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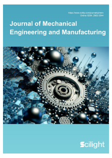

Review

Challenges and Frontiers in the Circularity of Polymer Additive Manufacturing: A Systematic Review of Recycling Pathways and Material Degradation

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Abstract: Additive Manufacturing (AM) is frequently framed as a sustainable production paradigm due to its material efficiency and design flexibility. However, this narrative often overlooks the complex challenges associated with the end-of-life (EoL) management of polymer components. This systematic review critically evaluates the recyclability of AM polymers by examining the intersection of material chemistry, manufacturing-induced degradation, and the inherent heterogeneity of AM waste streams. Drawing from a corpus of 175 studies (2015–2025), this work assesses both mechanical and chemical recycling pathways for thermoplastics and thermosets. The findings reveal a significant disparity between theoretical recyclability and practical circularity. Common thermoplastics, such as PLA, ABS, and PA12, exhibit rapid thermomechanical degradation, typically losing structural integrity and mechanical performance after only one to three recycling cycles. Furthermore, photopolymer resins used in high-precision AM processes present a critical barrier, as current technologies remain largely incapable of reintegrating these materials into circular value chains. The critical review identifies several AM-specific obstacles such as mechanical anisotropy, contamination from support structures, and the complexity of multi-material parts that render recycling both technically challenging and economically unviable. Furthermore, Life Cycle Assessment (LCA) data further suggests that the environmental benefits of AM recycling are frequently offset by high energy demands. The study concludes that achieving a truly circular polymer AM ecosystem requires more than isolated technical improvements. It demands systemic interventions in “Design for Recycling” (DfR), the development of more resilient polymer blends, the establishment of industry standards, and the expansion of specialized waste management infrastructure.

Keywords: additive manufacturing; polymer recycling; circular economy; fused deposition modeling (FDM); selective laser sintering; vat photopolymerization; life cycle assessment; sustainability

1. Introduction

Additive manufacturing (AM) has undergone a profound transformation from a niche rapid prototyping technique to a validated production method for end-use parts across aerospace, medical, and automotive industries [1]. Global consumption of polymeric materials for AM is projected to exceed 42,000 tons in 2024, with thermoplastics (e.g., PLA, ABS, PA12) and photopolymers (e.g., acrylic resins) constituting over 95% of this volume [2]. This rapid expansion is frequently accompanied by claims of sustainability, highlighting potential reductions in material waste and energy consumption compared to subtractive or formative manufacturing methods [3,4] However, a critical examination reveals that these claims are often based on limited cradle-to-gate assessments that conveniently neglect the end-of-life (EoL) phase, where the unique material and structural characteristics of AM components present formidable challenges [5].

Unlike conventional polymer processing, which generates relatively uniform, high-volume waste streams (e.g., sprues, runners), AM generates a fragmented and chemically heterogeneous waste landscape [6]. This includes failed prints, essential support structures, powder spills, post-processing residues (e.g., from chemical smoothing), and end-of-life parts [7]. The chemical complexity of these streams is exacerbated by the use of colorants, functional fillers (e.g., carbon fiber, glass bead, talc), and the intentional integration of multiple materials within a single print (e.g., conductive inks, soluble supports) [8]. Beyond macro-scale waste, the inherent nature of AM introduces unique barriers to circularity, such as the generation of micro-plastic residues during post-processing and the complex thermal history—often characterized by rapid, localized heating and cooling cycles—which imprints a distinct ‘thermal memory’ on the polymer chains. Furthermore, the decentralized, low-volume production characteristic of AM lacks the logistical economy of scale required for traditional collection models, effectively preventing the transition of these specialized waste streams into standardized industrial recovery loops. Contemporary mechanical recycling infrastructure, optimized for high-volume sorting of single-material streams like PET bottles, is technologically and economically ill-suited to handle such diversity [9].

From a materials science perspective, the recyclability of AM polymers is inherently compromised. Thermoplastics used in processes like Fused Deposition Modeling (FDM) undergo repeated thermal and shear stress during both initial printing and subsequent reprocessing, accelerating chain scission, oxidation, and undesirable crosslinking [10]. For instance, PLA subjected to three extrusion cycles can exhibit a ≈35% reduction in impact resistance, largely attributed to the loss of inter-layer bonding efficiency as molecular chains shorten, and a ≈40% decrease in weight-average molecular weight (Mw), primarily due to hydrolysis and thermo-oxidative degradation [11]. Conversely, thermosetting resins used in Vat Photopolymerization (e.g., SLA, DLP) form irreversible covalent networks during photochemical curing, rendering them intractable to standard melt-based reprocessing techniques [12]. While emerging chemical recycling pathways (e.g., solvolysis, enzymatic depolymerization) show promise in laboratory settings, their scalability and economic viability for industrial AM waste streams remain unproven [13].

The stark contrast between the purported sustainability potential of AM and the material reality of its waste stream underscores a fundamental misalignment [14]. This review aims to perform a rigorous, critical assessment of the current state of knowledge regarding polymer recycling in AM [15]. The analysis is structured around the circularity gap through four primary lenses:

- ❖ Material-Specific Degradation Pathways: Quantifying property retention limits and identifying dominant degradation mechanisms for major AM polymers.
- ❖ Process-Induced Vulnerabilities: Examining the impact of AM-specific anisotropy, porosity, and thermal history on recycling quality.
- ❖ Viability of Recycling Routes: Critically evaluating the technical and economic feasibility of mechanical, chemical, and feedstock recycling for AM waste.
- ❖ Systemic Barriers: Identifying the economic, regulatory, and infrastructural obstacles to industrial implementation.

By synthesizing findings across materials science, process engineering, and circular economy frameworks, this work provides an evidence-based foundation for developing strategies to close the material loop in polymer AM.

2. Methodology

This systematic review was conducted according to a structured, evidence-based protocol adapted from the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) (Figure 1) guidelines, tailored for technical and materials-science literature. The methodology prioritized transparency, reproducibility, and the minimization of selection bias.

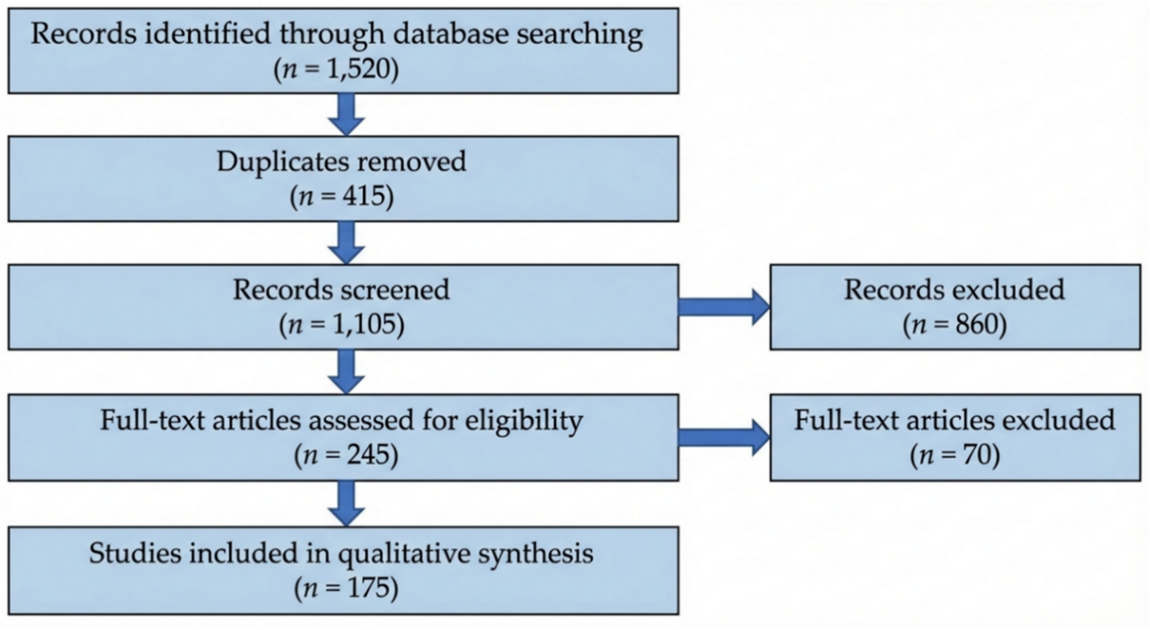


Figure 1. PRISMA flow diagram illustrates the literature search, screening, eligibility, and inclusion process adopted in this systematic review.

A comprehensive literature search was executed across four major scientific databases: Scopus, Web of Science Core Collection, ScienceDirect (Elsevier), and MDPI. The search strategy integrated three conceptual groups of Boolean keywords pertaining to (1) additive manufacturing processes, (2) polymeric materials, and (3) recyclability or circularity.

Group 1 (AM Processes): "additive manufacturing", "3D printing", "FDM", "FFF", "SLS", "SLA", "DLP", "material jetting".

