recycling

MDPI

Systematic Review

Closing the Loop Locally: A Systematic Review and Framework for Distributed Recycling of Post-Consumer Plastics with a Focus on HDPE and PP

Johan Montenegro [1], Carmen Castaño [1,2,*], María De Los Ángeles Ortega-Del-Rosario [2,3,4,*], Ricardo Caballero [5], Max Medina [1], Dennis Keiser [5] and Michael Freitag [5,6]

1 Research Group in Industrial Engineering (Giii), Faculty of Industrial Engineering, Universidad Tecnológica de Panamá, Panama City 0819-07289, Panama; johan.montenegro1@utp.ac.pa (J.M.); max.medina1@utp.ac.pa (M.M.)
2 Centro de Estudios Multidisciplinarios en Ciencia, Ingeniería y Tecnología (CEMCIT-AIP), Panama City 0819-07289, Panama
3 Research Group in Design, Manufacturing and Materials (DM + M), School of Mechanical Engineering, Universidad Tecnológica de Panamá, Panama City 0819-07289, Panama
4 Sistema Nacional de Investigación (SNI), Clayton, Panama City 0819-07289, Panama
5 BIBA—Bremer Institut für Produktion und Logistik GmbH at the University of Bremen, Hochschulring 20, 28359 Bremen, Germany; cab@biba.uni-bremen.de (R.C.); ked@biba.uni-bremen.de (D.K.); fre@biba.uni-bremen.de (M.F.)
6 Faculty of Production Engineering, University of Bremen, Badgasteiner Straße 1, 28359 Bremen, Germany
* Correspondence: carmen.castano@utp.ac.pa (C.C.); maria.ortega@utp.ac.pa (M.D.L.Á.O.-D.-R.)

Abstract

This systematic review evaluated technical evidence and system-level conditions for Distributed Recycling and Additive Manufacturing (DRAM) of post-consumer high-density polyethylene (HDPE) and polypropylene (PP). Peer-reviewed journal articles, conference papers, and reviews published from 2020 to 2025 were eligible when they addressed recycled-polymer preparation, feedstock conversion, extrusion-based additive manufacturing, printing performance, or circularity-related implementation; studies focused only on virgin polymers, outside the publication period, or lacking relevance were excluded. Scopus and Web of Science were searched on 17 October 2025 using four thematic strategies. Methodological completeness and applicability were appraised across six domains for the HDPE/PP material-specific evidence. Findings were synthesized narratively and thematically; meta-analysis was not performed because of substantial heterogeneity in feedstock, formulation, equipment, specimens, test methods, and outcomes. The final corpus comprised 119 unique sources: 28 material-specific sources (11 HDPE and 17 PP) and 91 contextual or system-level sources. Of the material-specific subset, 24 provided direct or partially direct recycled experimental evidence and four provided indirect or secondary evidence. Most appraised material-specific sources showed methodological concerns related to feedstock provenance, processing history, parameter reporting, replication, or test conditions. Recycled HDPE and PP could be converted into extrusion-based additive manufacturing feedstocks under study-specific conditions, but the evidence did not support universal processing windows, property ranges, degradation rates, cost competitiveness, environmental superiority, or generalized industrial readiness. Most evidence remained at laboratory or demonstrator scale. The Circular DRAM Viability Framework provides an evidence-informed structure intended to support application-specific diagnosis, monitoring, and qualification.

Check for updates

Academic Editor: Denis Rodrigue

Received: 15 June 2026
Revised: 4 August 2026
Accepted: 5 August 2026
Published: 11 August 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

Keywords: additive manufacturing; circular economy; distributed recycling; filament extrusion; HDPE; recycled polymers; polypropylene

1. Introduction

The linear "take–make–dispose" model of plastic consumption has created a significant global environmental challenge. Since the onset of mass plastic production in 1950, over 8.3 billion metric tons of plastic have been produced worldwide, with nearly 80% accumulating in landfills or contaminating natural ecosystems [1]. The production of virgin plastic is highly resource-intensive, requiring approximately 1.3 billion barrels of oil annually and contributing substantially to greenhouse gas emissions and continued reliance on fossil fuels [2,3].

Despite increased recycling efforts, only about 10% of plastic waste was recycled in 2024 [4]. This limited progress is particularly problematic for post-consumer plastics, which constitute highly heterogeneous waste streams characterized by contamination, material degradation, and significant variability in polymer properties [5]. In contrast to the relatively clean and uniform post-industrial scrap, post-consumer plastics frequently contain residues, inks, and additives that impede recycling processes and reduce the quality of secondary materials [6].

The scale of plastic waste continues to increase, with global plastic production reaching approximately 436 million metric tons in 2023 [7]. High-density polyethylene (HDPE) and polypropylene (PP) together accounted for about 30.1% of global plastic demand, with PP comprising 19% and PE-HD and MD as 12.1% [4]. In comparison to more established recycled-polymer streams in additive manufacturing (AM), such as PET, PLA, and ABS, recycled HDPE and PP remain relatively underexplored despite their high prevalence in post-consumer waste streams. These polymers are particularly relevant as members of the olefin-based polymer family, which constitutes a substantial fraction of global plastic waste and necessitates effective and economically viable recycling strategies to support circular manufacturing applications [8]. Broader reviews of recycled filament production indicate that challenges related to material consistency, process standardization, application-specific deployment conditions, and performance remain significant barriers to the widespread adoption of recycled plastics as feedstocks for AM [9]. The use of post-consumer plastic waste as a feedstock for filament production has received increasing attention due to its potential role in localized material recovery and circular production [10]. However, the semicrystalline structure, low melt strength, and susceptibility to thermal degradation of these polymers complicate their recycling into high-quality filaments [8].

AM, especially when integrated with post-consumer recycled materials, has emerged as a promising approach to address current production and waste-management challenges [11]. Fused filament fabrication (FFF), also known as fused deposition modeling (FDM), is particularly relevant in this context [12]. FFF produces three-dimensional objects by melting thermoplastic filaments and depositing them in successive layers based on computer-aided design (CAD) models [2,3]. Although originally developed for rapid prototyping, AM is now employed across diverse industries, including aerospace, construction, healthcare, and consumer goods, due to its design flexibility, reduced material waste, and potential for decentralized production [2,13,14].

An important development in this area is Distributed Recycling and Additive Manufacturing (DRAM), which addresses plastic waste and low recycling rates by enabling local recycling and decentralized production pathways [15,16]. DRAM facilitates community-based recycling initiatives and supports the transition to a CE approach [15]. Key attributes of DRAM include the reuse of shredded waste, targeted research on prevalent thermoplastics such as HDPE and PP, and reported potential for cost reductions under specific operating and comparison conditions [17]. Despite its potential, DRAM faces persistent technical challenges, such as achieving uniform material properties across heterogeneous feedstocks and optimizing printing parameters for recycled polymers [18,19]. Recent studies have focused on improving material performance, refining recycling processes, and enhancing the durability of recycled 3D-printed components [15]. However, unresolved problems include significant reductions in mechanical performance after recycling, inconsistent filament quality, and the lack of standardized processing protocols for highly variable feedstocks [5,8,9].

Although local recycling can alter transport, material, and logistics requirements, the economic and environmental implications of DRAM depend on factors such as feedstock quality, material yield, washing and drying requirements, energy conditions, labor, equipment utilization, print failures, additives, local logistics, and the selected comparator. Therefore, this review does not establish that DRAM pathways are cost-competitive, environmentally beneficial overall, or ready for industrial-scale deployment.

This review examines the waste-to-filament-to-print pathway for post-consumer plastics, with HDPE and PP serving as the primary analytical lens. Its objectives are to:

- Synthesize direct material-specific evidence on recycled HDPE and PP feedstock preparation, extrusion behavior, filament quality, printability, and reported mechanical and thermal performance;
- Distinguish this direct evidence from contextual or system-level evidence drawn from other polymers, broader DRAM systems, circular economy studies, and the implementation literature;
- Develop an evidence-informed diagnostic structure that organizes reported upstream feedstock conditions, material and process constraints, print-stage outcomes, and system-level assessment considerations.

Accordingly, this review addresses the following question: which reported feedstock, material, and process conditions influence the conversion of post-consumer HDPE and PP into usable feedstocks for extrusion-based additive manufacturing, and which trade-offs require application-specific assessment?

Several systematic reviews have examined the intersection of recycled polymers and AM. Al Rashid and Koç [8] provided a broad overview of needs, challenges, and opportunities for 3D printing with recycled polymeric waste, while Leon-Ayala et al. [9] focused specifically on filament production from recycled plastics. Cruz Sanchez et al. [20] conducted a systematic literature review on plastic recycling in AM, identifying research trends and opportunities for CE.

Prior reviews have documented recurring challenges in recycled-polymer additive manufacturing, including feedstock variability, extrusion instability, thermo-mechanical degradation, shrinkage, warpage, and inconsistent printed-part performance [5,20,21]. The present review does not claim to identify previously unknown physical mechanisms or to establish a new causal theory of recycling and additive manufacturing failure. Instead, it provides an integrative, traceable synthesis that distinguishes material-specific HDPE/PP evidence from the broader contextual literature and organizes reported findings across the waste-to-feedstock-to-print pathway.

The Circular DRAM Viability Framework is therefore positioned as an evidence-informed diagnostic and hypothesis-generating structure. It identifies where feedstock characterization, material and process controls, and print-stage validation are required [21–23]. Application qualification and system-level environmental and economic assessment require additional evidence and clearly defined functional units, comparators, and system boundaries [1,20,24,25]. It does not establish deterministic causal relationships, rank intervention effectiveness, certify implementation readiness, or demonstrate industrial-scale deployment.

This review addresses these gaps through five contributions, which are summarized in Table 1 and detailed throughout the manuscript.

Table 1. Comparison of this review with prior systematic reviews on recycled polymers ind additive manufacturing.

Aspect	Prior Reviews	This Review
Value-chain perspective	Predominantly sequential or material/process focused [8,9,20].	Evidence-informed diagnostic organization across the pathway.
Intervention domains	Not differentiated in the same manner [8,9,13,20,21].	Feedstock, material/process, print-stage, and system-assessment domains.
Role of printing	Primarily treated as a fabrication endpoint [8,9,20,21,26].	Integrative diagnostic and application-qualification stage.
Circularity–viability trade-offs	Discussed indirectly; not operationalized as a unified matrix [1,8,9,13,20,21].	Hypothesis-generating matrix linked to technical, circularity, TEA, and LCA indicators.
Polymer scope	Broad recycled-polymer coverage [8,9,20].	HDPE/PP material-specific synthesis with separately classified contextual evidence.
Implementation relevance	General discussion of deployment barriers.	Maturity, applications, quality, throughput, policy, and business-model requirements.

The CDV Framework developed in this study provides an evidence-informed diagnostic structure for organizing reported feedstock conditions, material and process constraints, print-stage outcomes, intervention options, and system-level assessment requirements.

The remainder of this paper is organized as follows. Section 2 outlines the systematic review methodology. Section 3 presents the study-selection and evidence profile. Section 4 reviews circular economy concepts relevant to additive manufacturing. Section 5 analyzes the waste-to-filament value chain using the CDV Framework; Section 6 examines printing as an integrative diagnostic and qualification stage; and Section 7 discusses the circularity–viability paradox and implementation requirements.

2. Methodology

This systematic review was conducted in accordance with the PRISMA 2020 reporting guideline [27,28]. It examined technical evidence and system-level constraints relevant to local, distributed, and application-specific circular production pathways for post-consumer HDPE and PP. The complete PRISMA 2020 checklist, database-specific executable searches, search log, screening records, full-text exclusion log, source-level extraction registry, methodological appraisal, and coding records are provided in Supplementary Material S1.

2.1. Eligibility Criteria and Evidential-Role Classification

Sources were eligible if they met all of the following criteria: (i) published between 2020 and 2025; (ii) publication as a peer-reviewed journal article, conference paper, or review article; (iii) relevant to recycled-polymer feedstock preparation, distributed recycling, extrusion-based additive manufacturing, filament or pellet conversion, printing behavior, printed-part performance, or circularity-related implementation; and (iv) sufficient technical, process, material, application, or system-level information relevant to the review objectives. Sources were excluded if they addressed only virgin polymers without a recycled material component, were outside the publication window, did not concern the review pathway, were duplicates, or lacked sufficient information to assess topical relevance. Reports not retrieved because the full text was unavailable were documented separately and were not treated as full-text eligibility exclusions. Each source was classified by publication type and evidential role. The final corpus comprised 119 unique sources. Twenty-eight sources were specifically related to HDPE or PP systems: seven were direct recycled experimental sources, 13 were recycled blend/composite sources, four were controlled recycling-cycle sources, and four were indirect material-specific or secondary sources. These categories included 24 direct or partially direct recycled experimental sources and four indirect sources. The remaining 91 sources provided contextual or system-level evidence. Contextual and indirect sources informed mechanisms, implementation conditions, and evidence gaps but were not used to derive direct HDPE/PP property ranges or universal processing thresholds.

Each included source was classified independently by publication type and evidential role. The publication type distinguished original journal articles, conference papers, and review articles. The evidential role distinguished:

- Direct recycled experimental evidence, in which recycled HDPE or recycled PP was a principal material and experimental results were attributable to that material system;
- Blended, composite, or controlled recycling-cycle evidence, in which recycled HDPE or PP was combined with virgin polymer, another polymer, a compatibilizer, filler, or reinforcement, or was evaluated through controlled reprocessing cycles;
- Indirect material-specific or secondary evidence, including HDPE/PP studies based on virgin matrices and reviews specifically addressing HDPE or PP;
- Contextual or system-level evidence, including other polymers, broad DRAM reviews, supply-chain studies, life-cycle studies, circular economy analyses, governance, policy, and the implementation literature.

The first two categories informed the study-level synthesis of materials and processes. Indirect and contextual sources supported interpretation, framework development, and system-level assessment. However, they were not used to establish numerical ranges for recycled HDPE/PP properties, universal processing windows, or performance thresholds.

2.2. Information Sources and Search Strategy

The literature search was structured around four key thematic pillars, each expanded with synonyms and related terms to maximize search sensitivity and coverage:

- Recycled plastic: Focused on polymer types central to this study, especially HDPE and PP, and the broader concept of plastic waste reuse. Related terms: HDPE, PP, polypropylene, high-density polyethylene, and plastic recycling.
- Additive manufacturing: Encompassing digital fabrication methods, such as fused filament fabrication (FFF) or fused deposition modeling (FDM). FFF refers to the open-source term for this process, while FDM is a trademarked name for essentially the same technology; this distinction is maintained to avoid confusion in subsequent sections. Related terms: 3D printing, FDM, and FFF.
- Filament extrusion: The conversion process of recycled polymers into printable filaments. Related terms: Extrusion process, filament production, and material extrusion.
- Sustainability: Addressing the environmental dimension through CE principles, upcycling, and sustainable production. Related terms: CE, sustainable manufacturing, and upcycling.

The database queries combined the defined keyword clusters using Boolean operators to construct four focused search strings. Scopus and Web of Science were selected for their extensive multidisciplinary coverage, high indexing standards, and broad adoption across scientific disciplines. Both databases were searched on 17 October 2025 and are recognized as comprehensive, continuously updated bibliographic databases that ensure robust, reliable literature retrieval [29]. Each search of the four strings targeted a distinct intersection of the main themes, ensuring the comprehensive capture of the relevant literature.

The complete search strategies, database-specific syntax, filters, dates, and retrieval counts are reported in Table 2 and Supplementary Material S1.

Table 2. Search strings by their objective.

Search String	Objective	Query
Plastic Recycling in Additive Manufacturing	To identify research using recycled plastics, especially HDPE and PP, in AM processes	TITLE-ABS-KEY ((“plastic recycling” OR “recycled plastic” OR “HDPE” OR “PP” OR “polypropylene” OR “high-density polyethylene” OR “waste plastic”) AND (“additive manufacturing” OR “3D printing” OR “fused deposition modeling” OR “fused filament fabrication” OR “distributed recycling” OR “distributed recycling via additive manufacturing”))
Filament Production from Recycled Plastic	To find studies focusing on the extrusion of recycled HDPE and PP into filaments for 3D printing	TITLE-ABS-KEY ((“filament” OR “3D printing filament” OR “HDPE filament” OR “PP filament” OR “polymer filament” OR “recycled plastic filament”) AND (“extrusion” OR “extrusion process” OR “filament extrusion” OR “material extrusion”))
Additive Manufacturing with Recycled Plastics	To capture how recycled HDPE and PP are integrated into additive manufacturing processes, particularly through material extrusion	TITLE-ABS-KEY ((“recycled plastic” OR “recycling” OR “HDPE” OR “PP” OR “high-density polyethylene” OR “polypropylene”) AND (“additive manufacturing” OR “3D printing” OR “fused deposition modeling” OR “fused filament fabrication”) AND (“material extrusion” OR “extrusion process” OR “filament extrusion”))
Sustainability in Additive Manufacturing using Recycled Plastics	To explore research on sustainability and circular economy aspects using recycled polymers in additive manufacturing	TITLE-ABS-KEY ((“sustainability” OR “circular economy” OR “sustainable manufacturing” OR “upcycling”) AND (“recycled plastic” OR “recycling” OR “HDPE” OR “PP” OR “high-density polyethylene” OR “polypropylene”) AND (“additive manufacturing” OR “3D printing” OR “fused deposition modeling” OR “fused filament fabrication”))

2.3. Record Management and Study Selection

Records retrieved from Scopus and Web of Science were imported into Citavi 7 (Lumivero, Denver, CO, USA) and exported to Excel for record management, duplicate reconciliation, screening documentation, and source-level tracking. Duplicate and overlapping records were reconciled using available bibliographic identifiers and source-level information. Google Colab was used only to support predefined bibliographic-data handling and preliminary record organization; it did not assess relevance, determine eligibility, classify evidence, extract data, appraise methodological quality, or make inclusion or exclusion decisions.

Title and abstract screening were conducted initially by one reviewer and verified by a second reviewer. Full-text assessment followed the same workflow, and disagreements or uncertain decisions were resolved through discussion and consensus. Reports that could not be retrieved were recorded separately from full-text eligibility exclusions.

VOSviewer (version 1.6.20) was used only after final source selection for descriptive keyword co-occurrence analysis.

2.4. Data Extraction and Management of Missing Information

Data were extracted using a structured source-level form. Extracted variables included publication type, evidential role, polymer system, feedstock origin, post-consumer or post-industrial classification, sorting and preparation route, recycling history, formulation and additives, extrusion route and conditions, filament characteristics, printing conditions, reported defects, mechanical and thermal outcomes, rheological or melt-flow information, and circularity-related or system-level information. Initial extraction and classification were performed by one reviewer and verified by a second reviewer. Discrepancies were resolved through discussion and consensus. Reported values were extracted as presented by the study authors. Units were converted only when conversion was direct and unambiguous. Missing, unclear, or non-comparable information was recorded as "not reported." No values were imputed, reconstructed, digitized from graphs, or inferred from incomplete results. Study authors were not contacted to obtain or confirm additional information.

