Journal Publication of International Research for Engineering and Management (JOIREM)
Volume: 04 Issue: 03 | Mar-2026
ISSN (O) 3107-6696

Microbial and Enzymatic Degradation of Polylactic Acid (PLA) and Related Polyesters: Molecular Mechanisms, Marine Environmental Dynamics, and Biotechnological Innovations

Siya Saji[1], Prannesh U R[2], Divya R[3], Umavathy R[4] & A M Ramachandran[5]

[1,2]Post Graduate Student, [3,4] Under Graduate Student, [5] Associate Professor
Department of Microbiology, Dr. N.G.P. Arts and Science College,
Coimbatore-641 048, Tamil Nadu, India.
**Corresponding Author: siyasajisisiram@gmail.com*

Abstract- Polylactic acid (PLA) is one of the most commercially used biodegradable polymers produced from renewable biomass sources. Even though PLA can be composted under controlled industrial conditions. Still, it persists in marine and natural environments, continues to cause environmental concern. This review examines the microbial and enzymatic pathways responsible for the degradation of PLA and related polyester, focusing on the structural biology of polyester hydrolases, thermophilic depolymerases, marine microbial ecology, degradation kinetics, and strategies in recombinant enzyme development. Advanced analytical techniques, metagenomic screening platforms, and protein engineering approaches are examined to bridge laboratory insights with real-world biodegradation outcomes. The review synthesizes findings from over fifteen peer-reviewed sources and identifies future directions for sustainable polymer management.

Keywords: Polylactic acid, polyester hydrolase, marine biodegradation, thermophilic depolymerase, protein engineering, microbial biotechnology.

1. Introduction

Current figures place with annual plastic production now reaching 390 million metric tons, the world faces a mounting crisis of over 6.3-billion-ton mark **[Geyer et al.,2017].** Biodegradable polymers like PLA have been developed as sustainable alternatives due to their renewable sources and compostability nature **[Auras et al., 2010].** Even though, it is biodegradable in nature, degradation efficiency is highly environment-dependent and it varies substantially in response to shifting environmental factors. While industrial composting uses high temperature to trigger rapid hydrolysis, thus resulting in slow degradation due to the cold and a scarcity of useful microbes. **[Tokiwa & Calabia, 2006].**

2. Chemical Structure, Crystallinity, and Physicochemical Determinants

Poly Lactic Acid is an aliphatic thermoplastic biopolymer produced by chemically linking lactide molecules through ring-opening polymerization. The degradation characterization of PLA is influenced by many factors including stereochemistry [L- and D- isomers], molecular weight distribution, and physicochemical properties like glass transition temperature (~60°C), and surface morphology **[Drumright et al., 2000].** Crystalline regions limit enzyme accessibility, while amorphous regions are more sensitive to degradation **[Karamanlioglu et al., 2017].** Whereas, composting conditions facilitate bulk erosion throughout the polymer's structure and more sensitive to the hydrolytic degradation of PLA in seawater remains largely confined to the surface.

3. Microbial Ecology of Polyester Degradation

Microbial degradation is initiated with surface colonization and develops a stable biofilm. Bacteria and fungi secrete enzymes that target and break ester linkages into oligomers and monomers **[Shah et al., 2008].** Common bacteria like *Bacillus, Pseudomonas, Thermus, and actinomycetes* have the natural ability to polyester-degradation **[Tokiwa & Calabia, 2009].** In Marine environments, microbial activity is reduced at lower metabolic rates due to temperature limitations, this results the delay in initiation of measurable degradation.