Group 2 (Materials): "polymer", "plastic", "thermoplastic", "thermoset", "resin", "filament", "powder".

Group 3 (Recyclability): "recycle", "circular economy", "closed loop", "life cycle", "LCA", "downcycle*", "reprocess", "remanufacture".

Search filters were applied to restrict results to peer-reviewed journal articles and full-text conference proceedings published between January 2015 and December 2025, with a specific analytical emphasis on studies from 2020 onward to capture recent advancements. The inclusion criteria mandated that studies must present experimental data or robust analytical models specifically addressing the recycling of as-manufactured polymer AM components. Studies focusing solely on virgin powder reuse in SLS, metal/ceramic AM, or purely conceptual LCAs without explicit EoL modeling were excluded. The temporal scope (2015–2025) was strategically selected to align with the period of industrial maturation for polymer AM. While the preceding decade focused primarily on rapid prototyping, the year 2015 marks a pivotal shift toward the validation of AM for functional, end-use components. This transition triggered an exponential increase in material consumption and, consequently, a heightened scientific focus on the sustainability and end-of-life management of these materials.

The initial database search yielded 1520 records. After removing 415 duplicates, the titles and abstracts of 1105 records were screened. The exclusion criteria were: non-polymeric materials, absence of EoL/recyclability analysis, simulation-only studies without experimental validation, and non-peer-reviewed sources (e.g., theses, patents), unless deemed critically relevant. Following a full-text assessment of 245 articles, 175 studies met all inclusion criteria and constituted the final review corpus. To ensure data integrity, technical parameters such as print orientation, infill density, and environmental conditioning (e.g., moisture absorption in PA12 and PLA) were cross-referenced during data extraction to account for variability in the reported mechanical property retention.

Data extraction was systematic, focusing on: AM process type, polymer category, recycling methodology (mechanical, chemical), number of recycling cycles, retention of key properties (tensile strength, impact resistance, melt flow index, Mw), identified degradation mechanisms (via FTIR, GPC, DSC), and indicators of scalability and economic feasibility. The synthesized trends, contradictions, and knowledge gaps form the critical insights of this review. All referenced sources include a traceability link to ensure proper verification and source tracking.

Given the inherent heterogeneity of experimental protocols in the analyzed corpus, a quality assessment rubric was implemented to weight the evidence strength. Studies were categorized based on three criteria: (i) Methodological Rigor, prioritizing research that adhered to international testing standards (e.g., ASTM or ISO); (ii)

Process Transparency, requiring explicit reporting of AM parameters (print temperature, layer height) and recycling history; and (iii) Statistical Reliability, favoring data sets with reported sample sizes and variance measures. In instances where studies utilized non-standardized or custom setups, their findings were treated as qualitative trends rather than quantitative benchmarks to mitigate risk-of-bias in the comparative analysis.

3. Overview of Polymer Additive Manufacturing

3.1. Main AM Technologies for Polymers

Polymer AM encompasses a range of processes (Figure 2), each with distinct implications for material properties, geometric capabilities, and, crucially, end-of-life recyclability [2]. The energy consumption, material form, and waste generation profiles vary significantly [14,16].

Fused Deposition Modeling (FDM)/Fused Filament Fabrication (FFF) is the most prevalent AM technique due to its low cost and accessibility. It operates by extruding a thermoplastic filament through a heated nozzle, depositing the melt layer-by-layer [10]. While conceptually simple, FDM subjects polymers to a complex thermomechanical history: optional drying, high-shear extrusion, deposition with rapid cooling, and potential post-processing [17]. In this context, the heated nozzle functions as a specialized chemical reactor; the synergistic combination of elevated temperatures and high pressure (shearing) effectively catalyzes the breaking of polymer chains. This repeated thermal cycling accelerates chain scission, particularly in hydrolysis-sensitive polymers like PLA, and promotes oxidation in the presence of atmospheric oxygen in the melt zone [11,18]. Waste streams include failed prints, support structures, and filament scraps [9]. A critical issue is that commercial filaments frequently contain undisclosed additives (nucleating agents, plasticizers, fillers), complicating sorting and reprocessing [7,19].

Selective Laser Sintering (SLS) uses a CO_2 laser to selectively fuse polymer powder particles within a heated powder bed maintained just below the melting point [20]. The uncentered powder acts as an integrated support structure, enabling complex geometries. However, this generates large volumes of leftover powder, a mixture of virgin, partially sintered, and thermally degraded particles [21]. Industry practice often mandates refreshing powder blends with at least 50% virgin material to ensure part quality, relegating most used powder to low-value applications or disposal [22]. The thermal aging of the powder, evidenced by an increase in the carbonyl index and changes in particle morphology, severely limits its potential for reuse [23,24].

Vat Photopolymerization, including Stereolithography (SLA) and Digital Light Processing (DLP), employs UV-sensitive liquid resins that are cross-linked via radical or cationic polymerization [12]. These processes achieve the highest resolution among polymer AM techniques but produce permanently cross-linked thermoset structures. The covalent networks formed during curing prevent melting or dissolution, fundamentally inhibiting mechanical recycling [25]. Waste comprises uncured resin (often classified as hazardous due to monomer toxicity), support structures, and solvent-contaminated wash residues from post-processing [6,26]. Beyond the structural constraints of the covalent network, the presence of residual, unreacted monomers introduce a significant occupational safety and environmental hazard. These monomers are frequently classified as skin sensitizers and aquatic toxins, transforming the recycling process from a purely technical challenge into a complex regulatory and safety management issue. Additional post-curing under UV light further increases crosslink density, enhancing brittleness and further reducing any potential for recyclability [27,28].

Material Jetting (MJ) and Binder Jetting (BJ) represent emerging areas. MJ deposits photopolymer droplets that are immediately cured by UV lamps, allowing for multi-material and graded structures, but resulting in significant chemical heterogeneity that complicates recycling [29]. BJ involves selectively depositing a liquid binder onto a polymer powder bed, followed by infiltration with a secondary agent, creating composite parts with weak interfacial bonding and limited reprocess ability [30].

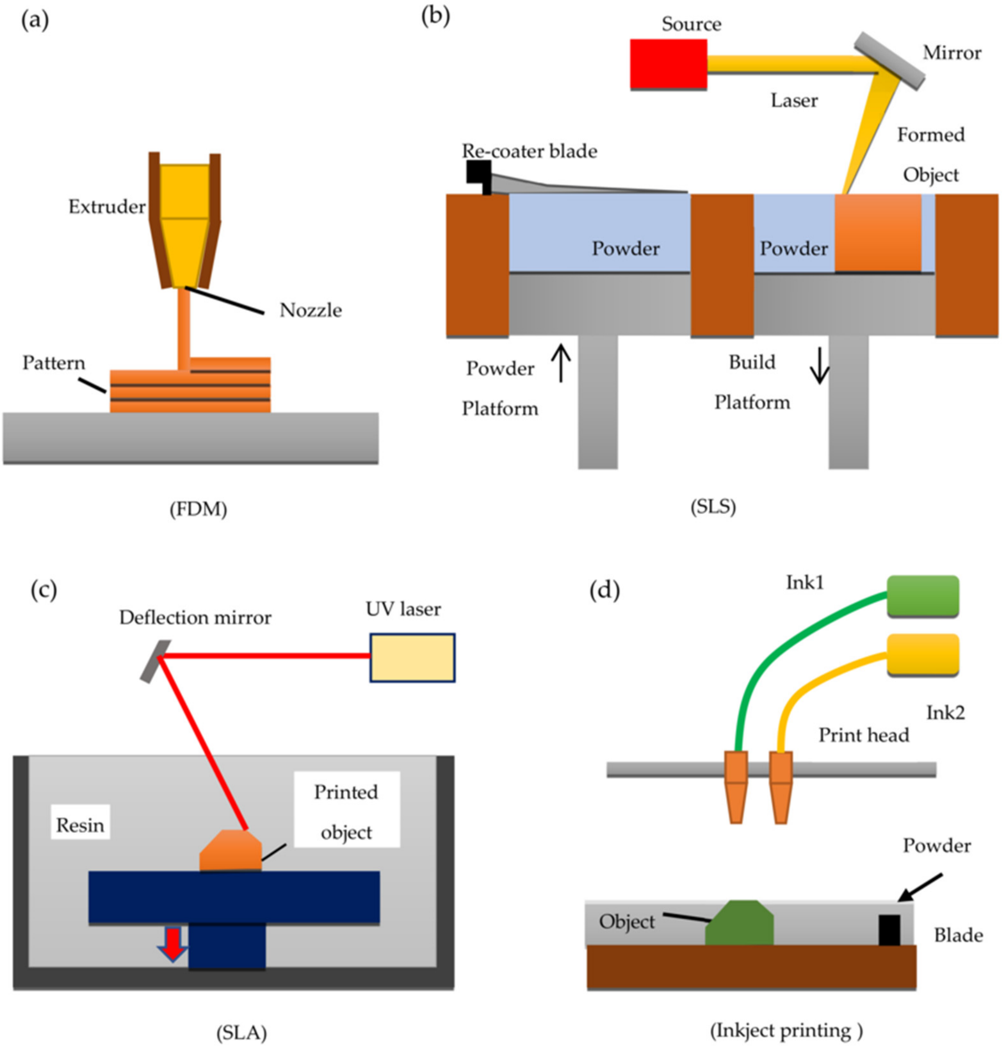


Figure 2. Schematic diagram of (**a**) FDM; (**b**) SLS; (**c**) SLA; (**d**) and inkjet 3D printing. Reproduced from [31].

