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# Strategies for recycling multi-material polymer blends for additive manufacturing

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## Abstract:

The rapid advancement of additive manufacturing (AM) technology, combined with the growing accumulation of plastic waste, has generated significant interest in utilizing materials derived from plastic waste and their composites within the AM industry. This paper examines the methods and approaches currently employed in recycling and blending thermoplastic waste into additive manufacturing feedstocks, aiming to enhance understanding and guide future advancements in this field. A systematic literature review including 82 papers from 2014 to 2024 was performed using the Scopus and Web of Science databases. The review findings indicate that approximately 83% of the research is concentrated in production of new materials combining various polymer waste with recycled bio-sourced materials, recycled fillers or other additives for property enhancement. The evaluation and characterization of these new materials was carry out mostly using 3D printing, predominantly employing fused filament fabrication technology (63%). The remaining 17% focus on the improvement of the printing quality and optimization, development or adaptation of 3D printers for the utilization of new materials, and material reprocessability. This review highlight the need of evaluating the behavior of recycled blends over multiple life cycles, the cost and environmental assessments, and primary end-use applications of these materials, including as well as further development and design of printers.

Keywords: 3D printing, plastic blend, recycling, additive manufacturing, distributed recycling, and additive manufacturing.

## List of Abbreviations

Acronym	Name
<b>ABS</b>	Poly(acrylonitrile-co-butadiene-co-styrene)
<b>AC</b>	Activated Carbon
<b>AM</b>	Additive Manufacturing
<b>ASA</b>	Acrylonitrile Styrene Acrylate
<b>Al<sub>2</sub>O<sub>3</sub></b>	Aluminum Oxide
<b>BAK</b>	Bakelite
<b>CB</b>	Carbon Black
<b>CF</b>	Carbon Fiber
<b>DIW</b>	Direct Ink Writing
<b>DLP</b>	Digital Light Processing
<b>DMA</b>	Dynamic Mechanical Analysis
<b>DRAM</b>	Distributed recycling via additive manufacturing

<b>DSC</b>	Differential scanning calorimetry
<b>EPS</b>	Expanded Polystyrene
<b>FA</b>	Fly Ash
<b>FDM</b>	Fused deposition modeling
<b>FFF</b>	Fused filament fabrication
<b>FGF</b>	Fused granular fabrication
<b>FPF</b>	Fused particle fabrication
<b>FTIR</b>	Fourier-transform infrared spectroscopy
<b>GF</b>	Glass Fiber
<b>HC</b>	Hydrolyzed collagen
<b>HDPE</b>	High-density polyethylene
<b>HIPS</b>	High-impact Polystyrene
<b>LCA</b>	Life Cycle Assessment
<b>LDPE</b>	Low-density polyethylene
<b>MA</b>	Maleic anhydride
<b>MCC</b>	Microcrystalline Cellulose
<b>MFI</b>	Melt flow index
<b>MWCNT</b>	Multi-walled Carbon Nanotubes
<b>PA12</b>	Polyamide 12
<b>PBT</b>	Poly(butylene terephthalate)
<b>PC</b>	Polycarbonate
<b>PCL</b>	Polycaprolactone
<b>PE</b>	Polyethylene
<b>PEG</b>	Polyethylene Glycol
<b>PET</b>	Polyethylene terephthalate
<b>PETG</b>	Polyethylene terephthalate glycol
<b>PHB</b>	Polyhydroxybutyrate
<b>PIEK</b>	polyaryletherketone
<b>PLA</b>	Poly(lactic acid)
<b>PME</b>	Powder Material Extrusion
<b>PP</b>	Polypropylene
<b>PS</b>	Polystyrene
<b>PSW</b>	Plastic Solid Waste
<b>PVC</b>	Polyvinyl Chloride
<b>SAG</b>	Methacrylate
<b>SEBS</b>	Poly(styrene-b-(ethylene-co-butylene)-b-styrene)
<b>SEM</b>	Scanning Electron Microscopy
<b>SLS</b>	Selective Laser Sintering
<b>SiC</b>	Silicon Carbide
<b>TEM</b>	Transmission Electron Microscopy
<b>TGA</b>	Thermogravimetric Analysis
<b>TPO</b>	Polyolefin
<b>TPU</b>	Thermoplastic polyurethane
<b>TR</b>	Tier Rubber
<b>TiO</b>	Titanium dioxide
<b>WEEE</b>	Waste Electrical and Electronic Equipment
<b>rABS</b>	Recycled Poly(acrylonitrile butadiene styrene)
<b>rCF</b>	Recycled Carbon Fiber
<b>rGF</b>	Recycled Glass Fiber

