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From Scraps to Wraps: Circular Economy Pathways for Biodegradable Plastics via Integrated Waste Biorefineries

Chrysanthi Michelaki[1], Napoleon Christoforos Stratigakis[1], Angeliki Maragkaki[2], Alexis Theodorou[1], Charis Gryparis[1], Lisa De Toni[1], Chrissie Isabella Maria Baltzaki[1], Thrassyvoulos Manios[2] and Kelly Velonia[1,*]

[1]*University of Crete, Greece*
[2]*Hellenic Mediterranean University, Greece*

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Abstract

The transition from fossil-based plastics to biodegradable polymers requires production systems that integrate renewable carbon substrates, process efficiency, and environmental performance within a circular economy framework. Polyhydroxyalkanoates (PHAs) and polylactic acid (PLA) are established bio-based polymer systems, however, their broader implementation remains constrained by feedstock cost, food-feed competition constraints, land-use considerations, process integration, downstream recovery efficiency, as well as intrinsic material limitations, including the brittleness and limited impact resistance of PLA and the composition-dependent mechanical variability and narrow processing window of PHAs (Al Battashi et al., 2020; Maragkaki et al. 2026). The development of an integrated biorefinery strategy for the valorisation of locally available agro-industrial waste streams, including cheese whey, olive mill wastewater, and food waste, as substrates for biopolymer production will be discussed. In this context, anaerobically digested streams were pre-treated and standardised to reduce variability and enhance compatibility with microbial cultivation systems, while enabling recovery of soluble fermentation products, including volatile fatty acids and hydrogen generated during acidogenic fermentation. For PHA production, process optimisation focused on microbial cultivation and intracellular polymer accumulation, with emphasis on maintaining robust performance across variable waste-derived feedstocks. For the PLA-related pathway, optimisation targeted efficient recovery of lactic acid from fermentation-derived streams, improving substrate availability for downstream polymer synthesis. Downstream extraction and purification strategies were refined to increase yield and purity while maintaining alignment with upstream bioprocess performance. Polymer structure-property relationships were further explored through targeted chemical modulation of material characteristics to extend functionality beyond the intrinsic limitations of the native biopolymers (Maragkaki et al. 2026, Maragkaki et al. 2023, Theodorou et al. 2023, aragkaki et al. 2025). Sustainability considerations were embedded across process chain optimization to ensure the development of scalable pathways leading to biodegradable polymers with lower carbon footprint. By combining waste pre-treatment, microbial conversion, product recovery, polymer modification and environmental assessment, this work demonstrates how locally sourced agro-industrial residues can be converted into higher-value biodegradable materials. The proposed strategy supports carbon loop closure, reduces dependence on refined substrates, and positions waste biorefineries as scalable platforms for circular bioplastic production.

Keywords: bioplastics, circular bioeconomy, Polyhydroxyalkanoates, Polylactic acid

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