For the comparative quantitative synthesis, direct or partially direct HDPE/PP material-specific sources were re-examined for reported numerical values, including tensile strength, elongation, modulus, flexural or impact properties, MFI/MFR or viscosity, melting and crystallization temperatures, crystallinity, thermal-degradation indicators, number of recycling cycles, extrusion temperature, printing temperature, bed condition, filament diameter, ovality, and dimensional deviation. Values were extracted only when explicitly reported. Missing values were recorded as not reported and were not estimated or reconstructed. All explicitly reported results compatible with the predefined outcome domains were sought. When multiple results were presented, values were retained with their corresponding material formulation, processing condition, specimen configuration, and test method rather than selecting a single preferred result.

2.5. Methodological Completeness and Applicability Appraisal

A domain-based methodological completeness and applicability appraisal was performed for the HDPE/PP material-specific evidence. The appraisal was designed for heterogeneous materials engineering studies and was not intended as a clinical risk-of-bias instrument. One reviewer conducted the initial appraisal, which a second reviewer verified. Disagreements were resolved through discussion and consensus. No automation tools were used. The evaluated domains were:

- Feedstock origin, identity, and traceability;
- Recycled-content fraction, preprocessing, and recycling-history reporting;
- Formulation, additives, and reinforcement reporting;
- Reproducibility of extrusion, feedstock production, and printing conditions;
- Outcome measurement, test method, replicate number, and variability reporting;
- Use of controls, reporting of unsuccessful conditions, limitations, and application relevance.

Each domain was classified as low concern, some concerns, high concern, or not applicable. Secondary material-specific sources were classified as not applicable for the experimental appraisal. The appraisal informed interpretation and confidence judgments but was not used as an exclusion criterion. Study-level results are provided in Supplementary Material S1.

2.6. Evidence Synthesis, Reporting Limitations, and Confidence

A meta-analysis was not conducted due to substantial differences in material-specific evidence, including feedstock origin, polymer grade, recycled-content fraction, contamination condition, formulation, reinforcement, recycling history, extrusion route, printer configuration, specimen geometry, orientation, test standard, and reported outcomes. Defining a common effect measure would have required combining fundamentally different systems.

Numerical values were reported at the study level and grouped by polymer type, feedstock origin, formulation (neat, blended, or reinforced), processing route, and outcome type. Filament properties were analyzed separately from printed-part properties, and results from additive manufacturing were not combined with those from compression-molded or injection-molded specimens.

Heterogeneity was assessed narratively by comparing polymer type, waste origin, formulation, recycling history, extrusion route, printer configuration, specimen orientation, test method, and application. Missing values were documented as “not reported” and were not estimated, digitized from figures, or inferred from secondary sources.

Reporting limitations were evaluated qualitatively, with particular attention to missing information regarding failed extrusion conditions, rejected filament, unsuccessful prints, negative mechanical results, process yield, economic data, and environmental data. Formal funnel-plot or regression-based publication bias assessments were not applicable, as the review did not include a homogeneous set of effect estimates.

Confidence in each synthesis statement was assessed qualitatively based on evidence directness, methodological completeness, consistency across material-specific sources, and robustness to the exclusion of indirect or methodologically limited evidence. This approach did not constitute a formal GRADE assessment.

Sensitivity analyses were conducted to compare: (i) all 28 HDPE/PP material-specific sources; (ii) the 24 direct or partially direct recycled experimental sources; and (iii) the 10 sources based on clearly identified post-consumer or post-use streams.

2.7. Framework Development and Source-Level Coding

The Circular DRAM Viability Framework was developed using qualitative thematic synthesis of the 119 included sources. This procedure organized reported conditions, constraints, interventions, print-stage outcomes, and system-level assessment requirements based on their position and functional role within the waste-to-feedstock-to-print pathway. The value-chain organization drew on prior DRAM syntheses, while the approach to system-level trade-offs was guided by the broader circularity and life-cycle literature [1,20,22]. The coding procedure did not infer causal necessity, quantify effect magnitude, rank intervention effectiveness, or establish universal implementation rules.

2.7.1. Stage 1: Extraction of Relevant Statements

Statements describing feedstock conditions, material or process constraints, print-stage outcomes, interventions, application requirements, and system-level considerations were extracted from the included sources. The extraction retained the evidential role and material system of each source. Statements from the contextual literature were not treated as direct evidence of HDPE/PP performance.

The reviewed evidence identified relationships and process phenomena, such as degradation-related viscosity changes, melt non-uniformity, crystallization-driven contraction, filament variation, and print-stage defects [30–32]. These observations were retained with their source and material context so that material-specific HDPE/PP evidence could be distinguished from contextual mechanisms reported for other polymer systems.

The literature characterizes DRAM as an interdependent process pathway that includes collection, sorting, cleaning, shredding, drying, melt processing, feedstock formation, and deposition. Technical performance is influenced throughout these stages and is further affected by intrinsic polymer behavior, formulation, equipment, geometry, cooling, bed adhesion, and printing conditions [14,16,33,34].

2.7.2. Stage 2: Inductive Categorization

Extracted statements were grouped inductively based on recurring terminology and their functional roles within the process chain. Statements could be assigned to multiple analytical categories if the source described cross-stage relationships. Categorization did not indicate that one domain necessarily caused outcomes in another.

https://doi.org/10.3390/recycling11080147

Insufficient melt strength, viscosity variation, crystallization response, dimensional inconsistency, interlayer adhesion, and warpage were considered as interacting material–process phenomena. Their placement within the framework indicates the points at which they are observed or controlled, instead of representing a unique analytical position.

2.7.3. Stage 3: Analytical Grouping by Value-Chain Positions and Functional Roles

The codes were organized into four analytical domains:

- Upstream feedstock conditions.
- Material and process constraints.
- Print-stage outcomes and failures.
- System-level assessment requirements.

The domains represent locations and functions within the pathway rather than a deterministic hierarchy. Feedstock, material, processing, printer, geometry, cooling, orientation, and application variables may interact across domains. No domain was interpreted as a necessary or sufficient cause of another.

2.7.4. Stage 4: Identification of Cross-Cutting Trade-Offs

Cross-analysis identified recurring trade-offs among technical performance, material circularity, process complexity, energy demand, cost, and end-of-use recoverability [1,35,36]. These relationships were organized as the circularity–viability paradox. The paradox is an evidence-informed, hypothesis-generating decision structure; it is not a universal law, quantified scoring model, causal hierarchy, or demonstrated system outcome.

2.8. Sankey Diagram Development and Source-Level Coding

For the source-coded relationship diagram, initial binary source-level coding was performed by one reviewer using predefined node definitions and decision rules, and subsequently verified by a second reviewer. Disagreements and ambiguous cases were resolved through discussion and consensus. A source was assigned a value of 1 only if the corresponding condition, intervention, or outcome was explicitly addressed; otherwise, it was assigned 0. Each source contributed no more than once to a specific node or edge, but could contribute to multiple distinct relationships. Edge frequencies were calculated from the finalized 28-source material-specific matrix and were not regenerated through automated text interpretation. The Sankey diagram was produced from reconciled source-level edge counts. Frequency reflects reporting occurrence and co-coding within the reviewed subset, and does not represent effect magnitude, causal strength, technical importance, evidence certainty, or intervention effectiveness.

2.9. Registration and Protocol

This systematic review was retrospectively registered in the Open Science Framework Registries on 6 July 2026 using the Generalized Systematic Review Registration form. The registration is available at https://doi.org/10.17605/OSF.IO/FZKTM. Because the literature search, screening, data extraction, and initial synthesis had commenced before registration, the record does not constitute a prospectively registered protocol. No formal review protocol was prospectively prepared or published before the review commenced. Because registration was completed retrospectively, it cannot serve as a prospective baseline against which methodological amendments can be assessed. Accordingly, no amendments to a prospectively registered protocol are reported.

3. Results of the Systematic Review

3.1. Study Selection and Evidence Profile

The searches identified 12,687 records, comprising 5740 records from Scopus and 6947 records from Web of Science. After removing 269 within-Web-of-Science duplicates and reconciling 4594 additional duplicate or overlapping records in the combined registry, 7824 unique records remained for title and abstract screening. A total of 7660 records were excluded, leaving 164 reports sought for retrieval, of which 44 could not be retrieved because full-text access was unavailable. Full-text eligibility was assessed for 120 reports, and one report was excluded after full-text assessment because it examined ABS/EVA pellet extrusion without recycled-polymer feedstock or evidence directly relevant to recycled HDPE/PP DRAM.

A total of 119 sources were included through database-search routes. The final systematic review corpus comprised 119 unique sources, as shown in Figure 1.

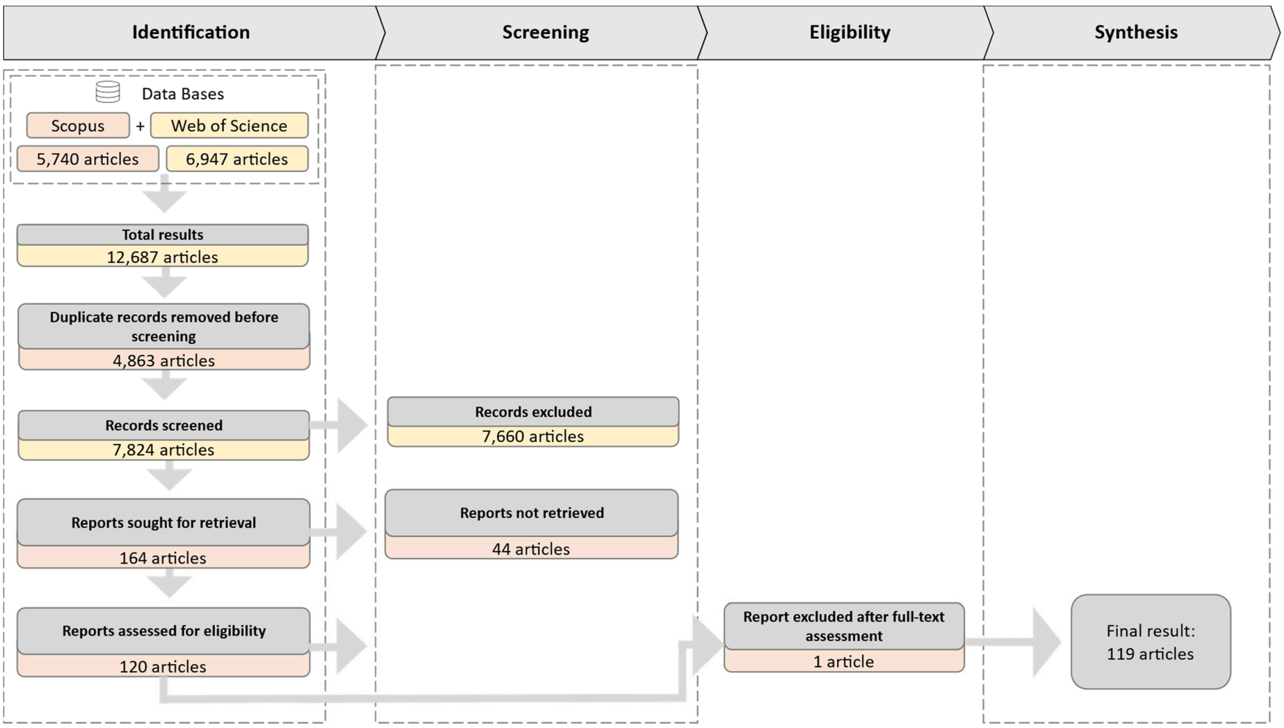

Figure 1. PRISMA 2020 flow diagram.

The final corpus comprised 119 unique sources. Twenty-eight were HDPE/PP material-specific sources, including 24 direct or partially direct recycled experimental sources and four indirect material-specific or secondary sources. The material-specific subset included 11 HDPE and 17 PP sources. The remaining 91 sources provided contextual or system-level evidence. Table 3 reports the disaggregated evidential roles used in the synthesis.

3.2. Bibliometric Mapping of the Evidence Base

A keyword co-occurrence visualization was generated with VOSviewer version 1.6.20 to describe thematic relationships within the final corpus. The visualization, input records, thesaurus, and run documentation are archived in Supplementary Material S1. This analysis provides contextual background only and was not used to derive material-specific HDPE/PP conclusions, causal relationships, or intervention rankings.

Table 3. Evidential role distribution across the 119 sources included in the review.

Evidential Role	HDPE	PP	Total	Use in the Review
Direct recycled experimental evidence	2	5	7	Main quantitative synthesis
Recycled blends/composites	6	7	13	Formulation-specific synthesis
Controlled recycling-cycle evidence	1	3	4	Cycle-response analysis
Indirect material-specific/secondary	2	2	4	Interpretation only; no direct ranges
Contextual/system-level	—	—	91	Mechanisms, implementation, and circularity
Total	11	17	119	—

3.3. Methodological Quality, Reporting Bias, Confidence, and Sensitivity Analysis

To enhance transparency in interpreting the reviewed evidence, Table 4 summarizes the appraisal conducted at the synthesis level. For each principal synthesis, the table identifies the contributing evidence base, the assessed concern regarding missing or selectively reported results, and the resulting confidence in the evidence. These judgments were intended to support interpretation of the findings rather than to exclude sources from the review.

Table 4. Synthesis-level evidence appraisal, reporting-bias concern, and confidence in the evidence.

Synthesis	Principal Evidence Base	Reporting-Bias Concern	Confidence
Feedstock heterogeneity and pretreatment	14 material-specific sources plus contextual process evidence	Some concerns	Moderate
Extrusion stability and filament quality	18 material-specific sources	Some concerns	Moderate
Thermo-mechanical degradation and multi-cycle behavior	7 material-specific sources	Some concerns	Low
Print-stage failures and printed-part performance	20 material-specific sources	Some concerns	Moderate
System-level assessment considerations and circularity	8 material-specific sources plus contextual/systemic evidence	High concern	Very low
Circularity–viability paradox	Direct blend/composite sources plus contextual circularity evidence	Some concerns	Low

The methodological completeness and applicability appraisal identified three sources with low concern, 24 with some concerns, no source with high concern, and one secondary source for which the experimental appraisal was not applicable. The most common limitations were incomplete reporting of feedstock provenance, limited characterization of prior thermal history, incomplete reporting of process parameters, and restricted replication or test-condition reporting.

The reporting-bias assessment identified concerns across the material-focused syntheses because unsuccessful extrusion or printing conditions, rejected filament batches, and negative results were not consistently reported. Reporting-bias concern was high for system-level assessment considerations because HDPE/PP-specific life-cycle and techno-economic evidence remained limited.

Confidence was moderate in the qualitative conclusions regarding feedstock heterogeneity, extrusion stability, and print-stage failures. Confidence in multi-cycle degradation was low because its direction and magnitude were material and route dependent. Confidence was very low for system-level assessment considerations, which relied substantially on contextual evidence and lacked comparable application-specific life-cycle and techno-economic assessments.

The sensitivity analysis showed that the four principal analytical domains remained identifiable when the synthesis was limited to the 24 direct or partially direct recycled experimental sources. Feedstock characterization, material and process control, crystallization-related dimensional effects, and print-stage integrity remained recurring themes. In contrast, economic, environmental, governance, policy, and business-model considerations relied more heavily on contextual or system-level evidence and were therefore treated as assessment requirements rather than as demonstrated HDPE/PP outcomes.

When the synthesis was limited to 10 clearly identified post-consumer or post-use streams, the principal analytical domains remained identifiable. However, conclusions about mechanical enhancement and multi-cycle performance became more limited because several reinforcement and recycling-cycle studies used controlled, industrial, or composite feedstocks.

4. Circular Economy as a Framing Concept for Additive Manufacturing

The shift from a linear "take–make–dispose" model to regenerative production systems has established the CE as a central paradigm in sustainability research [22]. In this study, the CE serves as the conceptual foundation for distributed polymer recycling through AM. Here, the CE is approached as a systemic framework that closes material loops, retains value, and enables localized manufacturing, thereby extending beyond its interpretation as a standalone sustainability concept.

4.1. Defining Characteristics of the Circular Economy

The CE is characterized by closed-loop material flows, resource efficiency, and regeneration, in which materials are continuously reused, repurposed, or recycled to minimize waste and extend their life cycles [8]. Implementation occurs at three interconnected levels: the micro level (products and firms), the meso level (industrial symbiosis and eco-industrial networks), and the macro level (cities, regions, and national systems). This multi-level approach facilitates the simultaneous pursuit of environmental sustainability, economic considerations, and social equity [37,38].

Decentralization is a fundamental component of the CE in polymer recycling. Distributed recycling systems, especially when integrated with AM, may reduce transport requirements and support localized value creation by positioning recycling and manufacturing activities near waste-generation sites; the net environmental outcome depends on the electricity mix, preprocessing burden, transport boundary, rejected material, and comparator [39]. Upcycling is a key strategy within the CE, transforming waste materials into products of equal or greater value. However, repeated mechanical recycling can alter polymer properties. The direction and magnitude of these changes depend on polymer grade, formulation, contamination, processing history, and the property measured. Such changes can affect the quality and performance of secondary products, underscoring the need for rigorous material characterization and process optimization to maintain functionality across multiple life cycles [40].

Life-cycle assessments further demonstrate that recycling phases can contribute disproportionately to the overall environmental impacts across the product life cycle, emphasizing that circularity strategies must be critically evaluated in terms of actual environmental performance rather than assumed sustainability benefits [41,42].

4.2. Circular Economy Approaches Enabled by Additive Manufacturing

The integration of AM with CE principles may support localized and on-demand polymer-recycling pathways. Its logistical and environmental implications remain case-specific and depend on feedstock supply, energy and water use, transport, material yield, failed production, and the selected reference system [8,43]. DRAM represents a structured CE pathway that includes material recovery, preparation, compounding, feedstock production, printing, and quality assurance [20]. Within this pathway, filament extrusion constitutes a critical enabling technology. As the backbone of FFF, extrusion supports both the fabrication of customized components and closed-loop recycling by converting waste plastics into printable feedstock [44].

Decentralized AM facilities, such as fab labs and living labs, exemplify how DRAM systems can transform local waste streams into functional products. These facilities also promote knowledge transfer, stakeholder collaboration, and the involvement of small- and medium-sized enterprises (SMEs) [20,45,46].

Commonly reported DRAM characteristics include local material recovery, feedstock preparation, extrusion- or pellet-based conversion, and additive manufacturing of application-specific parts. Some contextual sources report potential cost or environmental advantages under specific system boundaries and operating assumptions; these findings cannot be generalized to all recycled HDPE/PP DRAM pathways. The extended contextual summary is provided in Supplementary Material S1.

Achieving the benefits of AM-enabled circular systems requires supporting mechanisms such as material traceability, performance monitoring, and governance structures to ensure consistent quality and accountability throughout the value chain [21]. These outcomes depend on process selection, production scale, and material quality, highlighting the importance of life-cycle-level CE integration rather than isolated process optimization [47].

Beyond technological factors, CE implementation relies on organizational and business-model drivers. Key enablers comprise firm-level environmental commitment, sustainability performance measurement, compliance with recycled-material standards, optimization of recycling processes, and adoption of cost-driven operational models. Circular business-model frameworks highlight the interconnections between governance structures, feedback control systems, and recycling-oriented decision-making, emphasizing the necessity for integrated economic, environmental, and managerial approaches [35].

