research, 2020;14(2):145-54. https://doi.org/10.1007/s41742-020-00247-4.
34. Ghobadi Nejad Z, Yaghmaei S, Hajhosseini R. Production of extracellular protease by Bacillus licheniformis. Chemical Engineering Transactions, 2009;21:242-47. https://doi.org/10.3303/CET1021242.
35. Wichatham K, Piyaviriyakul P, Boontanon N, Surinkul N, Visvanathan C, Fujii S, Boontanon SK. Biodegradation of polypropylene plastics by Streptomyces sp. Environmental Technology & Innovation, 2024;35:103681. https://doi.org/10.1016/j.eti.2024.103681.
36. Lv S, Wang Q, Li Y, Gu L, Hu R, Chen Z, Shao Z. Biodegradation of polystyrene and polypropylene by deep-sea psychrophilic bacteria. Science of the Total Environment, 2024;948:174857. https://doi.org/10.1016/j.scitotenv.2024.174857.
37. Nyamjav I, Jang Y, Park N, Lee YE, Lee S. Physicochemical evidence of polypropylene biodegradation by Bacillus cereus from waxworm gut. Journal of Polymers and the Environment, 2023;31(10):4274-87. https://doi.org/10.1007/s10924-023-02878-y.
38. Wang Z, Li Y, Bai L, Hou C, Zheng C, Li W. Biodegradation of polypropylene microplastics by Bacillus pasteurii. Emerging Contaminants, 2025;11(1):100397. https://doi.org/10.1016/j.emcon.2024.100397.
39. He L, Ding J, Yang SS, Zang YN, Pang JW, Xing D, Zhang LY, Ren N, Wu WM. Molecular-weight-dependent degradation of polypropylene microplastics by mealworms. Environmental Science & Technology, 2024;58(15):6647-58. https://doi.org/10.1021/acs.est.3c06954.
40. Pawano O, Jenpuntarat N, Streit WR, Perez-Garcia P, Pongtharangkul T, Phinyocheep P, Thayanukul P, Euanorasetr J, Intra B. Metagenomic exploration of polypropylene-degrading enzymes from mangrove sediment. Frontiers in Microbiology, 2024;15:1347119. https://doi.org/10.3389/fmicb.2024.1347119.
41. Jeyavani J, Al-Ghanim KA, Govindarajan M, Nicoletti M, Malafaia G, Vaseeharan B. Bacterial screening for polypropylene microplastics biodegradation. Science of the Total Environment, 2024;918:170499. https://doi.org/10.1016/j.scitotenv.2024.170499.
42. Rana AK, Thakur MK, Saini AK, Mokhta SK, Moradi O, Rydzkowski T, Alsanie WF, Wang Q, Grammatikos S, Thakur VK. Recent developments in microbial degradation of polypropylene. Science of the Total Environment, 2022;826:154056. https://doi.org/10.1016/j.scitotenv.2022.154056.
43. Sadeghzadeh S, Ghazvini S, Hejazi S, Yaghmaei S, Ghobadi NZ. Immobilization of laccase from Trametes hirsuta onto CMC-coated magnetic nanoparticles. International Journal of Engineering, 2020;33(4):601-08. https://doi.org/10.5829/ije.2020.33.04a.01.
44. da Silva MR, Souza KS, Motteran F, de Araujo LC, Singh R, Bhadouria R, de Oliveira MB. Microplastic-degrading bacteria: a systematic review. Frontiers in Microbiology, 2024;15:1360844. https://doi.org/10.3389/fmicb.2024.1360844.
45. Lv S, Li Y, Zhao S, Shao Z. Biodegradation of typical plastics: microbial diversity and metabolic mechanisms. International Journal of Molecular Sciences, 2024;25(1):593. https://doi.org/10.3390/ijms25010593.
46. Zhu Y, Wang H, Bai J, Qi Y, Han D. Biodegradation potential of Gordonia spp. on polypropylene and polystyrene. Frontiers in Microbiology, 2025;16:1621498. https://doi.org/10.3389/fmicb.2025.1621498.
47. Eronen-Rasimus EL, Nakki PP, Kaartokallio HP. Degradation rates and bacterial communities of bioplastics in brackish marine environments. Environmental Science & Technology, 2022;56(22):15760-69. https://doi.org/10.1021/acs.est.2c06280.
48. Shafana Farveen M, Munoz R, Narayanan R, Garcia-Depraect O. Enhancing bioplastic degradation in anaerobic digestion. Polymers, 2025;17(13):1756. https://doi.org/10.3390/polym17131756.
49. Yu C, Dongsu B, Tao Z, Xintong J, Ming C, Siqi W, Zheng S, Yalei Z. Anaerobic co-digestion of commercial bioplastic bags with food waste. Science of the Total Environment, 2023;859:159967. https://doi.org/10.1016/j.scitotenv.2022.159967.
50. El Feky AR, Ismaiel M, Yilmaz M, Madkour FM, El Nemr A, Ibrahim HAH. Biodegradable plastic from chitosan with castor oil and starch. Scientific Reports, 2024;14(1):11161. https://doi.org/10.1038/s41598-024-61377-9.
51. Wang P, Zhao J, Ruan Y, Cai X, Li J, Zhang L, Huang H. Degradation of polypropylene by Pseudomonas aeruginosa strains. Journal of Polymers and the Environment, 2022;30(9):3949-58. https://doi.org/10.1007/s10924-022-02480-8.
52. Anggiani M, Kristanti RA, Hadibarata T, Kurniati TH, Shiddiq MA. Degradation of polypropylene microplastics by bacterial consortium. Water, Air, & Soil Pollution, 2024;235(5):308. https://doi.org/10.1007/s11270-024-07113-5.
53. Raee E, Kaffashi B. Biodegradable polypropylene/thermoplastic starch nanocomposites. Journal of Applied Polymer Science, 2018;135(4):45740. https://doi.org/10.1002/app.45740.
54. Fang J, Zhang L, Sutton D, Wang X, Lin T. Needleless melt-electrospinning of polypropylene nanofibres. Journal of Nanomaterials, 2012;2012:382639. https://doi.org/10.1155/2012/382639.
55. Abdullah AHD, Chalimah S, Primadona I, Hanantyo MHG. Physical and chemical properties of corn, cassava, and potato starches. IOP Conference Series: Earth and Environmental Science, 2018;160(1):012003. https://doi.org/10.1088/1755-1315/160/1/012003.
56. Park SY, Kim CG. Biodegradation of micro-polyethylene particles by bacterial colonization. Chemosphere, 2019;222:527-33. https://doi.org/10.1016/j.chemosphere.2019.01.159.
57. Sun Y, Zhang Y, Hao X, Zhang X, Ma Y, Niu Z. Degradation of additive-free polypropylene by Exiguobacterium marinum. Environmental Pollution, 2023;336:122390. https://doi.org/10.1016/j.envpol.2023.122390.
58. Schmitt H, Prashantha K, Soulestin J, Lacrampe MF, Krawczak P. Halloysite nanotubes/wheat starch nanocomposites. Carbohydrate Polymers, 2012;89(3):920-27. https://doi.org/10.1016/j.carbpol.2012.04.037.
59. Hanifi S, Oromiehie A, Ahmadi S, Farhadnejad H. Corn starch and montmorillonite nanocomposite-reinforced polypropylene. Journal of Vinyl and Additive Technology, 2014;20(1):16-23. https://doi.org/10.1002/vnl.21333.
60. Orue A, Corcuera MA, Pena C, Eceiza A, Arbelaiz A. Bionanocomposites based on thermoplastic starch and cellulose nanofibers. Journal of Thermoplastic Composite Materials, 2016;29(6):817-32. https://doi.org/10.1177/0892705714536424.
61. Jain K, Bhunia H, Sudhakara Reddy M. Degradation of polypropylene–poly-L-lactide blend by bacteria. Bioremediation Journal, 2018;22(3-4):73-90. https://doi.org/10.1080/10889868.2018.1516620.
62. Pires JP, Miranda GM, de Souza GL, Fraga F, da Silva Ramos A, de Araujo GE, Ligabue RA, Azevedo CM, Lourega RV, de Lima JE. Degradation of polypropylene in soil using an enzymatic additive. Iranian Polymer Journal, 2019;28(12):1045-55. https://doi.org/10.1007/s13726-019-00766-8.

