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Material–process integration and degradation engineering of biodegradable polymers in additive manufacturing

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Abstract

Biodegradable polymers are increasingly recognized as key enablers of sustainable additive manufacturing (AM), offering a unique combination of environmental degradability, tunable mechanical performance, and compatibility across diverse printing platforms. This review examines recent advances in the molecular design, composite formulation, and three-dimensional printing of biodegradable thermoplastics, including polylactic acid, polycaprolactone, poly(butylene adipate-co-terephthalate), and polybutylene succinate, across major AM platforms such as fused deposition modeling, direct ink writing, and digital light processing. Particular emphasis is placed on structure–property–function–degradation relationships that influence rheological behavior, interlayer adhesion, mechanical anisotropy, and life-cycle performance. Material engineering strategies, including polymer blending, reactive compatibilization, nanofiller reinforcement, and platform-specific parameter optimization, are critically examined for their capacity to enhance print fidelity and enable precise control over degradation kinetics. Representative applications in biomedical scaffolds, controlled drug delivery systems, agricultural devices, and compostable packaging demonstrate how deliberate material–process integration can achieve both functional performance and temporally programmed degradation. Furthermore, sustainable design paradigms, such as design for degradation, life-cycle synchronization, topology-driven material minimization, and circular manufacturing frameworks, are discussed as essential for transitioning AM from rapid prototyping to responsible large-scale production. Despite substantial progress, challenges remain in mechanical robustness, material standardization, and end-of-life infrastructure. Addressing these limitations will require coordinated advances in polymer chemistry, processing science, and life-cycle engineering to establish truly circular, high-performance biodegradable AM systems.

Keywords: Biodegradable polymers, Additive manufacturing, Three-dimensional printing, Sustainable design, Circular economy

1. Introduction

The pervasive use of petroleum-derived plastics over the past century has fundamentally transformed modern society. However, it has also generated a substantial ecological burden. Accumulated plastic waste, most of which is non-degradable, now contaminates terrestrial and marine environments, disrupts ecosystems, and contributes significantly to greenhouse gas emissions across its life-cycle.[1] In response to escalating environmental concerns, biodegradable polymers are increasingly being advanced as viable alternatives to conventional plastics.[2] Beyond their capacity to degrade under controlled conditions, these materials increasingly represent strategic, eco-conscious alternatives that align with the broader goals of sustainable development, circular economy frameworks, and climate mitigation.

Biodegradable polymers, such as polylactic acid (PLA), polybutylene succinate (PBS), poly(butylene adipate-co-terephthalate) (PBAT), and polycaprolactone (PCL), offer several advantages in this context.[3,4] Most are partially or fully derived from renewable feedstocks (e.g., PLA from starch or sugar), and they undergo enzymatic or hydrolytic degradation into non-toxic byproducts. Their end-of-life pathways may include industrial composting, controlled biodegradation, or, in certain cases, chemical recycling. Importantly, their mechanical and thermal properties can be tailored through molecular design and processing strategies, enabling performance levels that rival or complement those of conventional petrochemical polymers. Therefore, biodegradable polymers are no longer viewed solely as environmentally benign materials, but as functionally competitive substitutes suitable for a wide range of applications.[5,6]

Concurrently, additive manufacturing (AM), commonly referred to as three-dimensional (3D) printing, has developed into a transformative and resource-efficient manufacturing approach.[7-9] Unlike conventional manufacturing techniques such as injection molding, extrusion, or computer numerical control (CNC) machining, which often require energy-intensive tooling and generate considerable material waste, AM enables tool-free, layer-by-layer fabrication of complex geometries with minimal material loss.[10-12] This approach enhances material utilization, reduces production lead times, and facilitates on-demand manufacturing. When integrated with biodegradable polymers, AM provides a synergistic platform for fabricating eco-designed products optimized not only for mechanical and functional performance, but also for environmentally responsible end-of-life outcomes.

The integration of biodegradable polymers with AM technologies has already demonstrated potential across diverse sectors, including biomedical engineering (e.g., resorbable scaffolds and drug delivery systems), packaging (e.g., compostable containers and films), agriculture (e.g., degradable seedling pots and mulch films), and consumer products (e.g., lifestyle goods and wearable devices).[13,14] AM enables the simultaneous consideration of material composition, structural design, and product life-cycle at the design stage, an approach increasingly described as "design for degradation." Furthermore, this integration supports the vision of a circular manufacturing model where products are manufactured sustainably, used functionally, and disposed of responsibly.[15,16]

Recent studies have also highlighted the broader sustainability potential of AM beyond specific material classes. For instance, Su *et al.*[17] provided a comprehensive review of achieving sustainability through AM, emphasizing resource efficiency, reduced material waste, and life-cycle optimization strategies across diverse manufacturing systems.

Building on these perspectives, the present review focuses on biodegradable polymers and aims to systematically compare their material properties, processability, and degradation behavior in relation to AM platforms. In particular, this work seeks to elucidate how material–process integration can be leveraged to design functionally optimized and environmentally responsible 3D-printed systems.

Building upon these material- and process-level considerations, significant advances have been achieved in the design of complex multiphasic and nanocomposite scaffold architectures using biodegradable polymers in AM.[18,19] In particular, multiphasic constructs that mimic heterogeneous biological structures, such as the annulus fibrosus and nucleus pulposus of intervertebral discs, have demonstrated the importance of spatially controlled material composition and structural gradients in achieving functional performance. These design principles have further been extended through nanocomposite strategies, including the incorporation of bioactive or inorganic fillers (e.g., hydroxyapatite, bioactive glass) and nanoscale reinforcements.

Such approaches have enabled the fabrication of structurally reinforced and functionally enhanced scaffolds, particularly in extrusion-based platforms such as fused deposition modeling (FDM).[20-22] These developments collectively highlight the critical role of material–structure integration and advanced design strategies in expanding the functional scope of biodegradable polymer-based AM systems.

This review provides a comprehensive overview of recent advances in biodegradable thermoplastics and their integration into AM processes (Figure 1), with particular emphasis on structure–property–function relationships that govern mechanical performance, degradation behavior, and application-specific functionality. Sustainable design principles and current technical challenges are also discussed to delineate the opportunities and limitations shaping the future of 3D-printed biodegradable systems.

Importantly, beyond its role as a fabrication technology, AM introduces a new paradigm in biodegradation engineering. Unlike conventional polymer systems, where degradation is primarily governed by chemical composition, AM enables spatial and temporal programming of degradation behavior through precise control over internal architecture, material distribution, and processing-induced microstructure.

2. Overview of biodegradable thermoplastics and polyesters

Biodegradable thermoplastics are increasingly regarded as foundational materials for sustainable manufacturing, owing to their ability to undergo degradation under biological or environmentally relevant conditions and their potential to reduce reliance on fossil-derived resources. Among these materials, aliphatic polyesters, including PLA, PCL, PBS, and PBAT, have been extensively studied and commercialized. These polymers exhibit substantial differences in chemical structure, thermal behavior, mechanical properties, and degradation pathways, all of which directly influence their suitability for AM.

2.1. Chemical structure and feedstock origins

The chemical architecture of biodegradable polymers plays a central role in determining their degradation behavior, physicochemical properties, and compatibility with AM processes. Subtle variations in backbone composition, copolymer sequence distribution, and functional group density can significantly influence hydrolytic susceptibility, crystallization behavior, and rheological performance.[23,24] PLA is a thermoplastic aliphatic polyester synthesized from renewable biomass-derived feedstocks such as corn starch

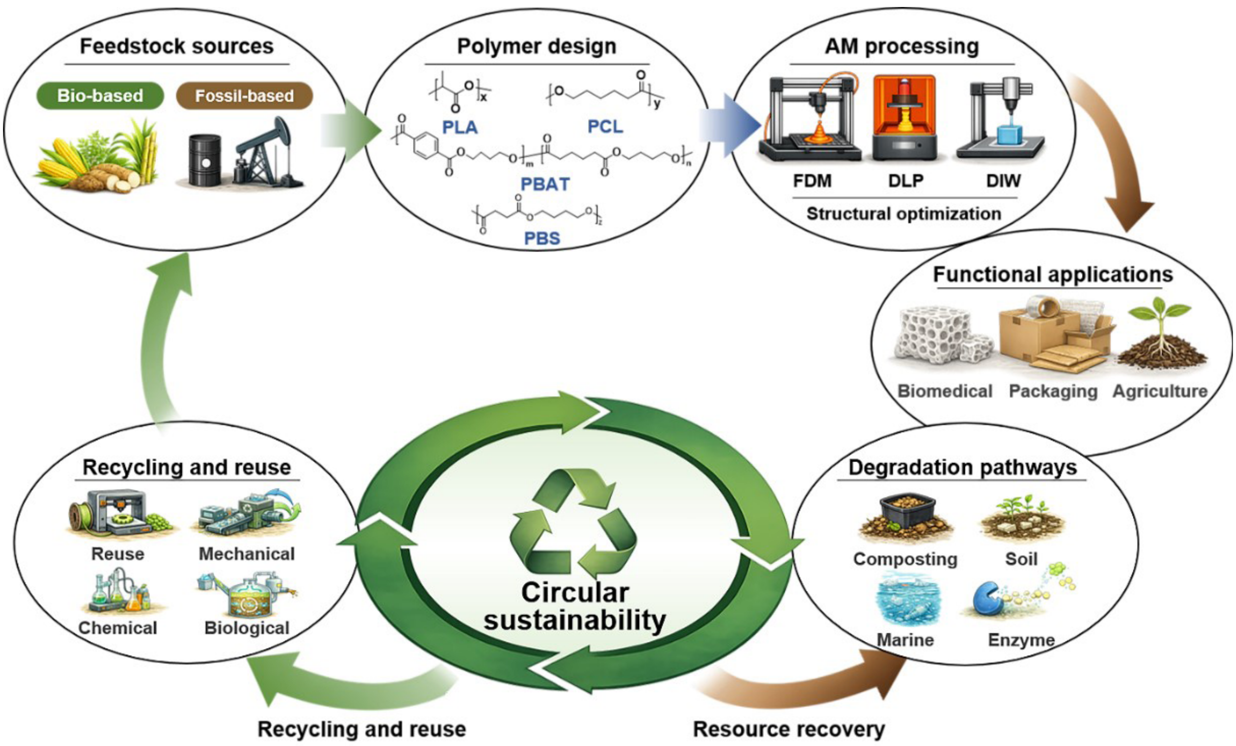

Figure 1. Conceptual illustration of the eco-integrated life-cycle of biodegradable polymers in AM, linking feedstock origin, polymer design, AM processing, structural optimization, functional deployment, and environmentally programmed degradation within a circular sustainability framework
Abbreviations: AM: Additive manufacturing; DIW: Direct ink writing; DLP: Digital light processing; FDM: Fused deposition modeling; PBAT: Poly(butylene adipate-co-terephthalate); PBS: Polybutylene succinate; PCL: Polycaprolactone; PLA: Polylactic acid. Image created by the authors.

or sugarcane. Its backbone consists of hydrolytically labile ester linkages, making it susceptible to bulk hydrolysis under elevated temperatures. PCL, in contrast, is typically produced from fossil-derived ε-caprolactone via ring-opening polymerization. Its flexible aliphatic backbone contributes to slow degradation kinetics and excellent low-temperature processability.

Polybutylene succinate is generally synthesized through polycondensation of succinic acid and 1,4-butanediol, both of which can be derived from bio-based routes. In contrast, PBAT is a fossil-based random copolyester composed of adipic acid, terephthalic acid, and butanediol. The occurrence of both aliphatic and aromatic segments in its chemical structure imparts a unique combination of biodegradability, flexibility, and enhanced ductility.

