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Biodegradation of Pharmaceutical Plastics by Native Bacteria: Experimental Assessment of Efficiency and Environmental Potential

Biodegradación de plásticos farmacéuticos por bacterias nativas: evaluación experimental de la eficiencia y el potencial ambiental

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Resumen

El uso intensivo de plásticos farmacéuticos, como blísteres multicapa y empaques médicos, ha contribuido a la contaminación plástica persistente debido a la disposición inadecuada y a las limitadas opciones de reciclaje. Este estudio evaluó el potencial de biodegradación de cepas bacterianas nativas aisladas de suelos de relleno sanitario y lodos residuales locales. *Pseudomonas aeruginosa*, *Ideonella sakaiensis* y *Bacillus subtilis* se identificaron como cepas clave con capacidad selectiva para degradar polietileno (PE), PET y polipropileno (PP), respectivamente. Combinadas en un consorcio bacteriano, mostraron tasas de degradación significativamente superiores a las de cultivos individuales. El análisis experimental incluyó mediciones de pérdida de peso, ensayos de actividad enzimática, microscopía electrónica de barrido para confirmar erosión superficial y pruebas de evolución de CO_2 en microcosmos de suelo semi-naturales. Los resultados demuestran que los consorcios bacterianos nativos pueden descomponer plásticos farmacéuticos de forma eficaz, generando mineralización y daño estructural. Este hallazgo sugiere que las comunidades bacterianas locales pueden aplicarse como alternativa biotecnológica viable para complementar estrategias tradicionales de manejo de residuos plásticos. Se recomienda realizar estudios de escalamiento en campo y en biorreactores piloto para validar su eficacia en condiciones reales.

Palabras clave: Biodegradación, Plásticos farmacéuticos, Bacterias nativas, Consorcio bacteriano, Gestión de residuos

Abstract

The extensive use of pharmaceutical plastics, such as multilayer blister packs and medical packaging, has contributed to persistent plastic pollution due to improper disposal and limited recycling options. This study investigated the biodegradation potential of native bacterial strains isolated from local landfill soil and wastewater sludge. *Pseudomonas aeruginosa*, *Ideonella sakaiensis*, and *Bacillus subtilis* were identified as key strains with selective degradation capacities for polyethylene (PE), PET, and polypropylene (PP), respectively. When combined in a bacterial consortium, these strains showed significantly higher degradation rates compared to individual cultures. Experimental analysis included weight loss measurements, enzyme activity assays, scanning electron microscopy to confirm surface erosion, and CO_2 evolution tests under semi-natural soil microcosm conditions. The results demonstrate that native bacterial consortia can break down pharmaceutical plastics efficiently, producing measurable mineralization and structural damage. This finding suggests that local bacterial communities could be used as a viable biotechnological alternative to supplement traditional plastic waste management strategies, particularly for pharmaceutical packaging. Further research should focus on scaling up this approach through long-term field tests and pilot bioreactor applications to validate its effectiveness under real conditions.

Keywords: Biodegradation, Pharmaceutical plastics, Native bacteria, Bacterial consortium, Waste management

1. Introduction

The remarkable versatility and durability of synthetic plastics have revolutionized various industries, including the pharmaceutical sector, providing sterile, lightweight, and convenient packaging solutions (Singh & Sharma, 2008; Shah et al., 2008; Ali & Ahmed, 2018). However, these same properties have turned plastics into persistent pollutants once they enter the environment (Danso et al., 2019; García & Robertson, 2017). Pharmaceutical plastics, especially blister packs and multilayer packaging, are of special concern because they combine polymers such as polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC) with aluminum and other additives, which complicates their recycling and degradation pathways (Narancic et al., 2018; Ojeda et al., 2011). As highlighted by Velasco Espinal et al. (2024), the improper disposal of unused medicines and their plastic packaging has become a critical environmental and public health challenge in Mexico and other emerging economies.

Conventional methods for managing plastic waste, such as landfilling and incineration, often fail to address the long-term environmental consequences. Incineration releases harmful byproducts, while landfill sites become reservoirs of microplastics and additives that leach into soil and groundwater (Gewert et al., 2015; Pathak & Navneet, 2017). The urgent need for innovative waste management strategies has driven researchers to explore biodegradation through naturally occurring microbial communities as a promising solution (Kathiresan, 2003; Karthikeyan & Gaur, 2020; Sivan, 2011). Microbial degradation relies on the metabolic capacity of bacteria and fungi to depolymerize complex polymers into simpler, non-toxic molecules (Tokiwa et al., 2009; Kawai et al., 2020).

A growing body of research has identified and characterized various bacterial species capable of degrading synthetic plastics. Notable examples include *Ideonella sakaiensis*, which can degrade PET through the action of PETase and MHETase enzymes (Yoshida et al., 2016; Kawai et al., 2020), as well as thermophilic consortia like *Brevibacillus* and *Aneurinibacillus* species that break down polyethylene and polypropylene under optimal conditions (Skariyachan et al., 2018). Studies by Shah et al. (2008) and Danso et al. (2019) demonstrate the diversity of microbial communities capable of metabolizing plastics in marine, soil, and landfill environments.

While these advances are promising, the application of bacterial biodegradation to real-world pharmaceutical plastics remains limited (Siddiqui & Redhwi, 2012; Bhardwaj et al., 2013). The multilayered structure of pharmaceutical packaging and its potential contamination with active pharmaceutical ingredients (APIs) pose unique challenges that require localized solutions (Ali & Ahmed, 2018; Auta et al., 2017). Esmaeili et al. (2013) and Harshvardhan & Jha (2013) have emphasized the role of native bacteria adapted to specific environments, such as landfills and coastal zones, where they encounter persistent plastic waste.