Persian Abstract

چکیده

برای مقابله با بحران زیست‌محیطی ناشی از تجمع پلاستیک‌ها، در این مطالعه پتانسیل تجزیه‌زیستی ظروف زیست‌پایه با استفاده از میکروارگانیسم‌های بومی جداسازی و خالص‌سازی‌شده از منابع آلوده به پلاستیک مورد بررسی قرار گرفت؛ بدین منظور دو نوع پلیمر شامل گرانول پلی‌پروپیلن خالص و بیوپلاستیک بر پایه نشاسته–پلی‌پروپیلن انتخاب شدند و فرآیند تجزیه‌زیستی از طریق مشاهده ظاهری، آنالیز وزنی، میکروسکوپ الکترونی روبشی گسیل میدانی، طیف‌سنجی مادون قرمز تبدیل فوریه و آنالیز گرماوزنی ارزیابی شد. نتایج نشان داد سویه باکتریایی بومی *Bacillus* sp. پس از ۱۵۰ روز انکوباسیون، کاهش وزن معادل۴/۷۳٪ برای نمونه‌های گرانولی و ۷/۱٪ برای محصول زیست‌پایه ایجاد کرده است. طیف‌سنجی مادون قرمز تبدیل فوریه بیانگر اکسیداسیون قابل‌توجه سطحی با ظهور گروه‌های هیدروکسیل بود و حذف پیک‌های کشش متیل و کشش نامتقارن متیلن به مصرف کربن پلیمر توسط میکروارگانیسم‌ها نسبت داده شد؛ همچنین در محصول زیست‌پایه، ناپدید شدن پیک‌های مرتبط با نشاسته در ۷۱۳، ۸۷۱ و ۹۹۸ cm^{-1}، تجزیه موفق اجزای نشاسته‌ای را تأیید کرد. نتایج آنالیز گرماوزنی نیز کاهش پایداری حرارتی هر دو نوع پلیمر را نشان داد، به‌طوری‌که آغاز کاهش وزن برای نمونه‌های گرانولی در ۱۲۰ درجه سانتی‌گراد و برای محصول زیست‌پایه در ۱۵۰ درجه سانتی‌گراد مشاهده شد که در مجموع کارایی میکروارگانیسم بومی را در تجزیه‌زیستی بیوپلاستیک‌ها و ارائه رویکردی هدفمند برای زیست‌پالایی و کاهش پسماندهای پلاستیکی پایدار برجسته می‌سازد.