Market dynamics also affect the adoption of recycled materials, as closed-loop supply-chain analyses indicate that material suppliers may avoid producing high-quality recycled filaments due to pricing pressures, perceived quality risks, and demand uncertainty [48]. The increasing availability of commercially accessible filament extruders has lowered entry barriers for waste-to-filament conversion, and has been associated in contextual studies with potential self-sufficiency, cost-related benefits, and public awareness; these outcomes are not established universally for HDPE/PP DRAM pathways [23].

Although AM offers advantages in customization and material efficiency, its role in circular manufacturing systems is increasingly seen as complement to, rather than a substitute for conventional processes. Established techniques, including injection molding, compression molding, and extrusion, continue to dominate high-volume production contexts. Therefore, the environmental performance of AM-based circular strategies should be compare with conventional manufacturing alternatives and specific application scenarios [49,50]. This review specifically examines the technical feasibility of the DRAM pathway for HDPE and PP, acknowledging that its ultimate viability depends on this broader systemic context.

5. Deconstructing the Filament Value Chain: A Framework for Advancing Innovation in Plastic Upcycling

The production of consistent, application-suitable feedstocks from post-consumer plastic waste remains a central technical challenge in distributed recycling. Although individual process steps such as sorting, shredding, extrusion, and spooling are well documented, the literature frequently presents them as a linear sequence rather than as interacting stages within a material–process system.

In recycled HDPE and PP pathways, feedstock preparation, extrusion behavior, filament quality, printing response, and part performance are linked but not deterministic. Cleaning, drying, particle-size control, thermal history, polymer identity, formulation, cooling, bed adhesion, geometry, printer configuration, and printing parameters may all influence the outcome. Therefore, the value chain should be interpreted as an interconnected diagnostic pathway rather than as a single causal cascade.

Within this system, feedstock preparation is a critical operational stage preceding extrusion. HDPE/PP material-specific evidence indicates that post-consumer HDPE and PP may require cleaning, drying, and particle-size reduction before melting because these preprocessing steps can affect melt behavior, extrusion stability, and filament quality [11,31,32]. This perspective reinforces a central premise of the CDV Framework: material properties, process conditions, and operational decisions interact to shape local DRAM performance under specific application conditions.

Recycled polymers have been widely investigated for AM applications, with studies reporting successful conversion of HDPE [51,52], PP [31,53], and other thermoplastics into printable filaments, such as PLA [33,43,54], PET [55–57], PETG [58], and HIPS [59]. Contextual studies involving PLA, PET, PETG, and HIPS are included here to illustrate broader processing phenomena, identify recurring material and process constraints, and support mechanistic interpretation; however, HDPE and PP remain the primary analytical focus of this review.

Among these materials, HDPE and PP are emphasized in this review due to their prevalence in waste streams and the technical challenges associated with their reprocessing. The value chain begins before melting, with feedstock preparation playing an important role in shaping downstream processing conditions. HDPE/PP material-specific evidence reports that source-defined recycled materials, such as HDPE bottle caps, require washing, drying, and shredding before extrusion, while process mapping identifies pretreatment as a distinct operational phase [11].

To organize these relationships, this review proposes the Circular DRAM Viability (CDV) Framework. The framework is not presented as a new causal theory or a validated predictive model. Instead, it provides an evidence-informed diagnostic structure for organizing reported feedstock conditions, material and process constraints, print-stage outcomes, intervention options, and system-level assessment requirements.

The framework is built on three principles:

- Diagnostic organization: Reported conditions and outcomes are grouped according to their location and role within the waste-to-filament-to-print pathway.
- System interaction: Feedstock, material behavior, extrusion conditions, print settings, geometry, cooling, and adhesion can interact across stages.
- Application-specific assessment: Intervention priorities depend on the feedstock, equipment, intended part, acceptance criteria, and local operating context.

The CDV Framework was developed through the analytical procedure described in Section 2.7 and is depicted in Figure 2. The complete coding matrix, source-level mapping, and supporting evidence used for framework development are provided in Supplementary Material S1. Section 5 introduces the framework as a structured analytical tool for mapping reported conditions, constraints, outcomes, and intervention options across the filament value chain.

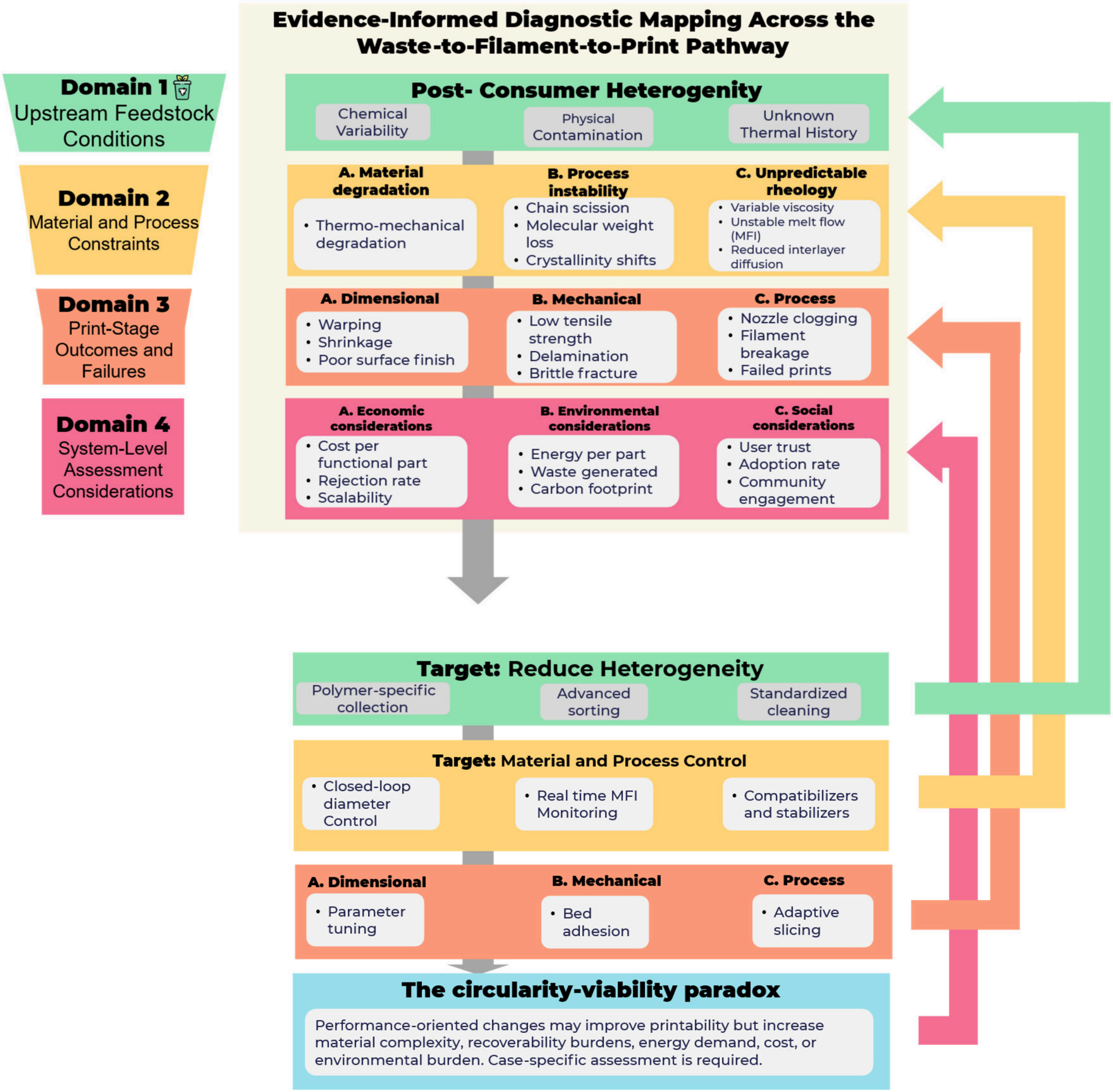

Figure 2. Circular DRAM Viability Framework: an evidence-informed diagnostic structure for examining relationships among upstream feedstock conditions, material and process constraints, print-stage outcomes, and system-level assessment considerations in local recycled HDPE/PP pathways. Arrows indicate analytical linkages and should not be interpreted as deterministic causal pathways, quantified effects, or intervention rankings. Cross-cutting modifiers may influence outcomes across all domains.

The CDV Framework is an evidence-informed diagnostic synthesis rather than a validated causal model. It organizes reported conditions and outcomes into four analytical domains: upstream feedstock conditions, material and process constraints, print-stage outcomes and failures, and system-level assessment considerations.

The framework does not assume that a condition in one domain is necessary or sufficient to produce an outcome in another. Feedstock conditions may influence extrusion and printing behavior. However, intrinsic polymer properties, formulation, recycling history, geometry, print orientation, cooling, bed adhesion, printer configuration, and processing parameters may also modify or independently influence the outcome.

Accordingly, the framework should be used to guide diagnosis, monitoring, and future hypothesis testing. It does not quantify causal effects, establish universal intervention priorities, demonstrate industrial readiness, or guarantee that an upstream intervention will resolve a downstream printing limitation.

The monitoring and control points shown in Figure 3 correspond to potential intervention locations within the upstream-feedstock and material/process domains of the CDV Framework. For example, moisture and contamination assessment relate to upstream feedstock conditions, whereas extrusion temperature, cooling, melt-flow behavior, and filament diameter relate to material and process constraints. These points are not ranked by universal importance; their priority depends on the feedstock, equipment, intended application, and locally defined acceptance criteria.

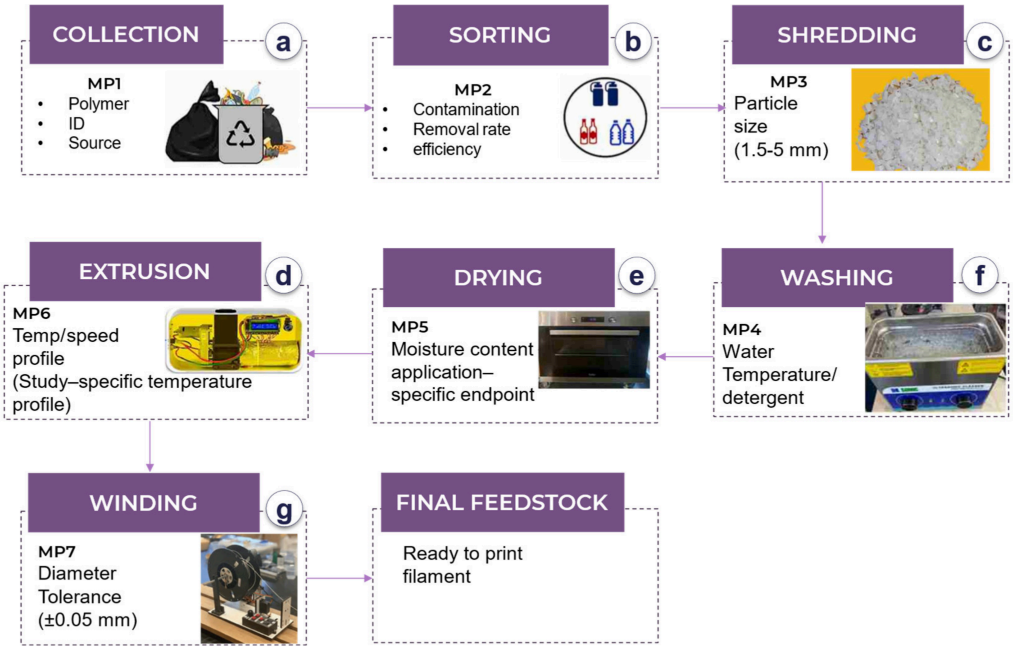

Figure 3. Integrated waste-to-filament process chain for distributed recycling of HDPE and PP. The diagram illustrates the collection, sorting, shredding, washing, drying, extrusion, winding, and feedstock production stages. Monitoring points identify process variables requiring local measurement to maintain feedstock quality and extrusion stability. Image sources: (**a**) Ref. [60]; (**b**) Ref. [60]; (**c**) Ref. [54]; (**d**) Ref. [61]; (**e**) Ref. [16]; (**f**) Ref. [16]; and (**g**) Ref. [2]. The indicated control points are examples of variables requiring application-specific monitoring; they are not universal acceptance thresholds.

5.1. Polymer Scope and Evidence Structure

This review uses HDPE and PP as its primary analytical lens. The 28 HDPE/PP material-specific sources comprise seven direct recycled experimental sources, 13 recycled blend/composite sources, four controlled recycling-cycle sources, and four indirect material-specific or secondary sources. Numerical synthesis was limited to direct or partially direct evidence and retained formulation, feedstock, processing, and testing context. The 91 contextual or system-level sources were used to interpret broader mechanisms, implementation requirements, policy, circularity, and research gaps, but not to establish HDPE/PP-specific property ranges or universal processing windows.

5.2. Comparative Quantitative Evidence for Recycled HDPE and PP

The material-specific evidence includes mechanical, thermal, rheological, dimensional, and process-related values, but these values are not directly comparable across studies. Recycled HDPE and PP were investigated using different waste streams, formulations, additive contents, recycling histories, conversion routes, printer systems, specimen geometries, orientations, and test methods.

Table 5 presents representative study-level quantitative evidence rather than pooled material property ranges. Neat recycled polymers, blends, composites, and controlled recycling-cycle studies are identified separately in the interpretation. The complete 28-source extraction matrix is provided in Supplementary Material S1.

Table 5. Representative quantitative evidence reported for recycled HDPE and PP in extrusion-based additive manufacturing.

Outcome Domain	Recycled HDPE: Representative Evidence	Recycled PP: Representative Evidence	Interpretation Boundary
Mechanical response	Bottle-cap rHDPE with 10 wt% glass powder: Filament tensile strength 25.52 MPa; printed tensile 13.94 MPa; flexural 41.15 MPa [11]. rHDPE filament study: Ultimate tensile strength 19.02 ± 0.35 MPa and modulus 605 ± 120.8 MPa [33].	Post-consumer rPP packaging: Tensile strength 20.73 MPa and modulus 806.35 MPa [62]. WEEE-rPP streams: Tensile strength 19.7–21.4 MPa and modulus 1.379–1.837 GPa [63]. Controlled-contamination rPP: Modulus 1180 ± 35 MPa and yield stress 22.71 ± 1.22 MPa [34].	Values differ by formulation, reinforcement, printing orientation, specimen geometry, porosity, and test method.
Elongation and ductility	Comparable elongation values for neat post-consumer rHDPE were not consistently reported. Composite and route-comparison studies showed strong dependence on fiber fraction and consolidation quality [64,65].	After-use mask-derived PP formulations reported 2–3% elongation versus 52% for a commercial PP reference [49]. An rPP/HDPE formulation reported an approximately 66% improvement in elongation under a mixing-screw strategy [66].	Ductility is particularly sensitive to blending, fillers, porosity, raster orientation, and interlayer bonding.
MFI/MFR and rheology	Recovered nautical HDPE showed MFI 6.32 g/10 min versus 3.61 g/10 min for the virgin comparator [51].	Low-shear viscosity differed by approximately twofold between visually similar recycled PP feedstocks [67]. Composition, processing history, filler content, and stabilizer condition further influenced melt response [30,67].	MFI and rheological results are comparable only when temperature, load, shear range, and material conditions are reported.
Thermal response	Recovered HDPE showed crystallinity of 54% versus 48% for virgin HDPE and earlier degradation at approximately 365 °C versus 422 °C [51].	Controlled PP reprocessing showed Tm decreasing from 169.5 to 165.6 °C, Tc from 105.8 to 99.8 °C, and crystallinity from 44.61% to 40.61% [68].	Thermal values depend on grade, additives, contamination, heating rate, and prior thermal history.
Recycling-cycle response	Up to three cycles were reported for an HDPE/MWCNT composite; the response was formulation-specific and does not establish a neat-rHDPE cycle trend [69].	Across six PP cycles, tensile strength was non-linear: 32.4 MPa at cycle 2, 19.3 MPa at cycle 5, and 26.5 MPa at cycle 6 [14]. PP/flax evidence reported a decline from about 13 MPa at R0 to 7 MPa at R5 [70].	Controlled cycle studies are not equivalent to heterogeneous post-consumer feedstocks, and cycle effects should not be assumed monotonic.
Extrusion, printing, and filament geometry	rHDPE filament: 220 °C barrel, 20 rpm screw, 5 rpm pulling speed, and 1.75 ± 0.01 mm diameter [33]. Milk-jug rHDPE: 190 °C extrusion, 220–235 °C nozzle, and 30–45 °C bed [32].	Taguchi rPP extrusion: 200 °C, 40 rpm screw, 4 rpm winding, and approximately 1.60–1.65 mm filament [53]. WEEE-rPP: 250 °C nozzle, 110 °C bed, and diameters of 1.74 ± 0.07 and 1.75 ± 0.08 mm [63].	These are study-specific operating conditions, not universal optimum windows.

No pooled mean, universal processing window, or generalized property threshold was calculated. Values are reported as published and should be interpreted together with feedstock origin, formulation, process route, specimen condition, and test method. Only HDPE/PP material-specific sources were used. Values are representative rather than exhaustive and are not pooled across neat, blended, composite, reinforced, and controlled recycling-cycle systems. The complete extraction and comparability flags are provided in Supplementary Material S1.

The representative results demonstrate why a pooled mean or universal processing window would be misleading. Reported outcomes depended on feedstock provenance, recycled-content fraction, formulation, additives, reinforcement, recycling history, equipment, print orientation, specimen configuration, and test method. The full study-level extraction for all 28 HDPE/PP material-specific sources is provided in Supplementary Material S1. Missing values are reported as "not reported" and were not estimated.

5.3. Material-Specific Distinctions Between Recycled HDPE and PP

Although HDPE and PP are both semicrystalline polyolefins, the reviewed evidence does not support treating them as interchangeable feedstocks. Recycled HDPE evidence emphasizes crystallization-driven contraction, shrinkage, warpage, build-plate adhesion, and dimensional control. Recycled PP evidence shows pronounced source-dependent rheology, volumetric shrinkage, adhesion limitations, and sensitivity to oxidation, contamination, fillers, and stabilizer history. Table 6 summarizes the principal distinctions; reported conditions are study-specific rather than universal material windows. References include direct recycled-polymer evidence, controlled recycling-cycle studies, and formulation-specific blend or composite evidence. Blend and composite results should not be interpreted as property ranges for neat recycled HDPE or PP. Reported conditions are study-specific operating conditions rather than universal optimum processing windows.

Table 6. Material-specific comparison of recycled HDPE and PP for extrusion-based additive manufacturing.