<b>rHDPE</b>	Recycled High-density Polyethylene
<b>rLDPE</b>	Recycled Low-density Polyethylene
<b>rPC</b>	Recycled Polycarbonate
<b>rPET</b>	Recycled Polyethylene terephthalate
<b>rPETG</b>	Recycled Polyethylene terephthalate glycol
<b>rPLA</b>	Recycled Poly(lactic acid)
<b>rPP</b>	Recycled Polypropylene
<b>rPS</b>	Recycled Polystyrene
<b>vPET</b>	Virgin or commercial Polyethylene terephthalate
<b>vPLA</b>	Virgin Poly(lactic acid)
<b>μ-CT</b>	Micro-computed tomography

## 1. Introduction

The accumulation of plastic waste present a significant challenge in today's world, due as most of them have high time of degradation, which is estimated between 10 to 450 years [1], [2]. The production and disposal of plastics in our ecosystem have reached significant levels, contributing to severe environmental problems and posing risks to human health [3]. In 2021, approximately 390.7 million tons of plastic were produced globally, where 90.2% were fossil-based, 8.3% post-consumer recycled, and just 1.5% bio-based or bio-attributed plastic [4]. Projections indicate that by 2060, worldwide plastic consumption and waste will almost triple, while plastic recycling will see only a slight rise, leading to a doubling of global plastic pollution [5]. The recycling and upcycling of wastes have emerged as a promising step towards optimized production processes and resource management, contributing to the adaptation of a circular economy as a sustainable long-term solution [2].

Despite the emergence of recycling as a solution over the past three decades [6], the rate of recycled plastics is relatively low (9%). Meanwhile, approximately 19% was incinerated, 50% end up in landfills, and 22% leak into the environment [1], [7]. Widespread adoption is hindered by high volume low value, cost inefficiencies [8], Infrastructure [9], International trades [10] China's national sword policy implementation, which banned import of many reclyables [11], [12]. Additionally, multi-material packaging, such as those used for food products, often consists of multiple layers of different polymers like polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and poly(lactic acid) (PLA) [13], [14], [15]. These complex structures are difficult to recycle due to the incompatibility of different polymers and the need for separation, as well as the challenge this represents [16]. Furthermore, recycled products often suffer from diminished quality due to impurities, contamination, degradation, and the mixing of incompatible polymers [17], [18], [19]. Understanding and studying recycled materials is essential to promoting sustainable manufacturing practices and supporting the principles of the circular economy Therefore, there is a critical need for innovative strategies to enhance recycling efforts of these more complex and abundant materials. An alternative solution could be the use of biopolymers derived from natural sources to replace their fossil-based counterparts [20], [21].

Another strategy that has received considerable attention is the blending of recycled thermoplastics to improve material properties and provide a second life to single-use plastics [3], [22], [23]. Typically, extrusion processes are employed to mix these blends, utilizing either twin or single-screw extruders. While extensive efforts have been devoted to characterizing these blends, the challenge of polymer incompatibility persists, impeding their full

implementation. Recent research has explored the use of additives to enhance inter- or intramolecular interactions between the different polymer chains [24], [25], [26], [27]. Organic additives have shown promise in addressing this challenge, for instance, copolymers [28], [29], elastomers [30], [31] and reactive functional groups like maleic anhydride (MA) [32], [33] and epoxides [34], [35], as well as inorganic fillers like carbon [36] and fiberglass [37]. These blending strategies can offer opportunities to enhance material properties and facilitate recyclability. Moreover, a strategy to overcoming the transportation economic limitations of recycling waste plastic that has gained attention is the concept of distributed recycling and additive manufacturing (DRAM) [38], [39], [40], [41]. In DRAM plastic waste is used as a feedstock for 3D printing on a localized scale either by producing consumers themselves (prosumers) or as part of community, business, or regional initiative. Additive manufacturing (AM), commonly known as 3D printing, enables the production of complex structures from digital designs by depositing material layer by layer [42].