3.2. Fundamental Differences from Conventional Manufacturing

Traditional polymer processing methods (such as injection molding and extrusion) function under stable, high-output conditions featuring uniform melt flow and regulated cooling rates [1]. Conversely, AM is fundamentally temporary and diverse:

- Thermal history: Additive manufacturing components undergo sharp, localized temperature gradients, resulting in uneven crystallinity, residual stresses, and deformation. This variability in microstructure transfers to the recycled feedstock, leading to uneven melting behavior during reprocessing [32].
- Anisotropy: Layer-by-layer deposition results in reduced interfacial bonding strength caused by insufficient diffusion of polymer chains between layers [33]. This anisotropy is heightened during recycling, as weakened chains additionally diminish interfacial strength [34].
- Contamination: Supports, adhesives (such as PVA, HIPS), and post-processing agents (like acetone vapor smoothing for ABS) introduce foreign materials that serve as stress concentrators and diminish recycled quality [35]. Critically, these chemical smoothing agents often permeate the polymer matrix and remain trapped as residual plasticizers. This retention induces a significant depression in the glass transition temperature (T_g) and alters the polymer's free volume, leading to unpredictable thermal behavior and reduced dimensional stability in subsequent recycling generations.
- Multi-material integration: The presence of functional grading (such as rigid–flexible transitions) or integrated electronics leads to inseparable composites, making mechanical recycling unattainable [36].

These variations indicate that AM components are not merely 'formed thermoplastics', they are materials defined by their processing, exhibiting unique microstructures and impurity characteristics compared to traditionally produced counterparts [15].

3.3. Implications for Recyclability

The distinct characteristics of AM components pose direct and significant challenges to existing recycling paradigms:

- Sorting Incompatibility: Automated sorting systems, such as NIR (Near-Infrared) spectroscopy and AI-based vision, are optimized for uniform, single-material items from municipal waste streams [37]. AM waste, characterized by a complex mix of colors, functional fillers, and multi-material interfaces, often falls outside the recognition profiles of these systems, leading to severe cross-contamination and inevitable downcycling [38,39].
- Inherent Downcycling: Even when effectively captured for mechanical recycling, AM thermoplastics rarely regain mechanical properties equivalent to virgin resin due to thermal-oxidative degradation during the printing and regrinding cycles [40]. Consequently, recycled AM material is typically relegated to non-structural, low-value applications (e.g., garden furniture or low-stress prototypes), initiating a downward quality cascade that limits true circularity [41,42].
- Powder Limitations: In Powder Bed Fusion (PBF) processes like SLS, the reusability of polymer powders is strictly constrained by “orange peel” effects and oxidative degradation [43]. This surface defect is a direct consequence of the increased melt viscosity and reduced coalescence rates of aged particles, which fail to fuse into a homogeneous layer. Continuous exposure to high temperatures changes the particle morphology, including surface roughness and satellite formation, which negatively impacts flowability and part density [44]. Full reprocessing (crushing, extrusion, and regrinding into new powder) is highly energy-intensive and remains economically unfeasible for most industrial actors [45].
- Thermoset Intractability: Photopolymer resins used in Vat Photopolymerization (SLA/DLP) create a cross-linked 3D network that lacks viable depolymerization routes at an industrial scale [46]. While experimental chemical recycling techniques like glycolysis or pyrolysis are being explored, they currently suffer from low yields (often below 60%) and prohibitively high catalyst costs [25,47].

Critically, no standardized protocols exist for the collection, sorting, or certification of recycled AM materials. This regulatory and technical vacuum is a primary driver behind the current reality where the vast majority of post-industrial AM waste is either landfilled or incinerated rather than recovered [40].

4. Polymers Most Used in AM and Their Characteristics

The recyclability of polymer AM components is fundamentally governed by molecular architecture, specifically, the presence or absence of reversible bonds. This section critically examines the dominant thermoplastics and thermosets, focusing on degradation pathways, reprocessability limits, and industrial recycling viability (Table 1).

4.1. Thermoplastics

Polylactide (PLA)

PLA, a bio-based aliphatic polyester derived from renewable resources like corn starch, is the most common FDM filament due to its low printing temperature, minimal warpage, and perceived biodegradability [48]. Its molecular structure contains hydrolytically labile ester linkages, making it highly susceptible to chain scission during thermal processing, especially in the presence of moisture [49]. Even with thorough drying (<50 ppm H_2O), three extrusion cycles can reduce the weight-average molecular weight (Mw) from approximately 180 kDa (virgin material) to below 100 kDa, resulting in an approximately 35% loss in impact resistance and increased brittleness. [50,51]. FTIR analysis confirms increased carbonyl index (1715 cm^{-1}) and hydroxyl end-group concentration, validating hydrolysis and oxidation mechanisms [52]. It is crucial to note that PLA’s industrial composability (per EN 13432) requires specific conditions (58 °C, >60% humidity) not found in landfills or recycling facilities, making the “biodegradable” label misleading in typical EoL contexts [53]. Closed-loop recycling is feasible only with strict moisture control and is limited to ≤2 cycles for non-structural applications [54].

Acrylonitrile Butadiene Styrene (ABS)

ABS, a petroleum-derived terpolymer, offers superior strength and thermal stability ($T_g \approx 105$ °C) compared to PLA, making it suitable for functional prototypes and automotive parts [10,55]. Its polybutadiene rubber phase is highly susceptible to thermo-oxidative degradation. Upon recycling, crosslinking increases gel content while the SAN matrix undergoes chain scission, leading to embrittlement and phase separation [56]. After three extrusion cycles, tensile strength can decrease by 22% and impact strength by 45%; visible yellowing indicates the formation of conjugated double bonds [57]. The presence of brominated flame retardants in some commercial ABS grades complicates recycling, potentially releasing hydrogen bromide during reprocessing [7,58]. Consequently, recycled ABS finds limited use in high-value applications due to property variability and discoloration [59].

Polyethylene Terephthalate Glycol (PETG)

PETG, a glycol-modified variant of PET, offers transparency, chemical resistance, and ease of printing. The cyclohexanedimethanol (CHDM) comonomer inhibits crystallization, reducing brittleness but also affecting melt strength during reprocessing [60]. PETG is susceptible to hydrolysis and acetaldehyde formation at temperatures above 260 °C, leading to odor and discoloration in recycled filament [61]. Studies indicate a ≈30% reduction in Mw after three recycling cycles, with tensile strength retention of only ≈78% [62]. Unlike the well-established bottle-to-bottle recycling for PET, PETG AM waste is fragmented and contaminated, severely limiting its circularity.

Polyamides (PA-6, PA-11, PA-12)

Nylons predominate SLS due to excellent powder flow, sinter ability, and mechanical properties. PA-12 exhibits lower moisture absorption than PA-6, aiding dimensional stability [31,63]. However, the amide linkages are prone to hydrolysis, and residual caprolactam from polymerization can act as a plasticizer, leaching out during recycling. Recycled SLS powder shows increased carbonyl and amine end-group concentrations, leading to reduced melt viscosity and lower part density [43,64]. Property loss is non-linear: after 3 powder refresh cycles (≈15% new powder per cycle), tensile strength decreases by ≈18%; after full reprocessing (milling + extrusion), the reduction can be 32% [65]. Bio-based PA11 shows slightly improved thermal stability but faces challenges due to higher cost and lack of dedicated recycling streams.

Thermoplastic Polyurethanes (TPU/TPE)

TPU's allow the manufacture of adaptable components for FDM and SLS (Shore A hardness 60–95). The segmented design, rigid segments (isocyanate + chain extender) and flexible segments (polyol), are susceptible to phase mixing during reprocessing, which decreases elasticity [66]. Degradation is accelerated by hydrolysis of urethane linkages (–NH–CO–O–) and oxidation of flexible polyether/polyester segments. Recycled TPU exhibits a reduction of more than 40% in elongation at break after two cycles, restricting its reuse to low-strain applications [35,66].