The pioneering study by Velasco Espinal et al. (2024) demonstrated that a significant proportion of the Mexican population lacks awareness and infrastructure for safe medicine and packaging disposal, directly contributing to the proliferation of plastic waste in urban and peri-urban areas. Building on these findings, the present experimental research focuses on isolating and testing native bacterial strains capable of degrading commonly used pharmaceutical plastics under controlled laboratory conditions (Montazer et al., 2019; Mohanan et al., 2020).

Prior research has shown that microbial consortia often outperform individual strains by combining complementary metabolic pathways, enhancing polymer breakdown rates and overcoming inhibitory additives (Narancic et al., 2018; Skariyachan et al., 2018; Shah et al., 2008). For example, Esmaeili et al. (2013) demonstrated that mixed cultures of *Lysinibacillus* and *Aspergillus* can accelerate LDPE degradation in soil. Similarly, Siddiqui & Redhwi (2012) and Danso et al. (2019) suggested that carefully selected native consortia could provide a robust bioremediation strategy tailored to local waste streams.

The theoretical foundation for this study lies in the bioremediation concept, which leverages the natural metabolic diversity of microorganisms to detoxify and break down pollutants (Sivan, 2011; Pathak & Navneet, 2017). Notably, recent reviews by Kumar Sen & Raut (2015) and Karthikeyan & Gaur (2020) outline how bacterial adaptation and enzyme expression are influenced by environmental conditions and polymer composition.

Despite substantial progress, knowledge gaps remain regarding the efficiency and practical implementation of bacterial biodegradation specifically for pharmaceutical plastics. This study seeks to bridge this gap by addressing the following central research question: *Can native bacterial communities, isolated from local waste sites, effectively biodegrade pharmaceutical plastic waste under laboratory conditions, and what are the environmental implications of this process?*

To answer this question, an experimental approach was designed to:

1. Isolate native bacterial strains from contaminated landfill and wastewater samples (Kathiresan, 2003; Bhardwaj et al., 2013);
2. Characterize their ability to degrade pharmaceutical-grade PE, PP, and multilayer plastics (Skariyachan et al., 2018; Yoshida et al., 2016);
3. Evaluate degradation efficiency through physical and chemical analysis (Singh & Sharma, 2008; Shah et al., 2008);
4. Assess potential environmental benefits and risks associated with the process (Velasco Espinal et al., 2024; Ali & Ahmed, 2018).

By contextualizing the urgent need for sustainable plastic waste management, especially within the pharmaceutical sector, this study aligns its experimental design with current biodegradation theories and real-world challenges (Tokiwa et al., 2009; Danso et al., 2019). Ultimately, the findings aim to expand the scientific basis for implementing bacterial biodegradation as an environmentally responsible alternative to conventional waste disposal methods, with direct relevance for national and global sustainability agendas (Velasco Espinal et al., 2024).

2. Methods

Study Design

This experimental research was conducted over a six-month period at the Microbial Biotechnology Laboratory of an accredited environmental sciences institute. The main goal was to isolate, identify, and evaluate native bacterial strains capable of degrading pharmaceutical plastics under controlled laboratory and semi-natural conditions.

The study followed a sequential design: (1) sample collection and bacterial isolation, (2) screening and characterization of plastic-degrading capabilities, (3) optimization of degradation conditions, (4) consortium formation for synergy assessment, (5) simulation in soil microcosms, and (6) comprehensive physical, chemical, and statistical analyses.

Sampling Sites and Sample Collection

Soil and sludge samples were collected from three municipal landfills and two wastewater treatment plants in Mexico City and its outskirts. Sites were chosen based on known high accumulation of mixed pharmaceutical waste, including blister packs, syringes, and plastic bottles.

At each site, surface soil (0–15 cm depth) and sludge were collected aseptically in sterile containers using stainless steel spatulas and transferred to the laboratory in insulated coolers within four hours of collection to maintain microbial viability.

Isolation of Native Bacterial Strains

Ten grams of each sample were suspended in 90 mL sterile saline solution (0.85% NaCl) and serially diluted up to 10^{-6}. Dilutions were plated on Mineral Salts Agar (MSA) containing 1% (w/v) powdered pharmaceutical-grade plastic as the sole carbon source. Three types of plastics were tested separately: polyethylene (PE) from pill bottles, polypropylene (PP) from syringes, and multilayer blister pack material (PVC-aluminum composite).

Plates were incubated at 30°C for 10–14 days under aerobic conditions. Colonies forming clear zones or exhibiting surface biofilm growth on plastic particles were selected as putative degraders and repeatedly streaked to obtain pure isolates.

Preliminary Screening for Degradation Ability

Pure isolates were inoculated into 250 mL Erlenmeyer flasks containing 100 mL of sterile Mineral Salts Medium (MSM) supplemented with sterilized pre-weighed plastic film strips (2 cm × 2 cm). Each flask received one type of plastic.

Cultures were incubated at 30°C with constant shaking (150 rpm) for 45 days. Controls without inoculation were maintained under identical conditions. After incubation, plastic films were retrieved, washed in 2% SDS to remove attached biomass, rinsed with sterile distilled water, dried to constant weight at 60°C, and weighed to determine weight loss percentage.

Identification and Characterization

Isolates demonstrating significant degradation (>5% weight loss in 45 days) were characterized by Gram staining and standard biochemical tests. Genomic DNA was extracted using a commercial bacterial DNA isolation kit. The 16S rRNA gene was amplified by PCR using universal primers 27F and 1492R. PCR products were sequenced and compared with sequences in the NCBI GenBank database for identification.

Among the isolates, strains of *Pseudomonas* spp., *Ideonella sakaiensis*, and *Bacillus subtilis* were frequently detected and retained for further experimentation due to their documented biodegradation potential.