This manufacturing method holds potential as an innovative solution for repurposing plastic waste into 3D printing feedstock because the value of the 3D printed articles can be substantial for a wide range of consumer goods [43], [44], [45], which have been shown to be economic [46], [47]. In addition, prosumer 3D printing of prototyping and scientific equipment [48], [49], [50], [51], sporting equipment [52] adaptive aids [53], toys [54], [55], and other goods is becoming widespread [56]. Various studies have demonstrated the feasibility of using recycled plastics, such as PET [57], [58], PLA [59], [60], Poly(acrylonitrile-co-butadiene-co-styrene) (ABS) [45], [61], and low-density polyethylene (LDPE) [62] in 3D printing applications, highlighting the potential for widespread adoption [39]. Romani et al (2024) [63] clearly illustrated the diverse applications of recycled materials in large-scale extrusion-based 3D printing, ranging from academic research to industrial activities. Despite this growing interest, their use remains limited by technical challenges such as inconsistent mechanical performance, limited printability, and variability in material composition. Studying recycled materials is therefore essential not only for improving their processing and performance but also for enabling scalable, sustainable solutions.

At this point most of the common thermoplastics have been demonstrated to be viable with DRAM and there is a growing interest in either developing new materials or blending multi-materials using additives for DRAM. This underscores the need for a deeper understanding of the strategies to process multi-material blends for additive manufacturing. Previous research highlights the potential of combining recycled plastics with various additives to enhance their properties, yet there remain significant gaps in fully implementing these strategies [64], [65].

This study addresses this need by conducting a systematic literature review focused on the research question: *What is the current state of different strategies used to recycle multi-material polymer blends using additive manufacturing technologies, and how can these strategies be improved?*. The objective is to provide a comprehensive overview of the methods and approaches currently employed, identify existing challenges, and suggest potential advancements for future research.

This paper is structured as follows. Section 2 presents a detailed background on the state of plastic recycling, polymer blend compatibilization, and advancements in additive manufacturing technologies. Then, Section 3 outlines the methodology employed to systematically review [66] to identify the relevant literature and ensuring a robust and thorough analysis. In Section 4, the main results are presented, and categorized into key areas such as innovations in 1) material development, 2) 3D printing with recycle materials, 3) technological advancements, and 4) reprocessing of the materials. The discussion in Section 5 delves into

these results and propose new understanding based on the broader view proposed here. Finally, the conclusion and directions for future research are presented in Section 6.

## 2. Theoretical Background

### 2.1 Plastic waste and recycling

Plastic solid waste (PSW) is referred as discarded plastic of material such as plastic bottles, containers, packaging, among others. Global plastic production has significantly increased over the past 50 years [67], with an annual production estimation of 260- 240 metric tons of waste from 2016 to 2030 [68]. This increment poses environmental and waste management challenges, with packaging accounting for nearly 46% of plastic waste by 2017 [69]. Recycling, a circular economy strategy, has emerged as a solution, with Europe targeting 60% recycling of packaging waste by 2035 [70].

In the 1990s plastic recycling emerged as a viable solution to manage plastic waste [6] and currently four primary approaches encompasses de recycling system: primary (closed-loop) [71] [65], secondary (downgrading), tertiary (chemical) [6], and quaternary (energy recovery) [72] [24]. Mechanical recycling, the most common, involves collection, sorting, and reprocessing but faces contamination and material degradation issues [67]. Chemical recycling breaks plastics into monomers but requires advanced technologies and high energy input. Finally, quaternary recycling, like incineration and pyrolysis, reduces waste volume but negatively impacts air quality [67].

The consolidation of recycling as a strategy for managing plastic waste has increased, however, the process still faces significant constraints linked to material heterogeneity, degradation, and high costs. Additionally, Centralized recycling models add transportation costs and carbon emissions. In response, decentralized recycling and additive manufacturing (DRAM) have emerged, promoting local processing of plastic waste into 3D-printed objects, offering an innovative pathway to enhance material revalorization.