Comparison Domain	Recycled HDPE	Recycled PP	Practical Implication
Thermal transition and processing	Reported rHDPE melting transitions are near 130–135 °C in direct studies; extrusion and printing temperatures depend on formulation and equipment [11,32,33,51].	Reported PP melting transitions and printing temperatures are generally higher, but vary with grade, fillers, contamination, and recycling history [14,30,31,49,67].	Temperature conditions must be qualified separately for each source and formulation.
Crystallization and shape stability	High contraction during cooling, warpage, and weak build-surface adhesion are recurring constraints [11,32,51].	High volumetric shrinkage and warpage also occur; crystallinity may increase or decrease depending on recycling history and additives [14,31,49].	Geometry, cooling, bed surface, and formulation can be as important as feedstock variability.
Rheology and reprocessing	Evidence is thinner; MFI and dimensional control vary with recovered source, fillers, and prior use [33,51].	Source-dependent viscosity, oxidation, chain scission, stabilizers, and minor PE contamination are prominent [30,67].	Rheological or melt-flow characterization should precede parameter transfer.
Dominant reported challenges	Shrinkage, warpage, adhesion, filament diameter variation, and limited neat post-consumer multi-cycle evidence [11,32,33,51].	Rheological variability, shrinkage, adhesion, oxidation, mixed-polymer contamination, and formulation-dependent ductility [14,30,31,49].	Material-specific diagnosis is required; a shared 'polyolefin' window is not justified.
Reported controls	Source identification, drying, particle conditioning, cooling/build-surface control, and diameter monitoring [11,32,33].	Source verification, rheological characterization, controlled blending or destabilization where justified, thermal management, and adhesion strategies. [30,32,67].	Controls must be validated against the intended part and recovery pathway.

5.4. The Circular DRAM Viability (CDV) Framework

Figure 2 organizes the reviewed evidence into four analytical domains:

- Domain 1—Upstream Feedstock Conditions: Polymer identity, contamination, moisture, particle condition, additives, and prior thermal or recycling history.
- Domain 2—Material and Process Constraints: Rheological or melt-flow variation, filament dimensional instability, thermo-mechanical degradation, crystallization response, and extrusion-control limitations.
- Domain 3—Print-Stage Outcomes and Failures: Warpage, shrinkage, dimensional deviation, weak interlayer adhesion, delamination, nozzle clogging, filament breakage, failed prints, and rejected parts.

- Domain 4—System-Level Assessment Considerations: Economic, environmental, governance, application, feedstock-continuity, and local operating questions requiring case-specific evaluation.

These domains are analytically linked but should not be interpreted as a deterministic sequence in which feedstock heterogeneity alone causes all downstream outcomes.

5.5. Domain 1: Upstream Feedstock Conditions

The framework identifies post-consumer feedstock heterogeneity as a major upstream source of variability, but not as the sole or unavoidable cause of all downstream outcomes. In contrast to post-industrial scrap, post-consumer HDPE and PP streams exhibit the following characteristics:

- Chemical Variability: Post-consumer waste streams are inherently heterogeneous. This heterogeneity is evident in variations in polymer composition, the presence of non-target polymers, residual additives from previous applications, and inconsistencies in molecular weight resulting from unknown thermal histories. The interplay of these factors creates significant challenges to process stability and material consistency [5,8,15,67].
- Physical Contamination: Post-consumer plastics carry surface contaminants, such as food residues, label adhesives, and printed inks, that introduce impurities and require rigorous cleaning before processing [67]. Cleaning methods range from pressurized warm water to chemical baths with surfactants or sodium hydroxide [16,55,71].
- Thermal History: Each plastic item has experienced an indeterminate number of thermal cycles during its previous life, affecting molecular weight distribution, crystallinity, and rheological properties through cumulative thermo-mechanical degradation [8,71,72].

In this context, feedstock preparation should be understood as a design variable and not merely a preliminary routine. The effectiveness of washing, drying, and particle-size conditioning can influence the stability of subsequent processing stages. For instance, inadequate drying introduces moisture, which disrupts melt homogeneity, while an irregular particle-size distribution leads to inconsistent feeding and melting behavior during extrusion [16,73]. This heterogeneity is not just a "problem to be solved"; it serves as a boundary condition that defines the feasible design space for the entire DRAM system. Failure to document and control these conditions can limit the transferability of downstream parameter optimization.

Accordingly, feedstock readiness helps define the operating conditions under which local DRAM pathways can be evaluated. Variability introduced at this stage may contribute to extrusion instability and filament inconsistency. However, downstream outcomes also depend on intrinsic polymer behavior, formulation, cooling, geometry, bed adhesion, printer configuration, and processing parameters. Feedstock heterogeneity should therefore be treated as a major upstream constraint interacting with material, design, and process factors rather than as a single causal origin for all failures.

5.6. Domain 2: Material and Process Constraints

From upstream feedstock conditions, several material and process constraints may emerge during conversion to printable feedstock. These include extrusion instability, melt non-uniformity, rheological inconsistency, filament diameter variation, thermo-mechanical degradation, crystallization-driven shrinkage, and cooling-related dimensional instability. These constraints are not independent categories, but they should also not be interpreted as a simple one-direction cascade. They interact with feedstock condition, formulation, equipment configuration, and processing parameters.

5.6.1. Constraint A: Extrusion Stability and Rheological Control

This constraint concerns process stability and control. Extrusion parameters, particularly barrel temperature and screw speed, significantly influence filament diameter consistency. Filament porosity and surface roughness can also affect downstream print quality [74,75]. Extrusion stability depends partly on maintaining a rheological range that supports continuous filament formation. Recycled-polymer systems, especially PP, display shear-thinning behavior, yield stress, and melt viscosity that must remain within controlled ranges to ensure stable extrusion and deposition. Departure from this range can contribute to flow irregularities, diameter fluctuations, and inconsistent filament morphology [30,49,76]. When the intrinsic rheological properties of recycled materials are inadequate, blending or the incorporation of additives may be necessary to restore processability. Therefore, rheological control, rather than extrusion as an isolated operation, represents an important material and process constraint affecting extrusion stability.

Feedstock preparation is critical to process stability. Homogenization, achieved through shredding, reduces volume and produces flakes or pellets that enable more consistent melting [15]. Uniform particle size, typically maintained by sieving within a 1.5–5 mm range, is essential for steady extrusion [16,73]. In polymer blends, melt mixing in compounders enhances dispersion before extrusion [43,64,77].

During extrusion, barrel temperature and screw speed are the primary variables, where increasing temperature at constant speed reduces filament diameter, while increasing screw speed at constant temperature increases it [78]. In HDPE systems, formulation-specific reported condition include a barrel temperature of 220 °C, a screw speed of 20 revolutions per minute (rpm), a pulling speed of 5 rpm, and a 2 mm die outlet [33]. Post-die cooling also influences diameter stability and roundness; multi-zone cooling tanks and air-blowing rings improve geometric control [57,79].

Filament dimensional consistency should be considered a material and process constraint rather than a minor quality-control issue, as it directly affects feeding behavior, extrusion pressure, and deposition during printing. It remains sensitive to upstream variability in particle size, moisture content, and melt flow behavior, even under the reported study-specific operating conditions [11,32,69].

Contextual equipment-focused studies and reviews further indicate that local filament production depends on the interaction among screw configuration, feeding stability, temperature control, pulling or winding conditions, filament geometry, equipment calibration, and operator capability. These factors determine whether experimental extrusion can progress toward repeatable feedstock manufacture, but they do not establish universal processing conditions for recycled HDPE or PP [80–85].

5.6.2. Constraint B: Thermo-Mechanical Degradation and Crystallization Response

This constraint is closely associated with material performance and output quality. Repeated thermo-mechanical processing can modify molecular weight, crystallinity, rheology, and mechanical response. The resulting changes may be beneficial, detrimental, or non-linear depending on the polymer, formulation, recycling route, and processing history [8,72]. Achieving uniform material properties from heterogeneous feedstocks remains a significant challenge [18]. Mechanical and interlayer responses may decline, remain stable, or change non-linearly across recycling cycles depending on formulation and processing history [8,86]. Additionally, contamination further compromises mechanical reliability, increasing the structural fragility of recycled feedstocks [5].

Beyond degradation from repeated thermo-mechanical processing, crystallization behavior is another mechanism that influences material performance. Semicrystalline polymers, such as HDPE and PP, undergo volumetric contraction during cooling, generating internal stresses that lead to warping, shrinkage, and geometric distortion. The magnitude of these effects is determined by crystallization kinetics and enthalpy, both of which are shaped by prior thermal history and material composition [30,67]. Therefore, crystallization should be regarded as a material-level factor that interacts with degradation processes, amplifying instability throughout the value chain rather than functioning independently.

5.6.3. Constraint C: Feedstock–Process–Print Interaction

This constraint reflects interactions between feedstock conditions, material responses, extrusion stability, and print settings. An inconsistent filament may contribute to nozzle clogging, warpage, dimensional deviation, or reduced interlayer adhesion, but these outcomes can also arise from the geometry, cooling, bed adhesion, printer configuration, and parameter selection.

The CDV Framework highlights interactions between material and process constraints. For example, extrusion instability may increase thermal or shear exposure, while a degraded material may become more sensitive to temperature, shear, cooling, and printing conditions. These interactions support diagnostic interpretation, but they do not establish a quantified causal hierarchy among all possible failure modes.

An extended evidence-informed mapping of reported barriers and intervention options is provided in Supplementary Material S1. The mapping is descriptive and does not rank intervention effectiveness or establish causal effects.

Figure 4 presents selected source-level-coded relationships among reported conditions, interventions, and outcomes. The most frequently coded relationships were melt blending or compounding to temperature control (n = 24/28, 85.7%), temperature control to parameter optimization (n = 23/28, 82.1%), parameter optimization to final product or reported performance (n = 23/28, 82.1%), thermo-mechanical degradation to melt blending or compounding (n = 22/28, 78.6%), and thermo-mechanical degradation to temperature control (n = 22/28, 78.6%). Additional recurrent relationships included homogenization to temperature control (n = 18/28, 64.3%), feedstock variability to homogenization (n = 18/28, 64.3%), and sieving or particle-size control to temperature control (n = 16/28, 57.1%). Complete edge counts, percentages, supporting study IDs, and coding rules are provided in Supplementary Material S1.

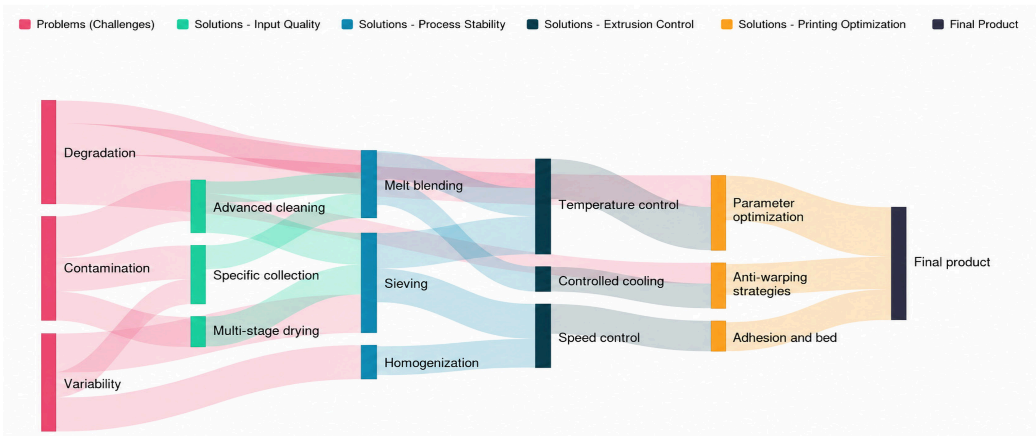

Figure 4. Source-coded Sankey-style relationship diagram across the 28 HDPE/PP material-specific sources. Link width represents source-level coding frequency for the displayed relationship. One source could support multiple nodes and multiple relationships; therefore, edge counts are non-exclusive and node inflows and outflows are not expected to balance. Frequency represents reporting occurrence within the reviewed subset and does not indicate effect magnitude, causal strength, technical importance, evidence certainty, or intervention effectiveness. The finalized source-level coding matrix, edge counts, supporting study IDs, and coding rules are provided in Supplementary Material S1.

5.7. Material Performance: Engineering Properties for Printability

The performance of recycled filaments is determined by both degradation mechanisms and crystallization dynamics, as well as their interaction with processing conditions. In semicrystalline polymers, crystallization affects shrinkage, interlayer bonding, and dimensional stability, which in turn influence the mechanical and geometric integrity of printed components [30,87]. These factors indicate that performance limitations result from the combined effects of rheological behavior, crystallization pathways, and process-induced structural changes rather than solely from material degradation.

Repeated thermo-mechanical processing can alter molecular weight, melt behavior, crystallization, ductility, interlayer integrity, and mechanical performance. However, the direction and magnitude of these changes were not uniform across the reviewed evidence [14,18,22,71]. Some controlled PP systems retained or improved selected flexural, impact, or hardness properties, whereas other neat, blended, or reinforced systems showed progressive tensile losses, greater porosity, or reduced printability. Multi-cycle behavior should therefore be interpreted according to the polymer grade, initial formulation, recycling route, processing history, and measured property rather than as a universal monotonic decline. Contamination further reduces mechanical reliability, increasing the structural fragility of recycled feedstocks.

To address these challenges, research has increasingly focused on material engineering strategies. The development of composite filaments represents a significant advancement, expanding the range of applications beyond those possible with conventional 3D printing materials [88].

Material engineering strategies can improve selected properties under specific formulations. Direct recycled HDPE/PP evidence reports improvements from glass powder, carbon fiber, biomass fillers, compatibilizers, and other reinforcements, but those results are formulation-specific and should not be transferred to neat recycled materials. The corresponding trade-offs in recycled content, material complexity, and recoverability are discussed in Section 7.

A source-level summary of additive effects on recycled filament properties is provided in Supplementary Material S1. Natural fiber-reinforced composite filaments (NFRCF) offer another approach, though they are limited by greater degradation and moisture absorption than other composites [89].

Examples of reported additives, blends, fillers, and reinforcements are documented in Supplementary Material S1. Their effects depend on polymer system, formulation, recycling history, processing conditions, and intended application.

Although additives may restore or enhance selected mechanical or dimensional properties, they can increase compositional complexity and reduce recoverability in later cycles. These strategies should therefore be evaluated against the intended application, recycled-content objective, material-yield consequences, and end-of-use pathway rather than treated as universal solutions.

Filament extrusion remains the most extensively documented feedstock route for recycled HDPE and PP, but reported parameters are formulation- and equipment-specific. For example, bottle-cap rHDPE with glass powder was processed at 180 °C and 7 rpm under the reported study conditions [11], whereas a separate rHDPE study reported 220 °C, 20 rpm, 5 rpm pulling speed, and 1.75 $\pm$ 0.01 mm filament [33]. Claims of cost or energy advantage require an explicit functional unit, boundary, and comparator and cannot be inferred from technical feasibility alone.

5.8. Domain 3: Print-Stage Outcomes and Failures

Print-stage outcomes are grouped into dimensional, mechanical/adhesion, and process categories:

- Dimensional failures include warping, shrinkage, and poor surface finish, all of which compromise the geometric fidelity of the printed component.
- Mechanical failures encompass reduced tensile strength, brittle fracture, and delamination between layers, each of which undermines the functional performance of the product.
- Process failures involve nozzle clogs, filament breakage, and failed prints, resulting in material waste and increased energy consumption per successful part.

From a diagnostic perspective, printing failures may indicate unresolved material or process incompatibilities. For instance, warping may reflect crystallization-driven shrinkage, thermal gradients, geometry, cooling strategy, bed adhesion, prior thermal history, or material degradation. Nozzle clogging may indicate rheological variation, contamination, particle inconsistency, or unsuitable print settings. Accordingly, print-stage outcomes should be interpreted as diagnostic signals rather than as evidence of a single upstream cause.

5.9. Domain 4: System-Level Assessment Considerations

Domain 4 identifies the economic, environmental, governance, application, and operating-continuity questions that must be assessed before a local DRAM pathway can be considered ready for practical implementation. Technical feasibility does not by itself establish economic competitiveness, environmental benefit, social acceptance, certification, or repeatable operation.

Economic considerations include the material yield, rejected filaments, failed prints, labor, electricity, additives, equipment use, maintenance, quality-control efforts, and local logistics. The reviewed literature did not provide sufficiently comparable monetary evidence to calculate a generalized cost per usable part or to establish cost competitiveness against virgin filaments, commercial recycled filaments, centralized recycling, or conventional manufacturing.

Environmental considerations include electricity use, washing, drying, shredding, extrusion, repeated reprocessing, rejected filaments, failed prints, additives, transport, and end-of-life assumptions. Reduced transport distance or avoided virgin material may be beneficial under specific conditions, but no harmonized life-cycle evidence was available to establish net environmental performance for recycled HDPE/PP DRAM pathways.

Governance and use considerations include batch traceability, feedstock documentation, operator capability, application-specific qualification, user requirements, and local accountability arrangements. These factors may support reliable local operation but do not demonstrate certification, product liability, social acceptance, or suitability for regulated or safety-critical use.

Accordingly, Domain 4 identifies assessment requirements and evidence gaps rather than demonstrated viability outcomes. Economic, environmental, social, market, and implementation questions require case-specific techno-economic assessment, life-cycle assessment, material-flow analysis, application qualification, and stakeholder evaluation.

5.10. Strategic Intervention Pathways Across the CDV Framework

The CDV Framework transforms a collection of reported technical challenges into a diagnostic map for organizing intervention options. Instead of ranking solutions by universal importance, the framework classifies them according to where they act within the waste-to-filament-to-print pathway and which trade-offs they may introduce. Accordingly, intervention strategies identified in the reviewed literature can be mapped onto the CDV domains as follows:

- Feedstock-management interventions: Strategies that address upstream variability, including source-defined collection, polymer identification, sorting, cleaning, drying, particle-size control, and batch traceability.
- Material and process control interventions: Strategies that address extrusion and filament-formation constraints, including melt-flow or rheological characterization, extrusion-temperature control, cooling control, filament-diameter monitoring, compatibilizers, stabilizers, and formulation validation.
- Print-stage control interventions: Strategies that address deposition and part-level outcomes, including parameter selection, build-plate adhesion, thermal management, orientation control, geometry adjustment, and print-failure monitoring.

These intervention categories are not ranked as "most impactful," "mitigation," or "palliative." Their relevance depends on feedstock condition, material formulation, equipment, intended application, local operating capacity, and acceptance criteria. Some interventions may improve printability while increasing material complexity, energy demand, cost, or future recycling difficulty.

This diagnostic mapping suggests that much of the reviewed literature emphasizes extrusion, formulation, and print-parameter optimization, while source-level feedstock control, traceability, repeated local operation, and application-specific qualification remain less developed. This imbalance represents an important research gap, but it does not imply that one intervention domain is universally more effective than another.

The filament value chain is a coupled material–process system in which feedstock characteristics, rheology, crystallization, equipment, geometry, and process parameters interact. The CDV Framework helps identify where monitoring and qualification may be required, but it does not rank upstream or downstream controls by universal impact. Intervention priority must be determined for the local feedstock, equipment, application, and acceptance criteria.

6. 3D Printing as an Integrative Diagnostic and Qualification Stage

The CDV Framework conceptualizes 3D printing as an integrative test stage in which material–process compatibility becomes observable under reported conditions. However, successful printing does not demonstrate that all upstream conditions have been resolved, nor does a failed print uniquely identify a single upstream cause. Print outcomes may reflect feedstock condition, filament quality, intrinsic polymer behavior, crystallization response, geometry, cooling, bed adhesion, printer configuration, and selected process parameters.

3D printing represents the final stage of the DRAM process, during which recycled feedstock is transformed into a part or component. Within the CDV Framework, this stage is treated as a diagnostic and qualification point rather than a definitive proof of system viability. Printability indicates material–process compatibility under the reported conditions, but it does not by itself establish long-term reliability, economic competitiveness, environmental benefit, or implementation readiness.