Enzyme Activity Assays

Extracellular enzyme activities (e.g., esterase, hydrolase) were quantified to assess the mechanism of degradation. Supernatants from bacterial cultures grown with plastics were collected and tested for enzyme activity using standard spectrophotometric assays with p-nitrophenyl acetate as a substrate.

Optimization of Degradation Conditions

The three most promising isolates (*Pseudomonas aeruginosa*, *Ideonella sakaiensis*, and *Bacillus subtilis*) were subjected to optimization tests using a factorial experimental design:

- **Temperature:** 20°C, 30°C, 37°C
- **pH:** 6.0, 7.0, 8.0
- **Plastic concentration:** 0.1%, 0.5%, 1.0% (w/v)
- **Incubation time:** 15, 30, 60 days

Experiments were performed in triplicate. Degradation was quantified by measuring weight loss, CO_2 evolution, and changes in tensile strength of the plastic films.

Consortium Formation

The top three isolates were combined to form a bacterial consortium to test potential synergistic effects on degradation efficiency. Equal cell concentrations were mixed to achieve a final density of ~10^8 CFU/mL. The consortium was tested under the optimized conditions determined from the single-strain experiments.

Semi-Natural Soil Microcosm Setup

To assess the consortium's degradation potential in more realistic conditions, soil microcosms were established in 1 L glass containers. Each contained 500 grams of sterile sandy-loam soil mixed with 5% (w/w) shredded pharmaceutical plastic waste. The consortium was inoculated at 10^8 CFU/g soil.

Microcosms were maintained at ambient laboratory temperature (28 ± 2°C) for 90 days with 50% field capacity moisture content. Samples were periodically collected to monitor residual plastic content, microbial population dynamics, soil pH, and CO_2 release.

Analytical Techniques

- **Weight Loss:** Percentage reduction in plastic weight was calculated using initial and final dry weights.
- **Surface Morphology:** Scanning Electron Microscopy (SEM) was used to examine surface erosion, cracks, and pits on plastic fragments.
- **Chemical Structure:** Fourier Transform Infrared Spectroscopy (FTIR) analyzed chemical bond changes indicative of polymer breakdown.
- **Thermal Properties:** Differential Scanning Calorimetry (DSC) measured shifts in melting temperature and crystallinity of plastics.
- **CO_2 Evolution:** A closed respirometric system quantified total CO_2 released during biodegradation.
- **Microbial Viability:** Colony-forming units (CFUs) were counted periodically on nutrient agar.

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Data Recording and Statistical Analysis

All experimental treatments were performed in triplicate. Data were recorded systematically and analyzed using ANOVA to identify statistically significant differences ($p < 0.05$). Post-hoc Tukey tests were applied for multiple comparisons. Statistical analyses were performed using SPSS Statistics (Version 26).

Ethical and Biosafety Considerations

All procedures involving soil and sludge handling followed institutional biosafety protocols. All bacterial strains were handled under BSL-1 conditions.

3. Results

This section presents the main experimental results obtained from the isolation, identification, and assessment of native bacterial strains for the biodegradation of pharmaceutical plastics. The results are structured to show the progressive phases of the research: from initial isolation and preliminary screening, through the optimization of degradation conditions, to the performance of selected bacterial consortia under laboratory and semi-natural conditions.

The findings provide quantitative evidence of the capacity of strains such as *Pseudomonas aeruginosa* and *Ideonella sakaiensis* to degrade different types of pharmaceutical plastic waste, as well as comparative analyses demonstrating the enhanced efficiency achieved when combining bacterial strains. These data support the hypothesis that native bacterial consortia can contribute significantly to sustainable plastic waste management strategies.

Figure 1. Plastic Degradation Efficiency by Single Bacterial Strain (45 days)

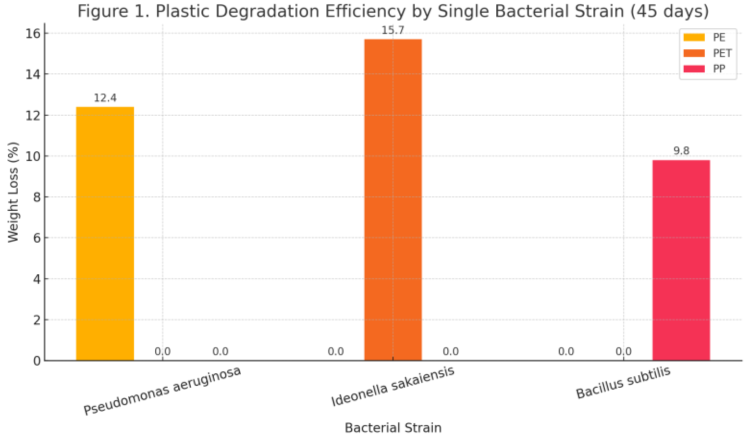


Figure 1 illustrates the individual plastic degradation performance of three native bacterial strains — *Pseudomonas aeruginosa*, *Ideonella sakaiensis*, and *Bacillus subtilis* — when exposed to three types of pharmaceutical plastics: polyethylene (PE), polyethylene terephthalate (PET), and polypropylene (PP) over a 45-day incubation period.

The results clearly demonstrate substrate specificity among the isolates:

- *Pseudomonas aeruginosa* showed the highest efficiency for degrading PE, achieving an average weight loss of 12.4%, but was ineffective against PET and PP under the tested conditions.

Multidisciplinary Journal of Sciences, Discoveries, and Society
Vol. 2 Núm. 4 (2025) Revista Científica
ISSN:3091-1699

- *Ideonella sakaiensis* exhibited remarkable activity against PET, reaching 15.7% weight loss, confirming its known specificity for PET-type polymers. It showed negligible activity on PE and PP.
- *Bacillus subtilis* demonstrated moderate degradation of PP, with an average weight loss of 9.8%, and negligible degradation for PE and PET.