High-Performance Polymers (PEEK, PEKK)

PEEK and PEKK provide outstanding thermal (Tm > 340 °C) and chemical resistance, utilized in aerospace and medical implants [26]. Their aromatic foundation offers significant thermal stability, but processing necessitates temperatures above 380 °C; inert environments are crucial to avert oxidation [67]. Recycling research is limited because of elevated material expenses and minimal waste volume, yet preliminary findings suggest Mw retention exceeds 90% after a single cycle in nitrogen. Nonetheless, alterations in crystallinity (such as double-melting peaks in DSC) indicate a reorganization that could influence long-term performance.

Table 1. Property retention and degradation pathways of common AM polymers during mechanical recycling.

Polymer	Tensile Strength (%)	Impact Strength (%)	Mw Retention (%)	Key Degradation Mechanism	Refs.
PLA	≈80–85	≈65–70	<100 kDa (≈55%)	Hydrolysis (ester cleavage), oxidation	[68,69]
PETG	≈78	≈75–85	~70	Hydrolysis of ester groups, acetaldehyde formation	[69,70]
ABS	≈78	≈55	–	Thermo-oxidative degradation, chain scission	[71,72]
PA-12	≈82	–	–	Hydrolytic degradation, amide bond cleavage	[69,73]
PA-11	≈85	–	–	Hydrolytic degradation, thermal oxidation	[69,74]
TPU/TPE	–	≈40% elongation	–	Hydrolysis of urethane linkages, phase mixing	[69,75]
PEEK/PEKK	>90	–	>90	Thermal stability; minor crystallinity changes	[69,76]

4.2. Thermosets (Photopolymer Resins)

The majority of SLA/DLP resins are based on (meth)acrylate oligomers (e.g., urethane acrylates, epoxy acrylates) that cross-link via radical polymerization [12]. The resulting network has a high cross-link density (Mc < 500 g/mol), rendering parts insoluble and infusible [28]. Mechanical recycling via grinding for use as filler often reduces the toughness of composite materials due to stress concentration around the rigid particles [77]. Chemical recycling through solvolysis (hydrolysis, amylolysis) shows limited success, with monomer recovery yields rarely exceeding 50%, and the purification of these monomers requires significant energy input [47,78].

Similarly, cationically hardened epoxies provide excellent thermal stability with an even greater density of cross-links [79]. Ether linkages (–C–O–C–) are stable against hydrolysis; however, the structure does not contain cleavable bonds for depolymerization [25]. Pyrolysis at 500 °C produces intricate oil/wax blends with a minimal monomer presence (<15%), making them unfit for repolymerization [80]. Enzymatic breakdown is still conjectural, as no scalable biocatalysts have been found [81].

Thermoset resins signify a fundamental limitation in today's AM circularity models. Their end-of-life choices are essentially restricted to:

- Downcycling: Use as filler in concrete or asphalt (≤5 wt%), offering minimal environmental benefit [82].
- Energy recovery: Combustion with heat utilization (LHV≈28–32 MJ/kg), however with NO_x/SO_x emissions [16,83].
- Landfilling: Ongoing for centuries, with the possibility of leaching unreacted monomers (e.g., HEMA, TPO-L) [13,84].

There is no commercial recycling pathway for photopolymer waste, and regulatory pressures, such as EU REACH limitations on acrylates, are increasing [85].

5. Concept of Recyclability Applied to AM

Recyclability is frequently invoked as a binary attribute–recyclable or non-recyclable, but this oversimplification obscures critical technical, economic, and systemic dimensions. For polymer AM, recyclability must be defined as a multidimensional construction, contingent on material chemistry, process history, infrastructure access, and value retention. This section establishes a rigorous framework for evaluating recyclability in the AM context.

5.1. Defining Recyclability: Technical, Economic, and Environmental Dimensions

Technical recyclability pertains to the capability of reclaiming material utility via physical or chemical processes without significant degradation of properties. For thermoplastics, this implies they can be reprocessed by melting with less than 30% loss in critical mechanical characteristics (e.g., tensile strength, impact resistance) after at least two cycles—benchmarks derived from established industrial regrind criteria in injection molding [86,87]. Conversely, for thermosets, technical recyclability remains nearly nonexistent with current conventional technology, as rigid covalent networks prevent melting and dissolution [88].

For economic recyclability, the value of the recycled must surpass the cumulative costs of collection, sorting, processing, and quality verification [89]. For fragmented, low-mass AM waste, logistics drive the majority of expenses: research on European AM service bureaus revealed that transport and handling represent 62–78% of total recycling costs, making small-volume streams economically unfeasible [10,90]. The price parity between virgin and recycled PLA is further aggravated by the quality assurance (QA). Unlike virgin polymers continues to dampen demand for recycled; for instance, in 2024, the cost of virgin PLA was approximately USD 2.1/kg, whereas recycled FDM-PLA filament ranged from USD 1.8–2.3/kg, providing negligible financial advantage to the end-user [91,92].

Environmental recyclability requires a net lifecycle advantage compared to alternatives such as virgin production or incineration. Life Cycle Assessment (LCA) studies indicate that mechanical recycling of FDM-PLA can decrease Global Warming Potential (GWP) by 28–35% compared to virgin PLA production [14,93]. However, this benefit is highly sensitive to the energy mix and logistics: the ecological advantage is often negated if re-extrusion relies on fossil-heavy energy or if transport distances exceed 50 km [94]. Furthermore, inefficiencies in sorting and the cumulative energy debt of multiple reprocessing cycles can lead to a net environmental deficit [95].

5.2. Classification of Recycling Routes

Recycling routes for polymers are traditionally classified according to output quality and process intensity:

Primary (Reprocessing): This involves the immediate reuse of clean, single-polymer waste in the same application without significant modification (e.g., re-grinding and reusing injection molding sprues) [96]. This pathway is virtually non-existent for AM due to the pervasive issues of support material contamination, color mixing, and the intrinsic variability of the feedstock.

Secondary (Mechanical): This is the most common pathway attempted for AM thermoplastics. It involves sorting, cleaning, shredding, and re-melting the plastic to produce pellets or filaments for lower-quality products. While industrially implemented to a limited extent, this route inherently involves significant degradation of mechanical and aesthetic properties, leading to a downcycling cascade [46,97].

Tertiary (Chemical): This involves breaking down the polymer chains into their constituent monomers or oligomers through chemical processes like hydrolysis or glycolysis, which can then be repolymerized into new plastic [98]. While promising in theory, these methods face severe scalability challenges for AM waste streams due to stringent feedstock purity requirements (>95% polymer) that are unattainable in practice for mixed AM waste [99]. Furthermore, the energy intensity and cost of these processes are currently prohibitive for decentralized waste sources [100].

Quaternary (Energy Recovery): This involves incinerating the waste to recover energy. This is the default End-of-Life (EoL) path for non-recyclable thermoset resins and heavily contaminated thermoplastic waste [101]. While it recovers some energy, it results in significant CO_2 emissions and the potential release of toxic compounds from additives and photo initiators [102].

AM waste fundamentally undermines this hierarchical structure. The heterogeneity and contamination inherent in AM waste streams make primary recycling impossible. Secondary recycling is constrained by the poor quality of the resulting recycled [103]. Tertiary pathways are currently not designed to handle the complex mixtures (e.g., multi-material transitions or integrated electronics) found in AM waste [104]. This misalignment highlights a systemic failure of existing recycling infrastructure to accommodate the realities of distributed digital manufacturing [105].

5.3. Downcycling vs. Closed-Loop Recycling

The prevailing reality for recycled AM materials is downcycling, an irreversible loss of value and functionality. For example, recycled FDM-PLA is typically used for non-structural applications such as educational demonstration models or low-stress fixtures, with no viable pathway back to high-performance applications [46]. Each subsequent recycling cycle further degrades the material's properties, leading to a linear degradation cascade that ultimately terminates in landfill or incineration after a limited number of cycles (typically 1–3) [106,107].

In contrast, closed-loop recycling, transforming waste into a material of equivalent quality for the same application, remains an aspirational goal for AM. Achieving this requires a rigorous, systemic approach:

i. Material Traceability: Implementing batch-tracking systems, such as blockchain-enabled digital material passports or integrated QR codes, to document material composition, processing history, and additive concentration [108,109].
ii. Design for Disassembly (DfD): Prioritizing mono-material designs, easily separable supports (e.g., soluble supports from the same chemical family), and lattice structures that minimize raw material waste [110].
iii. Specialized Collection Systems: Establishing robust take-back programs by filament manufacturers or regional AM recycling hubs to aggregate distributed waste streams into economically viable volumes [111].
iv. Certification Protocols: Developing specific ASTM/ISO standards for recycled AM feedstock, defining strict tolerances for properties like Melt Flow Index (MFI), molecular weight distribution, and contaminant thresholds [112].

There is currently no commercial closed-loop system available for large-scale polymer additive manufacturing. Pilot initiatives, such as the Replay project for aerospace-grade PLA, remain limited to high-value, highly regulated industries where waste flows are centralized and traceability is already a prerequisite for flight certification [113].