The performance of printed parts is determined by multiple interacting variables, including material composition, filament quality, and specific printing conditions.

Direct or partially direct material-specific evidence indicates that printability and material viability are not equivalent. Recycled-polymer systems may be printable yet exhibit reduced tensile strength, void formation, or structural heterogeneity. Consequently, successful printing should be considered a necessary but insufficient criterion for circular material viability [19,76].

Identical recycled materials can exhibit different mechanical behaviors depending on the processing route, such as AM, compression molding, or injection molding. This observation confirms that final part performance is determined not only by material composition but also by the interaction between material properties and the chosen processing pathway [66].

6.1. Print-Parameter Interpretation as a Diagnostic Tool

Print-parameter adjustment can improve deposition under specific conditions, but the response to nozzle temperature, bed temperature, print speed, cooling, and adhesion strategy does not uniquely diagnose earlier sorting, cleaning, or extrusion performance. Study-specific extrusion and printing conditions are provided in Supplementary Material S1. These conditions should not be interpreted as universal operating windows for recycled HDPE or PP.

Unusually high processing temperatures, repeated warpage, or unstable deposition may indicate feedstock, material, geometry, cooling, adhesion, or parameter-related incompatibilities. Such observations should trigger a source-traceable investigation rather than attribution to a single upstream cause.

6.2. Material Degradation: A Diagnostic Indicator

Repeated thermal and mechanical processing can modify recycled HDPE and PP through chain scission, oxidation, changes in crystallinity, and formulation-dependent interactions. The direction and magnitude of property change are not uniform across materials or recycling cycles. Within the CDV Framework, print-stage testing helps reveal whether these changes are compatible with the intended geometry and performance requirements. Materials may remain extrudable while failing to achieve adequate interlayer bonding, dimensional stability, or mechanical integrity during printing.

For PP, six-cycle studies show that mechanical and thermal responses can be non-linear [14,68]. For HDPE, available multi-cycle evidence is more limited and often composite-specific [69]. Brittleness or poor layer adhesion may be consistent with thermal or mechanical history, but these outcomes can also reflect formulation, porosity, crystallization, cooling, orientation, and print settings.

6.3. Interpreting Printing Failures as Multicausal Diagnostic Signals

Print-stage failures should not be attributed to a single predetermined upstream cause. In recycled HDPE, warpage and part removability were influenced by build-surface roughness, bed temperature, adhesion conditions, and printing parameters [32]. In recycled PP/carbon-fiber systems, filament diameter, surface roughness, viscosity, flow conditions, and fiber agglomeration affected printing quality under the tested formulation and equipment conditions [76]. Broader material-extrusion evidence also shows that printer configuration, layer conditions, bed temperature, and printing speed may interact rather than act as independent variables [90].

Taken together, these findings indicate that warpage, delamination, nozzle obstruction, porosity, surface defects, filament breakage, and dimensional deviation may arise from multiple interacting feedstock, material, process, and design conditions [32,76,90]. Additional characterization is required before attributing an observed failure to a specific condition. The extended diagnostic mapping is provided in Supplementary Material S1.

Table 7 summarizes representative associations between observable print-stage outcomes and potentially contributing feedstock, material, process, or design conditions. These associations are non-exclusive diagnostic possibilities and should not be interpreted as one-to-one causal relationships. The associations are diagnostic possibilities rather than unique causal relationships. Supporting references include HDPE/PP material-specific evidence and contextual material-extrusion evidence, identified by evidential role in Supplementary Material S1.

Table 7. Potential associations between print-stage outcomes and material or process conditions.

Print-Stage Outcome	Potentially Associated Feedstock Conditions	Potentially Associated Process or Design Conditions	Supporting References
Nozzle obstruction	Oversized particles, contaminants, agglomerates	Nozzle size, feeding system, insufficient mixing	[67,76,90]
Warpage	Polymer grade, crystallinity, fillers, prior history	Cooling, geometry, bed adhesion, temperature	[11,32,34,67]
Weak interlayer integrity	Degradation, contamination, incompatible blend	Nozzle temperature, speed, layer time, orientation	[19,22,76,90]
Surface defects	Moisture, particle variability, inconsistent formulation	Flow instability, temperature, extrusion rate	[67,76,90]
Filament breakage	Molecular degradation, voids, filler agglomeration	Diameter inconsistency, winding, handling	[22,76]
Dimensional deviation	Variable melt flow or filament geometry	Calibration, slicing, orientation, cooling	[32,33,53,76]

6.4. Print-Stage Parameter Control and Its Boundaries

Adjustments to nozzle temperature, bed temperature, cooling, speed, layer settings, orientation, and build-surface strategy may improve deposition reliability under study-specific conditions. However, parameter tuning cannot be assumed to compensate for incompatible feedstock, unstable filament geometry, unsuitable formulation, or application requirements. Print-stage controls should therefore be documented as part of a batch- and application-specific qualification plan rather than interpreted as proof that upstream conditions have been resolved.

Contextual studies involving recycled PET and PLA similarly show that mechanical and dimensional performance can vary with infill design, filament-production route, recycling history, formulation, coextrusion, rheological response, and print-parameter selection. These findings support the interpretation of interacting material–process conditions, but they were not used to establish HDPE/PP-specific processing windows or property ranges [91–98].

6.5. Linking Back to the CDV Framework: The Printer as Diagnostic Tool

Accordingly, 3D printing functions as an integrative test and qualification stage in which material–process compatibility becomes observable under defined conditions. A filament that appears adequate during extrusion may still fail during printing because of shrinkage, rheology, interfacial integrity, geometry, cooling, adhesion, or cumulative degradation.

This perspective reframes printing as an integrative diagnostic stage rather than definitive proof of system viability. Researchers should connect print outcomes with feedstock records, extrusion data, filament-quality measurements, batch identification, geometry, and application-specific performance requirements.

7. Discussion: Unpacking the Circularity–Viability Paradox

This systematic review provides a systems-level interpretation of local, distributed, and application-specific recycling pathways for post-consumer HDPE and PP. The discussion focuses on how HDPE/PP material-specific evidence and contextual system-level evidence inform the Circular DRAM Viability (CDV) Framework, without treating contextual evidence from other polymers as direct proof of HDPE/PP-specific behavior.

The discussion is organized around the circularity–viability paradox: the recurring trade-off in which interventions that improve short-term printability or mechanical performance may also increase material complexity, energy demand, cost, or future recycling difficulty. This paradox is interpreted as an evidence-informed qualitative decision structure, not as a quantified LCA, TEA, or universal scoring model.

7.1. The Central Finding: The Circularity–Viability Paradox

A central pattern emerging from the reviewed evidence is the circularity–viability paradox. In recycled HDPE and PP pathways, interventions such as blending, additive incorporation, reinforcement, intensified processing, or specialized print control may improve printability, stiffness, adhesion, or dimensional stability under specific conditions. However, these interventions may also reduce recycled-content purity, increase formulation complexity, add cost, increase energy demand, or complicate future recovery. This pattern is supported by HDPE/PP material-specific evidence where such trade-offs are reported, while contextual evidence from other polymer systems is used only to interpret broader circularity mechanisms. Therefore, the paradox should not be interpreted as a universal law across all recycled polymers or as proof that all performance-improving interventions reduce circularity [8,30,49].

For example, blending with virgin polymers improves mechanical performance but decreases the proportion of circular material, while the use of compatibilizers and reinforcements enhances interlayer adhesion but increases multi-material complexity [99,100].

These findings indicate that circular manufacturing systems should prioritize designing for functional adequacy under controlled variability rather than replicating the performance of virgin materials.

Figure 5 synthesizes the circularity–viability paradox by positioning intervention strategies along two competing dimensions: technical viability (process stability and mechanical performance) and circularity (material recoverability and environmental impact). This positioning is derived from recurring patterns reported across the reviewed studies, rather than from a single explicit framework proposed in the literature. The matrix visualizes this tension by mapping common intervention strategies along two dimensions: circularity (y-axis, the ability to be recycled at end-of-life) and technical viability (x-axis, the ability to produce consistent, functional printed parts).

Broader closed-loop and reprocessing evidence shows that repeated thermal histories, blending, multiple recycling cycles, dynamic bonding strategies, and large-format reprocessing may extend material use while also altering molecular, mechanical, processing, recoverability, or emissions-related behavior. These findings support interpreting circularity as an application-specific trade-off rather than assuming that additional recycling cycles or more complex formulations necessarily produce a net circular benefit [36,101–104].

https://doi.org/10.3390/recycling11080147

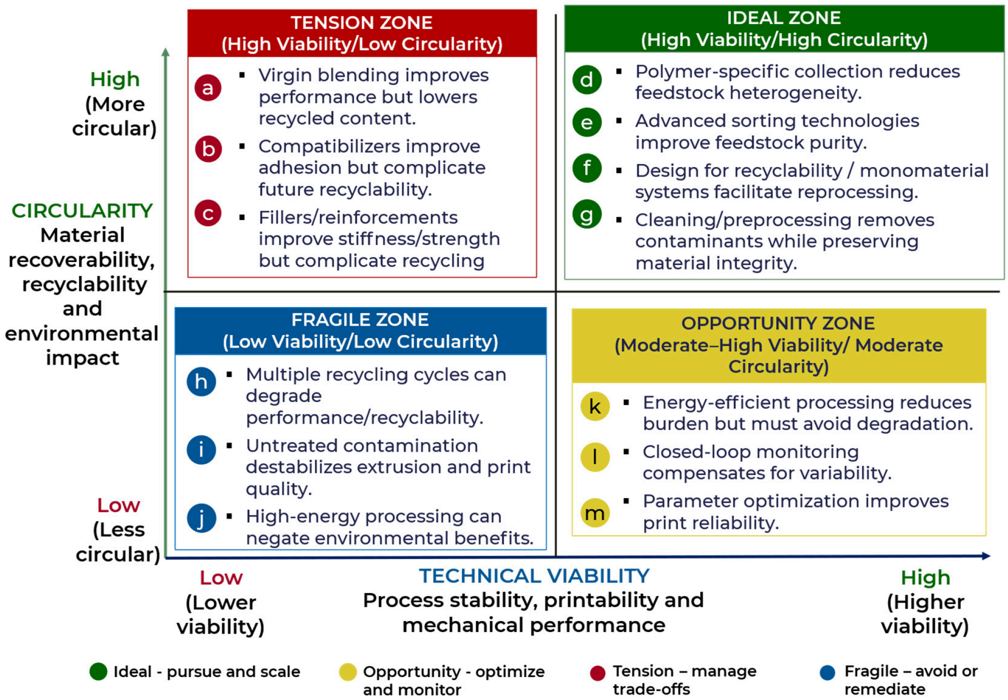

Figure 5. Circularity–viability paradox for local, distributed, and application-specific recycling of HDPE and PP. The matrix is an evidence-informed qualitative decision structure. Quadrant placement requires application-specific evidence of part compliance, process yield, recycled-content fraction, formulation complexity, recoverability, cost, and environmental boundary conditions. Economic and environmental outcomes require separate TEA and LCA using a defined functional unit and comparator. Representative evidence and measurement needs are summarized in Table 8.

Table 8. Evidence mapping and operational interpretation of the circularity–viability paradox.

Quadrant	Operational Interpretation	Candidate Indicators	Representative Evidence Role	Boundary	Supporting Studies
Ideal Zone	Higher technical compliance with retained recycled content and recoverability.	Feedstock purity; recycled content; qualified yield; print success; application compliance.	Direct source-defined HDPE/PP streams plus contextual CE evidence.	Target condition; not demonstrated universal readiness.	[11,32,33]
Opportunity Zone	Reliability improved without major formulation complexity.	Failure rate; dimensional deviation; energy per qualified part; batch repeatability.	Direct process control studies plus contextual monitoring evidence.	Requires local optimization and cost/energy measurement.	[32,44,53,90,105,106]
Tension Zone	Performance improved through virgin blending, compatibilizers, fillers, or reinforcement, with lower recoverability.	Virgin fraction; additive/filler fraction; formulation complexity; recovery pathway.	Direct blend/composite HDPE/PP evidence.	Performance improvement is not evidence of improved circularity.	[11,52,64,70,87]
Fragile Zone	Low process reliability and weak circular outcome because of contamination, degradation, rejection, or failed printing.	Contamination; failed builds; rejected material; mechanical retention; energy/waste per qualified output.	Direct evidence on instability and degradation where reported.	Condition to remediate; no universal threshold derived.	[5,14,32,104]

As shown in Figure 5, the Tension Zone captures the core of the paradox: interventions that enhance short-term performance impose constraints on long-term circularity. These strategies increase material complexity or introduce non-recyclable components, thereby improving printability while reducing the ability of the material to be reprocessed in subsequent cycles. This highlights a recurring trade-off between achieving mechanical performance and maintaining material circularity.

The Ideal Zone represents the target conditions in which both circularity and technical viability can be improved simultaneously. These strategies focus on reducing variability at the source, improving feedstock purity, and enabling reprocessing without introducing additional complexity [8,57,67]. However, the literature suggests that achieving this balance remains highly dependent on strict control of feedstock quality and processing conditions.

The reviewed evidence did not provide harmonized functional units, system boundaries, cost categories, environmental indicators, recycled-content definitions, or application-specific acceptance criteria. The review therefore proposes candidate indicators but does not derive universal thresholds. Quadrant placement should be based on a predefined functional unit and local acceptance criteria, while economic and environmental performance must be evaluated separately with consistent comparators.

The Opportunity Zone reflects process-level strategies aimed at mitigating variability without altering the material composition. These include monitoring, parameter optimization, and energy-efficient processing, which can improve system performance while preserving circularity [2,44,105]. This zone is critical for future development, as it offers pathways to balance performance and sustainability without introducing structural trade-offs.

These situations arise from uncontrolled variability, contamination, or inappropriate processing conditions, which collectively degrade material performance and limit recyclability [5,14,24]. Instead of representing isolated failures, this zone highlights the systemic consequences of poor feedstock control and process instability.

Overall, Figure 5 and Table 8 emphasize management of trade-offs rather than maximization of a single metric. The framework is intended to support transparent comparison of alternatives and evidence gaps, not to certify environmental superiority, cost competitiveness, or implementation readiness.

In summary, the literature shows that:

- Blending recycled HDPE/PP with virgin polymers improves processability and mechanical performance but introduces a trade-off with circularity by increasing dependence on virgin material inputs [8].
- Compatibilizers, additives, and reinforcements may improve selected properties while increasing formulation complexity and complicating future recovery; representative formulation-specific evidence is summarized in Supplementary Material S1.
- Intensive processing, such as multiple extrusion cycles with stabilizers, can homogenize the feedstock, but at the cost of increased energy consumption, potentially negating the environmental benefits of recycling [72,106].

Moreover, AM may be less suitable than conventional manufacturing for high-volume applications when throughput and unit-cost requirements dominate. Application-specific strategies should therefore align material-performance requirements with circularity and production constraints rather than attempt to maximize all dimensions simultaneously.

Is the goal to produce a part that is indistinguishable from virgin plastic, or to produce a part that is fit for purpose within a truly circular system? The CDV Framework suggests that the latter may require accepting a certain degree of material variability and designing products and processes that are robust to it rather than trying to engineer it away with energy-intensive or circularity-compromising methods.

For practical use, the paradox should be populated using measurable indicators. Technical viability may be assessed through the print-failure rate, qualified material yield, dimensional deviation, mechanical performance relative to an intended application, and repeatability across batches. Circularity may be assessed through recycled-content fraction, conversion yield, formulation complexity, and end-of-use recoverability. Economic considerations require cost per qualified usable part, including collection, sorting, washing, drying, shredding, extrusion, printing, labor, electricity, additives, equipment use, quality control, and rejected material. Environmental considerations require energy use, water demand, transport, electricity mix, additives, failed prints, reprocessing cycles, and end-of-life assumptions.

7.2. Implementation Readiness and Target Applications

Technical feasibility should not be interpreted as industrial readiness. Most recycled HDPE/PP studies used laboratory-scale material preparation, small-batch extrusion, desktop printing, controlled test specimens, or one-off demonstrators [11,14,16]. Fewer sources evaluated continuous feedstock supply, sustained production, automated quality control, recurring customer demand, product certification, or commercial operation; the strongest implementation evidence remained contextual or demonstrator-based [12,20,39].

Because the reviewed sources did not generally report standardized Technology Readiness Levels, this review uses descriptive evidence-context categories rather than assigning formal TRLs. Commercial availability of an individual dryer, shredder, extruder, sensor, additive, or printer does not demonstrate commercial maturity of an integrated DRAM pathway [20,21].

Material suitability must also be evaluated against the intended product and the consequences of failure. The reviewed evidence most strongly supports specimens, prototypes, educational products, customized objects, low-load demonstrators, acoustic structures, furniture-scale parts, and selected marine or workshop applications [11,16,37]. General qualification for structural, safety-critical, food-contact, medical, or other regulated applications was not established [21,46,86].

The contextual literature describes broader application opportunities involving renewable polymers, biomedical prototyping, sustainable construction, and natural-waste composites. These sources help identify potential application classes and qualification requirements but were not treated as direct evidence that recycled HDPE or PP had been certified or validated for those uses. Accordingly, the evidence-context categories were assigned based on the highest level of integrated implementation demonstrated in the reviewed sources and should not be interpreted as formally reported Technology Readiness Levels [85,89,91,107–109].

Table 9 applies the CDV Framework to implementation readiness by distinguishing the evidential status of technical pathways and target applications. Experimentally demonstrated contexts are separated from potential use cases and from certified, regulated, recurrent, or commercially validated applications that were not established by the reviewed evidence. The final column identifies the additional validation and system-level assessment information required before broader deployment. These items represent future evaluation requirements rather than established acceptance criteria.

Within the broader analytical structure, the CDV Framework identifies the technical and system-level domains that require diagnosis, while Table 9 applies this structure to evidence status and application readiness. The circularity–viability paradox complements this assessment by highlighting potential trade-offs between improved processability or product performance and increased formulation complexity, cost, energy demand, or end-of-use recovery burdens. The system-level assessment requirements presented in Table 10 subsequently identify the information needed to evaluate these trade-offs under a defined local application and operating context.

Table 9. Evidence status, target applications, and additional validation requirements for local recycled HDPE/PP DRAM pathways.