These structural variations yield unique profiles of crystallinity, thermal transitions, and degradation pathways. Therefore, chemical composition directly influences not only biodegradation rates but also printability, interlayer bonding behavior, and overall product performance in AM systems.

2.2. Thermal and mechanical properties in the context of additive manufacturing

Thermal stability, glass transition temperature (T_g), and melting temperature (T_m) are critical determinants of a polymer's compatibility with specific AM platforms.[25-29] These parameters influence melt viscosity, solidification kinetics, dimensional stability, and interlayer adhesion. PLA exhibits a relatively high T_m (150–160 °C) and a high elastic modulus, which contribute to good shape retention and dimensional accuracy in FDM. However, its intrinsic brittleness and low impact resistance restrict its application in dynamically loaded or impact-sensitive components. PCL, with a low T_m (~60 °C), is ideal for direct ink writing (DIW) or low-temperature extrusion in biomedical applications. PBAT exhibits excellent elongation and toughness but may require blending with PLA to achieve dimensional stability during printing. PBS offers intermediate rigidity and thermal resistance, suitable for heat-resistant printed parts. Successful AM implementation requires careful alignment between polymer thermal and mechanical characteristics and platform-specific parameters to ensure successful printing and the desired product functionality.

2.3. Biodegradability profiles and degradation mechanisms

Biodegradable thermoplastics exhibit distinct degradation mechanisms, rates, and environmental sensitivities.[30] PLA and PBS degrade predominantly via hydrolysis of ester bonds, followed by microbial assimilation, while PBAT degrades under enzymatic or oxidative conditions in composting environments. PCL undergoes slow hydrolytic degradation but is enzymatically cleavable *in vivo*. The rate of degradation is influenced by crystallinity, molecular weight, and environmental conditions, such as temperature, pH, and humidity. For example, PLA often requires industrial composting facilities (temperatures above 50 °C, high humidity) to achieve complete mineralization within practical timeframes, whereas PCL can degrade slowly under physiological conditions. Understanding these pathways is essential for aligning material selection with application-specific end-of-life strategies.

2.4. Environmental and sustainability considerations

Beyond intrinsic degradability, the environmental performance of biodegradable polymers must be evaluated through life-cycle assessment, carbon footprint analysis, and resource renewability metrics.[31] PLA offers the advantage of being both bio-based and compostable, with comparatively lower greenhouse gas emissions during production relative to numerous conventional petrochemical polymers. PBS can also be synthesized from renewable precursors and exhibits low toxicity, enhancing its environmental compatibility. In contrast, PCL and PBAT are primarily derived from fossil resources, creating a trade-off between feedstock sustainability and end-of-life biodegradability. Therefore, material selection in AM must integrate functional requirements with upstream resource considerations and downstream environmental performance to support circular design principles and sustainable manufacturing goals.

2.5. Process-material matching for additive manufacturing

The suitability of biodegradable polyesters for AM is determined by their rheological behavior, melt viscosity, thermal processing window, and interlayer adhesion characteristics.[32] PLA remains the most widely utilized biodegradable polymer in FDM due to its melt stability and high stiffness. PCL is ideal for DIW due to its low processing temperature and moldability. PBAT, with its rubbery nature, is better suited for flexible filament extrusion or co-printing strategies in which it functions as a soft segment within multiphase systems. PBS can be processed via FDM and, when chemically modified or blended to enable photoreactivity, may also be adapted for digital light processing (DLP). Process-material matching is essential for achieving reliable part quality, dimensional fidelity, and sustainable performance in printed products. Recent developments in multicomponent formulations, such as PLA–PBAT blends or PCL–ceramic composites, have further expanded the versatility of biodegradable polymers across multiple AM platforms.[33]

2.6. Life-cycle-based sustainability evaluation of biodegradable thermoplastics

Life-cycle assessment has become an essential framework for evaluating material sustainability beyond simple biodegradability. For biodegradable thermoplastics to be considered truly sustainable, they must demonstrate low environmental impact across their production, use, and disposal. Key sustainability indicators include bio-based content, greenhouse gas emissions, cumulative energy demand, biodegradation potential, and compatibility with industrial composting infrastructure. These metrics collectively provide a systems-level perspective on environmental impact.[34,35]

Among biodegradable polyesters, PLA exhibits one of the strongest sustainability profiles. It is fully bio-based, highly compatible with industrial composting systems, and generally associated with lower greenhouse gas emissions during production compared to conventional petrochemical plastics. Nevertheless, its limited degradation under ambient soil or marine conditions may restrict post-use performance in unmanaged disposal scenarios. PBAT, although fossil-derived, demonstrates high compostability and efficient biodegradation under controlled conditions; however, its production footprint remains comparatively higher. PCL and PBS occupy intermediate positions, offering moderate environmental performance metrics alongside versatile processing capabilities.

To contextualize these findings, comparisons with conventional thermoplastics such as acrylonitrile butadiene styrene (ABS) and polyethylene terephthalate (PET) are critical. Unlike bioplastics, ABS and PET are entirely fossil-derived, non-biodegradable, and incompatible with composting systems. Their fossil origin and high greenhouse gas emissions limit their suitability for sustainable AM applications, particularly in sectors requiring responsible end-of-life strategies. As illustrated in the extended radar chart (Figure 2), biodegradable thermoplastics significantly outperform traditional polymers across multiple environmental metrics, reinforcing their role as credible eco-functional alternatives in next-generation manufacturing systems.

A comparative summary of these indicators is presented in Table 1[36-40] and Figure 2. Biodegradable polymers, such as PLA, PBAT, PBS, and PCL, exhibit clear advantages over conventional fossil-based polymers in biodegradability and compatibility with industrial composting. In particular, PLA is fully bio-based and is compatible with industrial composting under appropriate conditions, while PBAT shows high degradation efficiency under controlled composting conditions despite its fossil-derived nature. In contrast, conventional polymers, such as ABS and PET, exhibit marginal biodegradability and lack compatibility with composting systems, and are associated with relatively high greenhouse gas emissions.

Table 1. Highlighted biodegradable polymers in comparison with conventional fossil-based polymers to emphasize their relative sustainability advantages

Polymer		Bio-based content (%)	Biodegradability (compost/soil, %)	Greenhouse gas emissions (kg CO_2-eq/kg)	Industrial composting compatibility (%)	Refs
Biodegradable polymers	PLA	100	80	1.3–1.8	100	36-38
	PCL	0	60	2.0–3.0	~30	36,39
	PBAT	0	90	1.5–2.5	~90	36-38
	PBS	~50	70	1.8–3.0	~60	36,37,40
Conventional fossil polymers	ABS	0	0	3.5–4.5	0	36,38
	PET	0	0	2.5–3.5	0	37,38

Note: "Greenhouse gas emissions (kg CO_2-eq/kg)" values are derived from representative life-cycle assessment studies and widely used databases (e.g., Ecoinvent and GaBi), and may vary depending on system boundaries, feedstock source, and methodological assumptions.
Abbreviations: ABS: Acrylonitrile butadiene styrene; PBAT: Poly(butylene adipate-co-terephthalate); PBS: Poly(butylene succinate); PCL: Poly(caprolactone); PET: Polyethylene terephthalate; PLA: Polylactic acid.

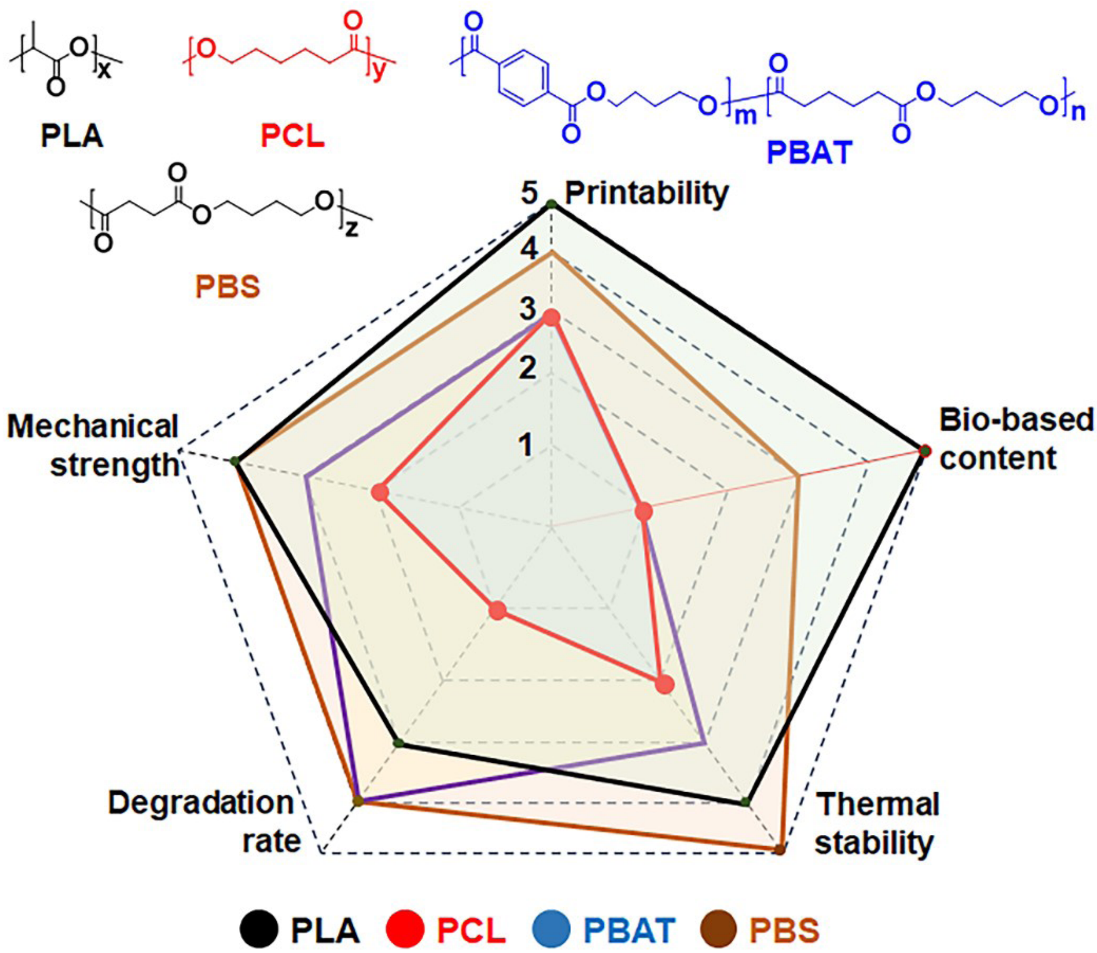

Figure 2. Radar chart illustrating relative trends in printability, mechanical performance, thermal stability, degradation behavior, and bio-based content of polylactic acid (PLA), polycaprolactone (PCL), poly(butylene adipate-co-terephthalate) (PBAT), and PBS (polybutylene succinate). The values reflect comparative tendencies derived from literature to support material–process selection in sustainable additive manufacturing. Image created by the authors.

These comparisons highlight the critical importance of integrating both feedstock origin and end-of-life performance when evaluating the sustainability of polymeric materials. This perspective reinforces the role of biodegradable polymers as practical and scalable alternatives in sustainable AM systems.