4. Polyester Hydrolases: Structure–Function Relationships

Most polyester hydrolases typically belong to the α/β-hydrolase fold family and which usually classify Ser–His–Asp catalytic triad **[Wei & Zimmermann, 2017].** Structural studies shows that substrate-binding grooves are uniquely tailored to the dimensions of the polymer chain. Mutagenesis studies show that even minor alterations in active-site residues can drastically influence catalytic turnover. By using

directed evolution, it has further pushed these limits successfully in enhancing thermostability and substrate affinity **[Arnold, 1998; Austin et al., 2018].**

5. Thermophilic Depolymerases and Industrial Relevance

Thermophilic enzymes work optimally at or above the glass transition temperature of PLA, where taking merit of the increased mobility in the polymer chains **[Jarerat et al., 2006]**. The high catalytic efficiency at 50–70°C range, enzymes align perfectly for the industrial composting and bioreactor-based recycling strategies. Thermostability is driven from increased salt bridges and hydrogen bonding networks create a particularly resilient and compact tertiary structures.

6. Polyhydroxyalkanoate Depolymerases as Model Systems

PHA depolymerases serves as a mechanistic groundwork for understanding the polyester breakdown pathways **[Jendrossek & Handrick, 2002]**. These extracellular enzymes start by surface erosion, releasing 3-hydroxybutyrate monomers for microbial assimilation. Comparing these two types of enzymes which highlights the structural analysis between PHA depolymerases and PLA hydrolases for conserved catalytic motifs.

7. Recombinant Production and Enzyme Engineering

Recombinant expression in Escherichia coli serves as an efficient platform for producing large quantities of enzymes that breakdown polyester **[Madison & Huisman, 1999].** Purification is done through affinity chromatography that facilitates kinetic characterization. Strategic tools like directed evolution and computational modeling specifically improve catalytic efficiency, substrate binding, and thermostability [Arnold, 1998]. Immobilized enzyme systems serve as critical strategy to shield enzymes from degradation by enhancing operational stability for industrial deployment.

8. Enzymatic Hydrolysis Mechanism and Kinetics

Hydrolysis occurs in two stages: first, via nucleophilic attack by the enzyme's active-site serine acts as a ester carbonyl carbon, forming an acyl-enzyme intermediate followed by hydrolytic cleavage **[Wei & Zimmermann, 2017]**. The enzyme's performance defined by its binding affinity (Km) and turnover rate (Vmax) is not fixed constant according to polymer crystallinity and molecular weight. By applying Arrhenius-based models reveals that strong temperature dependence of reaction rates.

9. Marine Environmental Modeling

Marine degradation is shaped by many factors like salinity, UV radiation, microbial diversity, and hydrodynamic conditions **[Karamanlioglu & Robson, 2013].** They typically rely on first-order kinetic models to commonly applied to describe mass loss over time. However, field studies show that there is a persistent tension between our experimental predictions and the outcomes actually observed in real world marine environments.

10. Analytical and Characterization Techniques

FTIR spectroscopy identifies the chemical signature of ester bond cleavage, DSC monitors shifts in crystallinity while, GPC tracks molecular weight reduction respectively. These internal changes are further done by SEM imaging, which provides a visual record of soil erosion examines surface erosion **[Shah et al., 2008]**. CO_2 evolution remains a benchmark for quantifying mineralization, offering a quantitative bridge between theoretical biodegradation and the actual carbon turnover observed in the system. High throughput genomic and transcriptomic tools now act as a functional mapping of the marine microbiome, uncovering the diverse array of genes which perform to breaking down the complex polymers.

11. Environmental and Ecotoxicological Considerations

When degradation is incomplete, it can contribute to microplastic **[Song et al., 2017].** Life cycle studies remind us that it's true environmental impact depends on proper waste management infrastructure **[Auras et al., 2010].** As PLA degrades physically, the long-term biological 'cost' of its chemical byproduct in the ocean remains a critical unknown.

12. Future Research Directions

The integration of Metagenomic and meta transcriptomic analysis can provide a high-resolution map of the marine enzymatic landscape from uncultured marine microbes. Synthetic biology has transformed our ability to construct or to assemble engineered microbial consortia with the specific metabolic machinery needed to tackle the most persistent plastic bond. The future of material science lies in the synergy of digital protein engineering and ecological modelling, allowing us to test the biodegradability efficiency of new polymers in a virtual ocean before a single molecule is even developed.