Area or Pathway	Evidence Status in the Reviewed Sources	Supporting References	Additional Validation or Future Assessment Requirements
Feedstock identification, sorting, and washing	Experimentally demonstrated; laboratory-to-pilot context	[11,15,20]	Source-specific polymer-identification accuracy, contamination limits, sorting yield, water demand, wastewater management, and qualified material yield.
Drying and particle-size preparation	Experimentally demonstrated; laboratory-to-pilot context	[21,44,84]	Validated moisture endpoints, particle-size distribution, drying-energy demand, processing throughput, and rejected-material fraction.
Filament extrusion and dimensional control	Experimentally demonstrated; laboratory-to-early-pilot context	[44,53,57,74]	Continuous operating capability, filament-diameter mean and variability, ovality, calibration frequency, rejection rate, maintenance, and operator requirements.
Automated filament-diameter monitoring and control	Experimentally demonstrated in limited early pilot context	[57,106,110,111]	Sensor calibration, closed-loop stability, repeated-batch validation, statistical process capability, and compatibility with different recycled feedstocks.
Blending, compatibilizers, fillers, and reinforcement	Experimentally demonstrated; laboratory-to-demonstrator context	[1,19,30,112]	Formulation consistency, long-term durability, recycled-content verification, recoverability in subsequent cycles, and application-specific TEA and LCA.
Pellet, granular, or direct-waste printing	Application-specific demonstrators with limited pilot evidence	[16,39,43,51]	Stable feeding, continuous throughput, material yield, accepted-part yield, dimensional repeatability, maintenance demand, and product qualification.
Prototypes, educational models, souvenirs, and customized products	Experimentally demonstrated; most consistent application evidence	[16,37,45]	Dimensional consistency, appearance, safe handling, repeated-batch printability, user requirements, and quality acceptance criteria.
Low-load products, jigs, fixtures, workshop aids, and non-structural spare parts	Experimentally demonstrated in limited or application-specific cases	[16,46,52]	Load definition, fit, wear, creep, impact resistance, service environment, repeated use, tolerances, and product-liability assessment.
Acoustic, furniture-scale, marine, outdoor, and large-format products	Experimentally demonstrated as application-specific prototypes or demonstrators	[16,39,51]	Creep, fatigue, weathering, ultraviolet exposure, moisture and chemical resistance, fire behavior, load capacity, and long-term dimensional stability.
Agricultural or construction aids	Potential use case; direct recycled HDPE/PP validation remains limited	[113–115]	Field testing, ultraviolet and moisture exposure, impact resistance, service loading, durability, user safety, and local application requirements.
Structural, safety-critical, food-contact, medical, or other regulated products	Not validated or established by the reviewed evidence	[46,86,116]	Full engineering qualification, applicable standards, regulatory conformity, contamination control, traceability, certification, safety evidence, and assigned product liability.
Certified recurrent recycled HDPE/PP production	Not established by the reviewed evidence	[21,23,45]	Material specifications, feedstock-supply agreements, process-capability evidence, batch certification, quality-management systems, operator competence, and audit trails.
Commercially validated local DRAM pathway	Not generally established by the reviewed evidence	[20,75,117,118]	Recurrent sales or demand, stable feedstock quantity and quality, validated TEA and LCA, sustained operating data, governance, accountability, and demonstrated business continuity.

The evidence-status categories presented in Table 9 reflect the highest integrated implementation demonstrated in the reviewed sources and should not be interpreted as formal Technology Readiness Levels. "Experimentally demonstrated" indicates that a process, specimen, prototype, or application was produced or evaluated under study-specific conditions; however, it does not imply certification, recurrent production, commercial validation, market readiness, or suitability for regulated use. "Potential use case" identifies an application for which direct recycled HDPE/PP validation remains limited or absent. In addition, the items listed in the final column include both measurements reported in individual studies and requirements identified for future application-specific evaluation. Therefore, they should not be interpreted as established acceptance criteria, demonstrated viability outcomes, or validated universal thresholds.

Table 10. System-level assessment requirements for local recycled HDPE/PP DRAM pathways.

Assessment Domain	Components to Include	Required Metric or Method	Comparator/Boundary
Economic	Collection, sorting, washing, drying, shredding, extrusion, printing, labor, electricity, additives, equipment depreciation, maintenance, failed prints, and quality control.	Cost per kg qualified feedstock and/or cost per qualified usable part; price year and utilization rate stated.	Virgin filament, commercial recycled filament, centralized recycling, or conventional manufacturing using the same functional unit.
Environmental	Electricity mix, water, washing, drying, transport, extrusion, printing, rejected material, additives, reprocessing cycles, and end-of-life.	Application-specific LCA or process inventory per qualified kg or qualified part.	Landfill, incineration, centralized mechanical recycling, virgin filament production, injection molding, or another explicit reference system.
Feedstock continuity and throughput	Source-separated supply, storage, contamination, batch size, conversion yield, operating hours, rejects, demand, and seasonal variation.	The kg input and qualified output per batch or period; yield %, failure %, and uptime.	Local supply and demand scenario; no universal minimum facility volume derived.
Quality, governance, and use	Batch identity, feedstock origin, recycled-content declaration, pretreatment, formulation, process conditions, test records, operator competence, and accountability.	Material passport/batch record, application-specific test plan, acceptance criteria, and audit trail.	Applicable standards, risk category, customer requirements, and jurisdictional regulation.
Social and market conditions	Training, health and safety, stakeholder participation, customer confidence, market demand, procurement, and business continuity.	Stakeholder and user-acceptance assessment; demand and business-model evaluation.	Local institutional and market baseline.

Application-specific assessment should rely on measurable indicators rather than universal thresholds. Candidate indicators include contamination and moisture records, rheological or melt-flow characterization, filament-diameter consistency and process capability, print-failure rate, qualified material yield, tensile or thermal performance relative to the intended application, energy use per qualified kilogram or part, cost per accepted functional part, batch repeatability, and rejected-material fraction.

7.3. System-Level Assessment Requirements

Practical implementation requires assessment beyond technical printability. Economic performance, environmental consequences, quality assurance, feedstock continuity, governance, policy, and market conditions must be evaluated using defined functional units, explicit comparators, local operating data, and application-specific acceptance criteria.

The reviewed literature does not provide sufficiently harmonized evidence to establish universal economic, environmental, quality, supply, or market thresholds for local recycled HDPE/PP DRAM pathways. Accordingly, these dimensions are presented as minimum system-level assessment requirements rather than demonstrated viability outcomes, and the proposed indicators should not be interpreted as validated universal thresholds because they were not measured consistently across the included sources.

Table 10 consolidates the principal economic, environmental, feedstock, quality, governance, social, and market dimensions that should be evaluated before practical implementation. The listed indicators and comparators are review-derived assessment elements and should not be interpreted as validated universal thresholds.

https://doi.org/10.3390/recycling11080147

7.3.1. Techno-Economic Assessment Requirements

Economic performance should not be inferred from feedstock price alone. Diameter instability, rejected filament, purging, calibration, failed prints, supports, labor, maintenance, and quality control may substantially increase the effective cost of production. The preferred functional unit for future assessments is therefore cost per accepted functional part. The proposed cost structure synthesizes cost, capacity, utilization, and comparator considerations reported in the reviewed supply-chain, direct-pellet-printing, pricing, and sustainability literature [25,41,48].

To operationalize the economic dimension of the CDV Framework, the assessment should consider the full cost of transforming post-consumer plastic into a part that satisfies predefined technical and quality requirements. Evaluating only the purchase or collection cost of the recycled feedstock would underestimate the effective production cost because material may be lost during preparation, extrusion, printing, and quality-control activities. The calculation should therefore include both direct processing expenses and the costs associated with rejected filament, failed prints, equipment use, and supporting operations. Accordingly, the cost per accepted functional part can be expressed as follows:

$$C_{Accepted\ Part} = (C_{feedstock\ preparation} + C_{conversion} + C_{printing} + C_{quality\ control} + C_{rejection} + C_{overhead})/N_{accepted\ parts} \quad (1)$$

In this expression, $C_{feedstock\ preparation}$ includes collection, sorting, washing, drying, and size reduction; $C_{conversion}$ covers compounding and filament, pellet, or granular feedstock production; $C_{printing}$ includes material deposition, electricity, labor, and machine use; $C_{quality\ control}$ represents inspection, testing, and batch-documentation costs; $C_{rejection}$ accounts for rejected feedstock, failed prints, purging, and rework; and $C_{overhead}$ includes depreciation, maintenance, facilities, and other indirect expenses. The denominator, $N_{accepted\ parts}$, includes only parts that meet the predefined application and quality criteria. This formulation is consistent with the manuscript's emphasis on cost per qualified output rather than cost per nominally produced part.

Only parts meeting predefined application and quality criteria should be included in the denominator. Equipment depreciation should reflect actual utilization rather than nominal capacity. Comparators should be defined explicitly and may include virgin commercial filament, commercial recycled filament, virgin pellets, centralized mechanical recycling, injection molding, or purchase of a conventionally manufactured product [12,43,106].

The reviewed evidence did not provide sufficiently harmonized economic data to derive a generalized DRAM cost advantage. Reported savings should therefore be presented only with their original comparators, functional units, locations, scales, and system boundaries [106].

The available economic evidence is summarized in Supplementary S1 (Economic_Evidence_S3). Reported values used different functional units, locations, scales, utilization assumptions, and comparators; therefore, they were not combined into a single cost-per-kilogram or cost-per-part estimate.

7.3.2. Environmental Comparison and System Boundaries

Environmental claims depend on the reference pathway and system boundary. Potential comparators include landfill, incineration, centralized mechanical recycling, virgin-filament production and delivery, commercial recycled-filament production, injection molding, and conventional product supply [51,104,106].

Local processing may reduce transport and avoid virgin-material production, but these benefits may be offset by carbon-intensive electricity, repeated drying or extrusion, low equipment utilization, additives, rejected filament, failed prints, short product life, or limited end-of-use recoverability [24,25,41]. The use of recycled material is therefore not sufficient evidence of environmental superiority.

7.3.3. Quality Assurance, Traceability, and Product Responsibility

Industrial adoption requires a documented specification for incoming waste, processed feedstock, filament or pellets, printed parts, and rejected material. The minimum batch-record fields proposed below synthesize qualification, melt-flow, dimensional-control, process-monitoring, and application-testing needs reported across the reviewed literature [20,21,32]. A minimum batch record should include:

- Waste source and previous application;
- Polymer-identification method;
- Collection and processing dates;
- Contamination and moisture;
- Particle-size distribution;
- Recycled-content fraction;
- Known recycling history;
- Additives, fillers, and compatibilizers;
- MFI/MFR or rheological result;
- Extrusion and printing parameters;
- Filament diameter, variability, and ovality;
- Test methods, replicate numbers, and results;
- Failed-print and rejected-material fractions;
- Operator and equipment identification;
- Disposition of rejected material.

Material passports and batch certificates should distinguish verified information from assumptions. The level of testing should increase with the consequence of product failure. Responsibility for product conformity should be assigned to an identifiable manufacturer or operator rather than remaining ambiguous among waste supplier, recycling hub, feedstock producer, printer operator, and designer [44,57,63].

The reviewed studies did not apply a single harmonized qualification standard across recycled HDPE/PP feedstocks and printed parts. A minimum qualification protocol should therefore identify the test standard or documented laboratory method used for polymer identification, moisture, melt-flow or rheology, filament diameter, tensile or flexural behavior, dimensional accuracy, thermal response, and application-specific durability. Batch certification should report the method, sample size, replicate number, acceptance criterion, result, uncertainty where available, and disposition of non-conforming material.

7.3.4. Feedstock Continuity and Throughput

A printable waste stream is not sufficient for sustained operation unless adequate quantity and quality can be supplied over time. Material-flow planning should distinguish collected mass, accepted mass after sorting, retained mass after washing and drying, usable feedstock yield, printing yield, and accepted-product yield [43,45,48].

In addition to economic performance, the implementation of a local DRAM pathway depends on whether the available post-consumer waste stream can provide a sufficient and stable quantity of qualified output. Material losses occur throughout sorting, washing, drying, size reduction, feedstock production, and printing. Therefore, the initially collected mass cannot be treated as equivalent to the mass of usable products obtained at the end of the process. To represent this relationship, the accepted-product mass is calculated from the collected mass and the cumulative yield of the complete conversion pathway:

$$M_{accepted\ products} = M_{collected} \times Y_{total} \quad (2)$$

Here, $M_{accepted\ products}$ represents the mass of printed products that satisfy the established acceptance criteria, $M_{collected}$ is the total mass of post-consumer plastic entering the system, and Y_{total} is the overall material yield from collection to accepted final product. This equation provides a simplified mass-balance relationship for estimating how much qualified output can be produced from a defined quantity of collected waste.

The total yield used in Equation (2) is not determined by a single processing step. Instead, it reflects the cumulative effect of material retention and rejection across the successive stages of the DRAM pathway. Because losses occurring during an earlier stage reduce the quantity available for every subsequent operation, the overall yield is calculated as the product of the individual stage yields:

$$Y_{total} = Y_{sorting} \times Y_{washing} \times Y_{sizereduction} \times Y_{feedstock} \times Y_{printing} \quad (3)$$

In this expression, $Y_{sorting}$ is the fraction of collected material retained after polymer identification and contaminant removal; $Y_{washing}$ is the fraction retained after washing and drying; $Y_{\text{size reduction}}$ represents the material retained after shredding, grinding, and particle-size conditioning; $Y_{feedstock}$ is the yield obtained during compounding and filament, pellet, or granular feedstock production; and $Y_{printing}$ is the fraction converted into accepted printed products after accounting for failed prints, supports, rejected parts, and other printing losses. Each yield should be expressed as a decimal fraction under consistent mass boundaries. The multiplicative structure shows that even moderate losses at individual stages can substantially reduce the final accepted-product yield.

A deployment assessment should report monthly feedstock availability, seasonal variability, polymer-specific fraction, contamination, yield by stage, effective machine capacity, machine availability, demand, and feedstock inventory [39,43,48]. Polymer-specific collection may improve quality but reduce available volume; mixed collection may increase supply but also increase sorting and quality-control requirements.

7.3.5. Policy and Organizational Models

Industrial adoption depends on policy, ownership, demand, and allocation of responsibility in addition to technical performance. Potential supporting mechanisms include extended producer responsibility, recycled-content requirements, green public procurement, disposal taxes, certification assistance, local-manufacturing grants, repair policies, and traceability requirements [12,15,20].

Potential deployment models include community recycling hubs, university fab labs, municipal partnerships, SME-based local manufacturing, corporate closed-loop systems, producer take-back systems, and regional microfactories [15,20,39,45]. Closed-loop institutional or corporate systems may offer favorable initial conditions because feedstock identity, ownership, demand, and accountability are easier to define. Community and municipal systems may provide broader social reach but require stronger sorting, training, governance, market development, and quality assurance.

Implementation-oriented studies further indicate that distributed recycling depends on regional waste availability, equipment ownership, sustained demand, business-model design, strategic control, and supply-chain coordination in addition to the technical ability to manufacture a printable specimen. These findings support the inclusion of organizational continuity and market validation as assessment requirements, but they do not demonstrate commercial readiness for local recycled HDPE/PP DRAM systems [117,119,120].

Direct evidence on user acceptance, willingness to purchase, customer confidence, operator acceptance, and long-term market demand was limited in the material-specific HDPE/PP subset. These factors should therefore be evaluated prospectively through stakeholder interviews, user testing, procurement analysis, demand assessment, and business-model validation rather than inferred from technical printability or community participation alone.

These mechanisms are presented as contextual enabling conditions and were not evaluated as demonstrated outcomes of the direct recycled HDPE/PP evidence subset.

7.4. Evidence Gaps and Future Research

The reviewed material-specific literature was concentrated on formulation, extrusion conditions, filament production, and print-parameter optimization. Comparatively fewer sources examined source-level collection design, traceability, continuous local operation, feedstock continuity, repeated-batch capability, application qualification, market demand, and long-term product performance [8,9,60,84]. Post-consumer feedstock variability remains an important research area because polymer composition, contamination, additives, and prior thermal history can affect processing behavior and filament quality [5,31,67].

However, attempts to reduce variability through blending or additives may introduce additional cost, formulation complexity, or recovery limitations [1]. Future research should therefore prioritize source-defined collection and low-cost polymer, contamination, moisture, and melt-flow characterization [8,70], together with standardized preprocessing, extrusion, filament-quality, and batch-record protocols for recycled HDPE and PP [23,67]. Continuous and repeated-batch pilot studies should report material yield, process capability, rejected filament, failed prints, uptime, maintenance, and operator requirements.

Application-specific qualification should connect feedstock and print behavior with geometry, mechanical and thermal performance, durability, service conditions, and the consequence of failure [19,21,49]. Comparative techno-economic and life-cycle assessments should use consistent functional units, system boundaries, energy conditions, and reference pathways [51,104,106]. Future studies should also examine traceability, stakeholder acceptance, market demand, business-model continuity, and alignment between decentralized recycling and application-specific manufacturing needs [35].

External validation of the CDV Framework and circularity–viability paradox is required through industrial case studies, expert assessment, and application-specific decision testing. AI-assisted monitoring and adaptive control may represent future research directions for extrusion control, defect detection, filament-diameter monitoring, and print-parameter adaptation. However, these approaches were not systematically evaluated in the reviewed HDPE/PP evidence base and should not be presented as established findings of this review.

This review contributes an evidence-informed diagnostic and hypothesis-generating structure that distinguishes HDPE/PP material-specific evidence from contextual and system-level evidence [9,21]. It identifies where additional feedstock control, process qualification, application testing, TEA, LCA, traceability, and implementation evidence are required, but it does not constitute a validated causal model or an industrial-readiness certification method.

7.5. Limitations of the Evidence Base and Review Process

This review has several limitations. First, the material-specific evidence base comprised 28 HDPE/PP sources, including 24 direct or partially direct recycled experimental sources and four indirect material-specific or secondary sources. The remaining 91 sources served contextual or system-level roles and were not used to establish numerical recycled HDPE/PP property ranges.

Second, the included evidence differed substantially in waste origin, polymer grade, contamination, recycled-content fraction, formulation, reinforcement, processing history, equipment, specimen configuration, orientation, test method, and reported outcome. This heterogeneity prevented meta-analysis and the derivation of universal processing windows or property-retention rates.

Third, 44 reports could not be retrieved and were not assessed for eligibility, creating a potential availability limitation. The searches were limited to Scopus and Web of Science, and the relevant gray literature, repositories, or studies indexed elsewhere may have been missed.

Fourth, title and abstract screening, full-text assessment, and data extraction followed an initial-review and second-reviewer verification workflow rather than fully independent duplicate assessment. Reviewer-related selection or extraction error therefore cannot be excluded.

Fifth, unsuccessful extrusion trials, rejected filaments, print failures, null results, process yield, economic data, and environmental data were inconsistently reported. Formal statistical assessment of publication bias was not feasible, and the evidence may overrepresent technically successful conditions.

Sixth, a formal GRADE assessment was not applied because the sources did not address a common intervention-outcome comparison. Confidence was assessed qualitatively through directness, methodological completeness, consistency, and sensitivity analysis.

Seventh, the review was retrospectively registered after searching, screening, extraction, and initial synthesis had begun. The OSF record therefore improves transparency but does not represent a prospective protocol.

Finally, the CDV Framework and circularity–viability paradox were derived through evidence synthesis and structured coding but have not been validated through prospective industrial implementation, expert consensus, application-specific testing, or predictive-model evaluation. They should be interpreted as diagnostic and hypothesis-generating structures.

8. Conclusions

This systematic review synthesized 119 unique sources, including 28 HDPE/PP material-specific sources and 91 contextual or system-level sources. Within the material-specific subset, 24 sources provided direct or partially direct recycled experimental evidence, whereas four provided indirect or secondary material-specific evidence.