Integrating life-cycle considerations into early-stage material selection is essential for AM, where sustainability objectives must be embedded at the design phase rather than addressed retrospectively. These intrinsic material characteristics directly influence platform compatibility and process optimization, which are examined in detail in Section 3.

3. Processability and printability in three-dimensional printing platforms

Building upon the material-specific characteristics discussed in Section 2, including chemical structure, thermal transitions, mechanical performance, and biodegradation profiles, the successful implementation of biodegradable thermoplastics in AM depends fundamentally on their processability within platform-specific fabrication environments (Figure 3).[41,42] While intrinsic polymer properties dictate degradation kinetics and end-use functionality, they simultaneously determine melt flow behavior, viscoelastic response, crystallization dynamics, and interlayer adhesion during printing. Consequently, translating molecular- and materials-level attributes into platform-compatible printability is critical for achieving structurally robust and environmentally aligned products.

Additive manufacturing represents not only a technological advancement but also a structural shift toward resource-efficient fabrication. In contrast to

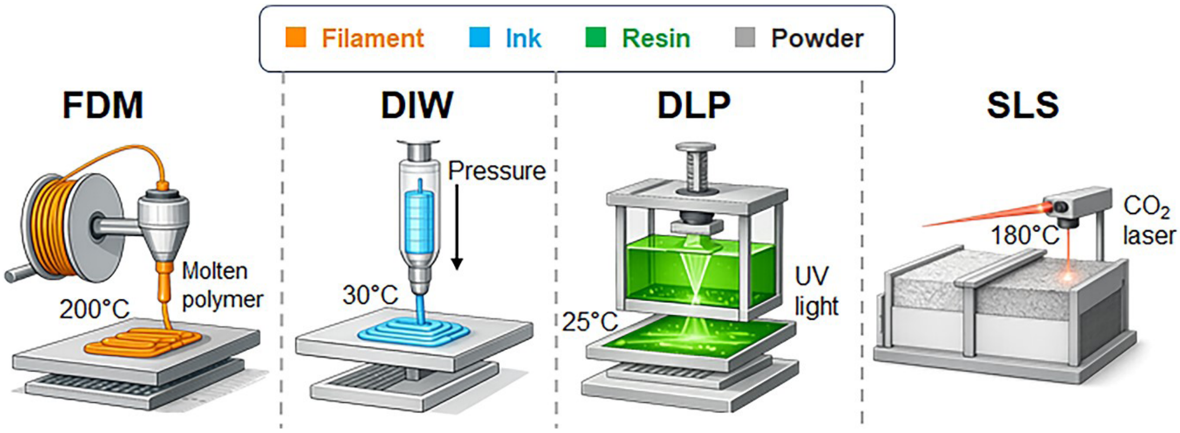

Figure 3. Schematic comparison of FDM, DIW, DLP, and SLS platforms used for biodegradable polymers, illustrating differences in material feed form (filament, ink, resin, powder), processing temperature, and consolidation mechanism. Platform-specific processing conditions govern microstructure, interlayer bonding, and degradation characteristics, underscoring the importance of material–process compatibility in sustainable additive manufacturing. Abbreviations: CO_2: Carbon dioxide; DIW: Direct ink writing; DLP: Digital light processing; FDM: Fused deposition modeling; SLS: Selective laser sintering; UV: Ultraviolet. Image created by the authors.

conventional manufacturing methods, such as injection molding, extrusion, or subtractive machining (e.g., CNC milling), AM constructs parts through layer-by-layer material deposition, significantly reducing material waste.[43,44] The elimination of dedicated molds and tooling lowers energy demand, shortens setup times, and enhances production flexibility. Furthermore, AM facilitates decentralized, on-demand manufacturing, enabling localized production that reduces transportation-related emissions and minimizes excess inventory.

These characteristics are particularly advantageous for biodegradable polymers. Numerous such materials exhibit sensitivity to prolonged thermal exposure and high shear conditions typical of traditional melt processing. AM platforms can provide comparatively milder and lower-temperature processing environments, thereby preserving the integrity and biodegradation potential of these polymers. Additionally, the ability to precisely control internal architecture (e.g., porosity, infill) enables eco-functional design strategies such as lightweighting and material minimization. As a result, AM offers a unique synergistic convergence of sustainable materials and resource-conscious processing, supporting responsible product development across biomedical, agricultural, packaging, and consumer applications.[45,46]

3.1. Fused deposition modeling

Fused deposition modeling is the most widely adopted AM technique due to its operational simplicity, affordability, and compatibility with a broad range of thermoplastic polymers.[47,48] In FDM, a continuous filament is heated above its melting temperature and extruded through a nozzle to fabricate 3D structures in a layer-by-layer sequence. The process is highly accessible, requiring minimal equipment and offering considerable flexibility in printing parameters, such as temperature, nozzle size, layer height, and print speed.

Biodegradable polymers, particularly PLA and its composite derivatives, are highly compatible with FDM due to their favorable thermal characteristics and printability. PLA exhibits a moderate melting temperature (150–160 °C), low warpage, and strong interlayer adhesion, which collectively enable reliable printing with minimal distortion. These characteristics have made PLA the dominant biodegradable filament for prototyping, educational applications, and environmentally conscious consumer products. Other biodegradable polymers, including PBAT and PBS, can be adapted for FDM through blending, copolymerization, or compatibilization strategies that improve rheological behavior and dimensional stability.[49]

In addition to its operational benefits, FDM offers significant environmental advantages when compared to conventional plastic manufacturing methods such as injection molding or thermoforming. Conventional fabrication approaches often require energy-intensive tooling, generate excess waste from trimming and support structures, and rely on centralized, high-volume production models that contribute to transportation-related emissions and inventory surplus. In contrast, FDM operates without molds and deposits material only where needed, resulting in near-zero production waste under optimized conditions. The ability to manufacture components on demand and near the point of use further reduces logistical burdens and material overproduction.

Furthermore, FDM also enables sustainable design strategies by allowing precise control over internal geometries. Optimizing infill density, incorporating lattice or hollow architectures, and adjusting wall thickness can substantially reduce material usage while maintaining mechanical performance. These capabilities align closely with eco-functional design principles and circular economy strategies. When combined with biodegradable polymers, FDM provides a uniquely synergistic platform for reducing material consumption, energy demand, and life-cycle impact across diverse applications.

3.2. Direct ink writing

Direct ink writing, also known as robocasting, is an extrusion-based AM technique that deposits shear-thinning inks to construct structures layer by layer at relatively low temperatures.[50] Unlike FDM, which relies on the melting and solidification of thermoplastic filaments, DIW systems extrude viscoelastic pastes or gels through a syringe or nozzle using pneumatic or mechanical pressure. This approach enables the processing of temperature-sensitive biodegradable polymers and composite formulations that are unsuitable for high-temperature printing.

Moreover, DIW is particularly compatible with soft and low-melting biodegradable polymers such as PCL, as well as hydrogel systems and biopolymer-based composites.[51,52] For example, shear-thinning bioinks used in DIW typically exhibit viscosities in the range of 10^2–10^5 Pa·s under low shear conditions, enabling smooth extrusion while maintaining structural integrity after deposition.[53-55] The storage modulus (G') of such systems often exceeds 10^3–10^4 Pa following printing, which is critical for shape fidelity and layer-by-layer stability.[53,54,56] These rheological properties can be systematically tuned by adjusting polymer concentration and molecular weight, and by incorporating thixotropic or nanocomposite additives. The method accommodates a wide range of rheological profiles and enables the incorporation of bioactive molecules, drugs, or living cells, making it highly suitable for biomedical applications such as tissue scaffolds and personalized drug delivery systems. Furthermore, DIW enables high-resolution patterning of functional gradients and porous architectures, which are often difficult to achieve with traditional manufacturing methods.

In terms of environmental sustainability, DIW offers notable advantages. Its low-temperature operation significantly reduces energy consumption compared to conventional processing methods that involve melting, curing, or solvent evaporation. Precise, digitally controlled deposition minimizes material waste and enables efficient use of multi-component or sensitive formulations. The tool-free and on-demand nature of DIW further supports small-batch and localized production, reducing overproduction and transportation-related emissions. When biodegradable or bio-based inks are employed, DIW provides a viable pathway for fabricating eco-designed functional structures with reduced environmental impact.

3.3. Digital light processing and stereolithography

Digital light processing and stereolithography (SLA) are vat photopolymerization techniques that fabricate 3D structures through light-induced curing of liquid resins. In SLA, a focused laser sequentially traces each layer, whereas DLP projects an entire patterned layer simultaneously using a digital light source.[57,58] Both approaches offer exceptional spatial resolution and surface quality, making them particularly suitable for fabricating microstructured biodegradable components, such as microneedle arrays, microfluidic devices, and bioresorbable implants.

Historically, DLP and SLA systems have relied predominantly on acrylate- and epoxy-based resins derived from petrochemical sources. However, recent advances in polymer chemistry have enabled the development of biodegradable photopolymer formulations. Examples include poly(ethylene glycol) (PEG)–PLA diacrylate networks, polymers incorporating enzyme-cleavable linkages, and photo-crosslinkable derivatives of natural polymers such as gelatin methacrylate. However, challenges remain in achieving complete degradation, non-toxicity of byproducts, and efficient post-curing.[59]

From an environmental perspective, DLP and SLA offer distinct sustainability benefits. Their additive-only fabrication strategy reduces raw material waste, and the maskless, tool-free workflow lowers preparatory energy inputs. These techniques are also well-suited for microscale, customized, or patient-specific applications, thereby reducing excess material use and minimizing reliance on subtractive machining. Sustainability can be further improved through the adoption of solvent-free or aqueous resin systems and energy-efficient LED curing technologies.

Although further material development is necessary to broaden the availability of fully biodegradable and non-toxic photoresins, DLP and SLA provide high-resolution, low-waste manufacturing pathways that align with sustainability objectives, particularly in precision biomedical and microscale applications.

3.4. Other emerging three-dimensional printing techniques

In addition to established platforms such as FDM, DIW, and DLP, several advanced 3D printing techniques have demonstrated potential for processing biodegradable polymers with enhanced resolution, structural complexity, and functional integration. These include selective laser sintering (SLS), electrohydrodynamic jetting (EHDJ), melt electrowriting (MEW), and hybrid multi-material printing systems.[60-63]

Selective laser sintering enables the fabrication of complex geometries by fusing polymer powders with a laser beam. Although typically applied to polyamides and high-performance engineering plastics, biodegradable powders have also been investigated in recent studies, including modified PLA- and PCL-based formulations. A key advantage of SLS is its support-free fabrication capability and partial recyclability of unfused powder, which reduces auxiliary material use and overall waste generation. In contrast to conventional molding processes, SLS is entirely mold-free and well-suited to small-batch, customized manufacturing, thereby lowering setup energy demands and material overproduction.

Techniques such as MEW and EHDJ operate at significantly finer spatial scales and enable precision deposition of biopolymers, often with minimal energy input and material consumption. These systems are particularly advantageous for producing lightweight and highly specific biomedical components such as microfibrous scaffolds or nerve conduits. Because of their high-resolution and digitally controlled deposition, they enable the use of expensive or rare biomaterials with extreme efficiency, which would be impractical in conventional fabrication settings.

Furthermore, hybrid and multi-material AM systems further expand design possibilities by enabling the integration of distinct mechanical, biological, or degradative functions within a single construct. These systems reduce the need for secondary assembly steps and lower the overall material and energy footprint of the manufacturing process. When paired with biodegradable feedstocks, these innovative techniques represent a significant step toward low-impact, high-function manufacturing paradigms.