13. Conclusion

Polylactic acid (PLA) represents a significant shift in polymer engineering, providing a scalable pathway to reduce our reliance on persistent, petroleum-derived synthetics. While

frequently categorized as a straightforward solution, PLA exhibits a nuanced degradation behavior that shifts significantly when transitioned from controlled composting to the erratic conditions of the open ocean. There is a stark contrast between the optimized heat of a compost facility and the stagnant reality of the sea. In industrial settings, heat acts as a catalyst that 'softens' the material, but in the frigid open ocean, that thermal spark is missing leaving microbial populations to struggle against a polymer that remains stubbornly locked in its glassy state. The enhanced performance of thermophilic catalysts highlights a critical design principle: the development of next-generation bioplastics must couple polymer chemistry with enzyme optimization to ensure that the material is physically accessible when the biological 'attack' begins. Bridging the gap between the lab and the ocean is a task of translation. We are taking the 'quiet logic' of the benchtop and asking it to perform in the 'loud complexity' of the natural world. A sustainable future requires this dual-lens perspective: where we use the power of computational design not to ignore the environment, but to finally, accurately, and honestly meet its demands. Only by subjecting our innovations to the erratic demands of the natural world can we ensure that we are truly reducing the ecological burden on our planet's most vulnerable habitats.
The transition from a lab-grown theory to a reliable environmental tool is our greatest collaborative challenge.

References

1.Arnold, F. H. (1998). Design by directed evolution. Accounts of Chemical Research, 31(3), 125–131. https://doi.org/10.1021/ar960017f

2. Auras, R., Harte, B., & Selke, S. (2010). An overview of polylactides as packaging materials. Macromolecular Bioscience, 4(9), 835–864. https://doi.org/10.1002/mabi.200400043

3. Austin, H. P., Allen, M. D., Donohoe, B. S., Rorrer, N. A., Kearns, F. L., Silveira, R. L., Pollard, B. C., Dominick, G., Duman, R., El Omari, K., Mykhaylyk, V., Wagner, A., Mikes, W. E., Woodcock, H. L., Abranches, B. L., Hoyt, G. T., Sun, J.-L., Beckham, G. T., & McGeehan, J. E. (2018). Characterization and engineering of a plastic-degrading aromatic polyesterase. *Proceedings of the National Academy of Sciences*, *115*(19), E4350–E4357. https://doi.org/10.1073/pnas.1718804115

4.Drumright, R. E., Gruber, P. R., & Henton, D. E. (2000). Polylactic acid technology. Advanced Materials, 12(23), 141–1846. https://doi.org/10.1002/1521-4095(200012)12:23%3C1841::AID-ADMA1841%3E3.0.CO;2-E

5.Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. Science Advances, 3(7), e1700782. https://doi.org/10.1126/sciadv.1700782

6. Jarerat, A., Tokiwa, Y., & Tanaka, H. (2006). Poly(L-lactide)-degrading activity in actinomycetes. *Applied and Environmental Microbiology*, *72*(3), 1933–1938. https://doi.org/10.1128/AEM.72.3.1933-1938.2006

7.Jendrossek, D., & Handrick, R. (2002). Microbial degradation of polyhydroxyalkanoates. Annual Review of Microbiology, 56, 403–432. https://doi.org/10.1146/annurev.micro.56.012302.160838
Cited by: 911

8.Karamanlioglu, M., & Robson, G. D. (2013). The influence of biotic and abiotic factors on PLA degradation. Polymer Degradation and Stability, 98(9), 1821–1827. https://doi.org/10.1016/j.polymdegradstab.2013.05.019

9.Karamanlioglu, M., Preziosi, R., & Robson, G. D. (2017). Abiotic and biotic degradation of PLA. Polymer Degradation and Stability, 137, 122–130. https://doi.org/10.1016/j.polymdegradstab.2017.01.009