The reviewed studies demonstrate that recycled HDPE and PP can be converted into filament, pellets, or granular feedstocks for extrusion-based additive manufacturing under study-specific conditions [14,31,53]. However, the evidence does not establish universal processing windows, mechanical-property ranges, degradation rates, cost competitiveness, environmental superiority, or industrial readiness. Reported outcomes were strongly dependent on feedstock origin, polymer grade, recycled-content fraction, formulation, reinforcement, processing history, equipment, specimen configuration, orientation, and test method.

Feedstock heterogeneity was a recurrent upstream source of variation, but it was neither a necessary nor a sufficient explanation for all downstream outcomes [5,8,20,34]. Intrinsic polymer behavior, crystallization, formulation, geometry, cooling, bed adhesion, printer configuration, and printing parameters could modify or independently influence extrusion and printed-part performance. Multi-cycle behavior was also non-uniform and should not be represented by a universal percentage loss per cycle [69,101,104].

https://doi.org/10.3390/recycling11080147

The Circular DRAM Viability Framework provides an evidence-informed diagnostic structure for organizing upstream feedstock conditions, material and process constraints, print-stage outcomes, intervention options, and system-level assessment requirements [1,36,72]. It does not quantify causal effects, rank intervention effectiveness, or demonstrate that a local pathway is economically, environmentally, socially, or commercially viable.

Most evidence remains at laboratory or demonstrator scale. Progress toward deployment requires stable and traceable feedstock supply, quantitative process capability, application-specific product qualification, cost per accepted part, material and energy yields, life-cycle comparison, quality assurance, governance, clearly assigned responsibility, and validated market demand [12,35,44,45,86]. The circularity–viability paradox further highlights that improved short-term printability may introduce additional formulation, energy, or end-of-use burdens [1,19,49,76]. These trade-offs must be evaluated through application-specific TEA, LCA, material-flow analysis, and technical qualification rather than assumed from recycled content alone.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/recycling11080147/s1, Supplementary Material S1: Evidence and Analysis Workbook. This workbook provides the final search and study-selection records; evidence registry and publication, polymer, and evidential-role classifications; study-level quantitative extraction; methodological appraisal; reporting-bias and confidence assessments; sensitivity analyses; framework coding and source-level analytical mappings; Sankey source coding and edge counts; Circularity–Viability Paradox evidence mappings and candidate indicators; system-level and economic assessment records; VOSviewer inputs and documentation; and the PRISMA 2020 reporting crosswalk.

Author Contributions: Conceptualization, J.M., C.C., M.D.L.Á.O.-D.-R. and R.C.; methodology, J.M. and C.C.; validation, J.M., C.C. and M.D.L.Á.O.-D.-R.; formal analysis, J.M., C.C. and M.D.L.Á.O.-D.-R.; investigation, J.M. and C.C.; resources, J.M., C.C., M.D.L.Á.O.-D.-R. and R.C.; data curation, J.M. and M.M.; writing—original draft preparation, J.M., C.C. and M.D.L.Á.O.-D.-R.; writing—review and editing, M.D.L.Á.O.-D.-R., R.C., M.M., D.K. and M.F.; visualization, J.M., C.C., M.D.L.Á.O.-D.-R. and R.C.; supervision, C.C. and M.D.L.Á.O.-D.-R.; project administration, J.M.; funding acquisition, J.M., C.C. and M.D.L.Á.O.-D.-R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Secretariat for Science, Technology, and Innovation (Secretaría Nacional de Ciencia, Tecnología, e Innovación, SENACYT) under the grant APY-NI-2024A-61.

Data Availability Statement: No new experimental data were generated. The systematic review dataset was derived from the 119 included peer-reviewed sources. Additional background statistics and contextual information were obtained from cited governmental and institutional publications. The extraction, classification, appraisal, and coding datasets are provided in Supplementary Material S1.

Acknowledgments: The authors would like to thank the Research Groups in Industrial Engineering (Giii) and Design, Manufacturing, and Materials (DM + M) within the Technological University of Panama https://utp.ac.pa/ (accessed on 10 June 2026) for their collaboration. Likewise, special thanks go to the Sistema Nacional de Investigación (SNI) for its support. During the preparation of this manuscript, the authors used generative AI tools to support language editing, structural refinement, and manuscript readability. These tools were not used to generate research data, conduct the systematic review, select or fabricate references, perform evidence coding, or develop conclusions. After using these tools, the authors carefully reviewed, verified, edited, and approved all content and take full responsibility for the accuracy, integrity, and originality of the published article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Sola, A.; Trinchi, A. Recycling as a Key Enabler for Sustainable Additive Manufacturing of Polymer Composites: A Critical Perspective on Fused Filament Fabrication. *Polymers* **2023**, *15*, 4219. [CrossRef] [PubMed]
2. Kalinke, C.; Crapnell, R.D.; de Oliveira, P.R.; Janegitz, B.C.; Bonacin, J.A.; Banks, C.E. How to Improve Sustainability in Fused Filament Fabrication (3D Printing) Research? *Glob. Chall.* **2024**, *8*, 2300408. [CrossRef] [PubMed]
3. Madhu, N.R.; Erfani, H.; Jadoun, S.; Amir, M.; Thiagarajan, Y.; Chauhan, N.P.S. Fused deposition modelling approach using 3D printing and recycled industrial materials for a sustainable environment: A review. *Int. J. Adv. Manuf. Technol.* **2022**, *122*, 2125–2138. [CrossRef] [PubMed]
4. Plastics Europe. *Plastics the Fast Facts*; Plastics Europe: Brussels, Belgium, 2025.
5. Strano, M.; Farioli, D.; Di Landro, L.A.; Mussi, V. Printability of recycled feedstock for extrusion additive manufacturing. *Adv. Mater. Process. Technol.* **2023**, *11*, 46–71. [CrossRef]
6. Lisiecki, M.; Belé, T.G.A.; Ügdüler, S.; Fiorio, R.; Astrup, T.F.; de Meester, S.; Ragaert, K. Mechanical recycling of printed flexible plastic packaging: The role of binders and pigments. *J. Hazard. Mater.* **2024**, *472*, 134375. [CrossRef] [PubMed]
7. UN Trade & Development. *Global Trade Update*; UN Trade & Development: Geneva, Switzerland, 2025.
8. Al Rashid, A.; Koç, M. Additive manufacturing for sustainability and circular economy: Needs, challenges, and opportunities for 3D printing of recycled polymeric waste. *Mater. Today Sustain.* **2023**, *24*, 100529. [CrossRef]
9. Leon-Ayala, W.; Ramos-Cosi, S.; Marrujo-Ingunza, C. A Systematic Review on the Reuse of Recycled Plastics in 3D Printing Filament Production. *Int. J. Mech. Eng.* **2025**, *12*, 87–95. [CrossRef]
10. Anastasiadou, C.; Vettese, S. "From souvenirs to 3D printed souvenirs". Exploring the capabilities of additive manufacturing technologies in (re)-framing tourist souvenirs. *Tour. Manag.* **2019**, *71*, 428–442. [CrossRef]
11. Atsani, S.I.; Sing, S.L. Optimization of Glass-Powder-Reinforced Recycled High-Density Polyethylene (rHDPE) Filament for Additive Manufacturing: Transforming Bottle Caps into Sound-Absorbing Material. *Polymers* **2024**, *16*, 2324. [CrossRef] [PubMed]
12. Santander, P.; Cruz Sanchez, F.A.; Boudaoud, H.; Camargo, M. Closed loop supply chain network for local and distributed plastic recycling for 3D printing: A MILP-based optimization approach. *Resour. Conserv. Recycl.* **2020**, *154*, 104531. [CrossRef]
13. Mikula, K.; Skrzypczak, D.; Izydorczyk, G.; Warchoł, J.; Moustakas, K.; Chojnacka, K.; Witek-Krowiak, A. 3D printing filament as a second life of waste plastics—A review. *Environ. Sci. Pollut. Res.* **2021**, *28*, 12321–12333. [CrossRef] [PubMed]
14. Vidakis, N.; Petousis, M.; Tzounis, L.; Maniadi, A.; Velidakis, E.; Mountakis, N.; Papageorgiou, D.; Liebscher, M.; Mechtcherine, V. Sustainable Additive Manufacturing: Mechanical Response of Polypropylene over Multiple Recycling Processes. *Sustainability* **2021**, *13*, 159. [CrossRef]
15. Kassab, A.; Al Nabhani, D.; Mohanty, P.; Pannier, C.; Ayoub, G.Y. Advancing Plastic Recycling: Challenges and Opportunities in the Integration of 3D Printing and Distributed Recycling for a Circular Economy. *Polymers* **2023**, *15*, 3881. [CrossRef] [PubMed]
16. Gonzalez, C.S.; Sanchez, F.A.C.; Boudaoud, H.; Nouvel, C.; Pearce, J.M. Multi-material distributed recycling via material extrusion: Recycled high density polyethylene and poly (ethylene terephthalate) mixture. *Polym. Eng. Sci.* **2024**, *64*, 1555–1570. [CrossRef]
17. Little, H.A.; Tanikella, N.G.; Reich, M.J.; Fiedler, M.J.; Snabes, S.L.; Pearce, J.M. Towards Distributed Recycling with Additive Manufacturing of PET Flake Feedstocks. *Materials* **2020**, *13*, 4273. [CrossRef] [PubMed]
18. Kuclourya, T.; Monroy, R.; Ahmad, R. Design of experiments to compare the reprocessing effect with Fused Deposition Modeling printing parameters on mechanical properties of Polylactic Acid specimens towards circular economy. *Prog. Rubber Plast. Recycl. Technol.* **2023**, *39*, 111–140. [CrossRef] [PubMed]
19. Petousis, M.; Kalderis, D.; Michailidis, N.; Papadakis, V.; Mountakis, N.; Argyros, A.; Spiridaki, M.; David, C.; Sagris, D.; Vidakis, N. Sustainable high-density polyethylene/ferronickel slag composites for material extrusion additive manufacturing: Engineering, morphological, rheological, thermal, and chemical aspects. *Sustain. Mater. Technol.* **2025**, *43*, e01227. [CrossRef]
20. Cruz Sanchez, F.A.; Boudaoud, H.; Camargo, M.; Pearce, J.M. Plastic recycling in additive manufacturing: A systematic literature review and opportunities for the circular economy. *J. Clean. Prod.* **2020**, *264*, 121602. [CrossRef]
21. Djonyabe Habiba, R.; Malça, C.; Branco, R. Exploring the Potential of Recycled Polymers for 3D Printing Applications: A Review. *Materials* **2024**, *17*, 2915. [CrossRef] [PubMed]
22. Gomes, T.E.P.; Cadete, M.S.; Dias-de-Oliveira, J.; Neto, V. Controlling the properties of parts 3D printed from recycled thermoplastics: A review of current practices. *Polym. Degrad. Stab.* **2022**, *196*, 109850. [CrossRef]
23. Sharma, A.; Kumar, M.; Sharma, A. Sustainable additive manufacturing: Challenges and opportunities of recycling plastic waste for 3D printing filaments. *Sādhanā* **2025**, *50*, 14. [CrossRef]
24. Sola, A.; Rosa, R.; Ferrari, A.M. Environmental Impact of Fused Filament Fabrication: What Is Known from Life Cycle Assessment? *Polymers* **2024**, *16*, 1986. [CrossRef] [PubMed]
25. Shah, H.H.; Tregambi, C.; Bareschino, P.; Pepe, F. Environmental and economic sustainability of additive manufacturing: A systematic literature review. *Sustain. Prod. Consum.* **2024**, *51*, 628–643. [CrossRef]

26. Patel, A.; Taufik, M. Extrusion-Based Technology in Additive Manufacturing: A Comprehensive Review. *Arab. J. Sci. Eng.* **2024**, *49*, 1309–1342. [CrossRef]
27. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 Statement: An Updated Guideline for Reporting Systematic Reviews. *BMJ* **2021**, *372*, n71. [CrossRef] [PubMed]
28. Page, M.J.; Moher, D.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. PRISMA 2020 explanation and elaboration: Updated guidance and exemplars for reporting systematic reviews. *BMJ* **2021**, *372*, n160. [CrossRef] [PubMed]
29. Silva, F.J.G.; Ferreira, L.P.; Sá, J.C.; Pereira, M.T.; Pinto, C.M.A. (Eds.) *Flexible Automation and Intelligent Manufacturing: Establishing Bridges for More Sustainable Manufacturing Systems*; Springer Nature: Cham, Switzerland, 2024.
30. Arrigo, R.; Battegazzore, D.; Bernagozzi, G.; Cravero, F.; Ribero Pedraza, D.N.; Frache, A. Recycled PP for 3D Printing: Material and Processing Optimization through Design of Experiment. *Appl. Sci.* **2022**, *12*, 10840. [CrossRef]
31. Chu, J.S.; Koay, S.C.; Chan, M.Y.; Choo, H.L.; Ong, T.K. Recycled plastic filament made from post-consumer expanded polystyrene and polypropylene for fused filamant fabrication. *Polym. Eng. Sci.* **2022**, *62*, 3786–3795. [CrossRef]
32. Phillis Teng, S.P.; Hiong Tee, C.; Boon Tan, H.; Fai Leong, K. Material extrusion-based printing optimization of recycled HDPE filaments made from used milk jugs. *Mater. Sci. Addit. Manuf.* **2024**, *3*, 4084. [CrossRef]
33. Shiferaw, M.Z. Developing Filament Extruder and Characterization of Recycled High-Density Polyethylene for 3D Printing Filament Material. *Eng. OA* **2023**, *1*, 5–20. [CrossRef]
34. Spina, R.; Gurrado, N. Green Recycling for Polypropylene Components by Material Extrusion. *Polymers* **2024**, *16*, 3502. [CrossRef] [PubMed]
35. Islam, M.T.; Iyer-Raniga, U.; Trewick, S. Recycling Perspectives of Circular Business Models: A Review. *Recycling* **2022**, *7*, 79. [CrossRef]
36. Di, L.; Yang, Y. Towards closed-loop material flow in additive manufacturing: Recyclability analysis of thermoplastic waste. *J. Clean. Prod.* **2022**, *362*, 132427. [CrossRef]
37. Firtkiadis, L.; Minaoglou, P.; Manavis, A.; Aidinli, K.; Efkolidis, N. Circular economy through customised 3D printed products: A case of souvenir. In Proceedings of the 11th International Symposium on Graphic Engineering and Design, Novi Sad, Serbia, 3–5 November 2022; pp. 467–471. [CrossRef]
38. Gil-Lamata, M.; Latorre-Martínez, M.P. The Circular Economy and Sustainability: A Systematic Literature Review. *Cuad. Gest.* **2022**, *22*, 129–142. [CrossRef]
39. Byard, D.J.; Woern, A.L.; Oakley, R.B.; Fiedler, M.J.; Snabes, S.L.; Pearce, J.M. Green fab lab applications of large-area waste polymer-based additive manufacturing. *Addit. Manuf.* **2019**, *27*, 515–525. [CrossRef]
40. Fragapane, G.; Lodgaard, E.; Lyngstad, O.V. A Survey on Current Practices, Strategies and Research Needs for Circular Manufacturing of Plastics. In *Flexible Automation and Intelligent Manufacturing: Establishing Bridges for More Sustainable Manufacturing Systems*; Silva, F.J.G., Ferreira, L.P., Sá, J.C., Pereira, M.T., Pinto, C.M.A., Eds.; Springer Nature: Cham, Switzerland, 2024; pp. 842–849.
41. Kumar, R.; Sharma, H.; Saran, C.; Tripathy, T.S.; Sangwan, K.S.; Herrmann, C. A Comparative Study on the Life Cycle Assessment of a 3D Printed Product with PLA, ABS & PETG Materials. *Procedia CIRP* **2022**, *107*, 15–20. [CrossRef]
42. Lu, L.; Yang, Y.; Sheng, K.; Du, X.; Song, Y.; Mi, Z. Green design and manufacturing processes based on additive manufacturing: A review. *MRS Commun.* **2025**, *15*, 760–776. [CrossRef]
43. Alexandre, A.; Cruz Sanchez, F.A.; Boudaoud, H.; Camargo, M.; Pearce, J.M. Mechanical Properties of Direct Waste Printing of Polylactic Acid with Universal Pellets Extruder: Comparison to Fused Filament Fabrication on Open-Source Desktop Three-Dimensional Printers. *3D Print. Addit. Manuf.* **2020**, *7*, 237–247. [CrossRef]
44. Bhanuprakash, L.; Kumar, H. A Review of Thermoplastic Filament Extruder Design and Fabrication Technologies. *J. Phys. Conf. Ser.* **2024**, *2837*, 12083. [CrossRef]
45. Berkemeier, A.; Kühnel, L.; Dürigen, D.; Hoffmann, H.; Zeidler, H.; Bullinger, A.C.; Wagenführ, A. SAMSax—An Innovative Living Lab for the Advancement of a Circular Economy through Additive Manufacturing Technologies. *Sustainability* **2024**, *16*, 823. [CrossRef]
46. Ruiz, L.E.; Pinho, A.C.; Resende, D.N. 3D Printing as a Disruptive Technology for the Circular Economy of Plastic Components of End-of-Life Vehicles: A Systematic Review. *Sustainability* **2022**, *14*, 13256. [CrossRef]
47. Dinka, M.; Nyika, J. The Progress in Using 3-D Printing Wastes Towards a Circular Economy. *E3S Web Conf.* **2023**, *430*, 1237. [CrossRef]
48. Sun, L.; Wang, Y.; Hua, G.; Cheng, T.; Dong, J. Virgin or recycled? Optimal pricing of 3D printing platform and material suppliers in a closed-loop competitive circular supply chain. *Resour. Conserv. Recycl.* **2020**, *162*, 105035. [CrossRef]
49. Battegazzore, D.; Cravero, F.; Bernagozzi, G.; Frache, A. Designing a 3D printable polypropylene-based material from after use recycled disposable masks. *Mater. Today Commun.* **2022**, *32*, 103997. [CrossRef]