3.5. Material–printer compatibility and optimization strategies

The mechanical performance, print quality, and environmental footprint of 3D-printed biodegradable polymers are strongly governed by the compatibility between intrinsic material properties and printer-specific parameters.[64,65] Critical material variables include viscosity, melting temperature, crystallization behavior, and surface tension. These must be harmonized with equipment-dependent factors such as nozzle diameter, extrusion rate, laser power, curing energy, and bed temperature, as well as cooling conditions. Achieving high material–printer compatibility is essential not only for ensuring print fidelity and mechanical performance but also for minimizing material waste and energy consumption, both of which are central metrics of sustainable manufacturing.

Unlike traditional manufacturing methods such as injection molding, where extensive trial-and-error and tooling are often required for each material or product variant, AM enables rapid digital iteration and real-time parameter adjustment. This capability reduces the need for multiple physical prototypes and shortens development cycles, thereby lowering embodied energy and material consumption during product optimization. Furthermore, digital control over infill density, raster orientation, lattice topology, and support generation allows designers to minimize raw material usage while preserving structural integrity.

Process optimization further enables lower-temperature printing and reduced power consumption, which is especially important for biodegradable polymers susceptible to heat-induced degradation. Effective thermal management minimizes material loss from thermal decomposition and reduces the embodied energy associated with each printed component. In this context, optimization strategies fulfill a dual function: enhancing mechanical and structural performance while simultaneously improving the eco-efficiency of the fabrication process. Accordingly, material–printer pairing should be guided not only by functional performance requirements but also by sustainability targets aligned with life-cycle assessment and circular design principles.[66]

To synthesize these considerations and facilitate practical implementation, a comparative overview of major 3D printing platforms is presented in Table 2.[67-73] The table summarizes representative biodegradable polymers compatible with each technology, highlights their environmental advantages relative to conventional fabrication methods, and identifies key sustainability challenges. This comparative framework serves not only as a technical reference but also as a decision-support tool for environmentally informed material–process selection, particularly in applications requiring a careful balance between ecological responsibility and functional customization.

Collectively, these comparisons demonstrate that AM not only enables the fabrication of biodegradable polymer-based structures with functional complexity but also introduces tangible environmental benefits over traditional plastic processing methods. Nevertheless, fabrication efficiency alone does not determine overall sustainability.

Table 2. Comparative summary of 3D printing platforms for biodegradable polymers

3D printing platform	Typical biodegradable polymers	Environmental advantages over traditional processing	Sustainability challenges	Refs
FDM	PLA, PBAT blends, PBS	Low material waste; tool-free; on-demand production	Filament waste; energy use for heating	67-69
DIW	PCL, GelMA, hydrogel composites	Low-temp operation; minimal waste; bio-ink precision	Ink formulation stability; shelf life	22,67-69
DLP/SLA	PEG–PLA diacrylates, GelMA, modified PLA	High resolution; minimal excess resin; mold-free	Toxic photoinitiators; limited truly biodegradable resins	67-70
SLS	PLA powder, PCL-based blends	Reusable powder; no support needed; zero tooling	High laser energy input; powder degradation with reuse	67-69
EHDJ/MEW	PCL, PLGA, natural polymer solutions	High-precision with minimal material; low energy input	Low throughput; complex setup	68,69,71,72
Hybrid	Combinations of PLA, PCL, GelMA	Multi-function in one step; fewer assembly/waste steps	Material compatibility; process complexity	67-69,73

Notes: This table summarizes the compatibility of various 3D printing platforms with biodegradable polymers, highlighting their environmental advantages over conventional plastic manufacturing processes as well as associated sustainability challenges. It is intended to guide material–process matching in eco-conscious design contexts.
Abbreviations: 3D: Three-dimensional; DIW: Direct ink writing; DLP: Digital light processing; EHDJ: Electrohydrodynamic jetting; FDM: Fused deposition modeling; GelMA: Gelatin methacrylate; MEW: Melt electrowriting; PBAT: Poly(butylene adipate-co-terephthalate); PBS: Poly(butylene succinate); PCL: Poly(caprolactone); PEG: Poly(ethylene glycol); PLA: Polylactic acid; PLGA: Poly(lactic-co-glycolic acid); SLA: Stereolithography; SLS: Selective laser sintering.

The structure–property relationships of printed constructs play a decisive role in defining their end-use performance and sustainability profile.

4. Structure–property–function relationship in biodegradable printed materials

Beyond single-phase materials, recent advances have emphasized the importance of multiphasic and hierarchical scaffold designs, where distinct material regions are spatially organized to mimic native tissue structures.[74] Such strategies are particularly relevant in intervertebral disc regeneration, where gradient mechanical properties and region-specific degradation are required across distinct regions, such as the annulus fibrosus and nucleus pulposus.[75,76] AM enables precise control over such heterogeneous architectures, facilitating the fabrication of functionally graded scaffolds that closely mimic native tissue organization.[72,74] In parallel, nanocomposite reinforcement further enables the design of structurally robust and biologically active architectures in AM-fabricated systems.[77,78]

The interplay between internal architecture and material properties is a defining factor in the performance of 3D-printed biodegradable systems (Figure 4). In AM, the layer-by-layer deposition process enables precise control over structural parameters, such as pore geometry, infill density, wall thickness, filament spacing, and fiber orientation. These features directly influence mechanical strength, degradation kinetics, mass transport behavior, and biological interactions, thereby determining the functional lifespan and environmental compatibility of the printed construct.[79-81]

For example, in tissue engineering scaffolds, pore size and interconnectivity critically influence cellular infiltration and nutrient diffusion, while simultaneously modulating degradation kinetics of the polymer matrix. A densely packed structure may enhance load-bearing capacity but delay degradation, whereas highly porous designs accelerate breakdown while potentially compromising mechanical integrity. Thus, the structural design must strike a delicate balance between function-specific performance and timely biodegradation.

Mechanical anisotropy, inherent to the layer-by-layer fabrication process of AM, further affects the stress response of printed components. Optimization of raster angle, layer orientation, and interlayer bonding strength is essential for ensuring sufficient durability without relying on excessive material use. Advanced design tools now allow for functionally graded structures, where mechanical or degradation properties vary across the geometry of a component, offering new dimensions of control aligned with eco-functional design strategies.

These relationships also play a vital role in environmental performance. By tailoring structural parameters, material use can be minimized while still achieving target functionality, reducing both resource demand and embodied energy. Biodegradable polymers amplify this benefit by ensuring that the breakdown process at the product's end-of-life occurs without harmful residues. In environmental or biomedical applications, such as biodegradable sensors, implants, or packaging, the internal microstructure often governs how quickly and safely the material decomposes under specific conditions (e.g., moisture, pH, enzymatic activity).[82-84]

Therefore, a comprehensive understanding of the structure–property–function relationship is essential not only for optimizing performance but also for ensuring material and process sustainability across the entire product life-cycle. Integrating computational modeling, mechanical testing, and environmental simulation will become increasingly necessary to guide the rational design of biodegradable 3D-printed systems that align with circular economy principles.

4.1. Additive manufacturing as a platform for biodegradation engineering

Additive manufacturing is not merely a fabrication

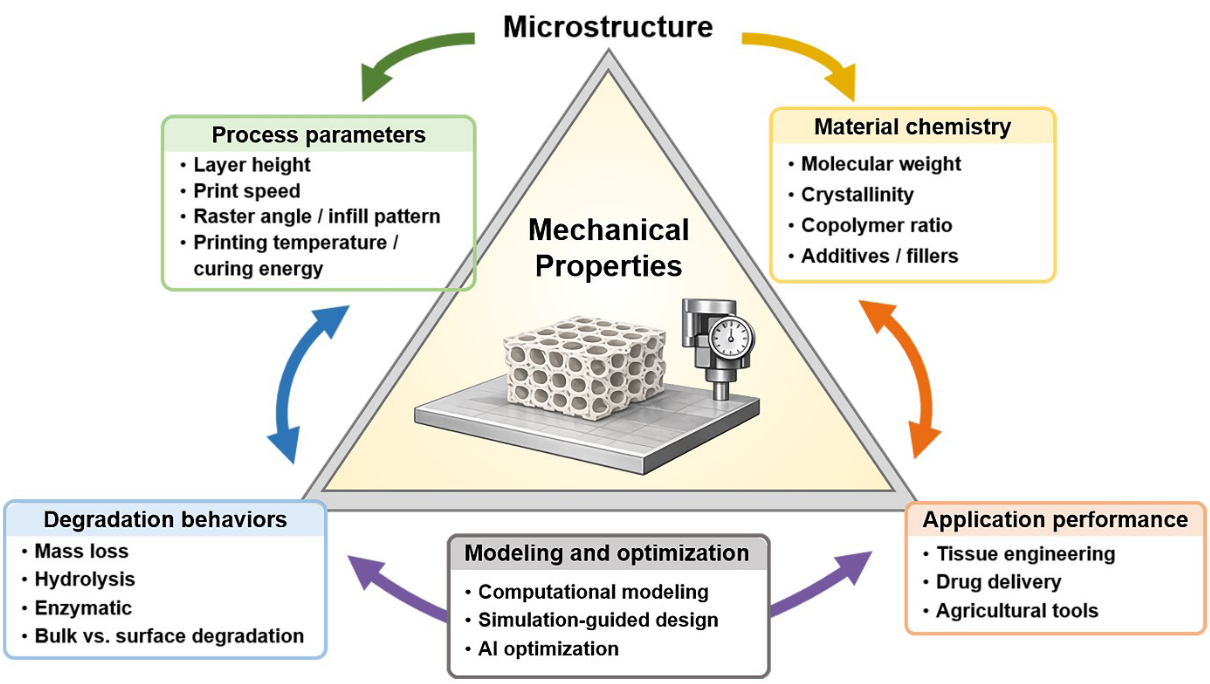

Figure 4. Schematic representation of the coupled structure–property–function–degradation relationship in biodegradable additive manufacturing systems. Microstructural design parameters control mechanical performance and degradation kinetics, which together determine application-specific functionality and life-cycle alignment. Image created by the authors.

technique, but an enabling platform for advanced biodegradation engineering.[41,65] In conventional polymer systems, degradation behavior is primarily governed by intrinsic material properties such as chemical composition, molecular weight, and crystallinity, which typically result in spatially uniform and temporally fixed degradation profiles.[30,34] As a consequence, the ability to precisely tailor degradation pathways for application-specific requirements remains inherently limited.

In contrast, AM introduces additional design variables, including internal architecture, spatial material distribution, and process-induced microstructure, which collectively enable programmable degradation behavior.[23,41] Through layer-by-layer fabrication, AM enables spatial control over degradation via features such as porosity gradients, hierarchical structures, and multi-material integration. Furthermore, temporal control can be achieved by designing structural parameters that regulate mass transport, fluid penetration, and mechanical stability over time.

This paradigm shift transforms degradation from a passive material property into an actively controlled design parameter. As a result, AM enables the development of application-specific degradation systems with spatially and temporally tunable behavior, which are difficult to achieve with conventional manufacturing approaches.[23,65]

4.2. Structure–property–function relationships by material class

Biodegradable thermoplastics exhibit distinct physicochemical characteristics that determine their printability, mechanical performance, and degradation behavior. In biodegradable polymer-based scaffolds, mechanical properties can be tailored over a broad range depending on material composition and structural design. For instance, compressive modulus values of PLA- or PCL-based scaffolds typically range from approximately 1 to 100 MPa, largely influenced by porosity, infill density, and architectural geometry.[85,86] Furthermore, the incorporation of inorganic fillers such as hydroxyapatite or bioactive glass can enhance mechanical strength by up to 2–5-fold, enabling the design of scaffolds with properties suitable for both soft and hard tissue applications.