10.Madison, L. L., & Huisman, G. W. (1999). Metabolic engineering of polyhydroxyalkanoates. Microbiology and Molecular Biology Reviews, 63(1), 21–53. https://doi.org/10.1128/mmbr.63.1.21-53.1999

11.Shah, A. A., Hasan, F., Hameed, A., & Ahmed, S. (2008). Biological degradation of plastics. Biotechnology Advances, 26(3), 246–265. https://doi.org/10.1016/j.biotechadv.2007.12.005

12. Song, Y. K., Hong, S. H., Jang, M., Han, G. M., Jung, S. W., & Shim, W. J. (2017). Combined effects of UV exposure duration and mechanical abrasion on microplastic fragmentation by polymer type. *Environmental Science & Technology*, *51*(8), 4368–4376. https://doi.org/10.1021/acs.est.6b06155

13. Tokiwa, Y., & Calabia, B. P. (2006). Biodegradability and biodegradation of poly(lactide). *Applied Microbiology and Biotechnology*, *72*(2), 244–251. https://doi.org/10.1007/s00253-006-0488-1

14. Tokiwa, Y., Calabia, B. P., Ugwu, C. U., & Aiba, S. (2009). Biodegradability of plastics. *International Journal of Molecular Sciences*, *10*(9), 3722–3742. https://doi.org/10.3390/ijms10093722

15. Urbanek, A. K., Rymowicz, W., & Mirończuk, A. M. (2018). Degradation of plastics and plastic-degrading bacteria in cold marine habitats. *Applied Microbiology and Biotechnology*, *102*(18), 7669–7678. https://doi.org/10.1007/s00253-018-9195-y

16. Wei, R., & Zimmermann, W. (2017). Microbial enzymes for the recycling of post-consumer polyethylene terephthalate (PET) *Microbial Biotechnology*, *10*(6), 1308–1322. https://doi.org/10.1111/1751-7915.12761

17. Narancic, T., & O'Connor, K. E. (2019). Plastic waste as a feedstock for biotechnology. *Microbial Biotechnology*, *12*(1), 20–22. https://doi.org/10.1111/1751-7915.13351

18. Zumstein, M. T., Schintlmeister, A., Nelson, T. F., Baumgartner, R., Woebken, D., Wagner, M., Kohler, H. P. E., McNeill, K., & Sander, M. (2018). Biodegradation of a synthetic polymer in marine sediments. *Environmental Science & Technology*, *52*(11), 6353–6361. https://doi.org/10.1021/acs.est.8b01336.

19. Jem, K. J., & Tan, B. (2020). The development and challenges of poly(lactic acid) and poly (glycolic acid). *Advanced Industrial and Engineering Polymer Research*, *3*(2), 60–70. https://doi.org/10.1016/j.aiepr.2020.01.002

20. Urbanek, A. K., Rymowicz, W., & Mirończuk, A. M. (2020). Degradation of poly (lactic acid): A review of the relevant plant and microbial enzymes, industrial additives and crystallization agents. *Polymers*, *12*(9), 2015. https://doi.org/10.3390/polym12092015

21. Qi, X., Ren, Y., & Wang, X. (2017). New advances in the biodegradation of Poly (lactic acid). *Green Chemistry*, *19*(21), 1521–1535. https://doi.org/10.1039/C7GC00014F

22. Tokiwa, Y., & Calabia, B. P. (2006). Biodegradability of plastics. *International Journal of Molecular Sciences*, *7*(9), 372–385. https://doi.org/10.3390/i7090372

23. Varma, I. K., Albertsson, A. C., Rajkhowa, R., & Srivastava, R. K. (2005). Enzyme-catalyzed synthesis of polyesters. *Progress in Polymer Science*, *30*(10), 949–981. https://doi.org/10.1016/j.progpolymsci.2005.06.010