#### 2.1 Distributed Recycling via Additive Manufacturing - DRAM

This innovative concept represents a departure from traditional recycling methods, merging the advantages of AM with recycling principles, with the aim of democratizing and streamlining recycling efforts. DRAM entails a shift from centralized to distributed recycling systems, empowering consumers to directly transform their own waste into usable products through 3D printing, with a particular emphasis on extrusion technology due to its cost-effectiveness and efficiency [73]. The higher costs associated with recycled plastics stem from various stages of the recycling process, including collection, sorting, cleaning, and transportation can be mitigated by the adoption of a distributed recycling model eliminating the need for transportation to centralized facilities, as well as reducing expenses related to electricity consumption during shredding activities.

The use of AM enables the fabrication of personalized objects by adding material layer by layer, significantly minimizing material waste during the fabrication process. Some studies have proved the efficacy of distributed recycling for repurposing plastic waste into new 3D printed products [43], [52], [74], [75],[76],[77], [78] reducing dependence on the virgin raw materials, energy, and water usually required for traditional manufacturing methods. This method demands less energy and a low carbon footprint [79] compared with virgin materials. Additionally, DRAM has already shown environmental benefits [39], [80], [81], and global applicability. Full implementation of DRAM still faces some challenges associated with the

collection and sorting procedures where the optimization of this process are required [73]. The selection of materials that can be processed without significant degradation of their properties is essential. Additionally, the blending of multi-materials, each with distinct flow, viscosity, and thermal characteristics, presents printing challenges such as warping, layer adhesion, shrinkage, and surface finish imperfections [82].

The practice of blending virgin and recycled polymers, often with the addition of a compatibilizer, has been employed to enhance the properties of the resulting polymer blends [83], [84]. This approach aims to optimize the mechanical, thermal, and rheological characteristics of the blends, thereby improving their overall performance and expanding their applicability in various industrial applications [85]. By combining the advantageous properties of both virgin and recycled polymers, and strategically introducing a third component, researchers can mitigate the inherent limitations of individual materials and achieve superior composite materials.

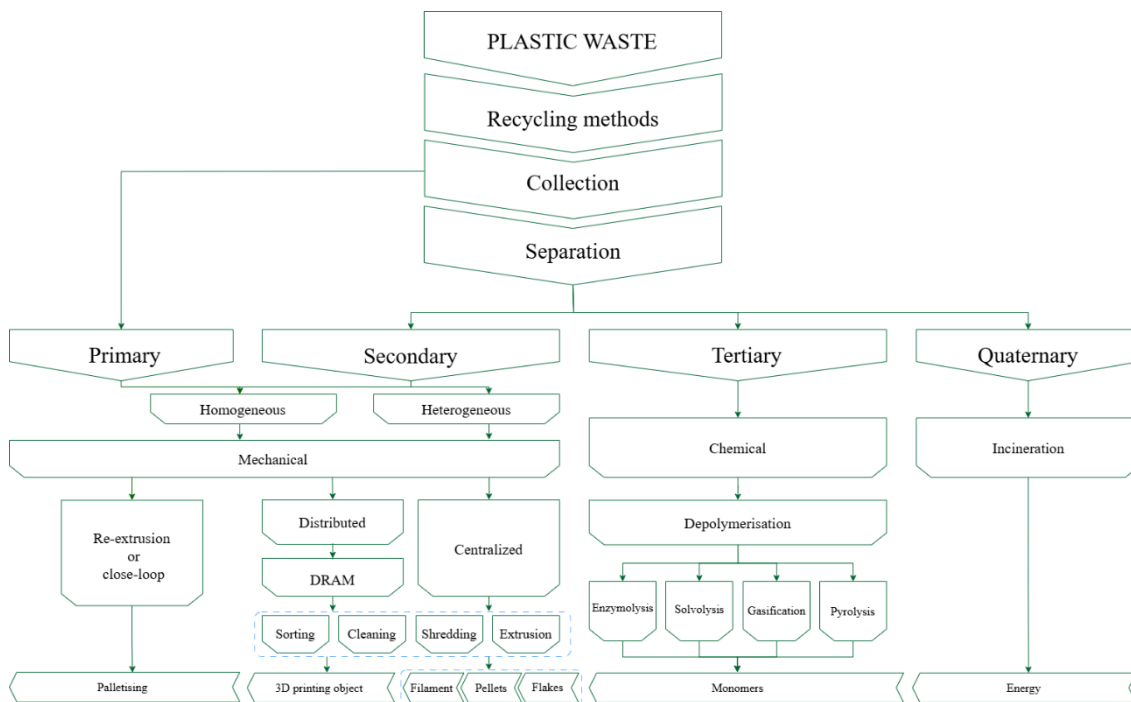


Figure.1 Different approaches available for recycling PSW. Adapted from [67], [86].