In particular, extrusion-based AM techniques such as FDM have been widely employed to fabricate nanocomposite scaffolds with enhanced mechanical strength and bioactivity. The incorporation of inorganic fillers and nanoscale reinforcements enables the development of structurally reinforced architectures tailored for hard tissue engineering applications, including bone regeneration.[86-88]

A thorough understanding of these material-specific attributes is essential for the rational structural design and application-driven deployment of 3D-printed biodegradable constructs. This section provides a comparative overview of major classes of biodegradable polymers commonly used in AM, with an emphasis on their structure–property–function relationships.

Polylactic acid is a rigid, strong polyester derived from renewable resources. Its relatively high elastic modulus and stiffness make it ideal for load-bearing applications such as orthopedic implants and structural components in consumer goods. However, PLA exhibits brittleness and limited elongation at break, which can result in crack propagation under mechanical stress. Its slow hydrolytic degradation in ambient conditions may also hinder use in rapidly resorbing devices. To compensate, PLA is often structurally designed with optimized infill patterns or copolymerized with softer segments (e.g., PCL) to enhance ductility and controlled degradation.

In contrast, PCL is a flexible, low-modulus polyester characterized by a low melting temperature (~60 °C) and high thermal stability during processing.[89] These properties enable low-temperature extrusion and minimize thermal damage to bioactive agents in applications such as drug delivery and tissue engineering. PCL exhibits a slow degradation rate, typically spanning months to years, making it particularly suitable for long-term scaffold applications.[90] Structural strategies, such as porous architectures and lattice geometries, are commonly employed to modulate mechanical strength and accelerate degradation by increasing surface area.

Poly(butylene adipate-co-terephthalate) is a ductile aliphatic–aromatic copolyester that combines high elongation at break with relatively rapid biodegradation, especially under composting conditions.[91-93] Although petrochemically derived, PBAT can match or surpass the mechanical performance of certain bio-based polymers in flexibility-demanding applications such as packaging. In extrusion-based 3D printing, PBAT is often blended with PLA to balance stiffness and toughness. Careful control of wall thickness, infill density, and blend composition is critical in PBAT-rich systems to manage deformation behavior and preserve dimensional stability after printing.

Polybutylene succinate is a semicrystalline polyester with mechanical properties comparable to conventional thermoplastics such as polypropylene.[94] This material exhibits moderate stiffness and biodegradability, and its performance can be tailored by adjusting crystallinity through thermal management or structural design. PBS exhibits favorable melt rheology for extrusion-based printing and is therefore suitable for environmentally degradable industrial applications. In PBS-based prints, fiber alignment and layer orientation are often optimized to enhance mechanical strength while mitigating warping and interlayer delamination.

Across these material classes, the final performance of a printed construct is closely linked to how its microstructure is engineered in accordance with material-specific behavior. For example, optimizing porosity in PCL-based scaffolds supports both mechanical integrity and biological integration, whereas enhancing interlayer adhesion in PLA prints can mitigate brittleness.[95,96] Accordingly, structure–property–function relationships in biodegradable polymers are inherently multiscale, extending from molecular configuration to macroscale print design. Effective material selection and structural optimization, therefore, require coordinated consideration of polymer chemistry, application context, and targeted life-cycle performance.

4.3. Influence of three-dimensional printing platform on structural performance

While the previous section emphasized the intrinsic properties of biodegradable polymer classes in guiding structural design, the choice of a 3D printing platform is equally decisive. The interaction between material behavior and platform-specific processing conditions, such as temperature gradients, shear stress, light exposure, or field intensity, strongly influences the resulting morphology, interlayer adhesion, and mechanical performance of printed components. Consequently, the same biodegradable polymer can exhibit markedly different functional and degradation outcomes depending on the fabrication method and solidification pathway.

This section examines the structural implications of platform selection, emphasizing how distinct fabrication mechanisms, including extrusion, photopolymerization, powder fusion, and field-assisted printing, modulate critical performance attributes. Understanding these relationships is essential for aligning material–platform combinations with specific application requirements while maintaining sustainability objectives. The structural and functional performance of biodegradable thermoplastics is highly dependent on the characteristics of the selected 3D printing platform. Each AM technique, whether extrusion-based, photopolymerization-based, or field-driven, introduces distinct thermal, mechanical, and rheological conditions during processing. These conditions ultimately dictate the morphology, interlayer adhesion, and mechanical behavior of the printed object.

In FDM, thermoplastic filaments are melted and deposited layer by layer. Processing parameters such as extrusion temperature, cooling rate, and layer deposition dynamics determine the extent of interfacial bonding and residual stress. Inadequate interlayer fusion due to suboptimal thermal control can lead to pronounced mechanical anisotropy, typically manifested as reduced tensile strength along the build direction. Semi-crystalline polymers such as PLA and poly(3-hydroxybutyrate) (PHB) are particularly sensitive to cooling kinetics, as rapid solidification may induce warping or dimensional distortion. Post-printing annealing is frequently applied to polymers such as PLA or PBS, resulting in improved stiffness and heat resistance. However, this treatment may reduce ductility and impact toughness. The incorporation of inorganic or bioactive fillers, including hyaluronic acid or cellulose nanofibers (CNFs), into filament matrices further reinforces structural integrity while imparting additional functional properties.

In DIW, materials are extruded at relatively low temperatures as viscoelastic inks, making rheological behavior a critical determinant of print fidelity. Shear-thinning characteristics facilitate flow through the nozzle under applied pressure, whereas rapid viscosity recovery following deposition supports shape retention. Polymer systems based on PCL, poly(lactic-co-glycolic acid) (PLGA), or PBAT are often modified with thixotropic agents to balance flowability and structural stability. For solvent-based inks, solvent evaporation represents a key processing variable, particularly in systems containing PLGA or Poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) dissolved in volatile carriers. Non-uniform drying can induce shrinkage, cracking, or collapse of fine features; such effects may be mitigated through controlled-humidity environments or staged solvent-exchange protocols. DIW also accommodates composite bioinks incorporating living cells or bioactive components, enabling the fabrication of tissue scaffolds with spatially tunable mechanical properties and degradation profiles.

Digital light processing employs photocrosslinkable resins that are polymerized layer by layer through projected light exposure.[97] In this platform, the degree of crosslinking directly governs mechanical stability, swelling behavior, and degradation kinetics. Resins derived from methacrylated PLA or PCL allow modulation of network density by adjusting the photoinitiator concentration and light-exposure parameters, thereby enabling precise control over stiffness and resorption time. Low-viscosity formulations are generally preferred to facilitate smooth recoating and high-resolution layer formation, typically requiring viscosities below 3 Pa·s. For biomedical applications, photoreactive biodegradable polymers such as PCL-diacrylate or PLGA-methacrylate are widely used to fabricate implants and drug delivery systems with well-defined microarchitectures and demonstrated cytocompatibility.

Beyond these established technologies, emerging 3D printing methods influence the structural properties of biodegradable polymers in distinct ways. SLS employs high-energy lasers to fuse polymer powders into dense structures. The effectiveness of SLS depends strongly on the thermal transitions and crystallinity of the polymer. Semi-crystalline materials such as PLA or PCL require carefully defined sintering windows to prevent incomplete fusion, thermal degradation, or excessive porosity.[98,99] Powder flowability and particle-size uniformity are also critical for achieving consistent layer deposition. Polymer blends, including PLA combined with PEG or PBAT, have been explored to broaden the sintering window and enhance interlayer bonding during SLS processing.

Inkjet printing operates through droplet-based material deposition and is highly sensitive to ink rheology, volatility, and substrate interactions. Biodegradable thermoplastics used in inkjet systems must be dissolved in low-viscosity, rapidly evaporating solvents, which often requires reducing molecular weight or introducing reactive functional groups. PLA and PCL oligomers have been incorporated into such formulations for printing micropatterned electronics, biosensors, and drug-loaded membranes. Precise control over droplet size, spreading dynamics, and solvent evaporation rate is essential to maintain high resolution and prevent defects such as nozzle clogging or coffee-ring formation. Surfactants and cosolvents are commonly added to regulate surface tension and drying behavior.

Electrohydrodynamic jetting printing, a field-driven technique, enables submicron-scale deposition by applying electric fields to generate fine jets from viscoelastic polymer solutions. This approach enables ultra-precise patterning of biodegradable materials such as PLGA or PCL dissolved in polar solvents (e.g., dimethylformamide or dimethyl sulfoxide). Print resolution in EHDJ systems depends on the conductivity and dielectric properties of the ink, as well as the applied voltage and nozzle-to-substrate distance. Ionic additives are frequently introduced to stabilize the jet and regulate the flow rate. Although EHDJ printing offers significant promise for microscale devices and bioelectronic applications, its broader adoption remains constrained by limited throughput and system complexity.

Collectively, material–platform compatibility must be carefully engineered to achieve optimal printability, mechanical robustness, and long-term functional performance. For instance, PLA is particularly well-suited to FDM due to its well-defined melting temperature and dimensional stability, whereas PCL and PLGA are more compatible with DIW and DLP systems that benefit from lower processing temperatures and solvent-based formulations. Novel platforms such as SLS and inkjet printing further expand the design space but require stringent control over powder morphology and ink rheology. By aligning the intrinsic properties of biodegradable thermoplastics with platform-specific processing requirements, it becomes possible to fabricate printed constructs that combine environmental responsibility with application-specific performance.

4.4. Composite formulation and functional reinforcement

Biodegradable thermoplastics often exhibit intrinsic limitations, including brittleness, limited toughness, and insufficient thermal stability. To overcome these constraints while preserving biodegradability, composite formulation represents a versatile and highly effective strategy. Through rational polymer blending or incorporation of functional fillers, it is possible to tailor mechanical strength, elasticity, degradation kinetics, and biological response in 3D-printed systems. These approaches substantially broaden the applicability of biodegradable polymers in structurally demanding and performance-critical domains (Figure 5).

A fundamental strategy in composite design involves polymer blending, in which two or more biodegradable polymers are combined to exploit complementary properties.[82] For example, blending PLA with ductile PBAT produces a tougher and more flexible material, mitigating the inherent brittleness of PLA while retaining compatibility with FDM and DLP processing. PLA–PBAT composites are therefore well-suited for flexible packaging, load-bearing scaffolds, and durable consumer products. Similarly, PBS–polyhydroxyalkanoate (PHA) blends integrate the moderate flexibility of PBS with the greater rigidity of PHA, yielding dimensionally stable yet biodegradable materials with tunable degradation rates appropriate for medical implants or agricultural mulch films.

Beyond polymer–polymer blends, particulate reinforcement plays a critical role in enhancing mechanical performance and introducing functional bioactivity. Inorganic fillers, such as hydroxyapatite, β-tricalcium phosphate, and bioactive glass, are frequently incorporated into PLA or PCL matrices to improve stiffness, compressive strength, and osteoconductivity, all of which are essential for bone tissue engineering. When processed via FDM or DIW, these composites demonstrate improved structural integrity alongside favorable cellular responses, including enhanced adhesion, proliferation, and mineralization.