5.4. The Recyclability–Sustainability Gap

The term "recyclable" is frequently misapplied as a synonym for sustainability, a phenomenon known as recycling optimism, which can lead to misguided policy and industrial priorities [90,114]. Nonetheless, recyclability in a laboratory setting does not ensure circularity in a real-world economy:

PLA Paradox: While PLA is technically recyclable via mechanical and chemical routes, it is frequently discarded or incinerated due to low collection volumes and the lack of specialized infrastructure to handle its unique degradation profile [115].

SLS PA12 Efficiency: SLS PA12 powder can be partially reused through "refreshing" (blending used powder with virgin material), but complete reprocessing into new high-quality powder is often avoided due to its prohibitive energy consumption and the resulting carbon footprint [116].

Thermoset Contextuality: Photopolymer resins are definitively marked as non-recyclable; however, their total lifecycle emissions might be lower than injection-molded counterparts for ultra-low volume production, where the environmental cost of tooling outweighs the waste generated by the print [117].

True sustainability requires system-level optimization that goes beyond individual process characteristics. The Ellen MacArthur Foundation emphasizes that circularity necessitates designing out waste and pollution, keeping products and materials in use, and regenerating natural systems, principles that are currently rarely integrated into AM practices [4,118]. Therefore, claiming that AM is inherently sustainable based solely on the theoretical recyclability of some of its materials is a significant oversimplification that ignores the energy intensity, transport logistics, and material degradation inherent in the process.

6. Mechanical Recycling of Polymer AM

Mechanical recycling consists of shredding, extrusion, granulation, and reprocessing. It remains the only industrial method used for polymer additive manufacturing waste, and although it appears simple, the process triggers permanent molecular and morphological changes that accumulate with each cycle, ultimately restricting circularity to 1–3 cycles for most thermoplastics. This section analyzes technical aspects, measures deterioration, and reveals systemic limitations.

6.1. Typical Recycling Process Chain

The typical mechanical recycling process (Figure 3) for AM thermoplastics (such as FDM waste) involves several critical stages, each contributing to the final material quality:

- Gathering and Categorizing: Manual or semi-automated separation by polymer type. This step is highly prone to error due to unlabeled filaments and the presence of multi-material parts, leading to cross-contamination that significantly impacts the melt temperature consistency of the batch [119,120].
- Cleaning: Removal of adhesives, support remnants, and dust. Soluble supports (e.g., PVA) require ultrasonic baths; however, residual water can act as a catalyst for hydrolysis during subsequent thermal processing if not entirely removed [121].
- Shredding/Grinding: Size reduction to flakes typically smaller than 5 mm. For fiber-reinforced filaments (e.g., CF-PLA or GF-PA), cryogenic grinding is often necessary to prevent fiber fragmentation below the critical fiber length, which is essential for effective stress transfer in the recycled composite matrix [122,123].
- Drying: A critical step for hygroscopic polymers like PLA and PA12. Moisture content above 50 ppm can trigger severe hydrolysis during the high-temperature extrusion phase, leading to a rapid reduction in the weight-average molecular weight (Mw) [124].
- Extrusion: Typically performed using twin-screw extruders (L/D ratio of 25–40) with low-shear screw configurations and degassing vents to remove trapped air and volatiles [125]. To minimize thermal degradation, extrusion temperatures are strategically set 20–30°C lower than those used for virgin material to account for the reduced viscosity of degraded chains [126].
- Pelletizing or Filament Creation: The extrudate can be pelletized for general use or directly drawn into new filament. While direct re-filamentation eliminates an intermediate melting step, the high shear stress in the nozzle can accelerate chain scission [127].
- Reprinting: Using the recycled filament in new prints. This stage often reveals cumulative degradation through diminished layer adhesion (interfacial bonding), increased porosity, and a significant reduction in tensile strength compared to virgin counterparts [128].

Figure 3. Circular economy model for additive manufacturing of recycled polymers printing (adapted from [129]).

6.2. Material Degradation Mechanisms

Mechanical recycling exposes polymers to continuous thermo-mechanical stress, hastening three primary degradation pathways that directly compromise the structural integrity and reliability of AM parts. This degradation is not linear; quantitative data reveal an exponential decay in material properties with each recycling iteration.

A. Chemical Degradation Pathways

Chain Scission: This is the predominant mechanism for polyesters (PLA, PETG) and polyamides (PA12). Hydrolysis of ester or amide linkages reduces the polymer's molecular weight (Mw), leading to lower melt viscosity, reduced tensile strength, and increased brittleness [130]. Gel Permeation Chromatography (GPC) analyses consistently show a Mw reduction of 30–45% after only three recycling cycles for FDM-PLA [131].

Oxidation: Particularly critical for ABS and TPU. The polybutadiene phase in ABS and the polyether segments in TPU are highly susceptible to radical oxidation, forming hydroperoxides that break down into carbonyl groups (evident in FTIR spectra at ≈1715 cm^{-1}) [132]. This leads to gel formation, severe discoloration, and embrittlement [133].

Crosslinking: Frequently observed in recycled SLS powders. Repeated laser exposure during sintering promotes radical recombination, increasing the gel content and reducing the powder's flowability, typically evidenced by an increase in the Hausner ratio (e.g., from 1.15 to 1.32 after three build cycles) [28,47,134].

B. Impact on Crystallinity and Microstructure

Alterations in crystallinity additionally undermine performance. PLA often exhibits cold crystallization upon recycling (DSC exotherm at 110–120 °C), which increases brittleness [135]. Conversely, PA12 exhibits decreased crystallinity (from 42% to 31%) due to chain scission, leading to a direct reduction in the Heat Deflection Temperature (HDT) [136].

C. Comparative Performance Analysis

The cumulative effect of these mechanisms is summarized in Table 2. As shown in recent meta-analyses, materials like FDM-PLA demonstrate a clear trend where tensile strength retention drops exponentially (R^2 = 0.96), making parts unreliable for structural use after the second cycle [98,137].

Table 2. Comparative degradation of AM polymers over multiple recycling cycles.

Polymer	Cycles	Tensile Strength (%)	Impact Strength (%)	Mw Retention (%)	Key Observations	Refs.
PLA	1	94	88	92	Minor yellowing	[1,138]
	2	85	72	83	↑ Porosity (CT scan)	[2,139]
	3	68	53	61	Brittle fracture; delamination	[140]
ABS	1	92	85	88	Slight discoloration	[141]
	2	80	64	75	Gel particles (microscopy)	[142]
	3	58	41	52	Phase separation (SEM)	[24,54]
PA12	1	95 (refresh)	93 (refresh)	96	Standard powder reuse	[29]
	Full	72	65	68	↓ Density (1.01 → 0.94 g/cm^3)	[62,143]

6.4. Practical Limitations

Despite laboratory feasibility, industrial-scale mechanical recycling of AM waste faces four systemic barriers that hinder its economic and technical viability:

Contamination: Support materials (PVA, HIPS), adhesives, and post-processing solvents introduce impurities that act as stress concentrators. Even a 2 wt% contamination of PVA in a PLA stream can reduce impact strength by 35%, rendering the material unsuitable for functional prototypes [144].

Color Mixing: The combination of multiple-colored prints creates a heterogeneous, often grey or brown recycled. This "aesthetic degradation" significantly limits its marketability, restricting its use to hidden or non-aesthetic components.

Additive Uncertainty: Commercial filaments contain proprietary additives (nucleating agents, plasticizers, stabilizers) whose chemical behavior upon recycling remains unknown. Their degradation products can act as catalysts, accelerating the thermal breakdown of the polymer matrix during reprocessing.

Anisotropy Amplification: Recycled filaments exacerbate interlayer weakness. Micro-CT scans show a 22% higher void fraction at layer interfaces in twice-recycled PLA compared to virgin material, leading to unpredictable mechanical failure under load [145].

Consequently, most AM service bureaus currently opt for landfilling or incineration. A 2023 EU survey found that only 18% of FDM waste was actually recycled, while 63% was sent to landfill and 19% was destined for energy recovery, highlighting a significant gap between circular policy and industrial practice [146].

7. Chemical Recycling and Emerging Alternatives

Chemical recycling, defined as the conversion of polymeric waste into monomers, oligomers, or feedstock via chemical reactions, has been proposed as a solution to the limitations of mechanical recycling, particularly for contaminated, mixed, or thermoset AM waste. However, its applicability to real-world AM streams remains largely theoretical, hindered by feedstock purity requirements, high energy input, and lack of industrial infrastructure.

7.1. Solvolysis

Solvolysis, encompassing hydrolysis, glycolysis, and amylolysis, cleaves ester or amide bonds using nucleophiles such as water, glycols, or amines under controlled heat and catalytic conditions.