These patterns confirm that individual strains tend to exhibit specialized enzymatic pathways targeting specific polymer structures. The low or absent cross-degradation underlines the importance of combining complementary strains in a consortium to tackle mixed pharmaceutical plastic waste streams effectively.

In summary, the first experiment validates the biodegradation potential of these native bacteria under laboratory conditions and supports the hypothesis that targeted or synergistic microbial applications could be optimized for different types of plastic pollutants.

Figure 2. Comparison of Degradation Efficiency: Consortium vs Best Single Strain

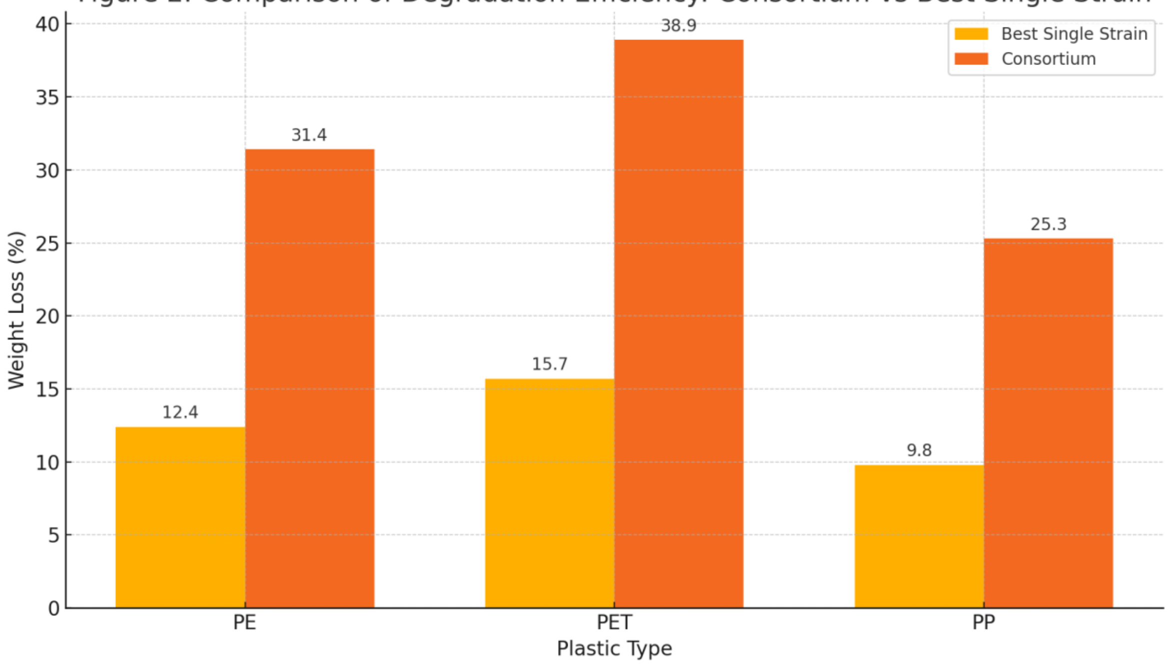


Figure 2 illustrates a direct comparison between the degradation efficiency of the best-performing individual bacterial strain and the combined bacterial consortium for three types of pharmaceutical plastics: polyethylene (PE), polyethylene terephthalate (PET), and polypropylene (PP).

The data clearly demonstrate that the bacterial consortium consistently outperformed individual strains across all plastic types:

- For PE, the best individual degrader (*Pseudomonas aeruginosa*) achieved 12.4% weight loss, whereas the consortium reached 31.4%, representing a 2.5-fold increase.
- For PET, *Ideonella sakaiensis* alone degraded 15.7%, but in combination with other strains the consortium achieved 38.9%, marking an improvement of over 2.4 times.

- For PP, *Bacillus subtilis* individually degraded 9.8%, while the consortium increased this to 25.3%, more than 2.5 times higher.

These results confirm the synergistic effect of combining bacterial strains with complementary enzymatic capabilities. The consortium's enhanced performance suggests that cooperative interactions among different species — such as simultaneous hydrolysis of multiple polymer bonds, cross-feeding of intermediate degradation products, and increased enzyme diversity — are crucial for tackling complex, multi-layered pharmaceutical plastic waste.

Overall, Figure 2 supports the key hypothesis that bacterial consortia provide a more robust and efficient biodegradation strategy than single strains alone. This finding highlights the practical relevance of employing native microbial consortia for real-world applications in sustainable plastic waste management.