24. Jalani, J. C., & Arshad, Z. I. (2022). PLA degradation and PLA-degrading bacteria. *Key Engineering Materials*, *932*, 103–110. https://doi.org/10.4028/p-6r7z6p

25. Xu, H., Sang, Z., Lan, T., Zhuang, W., Wu, J., & Guo, J. (2022). Microbial degradation of poly(lactic acid): A review. *Journal of Hazardous Materials*, *421*, 126728. https://doi.org/10.1016/j.jhazmat.2021.126728

26. Mistry, P., Patel, M., & Desai, K. (2022). Biodegradation of poly(lactic acid) by mixed microbial consortia: A review of current status and future perspectives. *Applied Microbiology and Biotechnology*, *106*(1), 123–135. https://doi.org/10.1007/s00253-021-11714-x

27. Pellis, A., Cantone, S., Ebert, C., & Gardossi, L. (2016). Evolving sustainability of enzymatic synthesis of polyesters: From basic research to strategic development. *Trends in Biotechnology*, *34*(4), 316–328. https://doi.org/10.1016/j.tibtech.2015.12.009

28. Kim, M. N., Lee, A. R., Yoon, J. S., & Chin, I. J. (2007). Biodegradation of poly (lactic acid) by a newly isolated-mixed culture. *Polymer Degradation and Stability*, *92*(2), 280–284. https://doi.org/10.1016/j.polymdegradstab.2006.10.013

29. Herrero Acero, E., Ribitsch, D., Dellacher, A., Zitzenbacher, S., Marold, A., Steinkellner, G., ... & Guebitz, G. M. (2013). Surface engineering of a cutinase from *Thermobifida cellulosilytica* for improved adsorption and hydrolysis of poly(ethylene terephthalate). *Biotechnology and Bioengineering*, *110*(10), 2581–2590. https://doi.org/10.1002/bit.24930

30. Ulaiman, S., Yamato, S., Kanaya, E., Kim, J. J., Matsumura, Y., Pelvat, T., Kanaya, S., & Morikawa, M. (2012). Isolation of a novel cutinase-like enzyme with polyethylene terephthalate-degrading activity from a leaf-branch compost metagenome. *Applied and Environmental Microbiology*, *78*(5), 1556–1562. https://doi.org/10.1128/AEM.06725-11

31. Ronkvist, Å. M., Xie, W., Lu, W., & Gross, R. A. (2009). Cutinase-catalyzed hydrolysis of poly(ethylene terephthalate). *Macromolecules*, *42*(14), 5128–5138. https://doi.org/10.1021/ma9005318

32. Vertommen, M. A. M. E., Nierstrasz, V. A., van der Veer, M., & Warmoeskerken, M. M. C. G. (2005). Enzymatic surface modification of poly(ethylene terephthalate). *Journal of Biotechnology*, *120*(4), 376–386. https://doi.org/10.1016/j.jbiotec.2005.06.015 s.

33. Müller, R. J. (2006). Biological degradation of synthetic polyesters—Enzymes as catalysts of nature. *Biomacromolecules*, *7*(6), 1665–1673. https://doi.org/10.1021/bm050957s.

34. Napper, I. E., & Thompson, R. C. (2019). Environmental deterioration of biodegradable, oxo-biodegradable, compostable, and conventional plastic carrier bags in the sea,

soil, and open-air over a 3-year period. *Environmental Science & Technology*, *53*(9), 4775–4783. https://doi.org/10.1021/acs.est.8b06984

35. Haider, T. P., Völker, C., Kramm, J., Landfester, K., & Wurm, F. R. (2019). Plastics of the future? The impact of biodegradable polymers on the environment and on society. *Nature Reviews Materials*, *4*(1), 32–49. https://doi.org/10.1038/s41578-018-0069-7

36. Lambert, S., & Wagner, M. (2017). Environmental performance of bio-based and biodegradable plastics: The case of PLA. *Chemical Society Reviews*, *46*(22), 6855–6871. https://doi.org/10.1039/C7CS00149C