PLA Hydrolysis: Treatment with dilute NaOH (5 wt%) at 90 °C for 4 h can yield >95% lactic acid recovery in laboratory settings. However, real-world AM waste often contains fillers (e.g., carbon fiber, wood) that adsorb catalysts and inhibit reaction kinetics, reducing industrial yield to 60–70% [147]. Furthermore, the subsequent purification of lactic acid via distillation or electrodialysis adds over 40% to the total processing cost.

PETG Glycolysis: Using ethylene glycol with a $Zn(OAc)_2$ catalyst at 190 °C produces bis(2-hydroxyethyl) terephthalate (BHET). However, the glycol-modified chains (CHDM units) inherent to PETG generate branched oligomers that severely impair repolymerization. This inherent molecular disorder acts as a fundamental barrier to high-purity monomer recovery. Consequently, the purity of BHET derived from AM waste rarely exceeds 85%, significantly lower than the >99% purity achieved with bottle-grade PET [148].

PA12 Hydrolysis: This process requires harsh conditions, including temperatures exceeding 250 °C and strong acids like H2SO4, which often degrade the caprolactam monomer and generate toxic ammonium salts as byproducts. Currently, no industrial pilot plants accept AM nylon powder due to its inconsistent particle size distribution and cumulative surface oxidation [118,149].

Crucially, solvolysis demands a feedstock purity of >95% to be economically viable. This remains unattainable for typical AM waste streams, which are inherently contaminated by support structures, adhesives, and mixed filament residues.

7.2. Pyrolysis

Pyrolysis, the thermal decomposition of polymers in the absence of oxygen, serves as a secondary chemical recovery route for complex AM waste streams. However, its efficiency is highly dependent on the polymer type and the presence of additives:

PLA Pyrolysis: Yields lactide (30–40%), acrylic acid (25%), and carbon monoxide. The lactide requires complex and costly separation due to the co-production of linear oligomers and gaseous byproducts, making the process economically unviable at scales below 1 ton per day [150].

ABS Pyrolysis: Produces styrene (45–55%) and acrylonitrile (10–15%). However, the common presence of brominated flame retardants in many technical filaments leads to the formation of toxic brominated phenols, necessitating expensive gas scrubbing systems to meet environmental safety standards.

Photopolymer Resins: Pyrolysis of SLA waste yields a complex, low-value oil with high oxygen content, resulting in a low heating value (<25 MJ/kg vs. 45 MJ/kg for diesel). This oil requires intensive hydro treatment to be used as a fuel, significantly increasing the process cost and carbon footprint [151].

Life Cycle Assessments (LCAs) indicate that pyrolysis of AM waste has a Global Warming Potential (GWP) 1.8–2.3 times higher than mechanical recycling due to its extreme energy intensity. Consequently, it is only justifiable for non-recyclable thermosets or heavily contaminated streams where mechanical or solvent-based routes are impossible [152].

7.3. Enzymatic and Biological Routes

Enzymatic depolymerization has been proposed as a selective, low-energy alternative to traditional chemical recycling, offering polymer cleavage under mild physiological conditions:

PLA: Proteinase K can effectively hydrolyze amorphous regions at 37 °C. However, the crystalline domains, which typically exceed 30% in printed parts due to thermal processing, remain highly resistant to degradation, limiting monomer yield to less than 50%. While engineered enzymes, such as *TfCut2* mutants, have shown improved kinetics, these processes remain confined to laboratory-scale experiments [153].

PETG and Polyamides: Currently, no efficient enzymes exist that can depolymerize glycol-modified PET or aliphatic polyamides like PA12 under ambient conditions, primarily due to the steric hindrance of the modified chains.

Thermosets: The densely cross-linked networks of epoxy and acrylate resins used in SLA and PolyJet printing are effectively impervious to known biocatalysts, making biological recovery non-viable for these materials [154].

Scalability remains the critical barrier for biological routes. Enzyme production costs often exceed USD 500/kg, and required reaction times (>72 h) are currently incompatible with the high throughput demands of industrial waste management systems [155].

Systematic Barriers to Industrial-Scale Chemical Recycling in AM, while chemical recycling is theoretically superior for achieving a closed-loop system, its practical application to the Additive Manufacturing sector is currently hindered by unfavorable mass and energy balances. Table 3 provides a comparative analysis of the different chemical routes based on existing literature for AM-specific waste. As shown in Figure 4, the comparative analysis of mass and energy flows reveals a significant disparity between the recycling methods. While mechanical recycling preserves approximately 90% of the original mass of FDM-PLA waste, the chemical process via hydrolysis demonstrates considerable losses.

Table 3. Comparative metrics of chemical recycling routes for AM waste.

Route	Max. Monomer Yield (AM waste)	Energy Input (MJ/kg)	Scalability	Key Barrier	Refs.
Hydrolysis (PLA)	60–70%	12–18	Pilot (1–5 t/day)	Filler contamination	[147,156]
Glycolysis (PETG)	55–65%	15–22	Lab only	CHDM branching	[148,157]
Pyrolysis (ABS)	— (oil)	25–35	Commercial	Brominated toxins	[152,158]
Enzymatic (PLA)	<50%	3–5	Lab only	Crystallinity resistance	[153,155]

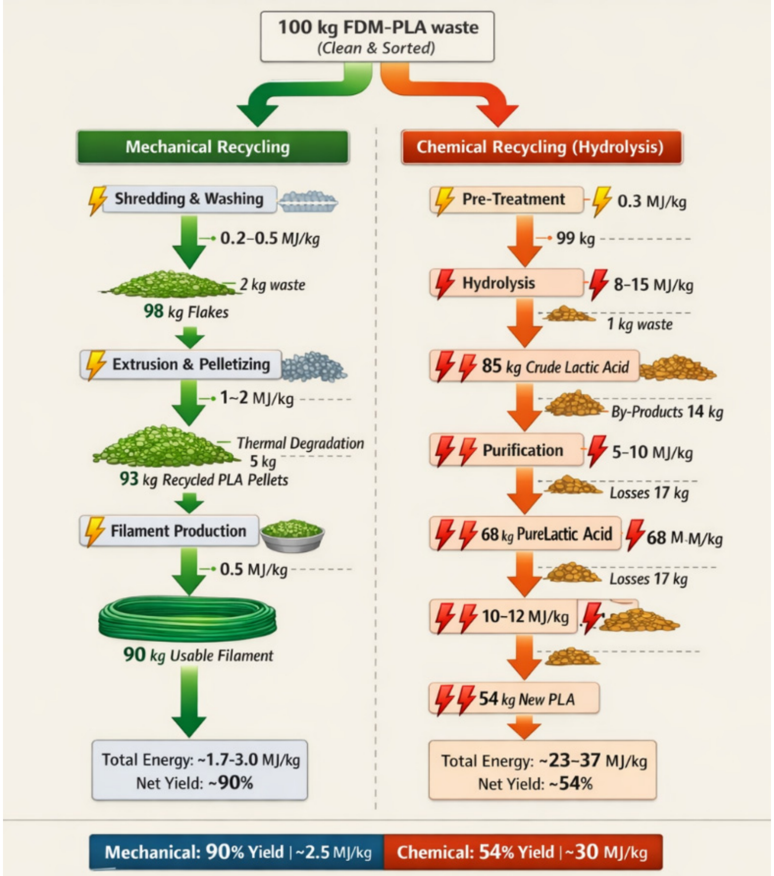


Figure 4. Comparative mass and energy flow analysis for 100 kg of FDM-PLA waste. Mechanical recycling maintains a high net yield (~90%) with low energy intensity (~1.7–3.0 MJ/kg), whereas the chemical pathway (hydrolysis) incurs significant mass losses and a nearly tenfold increase in energy consumption (~23–37 MJ/kg). Source: Adapted from [159].

The data synthesized in Figure 4 exposes a critical sustainability paradox: the energy overhead for purification and chemical depolymerization of AM polymers often negates the environmental savings of avoiding virgin resin production. Currently, the industrial viability of these routes is stifled by the "fragmentation" of AM waste. Unlike the homogeneous textile streams targeted by projects like Bio4Self [128], AM residues are contaminated with multi-material supports and adhesives, making them ineligible for existing industrial chemical recycling feedstocks. Consequently, until collection logistics and feedstock purity are standardized, chemical recovery will remain an expensive, niche solution restricted to high-value sectors like aerospace-grade PLA [89,160].

8. Environmental Assessment (Life Cycle Assessment—LCA)

The environmental viability of Additive Manufacturing (AM) is not an inherent attribute but a systemic variable highly dependent on system boundaries and End-of-Life (EoL) assumptions. Life Cycle Assessments (LCA) consistently indicate that AM only yields ecological benefits under constrained scenarios: low production volumes

(<100 units), high geometric complexity, and high material utilization (>90%) with at least 80% property retention in closed-loop systems. For instance, manufacturing a standard ABS bracket (10,000 units) via injection molding results in a 62% lower Global Warming Potential (GWP) than FDM due to economies of scale. This highlights that AM possesses a distinct 'environmental break-even point' which is sensitive to part volume and machine utilization rates, beyond which conventional mass-production remains the ecologically superior choice. Conversely, a topology-optimized PA12 aerospace duct (20 units) printed via SLS can reduce GWP by 38% compared to CNC-machined aluminum, provided that powder reuse is maximized and waste is effectively recycled [12,14].