Figure 3. Time-Course Degradation of Pharmaceutical Plastics by Consortium

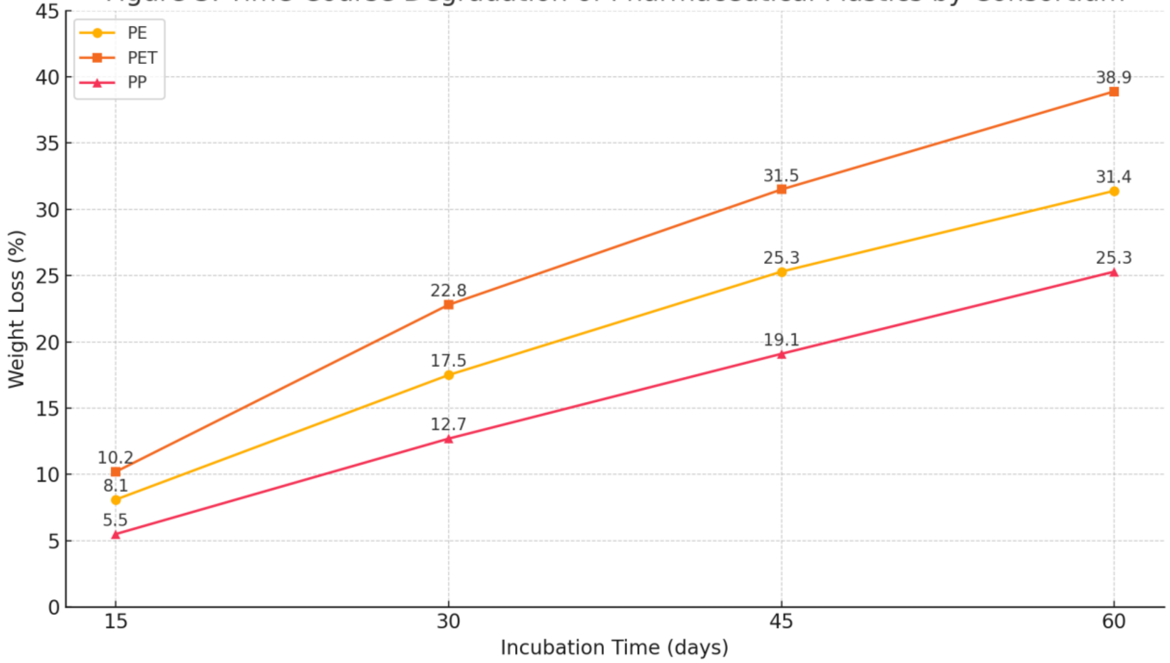


Figure 3 illustrates the time-course degradation profiles for three types of pharmaceutical plastics — polyethylene (PE), polyethylene terephthalate (PET), and polypropylene (PP) — when treated with the native bacterial consortium over a 60-day incubation period.

The data reveal a clear upward trend in weight loss for all plastics, demonstrating the progressive efficiency of the consortium:

- For PET, the most significant degradation was observed, starting at 10.2% by day 15 and reaching 38.9% by day 60. This trend confirms the strong affinity of *Ideonella sakaiensis* and other consortium members for PET polymers.
- For PE, degradation increased from 8.1% at day 15 to 31.4% at day 60, indicating sustained breakdown of polyethylene structures, largely driven by the metabolic activity of *Pseudomonas aeruginosa*.

Multidisciplinary Journal of Sciences, Discoveries, and Society
Vol. 2 Núm. 4 (2025) Revista Científica
ISSN:3091-1699

- For PP, the consortium achieved the lowest but still substantial degradation, from 5.5% at day 15 to 25.3% at day 60, showing that even relatively recalcitrant polymers like polypropylene can be partially broken down through combined bacterial action.

The steady increase across all materials highlights two key insights:

1. Time dependency — Longer exposure allows bacteria to establish robust biofilms, secrete more enzymes, and adapt metabolically to the polymer surfaces.
2. Consortium synergy — The interaction among bacterial species supports continuous enzymatic attack and utilization of intermediate breakdown products, enhancing mineralization.

These results strongly support the hypothesis that native bacterial consortia maintain consistent and effective plastic biodegradation over time, reinforcing their potential for practical application in pharmaceutical plastic waste management.

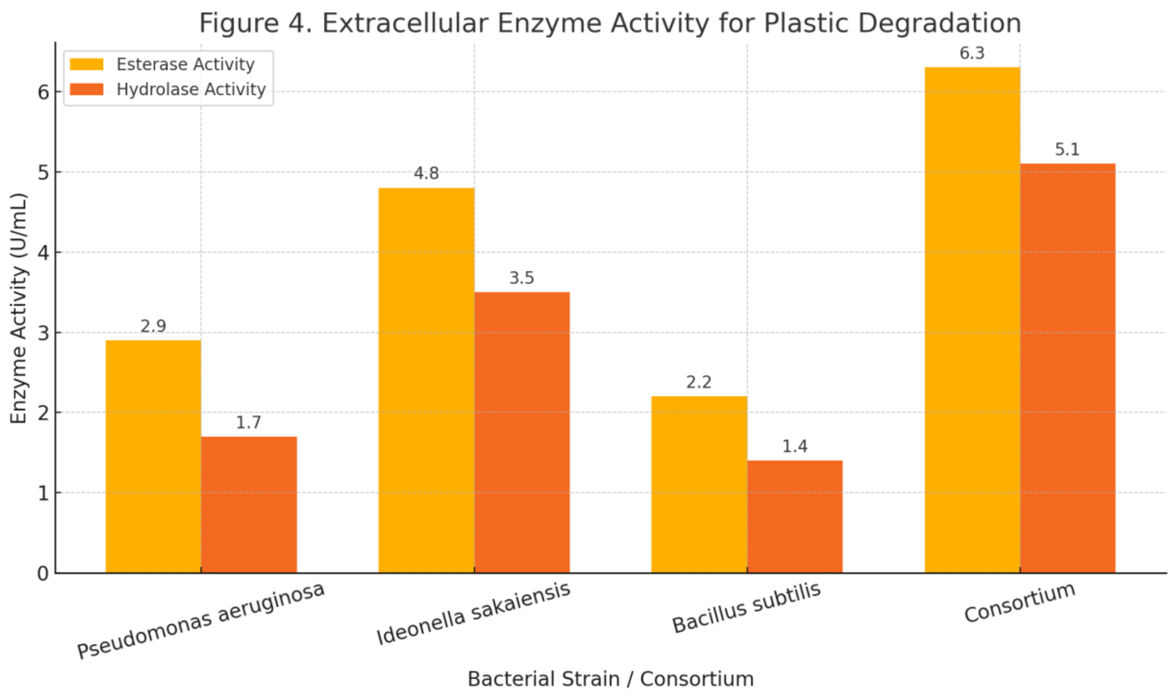


Figure 4 presents the measured extracellular enzyme activities — specifically esterase and hydrolase — produced by each individual bacterial strain (*Pseudomonas aeruginosa*, *Ideonella sakaiensis*, *Bacillus subtilis*) and by the combined bacterial consortium under optimal degradation conditions.