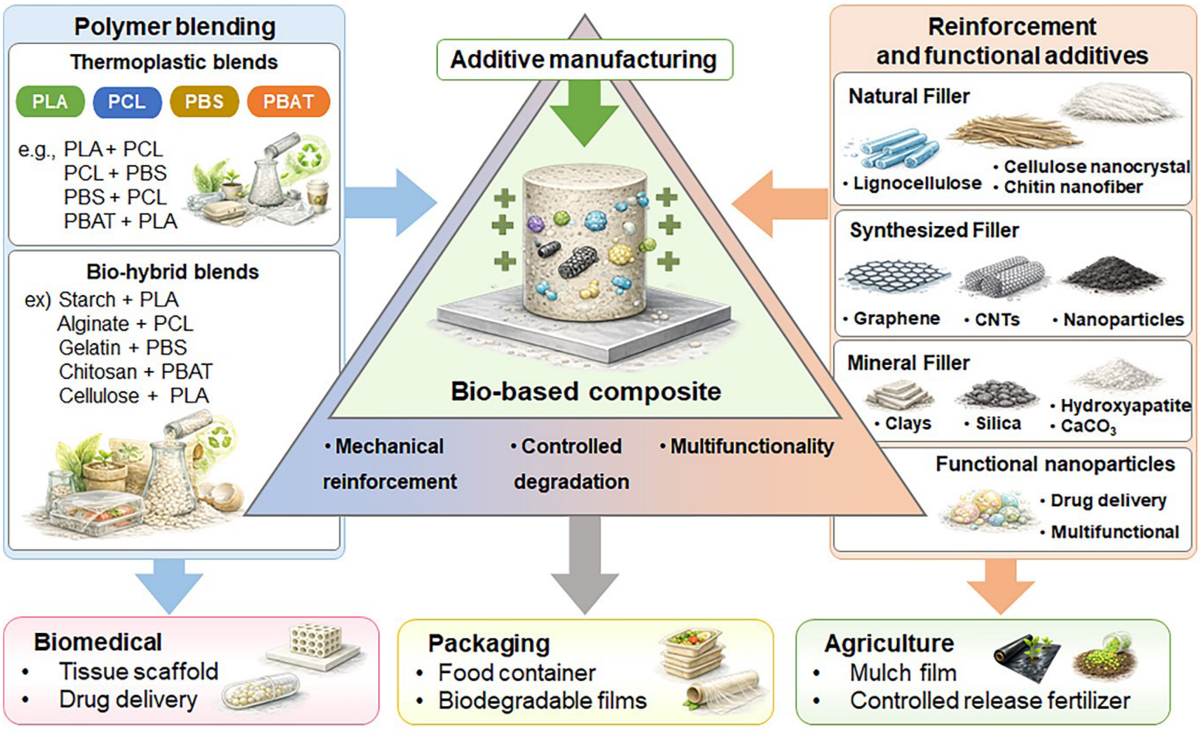

Figure 5. Overview of polymer blending and filler reinforcement strategies used to enhance mechanical performance, degradation control, and multifunctionality of biodegradable polymers in additive manufacturing. Typical approaches include PLA–PBAT blending to enhance toughness and the incorporation of bioactive fillers, such as hydroxyapatite, cellulose nanofibers, or graphene oxide, to improve mechanical strength, bioactivity, and degradation tunability across biomedical, packaging, and agricultural applications.
Abbreviations: $CaCO_3$: Calcium carbonate; CNTs: Carbon nanotubes; PBAT: Poly(butylene adipate-co-terephthalate); PBS: Polybutylene succinate; PCL: Polycaprolactone; PLA: Polylactic acid. Image created by the authors.

Nanoscale reinforcements, including graphene oxide, carbon nanotubes, and nanoclays, provide additional gains in tensile strength, thermal resistance, and electrical conductivity.[100,101] For instance, graphene oxide-reinforced PLGA or PCL systems exhibit increased modulus and fracture resistance, supporting applications in stretchable electronics and implantable sensing devices.[102] Natural fillers such as lignin, CNFs, and starch contribute not only to mechanical reinforcement but also to enhanced biodegradability, hydrophilicity, and reduced environmental impact. These bio-based additives introduce functional groups that influence water absorption, antimicrobial activity, and biological affinity.

In DIW systems, composite formulation is particularly important for tuning rheological behavior and structural reinforcement. Thixotropic agents, such as nanocellulose, fumed silica, and alginate, enhance shear-thinning behavior and viscosity recovery, enabling precise shape retention following deposition. When combined with bioactive components, such as gelatin, hyaluronic acid, or collagen, these formulations support the fabrication of tissue-specific scaffolds for cartilage, skin, and neural regeneration.

For photopolymer-based platforms such as DLP, fillers must be carefully engineered to prevent light scattering, phase separation, or inhibition of curing. Hydroxyapatite and graphene oxide can be uniformly dispersed in methacrylated PLA or PCL resins to impart stiffness and bioactivity without compromising light penetration or crosslinking efficiency.[103,104] Compatibilizers and reactive diluents are often introduced to regulate viscosity and promote chemical integration between matrix and filler, particularly in photo-crosslinkable systems.

Reactive compatibilization strategies, which employ coupling agents such as maleic anhydride or glycidyl methacrylate, are essential when blending immiscible polymers. These additives improve interfacial adhesion, reduce phase separation, and facilitate uniform filament extrusion in challenging systems, such as PLA–PBAT or PLA–PBS. They also help maintain compositional homogeneity in multiphase blends processed through DIW, FDM, or DLP platforms.

From a degradation engineering perspective, composite formulation offers a powerful means of controlling breakdown behavior. By adjusting polymer composition, filler type, and blend ratio, degradation pathways can be tuned toward hydrolytic, enzymatic, or microbial mechanisms. Such control is particularly important in drug delivery systems, where spatial and temporal control of matrix degradation dictates release kinetics, or in agriculture, where the lifespan of biodegradable films must match crop cycles.

In summary, composite design significantly extends the functional scope of biodegradable thermoplastics beyond their inherent material limitations. Through strategic formulation, whether via blending, reinforcement, compatibilization, or degradation control, it is possible to overcome material limitations while aligning with sustainable manufacturing principles. As 3D printing technologies advance, composite systems will play a central role in enabling multifunctional, high-performance biodegradable materials tailored to biomedical, industrial, and environmental applications.

4.5. Structure-driven degradation and life-cycle optimization

The degradability of biodegradable thermoplastics is not a fixed property, but rather a tunable characteristic influenced by structural, compositional, and processing parameters. In the context of AM, understanding how these variables govern degradation behavior is essential for designing materials with defined functional lifespans, ranging from hours to years.[105,106]

Through deliberate structural design and life-cycle-oriented engineering, 3D-printed biodegradable systems can be optimized to balance mechanical performance and environmental compatibility. These tunable characteristics are summarized in Table 3, highlighting key parameters that control degradation behavior.

Polymer crystallinity is a primary structural determinant of degradation rate. In semicrystalline polymers such as PLA, PHB, and PBS, degradation typically initiates in amorphous regions, which exhibit greater permeability to water and enzymes. Crystalline domains, characterized by dense chain packing, resist hydrolytic attack and therefore slow overall mass loss. Consequently, higher crystallinity generally corresponds to slower degradation. This principle is frequently applied in load-bearing applications, where post-print thermal annealing increases crystallinity, enhancing mechanical durability while extending service life. In contrast, predominantly amorphous copolymers such as PBAT or PLGA degrade more uniformly and rapidly, making them appropriate for short-term biomedical or agricultural applications.

Molecular weight is another decisive factor. High-molecular-weight polymers display greater resistance to chain scission and hydrolysis, thereby prolonging structural integrity. Lower-molecular-weight formulations, in contrast, facilitate accelerated degradation. For example, low-molecular-weight PLGA is widely employed in drug

Table 3. Tunable degradation behavior of biodegradable thermoplastics in additive manufacturing, highlighting the influence of material composition, structural design, and processing conditions

Material	AM method	Structural/processing parameter	Mechanical property (MPa)	Degradation behavior (% or time)	Tunability feature	Refs
PLA	FDM	Infill density (20–100%)	50–70	~90% (180 days)	Porosity-dependent degradation	17,36,65,86
PCL	FDM/DIW	Molecular weight and geometry	5–20	Months–years	Slow degradation, geometry-controlled	7,28,38,65,68,86
PBS	FDM	Crystallinity and blending	30–40	Moderate (~60%)	Composition-tunable	36,39,49,65
PHB	FDM	Crystallinity	30–40	80–90%	Structure-dependent degradation	9,36,65,77

Abbreviations: AM: Additive manufacturing; DIW: Direct ink writing; FDM: Fused deposition modeling; PBS: Poly(butylene succinate); PCL: Poly(caprolactone); PLA: Polylactic acid; PHB: Poly(3-hydroxybutyrate).

delivery systems requiring burst or sustained-release profiles, whereas high-molecular-weight PCL provides long-term mechanical support in implantable devices.

Copolymer composition offers additional control over degradation kinetics.[107,108] In PLGA, increasing glycolic acid content enhances hydrophilicity and accelerates hydrolysis, whereas higher lactic acid content slows degradation and preserves mechanical properties for longer durations. Comparable compositional tuning strategies apply to PLA–PBAT and PBS–PHA blends, in which the relative proportions of flexible and rigid domains influence the degradation rate and erosion mode. These copolymer systems enable the design of predictable resorption profiles tailored to application-specific requirements.

Composite formulation further expands degradation control. Hydrophilic fillers such as gelatin, CNFs, or starch promote moisture ingress and internal hydrolysis, accelerating material breakdown. Such systems are particularly valuable in agricultural applications requiring seasonal disintegration. Conversely, hydrophobic fillers such as graphene oxide or nanoclays can act as diffusion barriers, delaying water penetration and extending service life. Functional additives, including surfactants, compatibilizers, or pH-modulating agents, may also influence degradation by modifying the local chemical microenvironment or altering enzymatic accessibility.

Importantly, the AM process itself significantly affects degradation behavior by influencing microstructure. In FDM, interlayer bonding quality, void fraction, and residual stress distribution can either impede or accelerate hydrolytic attack. DIW processing may introduce residual solvents, while scaffold porosity and infill density directly govern fluid infiltration and the onset of degradation. In DLP systems, crosslink density is a dominant variable: densely crosslinked networks resist hydrolysis but may undergo rapid structural collapse once network integrity is compromised. By contrast, DIW-printed open-pore scaffolds promote more uniform and accelerated degradation due to increased surface area and fluid accessibility.

Effective cycle optimization requires aligning material degradation with functional timelines. In biomedical contexts, polymers such as PLGA and PCL are selected for their reproducible hydrolytic degradation under physiological conditions. Devices including drug-eluting stents, tissue scaffolds, and temporary fixation elements are engineered to maintain structural integrity during healing and subsequently degrade safely *in vivo*. In agricultural applications, PBAT or PHBV-based composites undergo microbial degradation in soil or compost environments, synchronizing with crop cycles. For packaging, PLA–PBAT blends are designed to ensure shelf stability during use and rapid compostability after disposal.

In applications requiring mid-term durability, such as consumer goods or certain electronic components, controlled and delayed degradation is preferable. PBS–PCL composites, for example, provide sufficient mechanical robustness during service while remaining degradable under industrial composting conditions. These systems help reduce persistent plastic waste without compromising performance during use.

Ultimately, designing for degradability extends beyond simply accelerating or slowing down material erosion; it involves engineering temporally aligned and environmentally appropriate degradation pathways. By integrating control over crystallinity, molecular architecture, composite composition, and process-induced microstructure, it becomes possible to fabricate 3D-printed biodegradable systems that degrade predictably under defined conditions. Such an approach supports circular material strategies and advances the sustainability of AM practices.