50. Negrete-Bolagay, D.; Guerrero, V.H. Opportunities and Challenges in the Application of Bioplastics: Perspectives from Formulation, Processing, and Performance. *Polymers* **2024**, *16*, 2561. [CrossRef] [PubMed]
51. Daniele, R.; Armoni, D.; Dul, S.; Alessandro, P. From Nautical Waste to Additive Manufacturing: Sustainable Recycling of High-Density Polyethylene for 3D Printing Applications. *J. Compos. Sci.* **2023**, *7*, 320. [CrossRef]
52. El Shakhs, A.; Elessawy, N.A.; El-Saka, M.F.; Hassan, G.E.; Ali, M.A.M. Developing Eco-Friendly 3D-Printing Composite Filament: Utilizing Palm Midrib to Reinforce High-Density Polyethylene Matrix in Design Applications. *Polymers* **2024**, *16*, 1135. [CrossRef] [PubMed]
53. Herianto; Atsani, S.I.; Mastrisiswadi, H. Recycled Polypropylene Filament for 3D Printer: Extrusion Process Parameter Optimization. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *722*, 12022. [CrossRef]
54. Agbakoba, V.C.; Webb, N.; Jegede, E.; Phillips, R.; Hlangothi, S.P.; John, M.J. Mechanical Recycling of Waste PLA Generated From 3D Printing Activities: Filament Production and Thermomechanical Analysis. *Macromol. Mater. Eng.* **2024**, *309*, 2300276. [CrossRef]
55. Aissa, C.B.; Gabsi, A.E.H.; Mathlouthi, S.; Ghanem, A. Easy Conversion of PET Bottles to Eco-Filament for 3D Printing and Process Characterization. In *Advances in Additive Manufacturing: Materials, Processes and Applications*; Mabrouki, T., Sahlaoui, H., Sallem, H., Ghanem, F., Benyahya, N., Eds.; Springer Nature: Cham, Switzerland, 2024; pp. 170–178.
56. Al Rashid, A.; Koç, M. Additive manufacturing for sustainability, circularity and zero-waste: 3DP products from waste plastic bottles. *Compos. Part C Open Access* **2024**, *14*, 100463. [CrossRef]
57. Bustos Seibert, M.; Mazzei Capote, G.A.; Gruber, M.; Volk, W.; Osswald, T.A. Manufacturing of a PET Filament from Recycled Material for Material Extrusion (MEX). *Recycling* **2022**, *7*, 69. [CrossRef]
58. Galațanu, S.-V.; Serralha, F.N.; Mărghitaș, M.-P.; Șoșdean, C.; Popa, C.-F.; Emanoil, L.; Marșavina, L. Mechanical behavior of recycled FDM printed parts from PETG in the circular economy. *Procedia Struct. Integr.* **2024**, *56*, 138–143. [CrossRef]
59. Singh, J.; Singh, R.; Sharma, S. Effect of processing parameters on mechanical properties of FDM filament prepared on single screw extruder. *Mater. Today Proc.* **2022**, *50*, 886–892. [CrossRef]
60. Ibrahim, I.; Ashour, A.G.; Zeiada, W.; Salem, N.; Abdallah, M. A Systematic Review on the Technical Performance and Sustainability of 3D Printing Filaments Using Recycled Plastic. *Sustainability* **2024**, *16*, 8247. [CrossRef]
61. Thakur, V.; Singh, R.; Kumar, R.; Sharma, S.; Singh, S.; Li, C.; Zhang, Y.; Eldin, S.M.; Alqarni, S.A. Mechanically sustainable and primary recycled thermo-responsive ABS–PLA polymer composites for 4D printing applications: Fabrication and studies. *Rev. Adv. Mater. Sci.* **2024**, *63*, 20230149. [CrossRef]
62. Rusdyanto, B.; Imaduddin, F.; Ubaidillah; Ariawan, D. The Tensile Properties of Recycled Polypropylene Filament (rPP) as 3D Printing Material. *Evergreen* **2023**, *10*, 489–495. [CrossRef]
63. Spirio, A.; Arrigo, R.; Frache, A.; Tuccinardi, L.; Tuffi, R. Plastic waste recycling in additive manufacturing: Recovery of polypropylene from WEEE for the production of 3D printing filaments. *J. Environ. Chem. Eng.* **2024**, *12*, 112474. [CrossRef]
64. Angulo, C.; Shackleford, L.; Ning, H.; Pillay, S. Comparative study on the mechanical behaviors of compression molded, additively manufactured, and injection molded recycled carbon fiber reinforced rHDPE composites. *Compos. Part B Eng.* **2024**, *275*, 111323. [CrossRef]
65. Borkar, A.; Hendlmeier, A.; Simon, Z.; Randall, J.D.; Stojcevski, F.; Henderson, L.C. A comparison of mechanical properties of recycled high-density polyethylene/waste carbon fiber via injection molding and 3D printing. *Polym. Compos.* **2022**, *43*, 2408–2418. [CrossRef]
66. Zhang, Y.; Bai, H.; Mi, D.; Zhang, L.; Jiang, J.; Yang, T.; Ren, Z. Mixing screw design and high density polyethylene toughening modification for recycled polypropylene based on screw 3D printing. *J. Appl. Polym. Sci.* **2024**, *141*, e56192. [CrossRef]
67. Zhu, Y.; Fink, W.; Yost, S.F.; Mather, P.T.; Vogt, B.D. Subtle differences in recycled polypropylene from rheology to additives impacts ease of circularity in materials extrusion additive manufacture. *Addit. Manuf.* **2024**, *86*, 104209. [CrossRef]
68. Spina, R.; Cavalcante, B. Preliminary Analysis of Extruded PP Filaments for FFF. *Procedia Manuf.* **2020**, *47*, 915–919. [CrossRef]
69. Kumar, S.; Ramesh, M.R.; Doddamani, M. Recycling potential of MWCNTs/HDPE nanocomposite filament: 3D printing and mechanical characterization. *J. Mater. Cycles Waste Manag.* **2023**, *25*, 1168–1178. [CrossRef]
70. Wang, B.; Pierre-Antoine, A.; Guillaume, M.; Yang, G.; Zhou, S. Sustainable additive manufacturing: Microstructural evolution and mechanical viability of recycled Flax/PP via fused granular fabrication. *Ind. Crops Prod.* **2025**, *236*, 121997. [CrossRef]
71. Hidalgo-Carvajal, D.; Muñoz, Á.H.; Garrido-González, J.J.; Carrasco-Gallego, R.; Alcázar Montero, V. Recycled PLA for 3D Printing: A Comparison of Recycled PLA Filaments from Waste of Different Origins after Repeated Cycles of Extrusion. *Polymers* **2023**, *15*, 3651. [CrossRef] [PubMed]
72. Zhu, C.; Li, T.; Mohideen, M.M.; Hu, P.; Gupta, R.; Ramakrishna, S.; Liu, Y. Realization of Circular Economy of 3D Printed Plastics: A Review. *Polymers* **2021**, *13*, 744. [CrossRef] [PubMed]
73. Mishra, V.; Ror, C.K.; Negi, S.; Kar, S.; Borah, L.N. Development of sustainable 3D printing filaments using recycled/virgin ABS blends: Processing and characterization. *Polym. Eng. Sci.* **2023**, *63*, 1890–1899. [CrossRef]

74. Mohammad Noor, H.; Ibrahim, M.; Norazaman, A.A.A.; Abu Bakar Sidik, D.; Mohd Adnan, R.; Mohd Aripen, N.S. Parameter Optimization in FDM Filament Fabrication via Single Screw Extruder. *PaperASIA* **2024**, *40*, 266–272. [CrossRef]
75. Wei, X.; Bähr, R. A comparative study of 3D printing with virgin and recycled polylactic acid filaments. *CIRP J. Manuf. Sci. Technol.* **2024**, *54*, 75–84. [CrossRef]
76. Ghabezi, P.; Sam-Daliri, O.; Flanagan, T.; Walls, M.; Harrison, N.M. Circular economy innovation: A deep investigation on 3D printing of industrial waste polypropylene and carbon fibre composites. *Resour. Conserv. Recycl.* **2024**, *206*, 107667. [CrossRef]
77. Mathew, J.; Das, J.P.; Tp, M.; Kumar, S. Development of poly (butylene adipate-co-terephthalate) PBAT toughened poly (lactic acid) blends 3D printing filament. *J. Polym. Res.* **2022**, *29*, 474. [CrossRef]
78. Hamat, S.; Ishak, M.R.; Sapuan, S.M.; Yidris, N.; Hussin, M.S.; Abd Manan, M.S. Influence of filament fabrication parameter on tensile strength and filament size of 3D printing PLA-3D850. *Mater. Today Proc.* **2023**, *74*, 457–461. [CrossRef]
79. Kuo, C.-C.; Chen, J.-Y.; Chang, Y.-H. Optimization of Process Parameters for Fabricating Polylactic Acid Filaments Using Design of Experiments Approach. *Polymers* **2021**, *13*, 1222. [CrossRef] [PubMed]
80. Hachimi, T.; Naboulsi, N.; Majid, F.; Rhanim, R.; Mrani, I.; Rhanim, H. Design and Manufacturing of a 3D printer filaments extruder. *Procedia Struct. Integr.* **2021**, *33*, 907–916. [CrossRef]
81. Kumar, S.; Singh, I.; Ali, A.; Bharti, S.; Koloor, S.S.R.; Siebert, G. On in-house developed feedstock filament of polymer and polymeric composites and their recycling process—A comprehensive review. *Sci. Eng. Compos. Mater.* **2024**, *31*, 20220238. [CrossRef]
82. Park, S.; Fu, K. Polymer-based filament feedstock for additive manufacturing. *Compos. Sci. Technol.* **2021**, *213*, 108876. [CrossRef]
83. Sanassee, L.; Henrage, K. Production of 3D printing filament from plastic bottles waste using a low-income settings extruder as an opportunity to reduce plastic pollution in small Island developing states. *J. Mater. Cycles Waste Manag.* **2024**, *26*, 2841–2852. [CrossRef]
84. Shiferaw, M.Z.; Gebremedhen, H.S. Recycled Polymer for FDM 3D Printing Filament Material: Circular Economy for Sustainability of Additive Manufacturing. In *Advances of Science and Technology: Recycled Polymer for FDM 3D Printing Filament Material: Circular Economy for Sustainability of Additive Manufacturing*; Gebremedhen, H.S., Shiferaw, M.Z., Eds.; Springer International Publishing: Cham, Switzerland, 2022; pp. 243–261.
85. Yadav, A.; Rohru, P.; Babbar, A.; Kumar, R.; Ranjan, N.; Chohan, J.S.; Kumar, R.; Gupta, M. Fused filament fabrication: A state-of-the-art review of the technology, materials, properties and defects. *Int. J. Interact. Des. Manuf.* **2023**, *17*, 2867–2889. [CrossRef]
86. Maraveas, C.; Kyrtopoulos, I.V.; Arvanitis, K.G. Evaluation of the Viability of 3D Printing in Recycling Polymers. *Polymers* **2024**, *16*, 1104. [CrossRef] [PubMed]
87. Flores-Hernández, C.G.; López-Barroso, J.; Ramos-Galván, C.E.; Salazar-Cruz, B.A.; Chávez-Cinco, M.Y.; Rivera-Armenta, J.L. Development of a Composite Filament Based on Polypropylene and Garlic Husk Particles for 3D Printing Applications. *Appl. Sci.* **2024**, *14*, 9139. [CrossRef]
88. Nekin Joshua, R.; Sakthivel, A.R. Reinforced Polymer Composite Filaments in Fused Deposition Modeling of 3D Printing Technology: A Review. *Adv. Eng. Mater.* **2025**, *27*, 2402509. [CrossRef]
89. RaviRamful, R. A review on development of eco-friendly natural fiber-reinforced composite filaments for 3D printing: Fabrication and characteristics. *Mater. Sci. Addit. Manuf.* **2025**, *4*, 8533. [CrossRef]
90. Braconnier, D.J.; Jensen, R.E.; Peterson, A.M. Processing parameter correlations in material extrusion additive manufacturing. *Addit. Manuf.* **2020**, *31*, 100924. [CrossRef]
91. Tabary, S.A.A.B.; Fayazfar, H.R. Circular economy solutions for plastic waste: Improving rheological properties of recycled polyethylene terephthalate (r-PET) for direct 3D printing. *Prog. Addit. Manuf.* **2024**, *10*, 2795–2804. [CrossRef]
92. Sasse, J.; Pelzer, L.; Schön, M.; Ghaddar, T.; Hopmann, C. Investigation of Recycled and Coextruded PLA Filament for Additive Manufacturing. *Polymers* **2022**, *14*, 2407. [CrossRef] [PubMed]
93. Ror, C.K.; Negi, S.; Mishra, V. Development and characterization of sustainable 3D printing filaments using post-consumer recycled PET: Processing and characterization. *J. Polym. Res.* **2023**, *30*, 350. [CrossRef]
94. Pongsathit, S.; Kamaisoom, J.; Rungteerabandit, A.; Opaprakasit, P.; Jiamjiroch, K.; Pattamaprom, C. Toughness Enhancement of PLA-Based Filaments for Material Extrusion 3D Printing. *Mater. Des. Process. Commun.* **2023**, *2023*, 2707510. [CrossRef]
95. Dave, H.K.; Prajapati, A.R.; Rajpurohit, S.R.; Patadiya, N.H.; Raval, H.K. Investigation on tensile strength and failure modes of FDM printed part using in-house fabricated PLA filament. *Adv. Mater. Process. Technol.* **2022**, *8*, 576–597. [CrossRef]
96. Dash, A.; Kabra, S.; Misra, S.; G, H.; Singh, R.P.; Patterson, A.E.; Chadha, U.; Rajan, A.J.; Hirpha, B.B. Comparative property analysis of fused filament fabrication PLA using fresh and recycled feedstocks. *Mater. Res. Express* **2022**, *9*, 115303. [CrossRef]
97. Ben Amor, R.; Souissi, S.; Elloumi, A.; Bentaher, H. Parametric optimization and modeling of fused filament fabrication (FFF) using recycled PET from water bottles: A comparative study with virgin PET. *Int. J. Interact. Des. Manuf.* **2025**, *20*, 561–580. [CrossRef]

98. Al Rashid, A.; Koç, M. 3D-Printed recycled polyethylene terephthalate (PET) sandwich structures—Influence of infill design and density on tensile, dynamic mechanical, and creep response. *Int. J. Lightweight Mater. Manuf.* **2025**, *8*, 442–452. [CrossRef]
99. Karaki, A.; Masad, E.; Khraisheh, M.; Ouederni, M. Fused deposition modeling of polyethylene (PE): Printability assessment for low-density polyethylene and polystyrene blends. *Compos. Part C Open Access* **2024**, *15*, 100499. [CrossRef]
100. Kristiawan, R.B.; Rusdyanto, B.; Imaduddin, F.; Ariawan, D. Glass Powder Additive on Recycled Polypropylene Filaments: A Sustainable Material in 3D Printing. *Polymers* **2021**, *14*, 5. [CrossRef] [PubMed]
101. Hasan, M.R.; Davies, I.J.; Paramanik, A.; John, M.; Biswas, W.K. Fabrication and Characterisation of Sustainable 3D-Printed Parts Using Post-Consumer PLA Plastic and Virgin PLA Blends. *Processes* **2024**, *12*, 760. [CrossRef]
102. Romani, A.; Perusin, L.; Ciurnelli, M.; Levi, M. Characterization of PLA feedstock after multiple recycling processes for large-format material extrusion additive manufacturing. *Mater. Today Sustain.* **2024**, *25*, 100636. [CrossRef]
103. Shahriari, L.; Kim, S. Toward Circular Polymer Materials and Manufacturing: Dynamic Bonding Strategies for Upcycling Thermoplastics and Thermosets. *Macromol. Rapid Commun.* **2025**, *46*, e2401011. [CrossRef] [PubMed]
104. Väisänen, A.J.K.; Alonen, L.; Ylönen, S.; Lyijynen, I.; Hyttinen, M. The impact of thermal reprocessing of 3D printable polymers on their mechanical performance and airborne pollutant profiles. *J. Polym. Res.* **2021**, *28*, 436. [CrossRef]
105. Kristiawan, R.B.; Imaduddin, F.; Ariawan, D.; Ubaidillah; Arifin, Z. A review on the fused deposition modeling (FDM) 3D printing: Filament processing, materials, and printing parameters. *Open Eng.* **2021**, *11*, 639–649. [CrossRef]
106. Fontana, L.; Minetola, P.; Khandpur, M.S.; Giubilini, A. Evaluating Self-Produced PLA Filament for Sustainable 3D Printing: Mechanical Properties and Energy Consumption Compared to Commercial Alternatives. *J. Manuf. Mater. Process.* **2025**, *9*, 172. [CrossRef]
107. Luo, T.; Hu, Y.; Zhang, M.; Jia, P.; Zhou, Y. Recent advances of sustainable and recyclable polymer materials from renewable resources. *Resour. Chem. Mater.* **2025**, *4*, 100085. [CrossRef]
108. Cano Vicent, A.; Serrano Aroca, Á. Impresión 3D por modelado por deposición fundida: Manejo, funcionamiento y aplicaciones biomédicas. *Nereis* **2021**, *13*, 227–238. [CrossRef]
109. Arif, Z.U.; Khalid, M.Y.; Sheikh, M.F.; Zolfagharian, A.; Bodaghi, M. Biopolymeric sustainable materials and their emerging applications. *J. Environ. Chem. Eng.* **2022**, *10*, 108159. [CrossRef]
110. Hartig, S.; Hildebrandt, L.; Fette, M.; Meyer, T.; Musienko, E.; Redlich, T.; Wulfsberg, J. Process parameter determination for small recycling plants for the production of filament for FFF printing using the Taguchi method. *Prog. Addit. Manuf.* **2022**, *7*, 87–97. [CrossRef]
111. Liu, D.; Basdeo, A.; Gonzalez, C.S.; Romani, A.; Boudaoud, H.; Nouvel, C.; Cruz Sanchez, F.A.; Pearce, J.M. Low-Cost Open-Source Melt Flow Index System for Distributed Recycling and Additive Manufacturing. *Materials* **2024**, *17*, 5966. [CrossRef] [PubMed]
112. Morales, M.A.; Atencio Martinez, C.L.; Maranon, A.; Hernandez, C.; Michaud, V.; Porras, A. Development and Characterization of Rice Husk and Recycled Polypropylene Composite Filaments for 3D Printing. *Polymers* **2021**, *13*, 1067. [CrossRef] [PubMed]
113. Tabassum, T.; Ahmad Mir, A. A review of 3d printing technology-the future of sustainable construction. *Mater. Today Proc.* **2023**, *93*, 408–414. [CrossRef]
114. Yousaf, A.; Al Rashid, A.; Polat, R.; Koç, M. Potential and challenges of recycled polymer plastics and natural waste materials for additive manufacturing. *Sustain. Mater. Technol.* **2024**, *41*, e01103. [CrossRef]
115. Babaremu, K.O.; Okoya, S.A.; Hughes, E.; Tijani, B.; Teidi, D.; Akpan, A.; Igwe, J.; Karera, S.; Oyinlola, M.; Akinlabi, E.T. Sustainable plastic waste management in a circular economy. *Heliyon* **2022**, *8*, e09984. [CrossRef] [PubMed]
116. Rigon, D.; Ricotta, M.; Meneghetti, G. A literature survey on structural integrity of 3D printed virgin and recycled ABS and PP compounds. *Procedia Struct. Integr.* **2020**, *28*, 1655–1663. [CrossRef]
117. Wu, H.; Mehrabi, H.; Naveed, N.; Karagiannidis, P. A business model for additive manufacturing of recycled plastics towards sustainability. *Int. J. Adv. Manuf. Technol.* **2022**, *120*, 7997–8011. [CrossRef]
118. Oladapo, B.I.; Bowoto, O.K.; Adebiyi, V.A.; Ikumapayi, O.M. Net zero on 3D printing filament recycling: A sustainable analysis. *Sci. Total Environ.* **2023**, *894*, 165046. [CrossRef] [PubMed]
119. Wu, H.; Mehrabi, H.; Naveed, N.; Karagiannidis, P. Impact of strategic control and supply chain management on recycled plastic additive manufacturing. *J. Clean. Prod.* **2022**, *364*, 132511. [CrossRef]
120. Oyinlola, M.; Okoya, S.A.; Whitehead, T.; Evans, M.; Lowe, A.S. The potential of converting plastic waste to 3D printed products in Sub-Saharan Africa. *Resour. Conserv. Recycl. Adv.* **2023**, *17*, 200129. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

https://doi.org/10.3390/recycling11080147