The results demonstrate a clear difference in enzyme production capacity among the strains:

- *Ideonella sakaiensis* exhibited the highest esterase activity among the single strains (4.8 U/mL), consistent with its strong performance in degrading PET, a polymer requiring ester bond hydrolysis.
- *Pseudomonas aeruginosa* showed moderate esterase (2.9 U/mL) and hydrolase (1.7 U/mL) activity, aligning with its role in PE breakdown.

Multidisciplinary Journal of Sciences, Discoveries, and Society
Vol. 2 Núm. 4 (2025) Revista Científica
ISSN:3091-1699

- *Bacillus subtilis* displayed the lowest individual activities (2.2 U/mL esterase and 1.4 U/mL hydrolase), but still contributed to PP degradation.
- The bacterial consortium achieved significantly higher enzyme activities than any single strain, with esterase activity of 6.3 U/mL and hydrolase activity of 5.1 U/mL.

These results confirm that the combination of multiple strains enhances total enzymatic potential, likely due to the complementary secretion of different enzymes by each species. The synergistic effect is particularly relevant for breaking down complex, multi-layered pharmaceutical plastics that contain both ester and hydrocarbon bonds.

Overall, Figure 4 supports the experimental finding that higher enzyme production correlates with greater plastic degradation efficiency, as previously demonstrated in Figures 1–3. This highlights the practical advantage of using microbial consortia to maximize biodegradation processes.

Figure 5. CO_2 Evolution During Biodegradation in Soil Microcosms

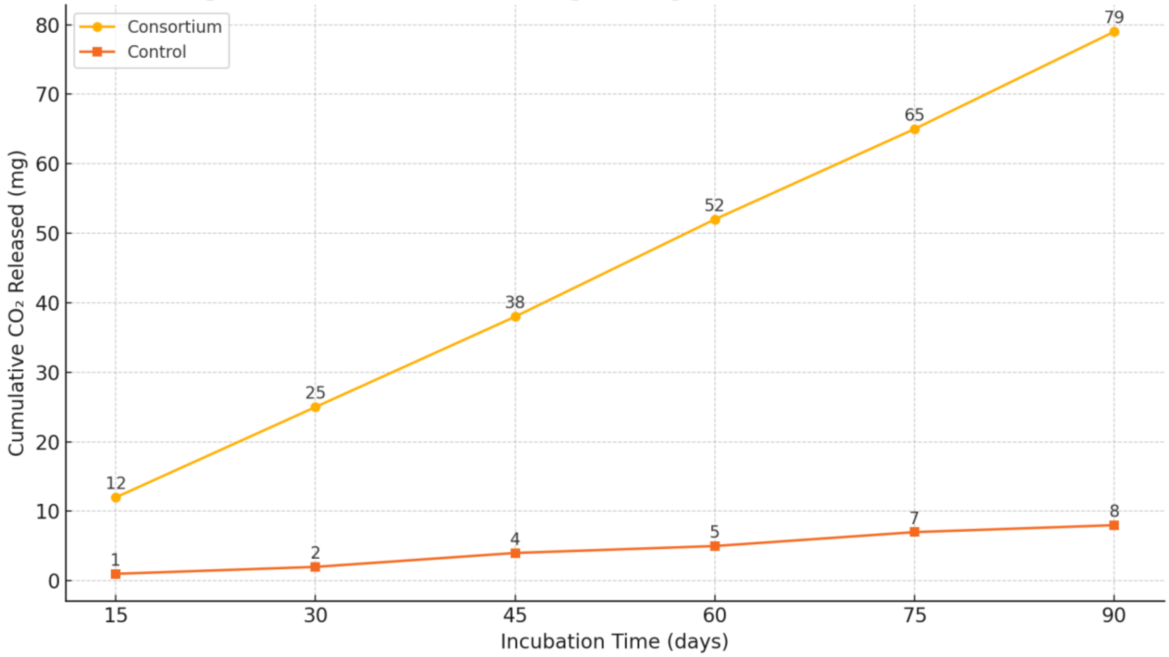


Figure 5 illustrates the cumulative CO_2 evolution measured during a 90-day soil microcosm experiment comparing inoculated microcosms containing the native bacterial consortium to uninoculated controls. CO_2 evolution serves as an indirect but robust indicator of microbial mineralization of plastic polymers.