In particular, AM plays a central role in enabling this design paradigm by transforming degradation from a passive material property into an actively designable parameter. Structural features such as porosity, gradient architectures, and layer-dependent anisotropy provide additional degrees of freedom unavailable in conventional manufacturing, thereby enabling programmable and application-specific degradation pathways.

5. Functional and sustainable applications

The evolution of biodegradable thermoplastics in AM has enabled a wide range of applications that integrate mechanical performance with environmental responsibility. From biomedical devices and agricultural systems to smart wearables and sustainable packaging, these applications benefit not only from inherent biodegradability but also from compatibility with platform-specific fabrication strategies and eco-design principles. This section highlights both established and emerging domains, emphasizing the convergence of functional performance and sustainability.

5.1. Biomedical devices and drug delivery platforms

In biomedical applications, polymers such as PCL, PLGA, and PLA are widely employed for their biocompatibility, tunable degradation profiles, and compatibility with FDM, DIW, and DLP platforms. PCL is particularly valued for its low processing temperature and long-term structural stability, making it well-suited for orthopedic scaffolds, nerve guidance conduits, and soft tissue supports. When reinforced with bioactive fillers such as hydroxyapatite or β-tricalcium phosphate, PCL-based scaffolds exhibit enhanced osteoconductivity and improved tissue integration.

Poly(lactic-co-glycolic acid) is frequently processed as solvent-based inks in DIW or as photo-crosslinkable resins in DLP systems. These fabrication routes enable precise manufacturing of drug-loaded architectures with programmable release kinetics. Incorporation of therapeutic agents, such as bone morphogenetic protein-2, dexamethasone, or antibiotics, allows PLGA-based constructs to perform dual functions, supporting tissue regeneration while delivering localized pharmacological therapy.

Polylactic acid remains widely used in surgical guides, fixation components, and bioresorbable structural supports due to its mechanical strength and printability. However, its inherent brittleness and relatively slow *in vivo* degradation can limit certain applications. To address these constraints, PLA is often blended with PBAT or PCL, or reinforced with bioactive fillers, thereby enhancing toughness and enabling more application-specific resorption timelines, particularly in load-bearing or temporally sensitive contexts.

Biological performance is also strongly influenced by scaffold composition and architecture, with cell viability in optimized biodegradable polymer scaffolds commonly exceeding 85–95%. In addition, controlled degradation profiles, ranging from several weeks to months, can be achieved by adjusting copolymer composition, crystallinity, and structural design. Such tunability enables the development of scaffolds that not only support cellular activities but also match the temporal requirements of specific biomedical applications.[109,110]

5.2. Packaging and compostable consumer products

The packaging sector has rapidly incorporated PLA, PBAT, and PBS as biodegradable alternatives to conventional petroleum-derived plastics.[111] PLA is commonly selected for rigid containers, disposable utensils, and customized packaging elements due to its excellent print fidelity and surface finish. PBAT is characterized by high flexibility and elongation at break, making it well-suited for applications requiring ductility. It is therefore frequently used in films, bags, and flexible pouches, and is often blended with PLA to balance stiffness and toughness.

Polybutylene succinate exhibits intermediate mechanical behavior between rigidity and flexibility, making it suitable for thermo-resistant trays, horticultural pots, and durable household products. Incorporation of lignin, CNFs, or starch-based fillers can further enhance mechanical performance, improve oxygen barrier properties, and promote compostability. Moreover, AM enables localized, on-demand production of packaging components, reducing material waste, transportation demands, and overproduction.

Recent developments in active packaging involve integrating antimicrobial agents or oxygen scavengers into biodegradable matrices, enabling controlled material degradation and extended product shelf life. Depending on formulation and geometric complexity, these smart packaging systems can be fabricated via FDM or DLP platforms.

5.3. Agriculture and soil-degradable systems

Agricultural and horticultural applications represent a major opportunity for biodegradable AM technologies, particularly where temporary functionality and *in situ* degradation are required. PBAT is widely utilized for thin mulch films, seedling trays, and compostable root barriers due to its susceptibility to microbial degradation in soil environments.[112]

Polybutylene succinate-based printed components offer greater structural rigidity and are applied in irrigation components, plant supports, and nursery containers. Their degradation behavior under composting or soil exposure can be optimized with fillers to improve water absorption, soil interaction, or structural porosity.

Although PHBV presents certain processing challenges in extrusion-based systems, its relatively rapid natural degradation makes it attractive for specialized uses such as nutrient plugs, protective netting, or slow-release fertilizer capsules. Additionally, PLGA or PCL composites fabricated via DIW or FDM can encapsulate agrochemicals for time-controlled release, thereby improving nutrient utilization efficiency and reducing environmental runoff.

5.4. Wearables, lifestyle goods, and custom consumer products

Biodegradable thermoplastics are increasingly integrated into consumer product design, where sustainability, customization, and lifespan alignment are central considerations.[17,37] PLA remains widely used for rigid desktop accessories, eco-promotional items, and modular household components due to its stability and print precision. However, its limited flexibility has led to the widespread adoption of PLA–PBAT blends in applications requiring enhanced toughness, such as flexible phone cases, utility tools, and snap-fit assemblies.[24,91]

Polybutylene succinate-based composites are applied in more durable consumer goods, including soap holders and furniture components, particularly when reinforced with natural fibers to improve mechanical robustness and thermal comfort.[39] PCL is especially attractive for wearable applications because of its softness, biocompatibility, and thermally remoldable behavior. It is commonly used in customized splints, orthopedic insoles, orthoses, and adaptive fashion elements, where user-specific customization is critical.[3]

Advanced printing strategies, including DIW and multi-material FDM, enable the integration of soft and rigid regions within a single wearable device. This capability supports ergonomic designs with spatially differentiated mechanical properties.[54,62]

5.5. Smart, responsive, and multifunctional systems

Recent advances in bio-based polymer engineering have expanded the applications of biodegradable thermoplastics to smart, stimuli-responsive systems.[36,82] Modified PLA, PCL, and PLGA systems are now utilized in four-dimensional printing, in which structures undergo programmed shape changes in response to external stimuli such as temperature, moisture, or pH.[63,85] These adaptive behaviors are particularly valuable in dynamic biomedical devices (e.g., shape-morphing stents) and intelligent packaging systems capable of responding to spoilage indicators.

Functional fillers, such as graphene oxide, carbon nanotubes, and lignin, further expand material capabilities by enhancing electrical conductivity, barrier performance, and antimicrobial activity.[77,78] These modifications enable the fabrication of biodegradable sensors, transient electronic components, and hybrid implants with integrated diagnostic functions.

Furthermore, photocurable biodegradable resins optimized for DLP printing are facilitating innovations in micro-optics, microneedle arrays, and soft robotic components.[57,97] By combining architecture-driven design with controlled degradability, these systems integrate short-term functional performance with long-term environmental compatibility.

6. Sustainable design

The integration of biodegradable polymers into AM provides a strategic opportunity to align material performance with sustainability and environmental stewardship (Figure 6). Unlike conventional thermoplastics, biodegradable AM materials enable life-cycle synchronization, material efficiency, and responsible end-of-life management. Sustainable design in 3D printing extends beyond the selection of environmentally preferable feedstocks. It also encompasses structural optimization to minimize waste, extend functional lifespan, and ensure safe, predictable degradation. Collectively, core principles such as design for degradation, life-cycle-aligned material selection, energy-efficient processing, and circularity planning can reduce environmental impact while preserving technical performance and resource efficiency.

6.1. Design for degradation and life-cycle synchronization

Design for degradation emphasizes aligning material breakdown with the intended functional lifespan of a product.[36,37] Achieving this objective requires precise control over molecular and structural parameters, including crystallinity, copolymer composition, and geometric structure.[34,38] By tuning these variables, degradation profiles can be engineered across a broad range of timescales. For example, agricultural products, including mulch films and seed trays, benefit from rapid degradation facilitated by polymers such as PBAT or PHBV, which degrade via microbial action in soil within weeks. In contrast, biomedical scaffolds made of high-molecular-weight PCL or PLGA are designed to degrade over several months, supporting tissue regeneration and eliminating the need for surgical removal.[3,84,91]

Additionally, 3D printing enables spatial control over geometry and porosity, allowing region-specific degradation and staged structural loss in response to biological or environmental stimuli. Open-pore scaffolds printed via DIW accelerate hydrolysis through enhanced fluid penetration, whereas dense FDM-fabricated components delay degradation due to reduced permeability.[54,65,95] Such strategies permit precise deployment of biodegradable polymers in systems requiring temporally controlled resorption, including drug-eluting implants and controlled-release agricultural carriers.

6.2. Platform-specific eco-design considerations

Each AM platform introduces distinct constraints and opportunities for sustainable design.[17,26] FDM enables efficient filament utilization and scalable production but typically requires elevated processing temperatures. DIW operates at ambient or moderately elevated temperatures, reducing energy demand and enabling compatibility with bioactive or thermally sensitive components. DLP, characterized by high resolution, supports the fabrication of lightweight lattice architectures that reduce material consumption and may accelerate degradation due to increased surface-area-to-volume ratios.[25,54,57]

Topology optimization and generative design algorithms, increasingly integrated into AM workflows, can reduce material consumption by up to 50% while maintaining mechanical integrity.[8,17] This capability is

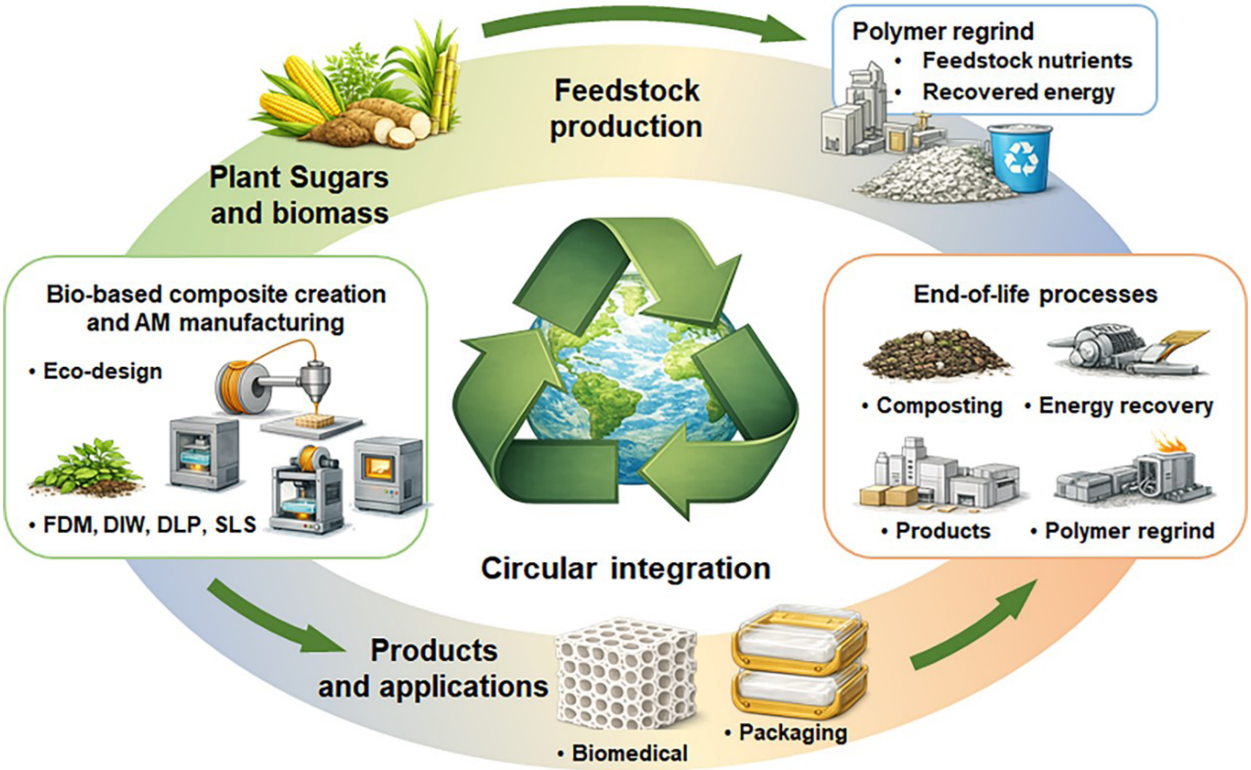

Figure 6. Schematic representation of a circular life-cycle model for biodegradable polymers in additive manufacturing, integrating bio-based feedstock production, eco-designed fabrication, functional deployment, and environmentally programmed end-of-life pathways to enable closed-loop material recovery and circular sustainability