## 2.2 Polymer blends and Compatibilization

Polymer blending involves mixing two or more polymers to create new materials with enhanced mechanical and physical properties.[87], [88]. These blends can be completely miscible, partially miscible, or immiscible, with performance largely influenced by blend morphology, molecular compatibility, and factors such as glass transition temperature.[89]. While polymer blending is a promising approach to develop new materials and facilitate recycling, it often faces challenges due to immiscibility, phase separation, and weak mechanical properties.[73]. Thus, characterizing these blends is essential for understanding their properties, which are influenced by factors such as morphology [90], geometrical arrangement [91], [92], and inherent polymer [93] characteristics.

Polymer blends offer a promising approach to create novel materials and might beneficial in polymer recycling, simplifying sorting processes. However, blending polymers often encounters challenges, primarily due to the immiscibility of many polymers. This immiscibility

arises from weak interactions between the phases of each polymer, leading to poor mechanical properties and unstable morphology.

To overcome these limitations, compatibilization strategies are employed. For instance, the use of additives called compatibilizers, which are introduced to enhance interfacial adhesion between different polymers can help to stabilize blend morphology, reduce interphase tension, and improve mechanical thermal, and rheological properties [27], [94], [95]. Compatibilization can be achieved through two primary methods: the incorporation of polymer-based additives or fillers and mechanochemical processes as shown in Fig. 3. The role of the compatibilizer is to function as an interfacial agent that reduces the interfacial tension between the two immiscible phases, thereby enhancing interfacial adhesion and improving the material properties [96] (Fig.2).