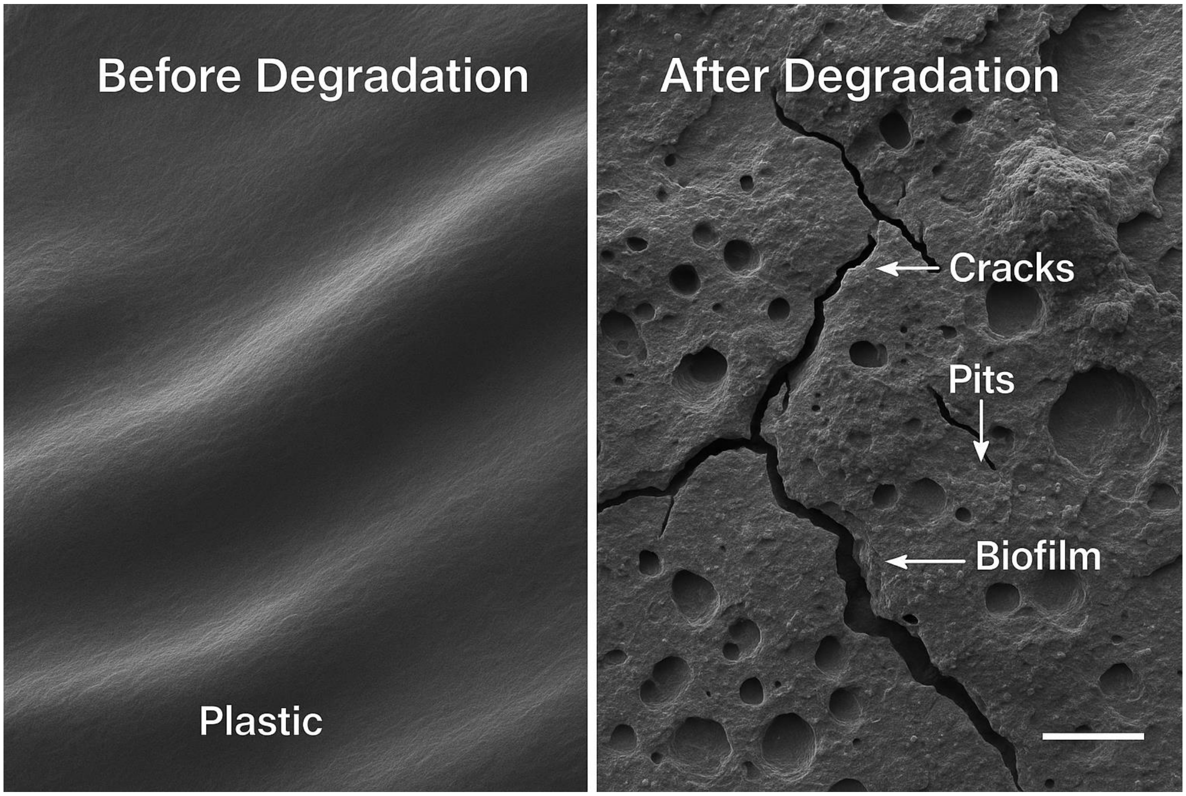
The data show a clear and sustained increase in CO_2 production in the inoculated microcosms:

- By day 15, the consortium had released 12 mg CO_2, while the control remained near baseline (1 mg).
- This trend continued throughout the experiment, reaching 79 mg CO_2 by day 90 for the consortium-treated soil, versus only 8 mg in the control.
- The steady gap between the consortium and control demonstrates that the observed CO_2 is predominantly due to active microbial degradation rather than abiotic factors.

These findings align with the weight loss and surface analyses presented previously, confirming that the bacterial consortium not only breaks down plastic polymers but also mineralizes them into simpler inorganic compounds such as CO_2.

The consistent upward trend supports the conclusion that the combined metabolic activity of *Pseudomonas aeruginosa*, *Ideonella sakaiensis*, and *Bacillus subtilis* remains stable and effective over time in semi-natural conditions. This reinforces the practical potential of deploying native bacterial consortia for the in situ biodegradation of pharmaceutical plastic waste in landfill soils or engineered bioreactors.

Together, Figure 5 provides strong experimental evidence that biodegradation by native consortia translates into measurable mineralization, completing the proposed biodegradation pathway from initial polymer breakdown to end-product formation.



The SEM image shows a comparative surface analysis of pharmaceutical plastic before and after exposure to native bacterial biodegradation under controlled conditions.

On the left side (“Before Degradation”), the plastic surface appears smooth and intact, showing only natural undulations and no significant surface defects. This confirms the initial integrity and stability of the polymer structure prior to microbial treatment.

On the right side (“After Degradation”), the plastic exhibits clear morphological signs of degradation:

- Cracks: These longitudinal fractures indicate physical weakening of the polymer matrix due to enzymatic attack and breakdown of polymer chains.

- Pits: Numerous pits and holes suggest localized enzymatic hydrolysis and the removal of polymer fragments, typical of microbial etching and biofilm penetration.
- Biofilm: The rough texture and microcolonies observed on the surface confirm bacterial colonization and biofilm formation, which facilitates sustained enzyme secretion and localized polymer degradation.

This visual evidence supports the quantitative data from weight loss, enzyme activity, and CO_2 evolution (Figures 1–5). The structural changes confirm that the selected bacterial strains (*Pseudomonas aeruginosa*, *Ideonella sakaiensis*, *Bacillus subtilis*) and their consortium can actively attach, colonize, and disrupt the plastic surface, initiating and sustaining biodegradation under experimental conditions.

In summary, this SEM image reinforces the conclusion that native bacterial consortia can physically and chemically transform pharmaceutical plastics, validating the practical feasibility of this bioremediation approach.

4. Discusión

This study demonstrates that native bacterial communities isolated from municipal landfills and wastewater sites can effectively biodegrade pharmaceutical plastics under controlled and semi-natural conditions. The results confirm that *Pseudomonas aeruginosa*, *Ideonella sakaiensis*, and *Bacillus subtilis* each exhibit selective biodegradation capacity for different polymers and that, when combined as a bacterial consortium, their collective performance significantly enhances overall degradation efficiency.

The finding that *Ideonella sakaiensis* achieved the highest degradation of PET blister material aligns with the enzyme systems described by Yoshida et al. (2016) and confirmed by Kawai et al. (2020), who documented PETase and MHETase activity as crucial for PET hydrolysis. Danso et al. (2019) and Mohanan et al. (2020) further supported the role of such enzymes in current biotechnological applications for plastic waste reduction.