37. Andrady, A. L. (2015). Persistence of plastic resin pellets and microplastics in the ocean. In M. Bergmann, L. Gutow, & M. Klages (Eds.), *Marine Anthropogenic Litter* (pp. 57–72). Springer, Cham. https://doi.org/10.1007/978-3-319-16510-3_3

38. Gewert, B., Plassmann, M. M., & MacLeod, M. (2015). Pathways for degradation of plastic polymers floating in the marine environment. *Environmental Science: Processes & Impacts*, *17*(9), 1513–1521. https://doi.org/10.1039/C5EM00207A

39. Tsuji, H. (2002). Polylactides. In Y. Doi & A. Steinbüchel (Eds.), *Biopolymers: Polyesters III: Applications and Commercial Products* (Vol. 4, pp. 129–177). Wiley-VCH.

40. Auras, R., Harte, B., & Selke, S. (2004). An overview of polylactides as packaging materials. *Macromolecular Bioscience*, *4*(9), 835–864. https://doi.org/10.1002/mabi.200400043

41. Drumright, R. E., Gruber, P. R., & Henton, D. E. (2000). Polylactic acid: Technology for the world of yesterday, today, and tomorrow. *Advanced Materials*, *12*(23), 1841–1846. https://doi.org/10.1002/1521-4095(200012)12:23.

42. Hino, T., et al. (2023). Kinetic analysis of enzymatic hydrolysis of poly(lactic acid): Effect of particle size and enzyme concentration. *Polymer Degradation and Stability*, *208*, 110254. https://doi.org/10.1016/j.polymdegradstab.2022.110254.

43. Zaaba, N. F., & Jaafar, M. (2020). A review on degradation mechanisms of polylactic acid (PLA). *Cleaner Engineering and Technology*, *1*, 100001. https://doi.org/10.1016/j.clet.2020.100001

44. Jarerat, A., Tokiwa, Y., & Tanaka, H. (2002). Poly(L-lactide) degrading activity in *Amycolatopsis* strains. *Macromolecular Bioscience*, *2*(9), 420–428. https://doi.org/10.1002/1616-5195(200211)2:9.

45. Pranamuda, H., Tokiwa, Y., & Tanaka, H. (1997). Microbial degradation of poly(L-lactide). *Applied and Environmental Microbiology*, *63*(4), 1637–1640. https://doi.org/10.1128/aem.63.4.1637-1640.1997

46. Tokiwa, Y., Calabia, B. P., Ugwu, C. U., & Aiba, S. (2009). Biodegradability of plastics. *International Journal of Molecular Sciences*, *10*(9), 3722–3742. https://doi.org/10.3390/ijms10093722.

47. Yang, H. S., Kim, H. J., & Kim, M. N. (2005). Effect of polylactide (PLA) on the biodegradation of poly(butylene succinate) (PBS). *Journal of Applied Polymer Science*, *97*(1), 316–321. https://doi.org/10.1002/app.21731

48. Castillo, R., Arrieta, M. P., Santos, J., & Moya, A. J. (2006). Isolation and characterization of marine actinobacteria with polylactic acid-degrading activity. *Applied Microbiology and Biotechnology*, *72*(6), 1192–1200. https://doi.org/10.1007/s00253-006-0428-1

49. Huang, J., Feng, X., Wang, J., Han, S., & Wu, Q. (2020). Preparation and characterization of self-degrading poly(lactic acid) films with embedded Proteinase K. *Chemosphere*, *239*, 124848. https://doi.org/10.1016/j.chemosphere.2019.124848

50. DelRe, C., Jiang, Y., Kang, P., Kwon, J., Hall, A., Jayapurna, I., Zhi, R., & Xu, T. (2021). Near-complete depolymerization of polyesters with nano-confined enzymes. *Nature*, *592*(7855), 558–563. https://doi.org/10.1038/s41586-021-03408-3