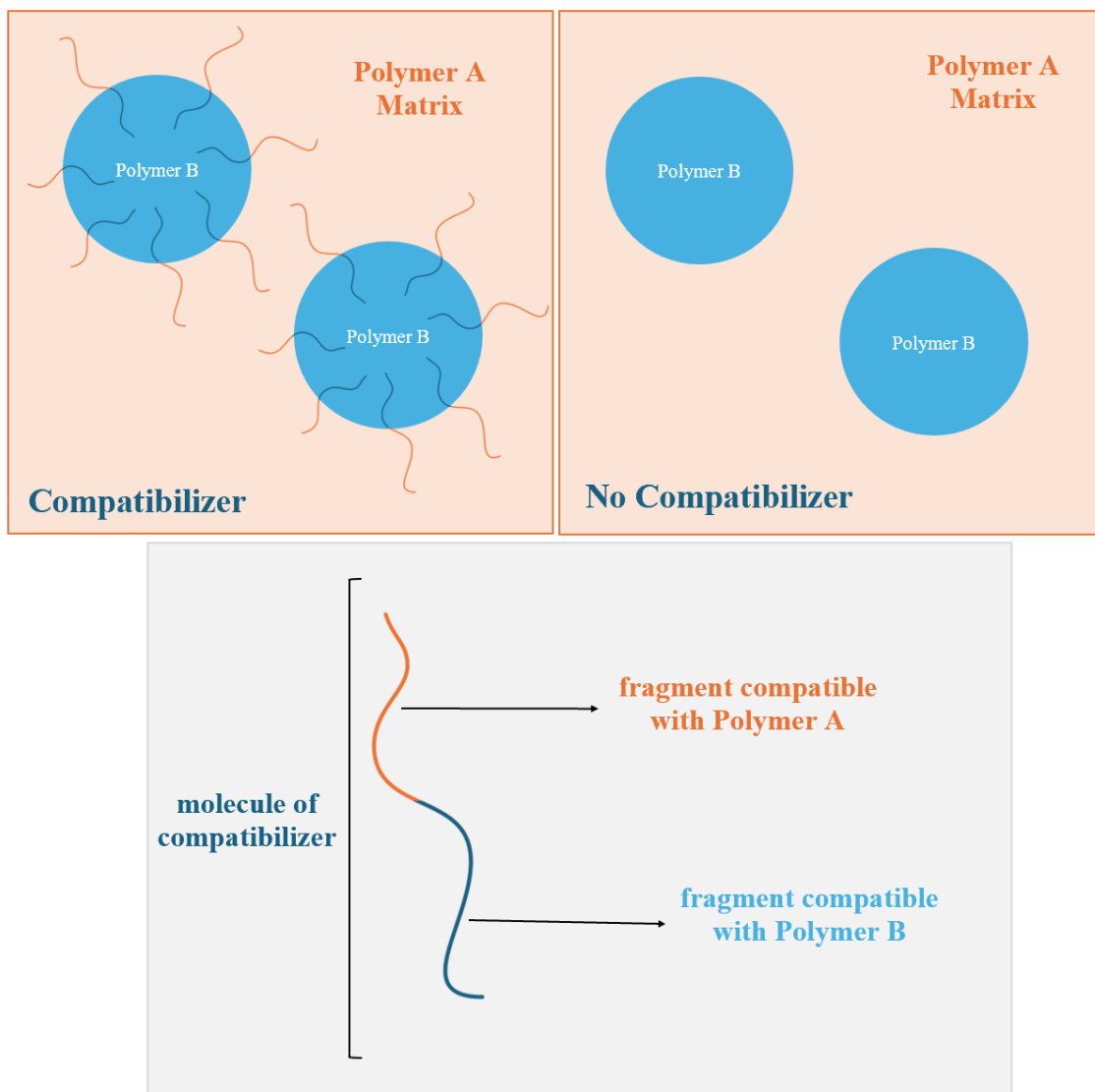


Figure 2. Ideal compatibilization of polymer A and B with and without additives. Adapted from [72].

Compatibilizers can act through physical interactions (using non-reactive polymer-based additives like copolymers or elastomers) [27], [97] or reactive interactions (involving chemical reactions and covalent bonding, using agents such as epoxy, maleic anhydride, or isocyanates) [95]. Additionally, fillers such as carbon nanotubes [101], clay [102], Janus nanoparticles (two or more chemically distinct particles with different properties) [25], [27], [100], or bio-sourced materials like biochar, wood flour [101], and rice husk [102] are used to reinforce blends and stabilize morphology. Their localization either within one phase or at the interface is critical for successful compatibilization.

Another innovative approach is mechanochemical compatibilization, where mechanical processes like solid-state shear pulverization [104], [105] or ball milling induce structural changes in polymers, generating free radicals that lead to cross-linking and improved self-compatibility [95]. These strategies are key to advancing polymer recycling and creating high-performance recycled materials.

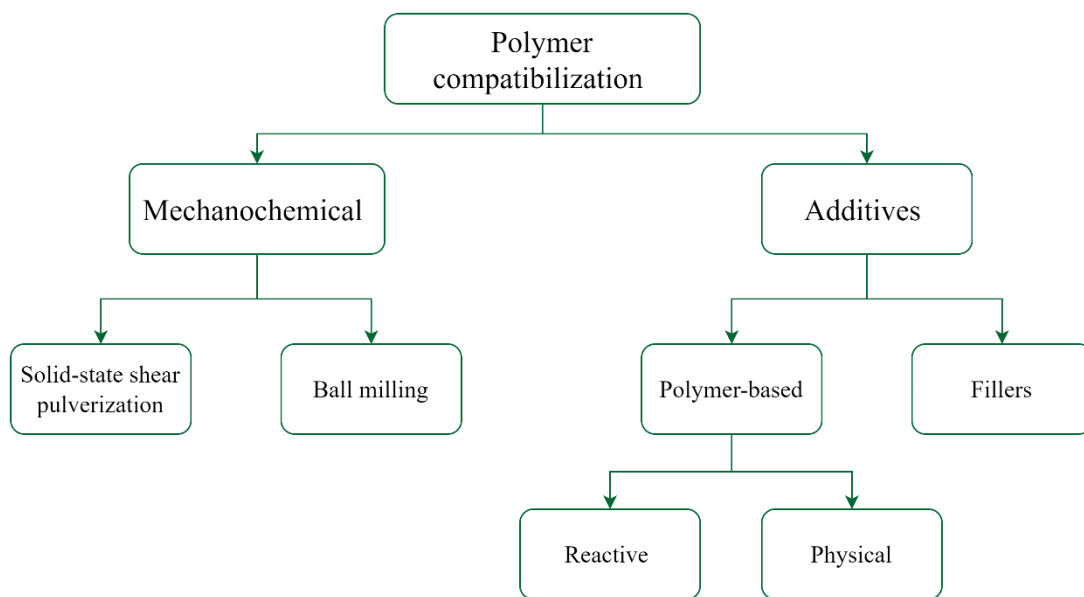


Figure 3. Polymer compatibilization routes.