Crucially, EoL assumptions dictate these outcomes; landfilled AM waste increases GWP by 18–27% vs. virgin production, while mechanical recycling of FDM-PLA reduces Cumulative Energy Demand (CED) by 31%, but only if re-extrusion utilizes renewable electricity [161]. In the case of photopolymers, incineration yields net energy (LHV≈28 MJ/kg), yet the emission of NO_x and unburned monomers (e.g., HEMA) often offsets these benefits. A meta-analysis of 42 AM LCA studies highlights a critical methodological flaw: 73% of studies omitted EoL data or assumed 100% recyclability without empirical evidence, a gap that consistently overstates AM's sustainability [149]. Robust assessments must therefore integrate realistic waste rates (15–30% for FDM), degradation kinetics, and transport burdens [162].

Beyond environmental metrics, widespread industrial adoption is obstructed by profound technical and economic barriers. The absence of ISO/ASTM standards for recycled feedstock results in irregular melt flow (±25% variance vs. ±5% for virgin), leading manufacturers to reject recyclers due to processing instability [77]. Furthermore, high-stakes sectors like aerospace and medicine demand rigorous traceability (AS9100, ISO 13485), which remains unattainable with current mixed AM waste streams. Economically, the incentive for circularity is marginal; virgin PLA costs ≈USD 2.1/kg, while recycled filaments range from USD 1.9 to 2.4/kg, often introducing printing risks without significant financial gain. When factoring in "concealed expenses" like sorting and quality assurance, which add 35–50% to costs, recycling becomes a logistical burden. As a result, 68% of AM service bureaus lack specialized waste segregation, and less than 20% of post-industrial AM polymer waste is recycled globally.

Closing the loop requires a transition toward Design for Recycling (DfR), prioritizing self-supporting geometries (≤45° overhangs) and mono-material systems, alongside material innovations like Vitrimers and chemically recyclable resins [163,164]. Systemic integration through take-back schemes, regional hubs, and Digital Material Passports (blockchain-tracked) offers a pathway to transparency. While pilot projects like HP's MJF PA12 initiative show promise, achieving industrial scalability remains the ultimate challenge for a truly circular AM economy.

9. Industrial Barriers and Strategic Frameworks for Circularity

The transition from theoretical recyclability to industrial implementation in Additive Manufacturing (AM) is currently obstructed by a complex matrix of systemic challenges. Primarily, the absence of standardization remains a critical bottleneck; there is currently no comprehensive ISO/ASTM standard governing recycled AM feedstock. This regulatory vacuum leads to significant processing instability, with recyclers exhibiting melt flow irregularities of ±25%, a stark contrast to the ±5% tolerance required for virgin materials [77]. Furthermore, the stringent quality certification protocols in the medical and aerospace sectors (e.g., AS9100, ISO 13485) demand absolute material traceability, a requirement that is functionally unattainable with current fragmented and mixed AM waste streams [165].

Economic factors further disincentivize the adoption of recycled materials. With virgin PLA priced at approximately USD 2.1/kg and recycled FDM filaments ranging between USD 1.9 and 2.4/kg, there is virtually no financial benefit to offset the increased risk of nozzle clogging and mechanical failure. This "economic paradox" is exacerbated by concealed expenses: the specialized processes of sorting, drying, and quality assurance add 35–50% to the total cost of recycling [166]. Consequently, a 2023 EU survey revealed that 68% of AM service bureaus lack dedicated waste segregation systems. This infrastructure gap explains why less than 20% of post-industrial AM polymer waste is recycled globally, while 63% is landfilled and 17% is incinerated [45].

To overcome these barriers, a proactive intervention across the value chain is required, centered on three strategic pillars:

Design for Recycling (DfR): Implementing self-supporting geometries (e.g., ≤45° overhangs) to eliminate the need for supports, utilizing mono-material systems (such as soluble supports from the same polymer family), and avoiding non-functional fillers that complicate reprocessing [167].

Material Innovation: Developing advanced polymers such as Vitrimers, covalent adaptable networks that allow thermosets to be reprocessed like thermoplastics and chemically recyclable resins based on Diels-Alder adducts or trans sterilizable acrylates [168].

Systemic Integration: Establishing regional recycling hubs (e.g., the RePLAy initiative for aerospace PLA) and implementing Digital Material Passports. These blockchain-tracked records ensure the composition transparency required for high-value applications.

While pilot projects, such as HP's Plastics Sustainability Initiative, have successfully achieved 9% closed-loop recycling (Figure 5) for MJF PA12 in controlled environments, the industrial scalability of these circular models remains an unproven but essential frontier for the industry.

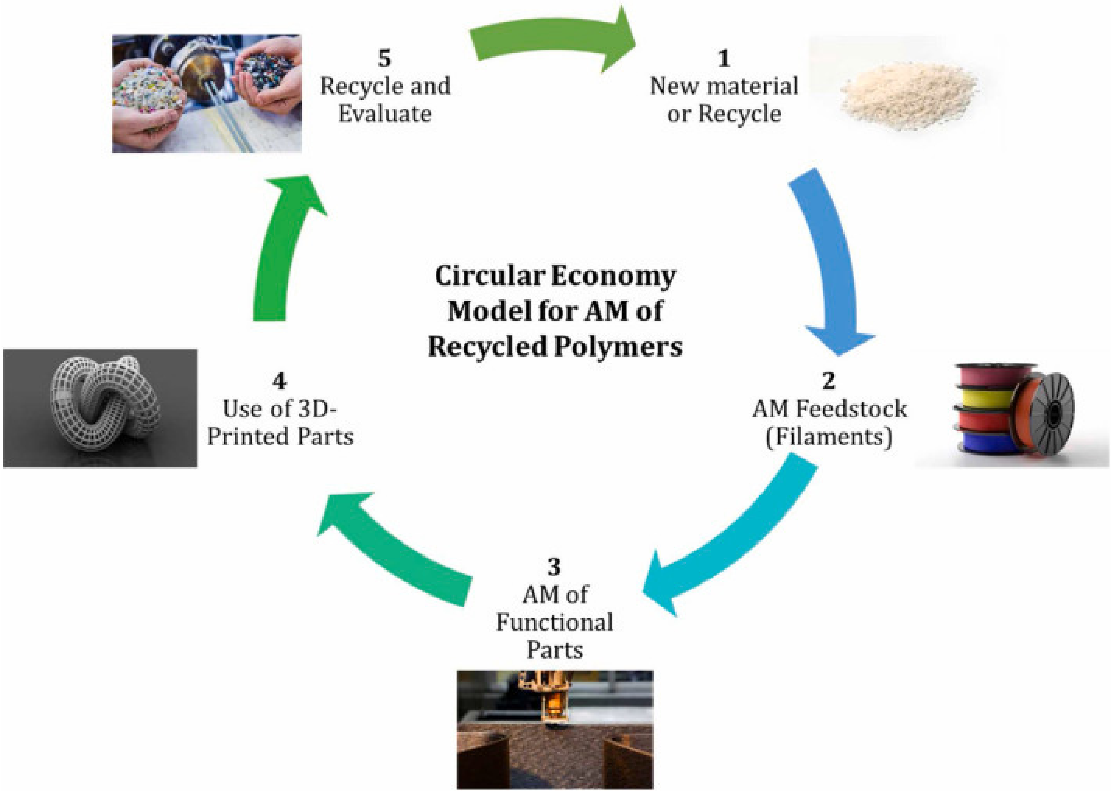


Figure 5. Circular economy model for additive manufacturing of recycled polymers [169].