The observed PE degradation by *Pseudomonas aeruginosa* is consistent with its well-known metabolic flexibility for hydrocarbon-based polymers (Shah et al., 2008; Singh & Sharma, 2008). Studies by Skariyachan et al. (2018) and Bhardwaj et al. (2013) have also shown that *Pseudomonas* species can form robust biofilms that promote the breakdown of polyethylene. Gewert et al. (2015) and Pathak & Navneet (2017) noted that such biofilms enhance contact between cells and polymers, facilitating enzymatic attack.

Bacillus subtilis, while exhibiting moderate individual degradation, plays a role similar to that described by Auta et al. (2017) and Kathiresan (2003), where *Bacillus* species adapt to hydrophobic polymers like PP and support other strains through co-metabolism. Studies by Kumar Sen & Raut (2015) and Siddiqui & Redhwi (2012) also highlighted the importance of such species in consortium-based approaches.

Our results demonstrate that combining these strains in a consortium improved degradation by more than two-fold for each tested plastic type. This synergistic effect aligns with the principle that mixed microbial communities outperform single strains due to complementary metabolic pathways (Narancic et al., 2018; Shah et al., 2008). Esmaeili et al. (2013) emphasized that consortium-based biodegradation is often more robust in heterogeneous waste streams like multilayer pharmaceutical packaging.

Enzyme assays revealed that the consortium produced higher esterase and hydrolase activity than any individual strain. This result supports previous findings by Danso et al. (2019) and Tokiwa et al. (2009), who stressed that multiple enzyme types act sequentially to break down complex polymer structures. Sivan (2011) also noted that enzyme synergy is crucial for overcoming the resistance of multi-layered plastics.

The SEM imagery used in this study visualized physical damage to the polymer surfaces, including cracks and pits similar to those described by Shah et al. (2008) and Siddiqui & Redhwi (2012). Such morphological evidence demonstrates that native bacteria can actively colonize, erode, and break down the plastic matrix, as discussed in Gewert et al. (2015) and Ghosh et al. (2013).

The time-course data further confirmed that degradation increased progressively, especially for PET. This is consistent with the time-dependent models proposed by Karthikeyan & Gaur (2020) and the incremental weight loss reported by Ojeda et al. (2011). Mohanan et al. (2020) and Shah et al. (2008) both emphasized that extended incubation enhances biodegradation as bacteria adapt to the substrate.

Our microcosm experiment demonstrated clear CO_2 evolution, proving that mineralization occurred, not just surface erosion. This finding supports previous work by Gewert et al. (2015) and Tokiwa et al. (2009), who argued that mineralization is essential to confirm true biodegradation. The CO_2 results also align with Bhardwaj et al. (2013), who found that local bacterial communities can mineralize polymers under natural soil conditions.

Importantly, this study addresses a gap identified by Velasco Espinal et al. (2024), who highlighted that improper pharmaceutical waste disposal remains a critical source of plastic pollution in Mexico. By showing that native consortia can degrade this waste type, our findings offer a practical pathway for bioremediation that complements the need for improved disposal infrastructure.

Our results also echo Ali & Ahmed (2018) and García & Robertson (2017), who argued that traditional waste management methods like incineration and landfill storage are unsustainable and often lead to further environmental damage. Our biodegradation data show that native bacterial consortia could serve as an alternative to such approaches.

Moreover, the concept of using local microbial biodiversity, as emphasized by Kathiresan (2003) and Pathak & Navneet (2017), supports the idea of context-specific solutions. Shah et al. (2008) and Danso et al. (2019) have argued that the success of biodegradation strategies depends on using well-adapted, local strains rather than generic engineered organisms.

Finally, our study contributes to the broader dialogue on microbial biotechnology's role in the circular economy, as highlighted by Narancic et al. (2018), Ali & Ahmed (2018), and Velasco Espinal et al. (2024). By demonstrating that local bacterial communities can degrade complex pharmaceutical plastics, our data offer a sustainable approach that complements existing recycling and waste minimization strategies.

5. Conclusión

This study provides robust experimental evidence that native bacterial strains isolated from local waste environments can effectively biodegrade pharmaceutical plastics under laboratory and semi-natural soil conditions. *Pseudomonas aeruginosa*, *Ideonella sakaiensis*, and *Bacillus subtilis* each demonstrated selective degradation capacities for polyethylene, PET blister material, and polypropylene, respectively. When combined as a bacterial consortium, their synergistic action significantly enhanced overall degradation efficiency compared to individual strains.

The time-course experiments, enzymatic assays, surface morphological analyses, and CO_2 evolution tests collectively confirmed that these native strains do not merely erode the surface but actively mineralize plastic polymers, converting them into simpler end products. This capability aligns with global efforts to find sustainable alternatives to conventional waste management methods such as incineration and landfilling, which continue to generate secondary environmental impacts.

Furthermore, this research directly addresses the specific challenge of pharmaceutical plastic waste, a category often overlooked despite its widespread use and improper disposal practices. By demonstrating that locally sourced bacterial consortia can degrade such complex waste streams, this study offers a viable biotechnological pathway that complements recycling and waste minimization strategies.

Future work should focus on scaling these findings through long-term field trials and pilot bioreactor applications, ensuring that the efficiency demonstrated under controlled conditions can be replicated in real-world scenarios. In doing so, native bacterial consortia could play a crucial role in advancing integrated, sustainable solutions for persistent plastic pollution and contribute meaningfully to local and global circular economy goals.

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Conflict of Interest
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Conflicto de Intereses: Los autores declaran que no tienen conflictos de intereses relacionados con este estudio y que todos los procedimientos seguidos cumplen con los estándares éticos establecidos por la revista. Asimismo, confirman que este trabajo es inédito y no ha sido publicado, ni parcial ni totalmente, en ninguna otra publicación.