Abbreviations: AM: Additive manufacturing; DIW: Direct ink writing; DLP: Digital light processing; FDM: Fused deposition modeling; SLS: Selective laser sintering. Image created by the authors.

particularly valuable in packaging and biomedical devices, where structures can be engineered not only for strength and functionality but also for material efficiency and controlled disassembly. Furthermore, print parameters (e.g., build orientation, infill density, and shell thickness) directly influence both degradation kinetics and energy consumption during fabrication and post-processing.[10,80]

6.3. Sustainability metrics and environmental performance

Life-cycle assessment has become a standard framework for quantifying environmental impacts, including carbon emissions, energy demand, water usage, and end-of-life effects. Compared to petrochemical-derived polymers, biodegradable materials such as PLA, PHA, and PBS are often sourced from renewable biomass. As a result, they generally exhibit lower greenhouse gas emissions and reduced embodied energy. Environmental performance can be further improved by employing lower-temperature AM platforms, such as DIW, which reduce fabrication-related energy consumption.

Additionally, recent comparative studies show that the AM of biodegradable polymers generates less material waste and consumes less toolpath energy than conventional subtractive or molding techniques.[17,26,43] For example, layer-by-layer deposition reduces overproduction, while print-on-demand models decrease inventory requirements and transportation-related emissions. Incorporating sustainability metrics directly into digital design tools can further support the development of environmentally optimized parts from the earliest stages of the design process.

6.4. Toward circular additive manufacturing

Achieving circularity requires integrating sustainability principles across the entire product life-cycle, from material sourcing to end-of-life management. In AM, this involves planning for reusability, compostability, and chemical recyclability at the design stage. Recent developments in closed-loop 3D printing systems have explored the mechanical reprocessing of PLA or PBS waste into new filaments or inks, thereby reducing reliance on virgin materials.[113,114] Advances in photocurable bioresins and enzymatically degradable polymer networks further support the development of materials that can safely return to the environment after use.

Moreover, structure-guided degradation enables component-level disassembly or staged breakdown, allowing the selective recovery of valuable fillers or bioactive agents. Such strategies are particularly promising for future multi-material or hybrid 3D-printed systems, in which life-cycle considerations can be embedded directly into the architectural design. Ultimately, integrating sustainable design principles at every stage, from feedstock selection to fabrication and disposal, will be critical to establishing biodegradable polymers as foundational materials in circular digital manufacturing ecosystems.

7. Challenges and outlook

Although sustainable design and functional integration have significantly broadened the applicability of biodegradable polymers in AM, widespread adoption still faces technical, infrastructural, and regulatory barriers. Bridging the gap between promising laboratory-scale materials and commercially viable solutions requires a comprehensive strategy that addresses limitations in material performance, processing compatibility, life-cycle evaluation, and economic feasibility.

7.1. Material property limitations

Most commercially available biodegradable thermoplastics, such as PLA, PBAT, PCL, and PBS, exhibit inherent limitations in mechanical toughness, thermal resistance, and environmental durability.[24,39,82] These constraints restrict their use in demanding applications, including load-bearing implants, high-temperature enclosures, and long-term packaging.[18,111] Although polymer blending and composite formulation strategies have yielded partial improvements, such modifications often come at the expense of printability, cost-effectiveness, or biodegradation rates.[5,65,82] In light-based AM platforms such as DLP and SLA, the development of photocrosslinkable biodegradable resins with high mechanical integrity remains a significant bottleneck.[57,97]

Furthermore, the limited availability of bio-based elastomers or impact-resistant resins narrows the design space for applications requiring flexibility, dynamic loading, or repeated use. Developing next-generation biodegradable polymers that combine structural robustness with controlled degradation behavior will be essential for expanding their practical adoption.

7.2. Processing and printability constraints

Additive manufacturing techniques impose stringent processing requirements that numerous biodegradable polymers struggle to satisfy.[41,65] In FDM, materials must exhibit high thermal stability and precise melt-flow characteristics, properties that are often lacking in low-molecular-weight or moisture-sensitive biopolymers. DIW systems require shear-thinning behavior with rapid structural recovery, whereas DLP platforms depend on resins with low viscosity, high photoreactivity, and uniform filler dispersion.[53,54,57]

Additionally, biodegradable polymers undergo premature degradation or thermal oxidation during printing, resulting in inconsistent performance and reduced shelf life.[25,27,64] Current mitigation strategies, such as *in situ* crosslinking, humidity-controlled storage, and encapsulated additive systems, show promise but require further refinement to achieve cost-effective scalability. As biodegradable polymers are increasingly tailored for platform-specific eco-design, improving their compatibility with AM workflows will be crucial.[26,65,71]

7.3. Regulatory, standardization, and environmental barriers

Despite growing industrial and academic interest, standardized certification pathways for 3D-printed biodegradable products remain poorly defined. Regulatory uncertainty affects products in critical sectors such as medical devices, food packaging, and agricultural films, where degradation behavior must comply with strict safety and performance requirements.

Existing biodegradability tests, such as International Organization for Standardization 14855 for composting or American Society for Testing and Materials D6400 for packaging, are not always well-suited to 3D-printed structures with complex geometries or variable porosity.[115,116] As a result, reported degradation rates and environmental claims can vary considerably. A new generation of application-specific, geometry-aware testing protocols is therefore urgently needed.

Furthermore, environmental assessments rarely account for the full AM life-cycle, including preprocessing steps (e.g., filament drying), toolpath planning, and post-processing operations, all of which influence energy consumption and degradation behavior.

7.4. Economic and infrastructure-related challenges

Biodegradable AM materials, particularly those designed for medical or structural applications, continue to face high production costs, limited scalability, and underdeveloped supply chains. Compared to commodity plastics such as ABS or PET, biopolymers are generally more expensive, and their availability in AM-ready formats (e.g., filament, resin, or ink) remains limited.

These challenges are compounded by the lack of decentralized infrastructure for composting, recycling, and material recovery, especially for post-consumer AM products. Closed-loop systems for PLA or PBS recovery remain in the early stages and require substantial investment in sorting, reprocessing, and material purification technologies. Although policy incentives, circular design mandates, and eco-labeling frameworks could help accelerate adoption, economic and infrastructural inertia remain significant barriers.

7.5. Outlook and future directions

Overcoming the current limitations of biodegradable polymers in AM will require a multidisciplinary strategy that integrates polymer chemistry, materials science, process engineering, and environmental policy. A primary objective is the development of new biodegradable polymers that combine mechanical robustness with intrinsic printability, ensuring compatibility with diverse 3D printing platforms while preserving environmental degradability. The scalable synthesis of photocurable bioresins that meet the demanding performance requirements of light-based systems such as DLP, without compromising sustainability, is also essential.

In parallel, digital tools capable of predicting and optimizing formulation parameters, such as artificial intelligence-driven rheological modeling and structure–property simulations, could accelerate the development of materials that are both high-performing and platform-specific. Incorporating these tools into generative design frameworks may enable real-time feedback among material selection, printability, and end-use degradation behavior.

Standardization efforts must also advance to establish consistent benchmarks for biodegradability and environmental performance, particularly those tailored to the geometric and functional complexity of 3D-printed products. Current protocols do not adequately account for layer-dependent microstructures, infill patterns, or post-processing effects, all of which significantly influence degradation profiles under real-world conditions.

Another important priority is developing regulatory frameworks and circular infrastructure to support the widespread deployment of biodegradable printed products. Certification pathways, material recovery systems, and decentralized composting solutions will need to evolve in tandem with advances in materials and printing. The convergence of policy support, economic incentives, and consumer education will play a decisive role in accelerating the adoption of sustainable AM.

Ultimately, the future of biodegradable polymers in 3D printing depends not only on overcoming technical challenges but also on rethinking product life-cycles, from conception and fabrication to use and reintegration into natural or industrial systems. As environmental regulations become more stringent and digital manufacturing technologies continue to mature, these materials are well-positioned to underpin a new production paradigm centered on circularity, local manufacturing, and ecological compatibility.

8. Conclusion

Biodegradable polymers have garnered increasing interest not only as viable alternatives to conventional plastics but also as foundational materials for a new generation of sustainable AM. Their inherent capacity to degrade in response to environmental or biological stimuli, combined with the design flexibility of 3D printing technologies, enables the integration of ecological responsibility with high functional performance. Across the biomedical, packaging, agricultural, and consumer sectors, these materials provide practical solutions for reducing long-term environmental impact while meeting application-specific requirements for strength, durability, and controlled degradation.

This review examines the current landscape of biodegradable thermoplastics and their composites, emphasizing how structural design, polymer chemistry, and platform-specific processing conditions influence printability, mechanical performance, and degradation behavior. By analyzing the relationships between material architecture and 3D printing techniques, such as FDM, DIW, DLP, and field-assisted methods, we outlined strategies to better align form, function, and sustainability. In particular, design principles such as lifespan tuning through controlled degradation, geometry-driven material efficiency, and platform–material compatibility serve as key tools for advancing environmentally responsible fabrication.

The incorporation of sustainable design strategies, including design for degradation, life-cycle synchronization, and circularity planning, demonstrates that biodegradable 3D-printed materials can evolve from prototyping tools into environmentally responsive end-use products. However, several important challenges remain. Limitations in material properties, processing constraints, and the lack of standardized biodegradability assessment methods continue to restrict broader implementation. In addition, economic barriers and insufficient infrastructure for composting, recycling, and certification hinder large-scale adoption.

To fully realize the potential of biodegradable polymers in AM, sustained multidisciplinary collaboration will be essential. Advances in polymer synthesis, rheological modeling, digital design tools, and life-cycle analysis should be consolidated into cohesive frameworks that guide both material innovation and product development. In parallel, regulatory progress and infrastructural investment are necessary to establish effective waste recovery systems and enable truly circular value chains.

Ultimately, biodegradable polymers represent more than a sustainable material alternative. They signal a shift in how products are conceived, manufactured, and reintegrated into natural or industrial systems. As digital manufacturing technologies continue to advance alongside increasingly stringent environmental requirements, the integration of biodegradable materials with advanced 3D printing platforms is poised to play a central role in shaping a circular, adaptable, and environmentally aligned manufacturing ecosystem. Looking forward, biodegradation engineering will increasingly rely on integrating material chemistry with digitally controlled structural design enabled by AM. This convergence is expected to shift the field from conventional, material-driven degradation toward design-driven degradation systems, in which structure serves as a programmable variable to control degradation behavior beyond intrinsic chemical properties.

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