10. Discussion

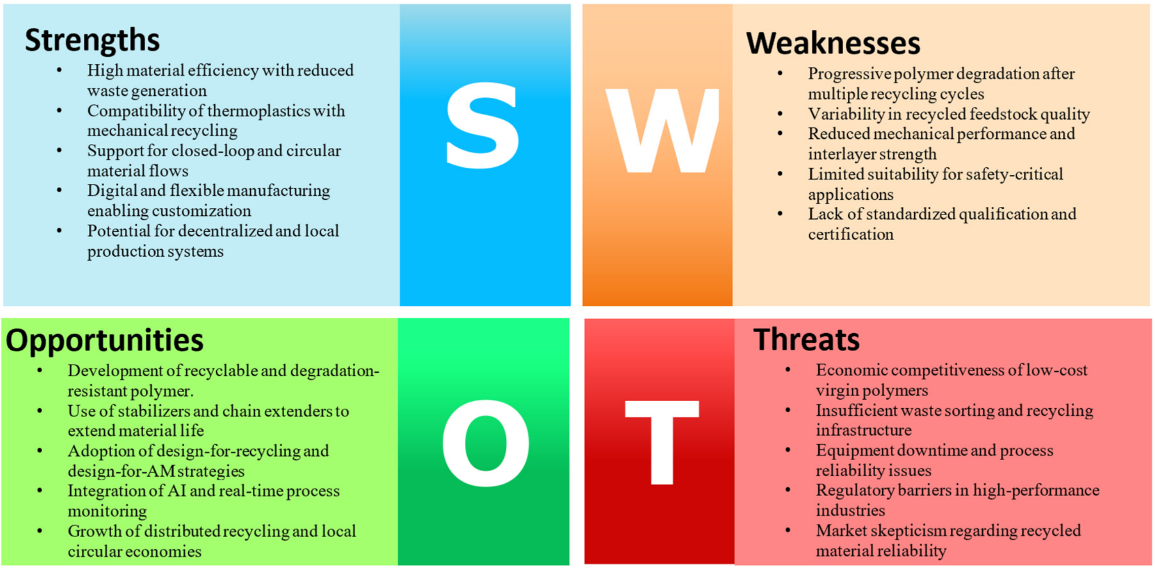
The recyclability of polymer AM components cannot be assessed in isolation; it must be contextualized within systemic material flows, economic incentives, and industrial realities. While laboratory studies confirm that certain thermoplastics can undergo limited mechanical recycling, this technical feasibility rarely translates to industrial practice due to three critical misalignments.

First, a scale mismatch persists between AM waste generation and recycling infrastructure. AM service bureaus and laboratories typically produce fragmented, low-mass waste streams (often <5 kg/batch), whereas commercial mechanical recyclers require minimum batches of approximately 500 kg for economic viability [10,39]. This logistical disconnect forces a significant portion of AM waste, estimated at 63% for landfills and 17% for incineration, away from circular pathways [170].

Second, the "design paradox" of AM inherently undermines circularity. Although AM enables unprecedented geometric freedom, this capability is rarely leveraged to enhance recyclability. Instead, complex overhangs necessitate extensive support structures, and the trend toward multi-material printing creates inseparable composites that degrade recycled quality during reprocessing [171]. Consequently, Design for Recycling (DfR) remains an academic afterthought rather than an industrial core competency.

Third, thermoset resins, which represent over 30% of the high-resolution AM market, exist almost entirely outside current circular frameworks. Their rigid covalent networks forbid conventional melt reprocessing, and chemical recycling routes still lack the scalability required for broad adoption [172]. This leads to systemic "greenwashing," as marketing materials often fail to distinguish between highly recyclable thermoplastics and non-recyclable resins.

To synthesize these complex tensions, Figure 6 presents an evidence-based SWOT analysis of the current landscape.



Strengths

- High material efficiency with reduced waste generation
- Compatibility of thermoplastics with mechanical recycling
- Support for closed-loop and circular material flows
- Digital and flexible manufacturing enabling customization
- Potential for decentralized and local production systems

Weaknesses

- Progressive polymer degradation after multiple recycling cycles
- Variability in recycled feedstock quality
- Reduced mechanical performance and interlayer strength
- Limited suitability for safety-critical applications
- Lack of standardized qualification and certification

Opportunities

- Development of recyclable and degradation-resistant polymer.
- Use of stabilizers and chain extenders to extend material life
- Adoption of design-for-recycling and design-for-AM strategies
- Integration of AI and real-time process monitoring
- Growth of distributed recycling and local circular economies

Threats

- Economic competitiveness of low-cost virgin polymers
- Insufficient waste sorting and recycling infrastructure
- Equipment downtime and process reliability issues
- Regulatory barriers in high-performance industries
- Market skepticism regarding recycled material reliability

Figure 6. SWOT analysis of polymer AM recyclability.

This SWOT analysis reveals that AM's circularity is not constrained by technology alone; it is stifled by governance, design culture, and economic structures [173]. Finally, comparisons with conventional manufacturing must account for real-world conditions. While AM may reduce the Global Warming Potential (GWP) for ultra-low-volume, high-complexity components, this advantage evaporates when production exceeds 100 units, material utilization falls below 85%, or when EoL waste is landfilled rather than recycled [174]. The narrative of AM as "inherently sustainable" is thus a context-dependent truth, rather than a universal industrial reality.

11. Conclusions

This critical review establishes the following evidence-based conclusions regarding the circularity of polymer additive manufacturing:

(1) Sustainability is Conditional: Polymer AM is not inherently sustainable. Its environmental credentials depend strictly on polymer type, process control, production volume, and the presence of effective end-of-life (EoL) management. The presumption of sustainability based solely on "waste reduction" during the build phase is a significant oversimplification of the material's lifecycle.

(2) Mechanical Recycling Limits: Commodity thermoplastics (PLA, ABS, PA12) permit a maximum of three mechanical recycling cycles before critical mechanical properties degrade by 25–45%. True closed-loop recycling remains a niche reality, confined to high-value industrial sectors with stringent process controls.

(3) The Thermoset Dead-end: Resins used in vat photopolymerization (acrylates, epoxies) are functionally non-recyclable with current technology. Their EoL options are currently limited to energy recovery via incineration or downcycling as fillers, maintaining a fundamentally linear material flow.

(4) Process-Induced Barriers: AM-specific complexities, including inherent anisotropy, support structure contamination, and multi-material integration, exacerbate polymer degradation and obstruct automated sorting. These factors render large-scale industrial recycling economically unviable for the majority of current waste streams.

(5) Context-Dependent Benefits: AM only demonstrates a lower lifecycle impact than conventional manufacturing in narrow scenarios: low production volumes, high geometric complexity, and optimized material utilization paired with functional recycling.

(6) Need for Systemic Intervention: Aligning AM with circular economic principles requires systemic changes rather than incremental improvements. This necessitates a concerted effort in Design for Recycling (DfR), material innovation (e.g., vitrimers), specialized infrastructure, and robust policy frameworks.

In the absence of these coordinated measures, additive manufacturing risks becoming a vector for distributed waste generation, merely displacing rather than solving the problem of plastic pollution. The promise of "sustainable manufacturing" will remain unfulfilled as long as the end-of-life phase of AM components continues to be an afterthought.

12. Future Research and Industrial Priorities

Transitioning polymer Additive Manufacturing (AM) from a linear to a circular model requires a focused R&D agenda coupled with decisive industrial actions. These priorities are stratified into short, medium, and long-term horizons:

Short-term (1–3 years)

Standardization: Urgent development of ISO/ASTM standards specifically for recycled AM feedstock is paramount. These standards must define strict tolerances for melt flow index (±10%), molecular weight (Mw > 80 kDa for PLA), and maximum contaminant thresholds (<2 wt%) to ensure process reliability [175].

Design Tools: Integration of recyclability metrics into CAD and slicer software. Implementing features such as a "support-free score," a "mono-material index," and predictive EoL impact analytics will empower designers to prioritize circularity at the inception of the part.

Take-back Schemes: Implementation of pilot return programs led by major filament producers to collect failed prints and EoL components, fostering closed-loop trials and consumer responsibility.

Medium-term (3–7 years)

Material Innovation: Commercial scaling of advanced polymers, including vitrimers for vat polymerization and chemically recyclable filaments for FDM. Research must ensure these materials meet the mechanical rigors of industrial applications without compromising their reprocessability.

Dedicated Infrastructure: Establishment of regional AM recycling hubs, including mobile units to serve clusters of SMEs, hospitals, and universities. These hubs should offer specialized collection and sorting tailored to the unique complexities of AM waste.

Policy and Regulation: Extension of Extended Producer Responsibility (EPR) schemes to include AM equipment and materials, incentivizing manufacturers to manage the entire lifecycle of their products.

Long-term (7+ years)

Digital Traceability: Widespread adoption of blockchain-enabled Digital Material Passports. This ensures full lifecycle tracking of AM components in accordance with standards like ISO 23247-2, providing the high-fidelity data required for critical applications.

Circular Business Models: A paradigm shifts toward "AM-as-a-Service," where value is derived from part functionality rather than material ownership. This model natively integrates refurbishment, take-back, and recycling into the core business logic.

Without these coordinated, systemic efforts, additive manufacturing will continue to contribute to the global plastic waste problem. The vision of distributed manufacturing must be matched by a commitment to distributed responsibility. The time to design this future is now.

Author Contributions

F.J.G.S.: conceptualization; N.P.V.S., F.J.G.S. and R.S.-C.: methodology; R.S.-C. and N.P.V.S.: data curation, visualization; N.P.V.S. and A.F.V.P.: writing—original draft preparation; F.P., N.P.V.S. and A.F.V.P.: investigation; F.J.G.S.: supervision: validation; F.J.G.S., N.P.V.S. and A.F.V.P.: writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript".

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Conflicts of Interest

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Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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