### 3. Review Methodology

The objective of this review is to identify the current work in the recycling of multi-material polymer blends using the additive manufacturing process, the challenges faced, and assess the possible opportunities. For this reason, a systematic review protocol was used to perform and evaluate studies following [66]. This protocol aims to avoid publications bias, search for gray literature, and enable future reviews performance in the identification of new research pathways. The research strategy used in this study is illustrated in Table 1, while the selection process of the papers, based in the PRISMA (flow diagram) is depicted in Fig. 4. A total of 233 studies were identified using two different scientific research engines (Web of Science and Scopus). The duplicated articles were discarded, and the retained studies were screened to select those in relation to the research. Within this screening, title, keywords, and abstract were assessed, and 98 papers being rejected by applying the inclusion criteria summarized in Table 1. Finally, a total of 100 articles were chosen for a full reading, and a total of 82 papers were selected for final analysis because 18 did not match the criteria.

Table 1. Protocol for the literature review

Stage	Principle	Description
Search Strategy	Type of studies	Journals papers
	Keywords	<ol style="list-style-type: none"> <li>1. Polymer blend to extract the different blending using different polymers.</li> <li>2. Additive Manufacturing and its synonym 3d printing to limit the type of technology used.</li> <li>3. Recycle, recycling and derivatives to focus on the recycling plastics.</li> </ol>
	Search equation	Polymer AND blend* AND (“Additive Manufacturing” OR “3D printing” OR “Rapid prototyping” OR “AM”) AND (recycl*)
	Period	2014-2024
Study Selection	Databases	Web of science and Scopus
	Criteria for data extraction	Only articles studying the blending of recycle polymers using additive manufacturing, blending to improve recyclability of the materials.
Data extraction	Procedure	<ol style="list-style-type: none"> <li>1) A first review based on title, abstract and keywords is done to select the articles to be completely read.</li> <li>2) From the previous selection, full articles are reviewed.</li> <li>3) A group of articles is selected based on the criteria for data extraction.</li> </ol>
		Studies involving materials that are sourced outside of the waste stream, exclude the use of 3D printing technology, or refrain from blending disparate materials have been discarded.

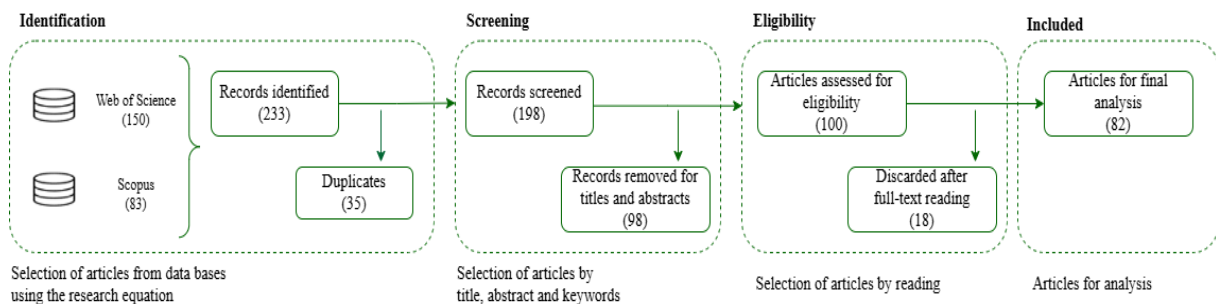


Figure 4. PRISMA flow diagram.

## 4. Results

From the 82 articles reviewed, Table A1 presents the detailed description and analysis criteria. Fig. 5 shows publications from 2017 to 2024, and the number of published articles on

the subject exhibited a notable upward trend, reflecting the increasing academic and research interest in this area. The overall trend suggests a growing recognition of the importance of this field, driven by advancements in technology and increased environmental awareness.

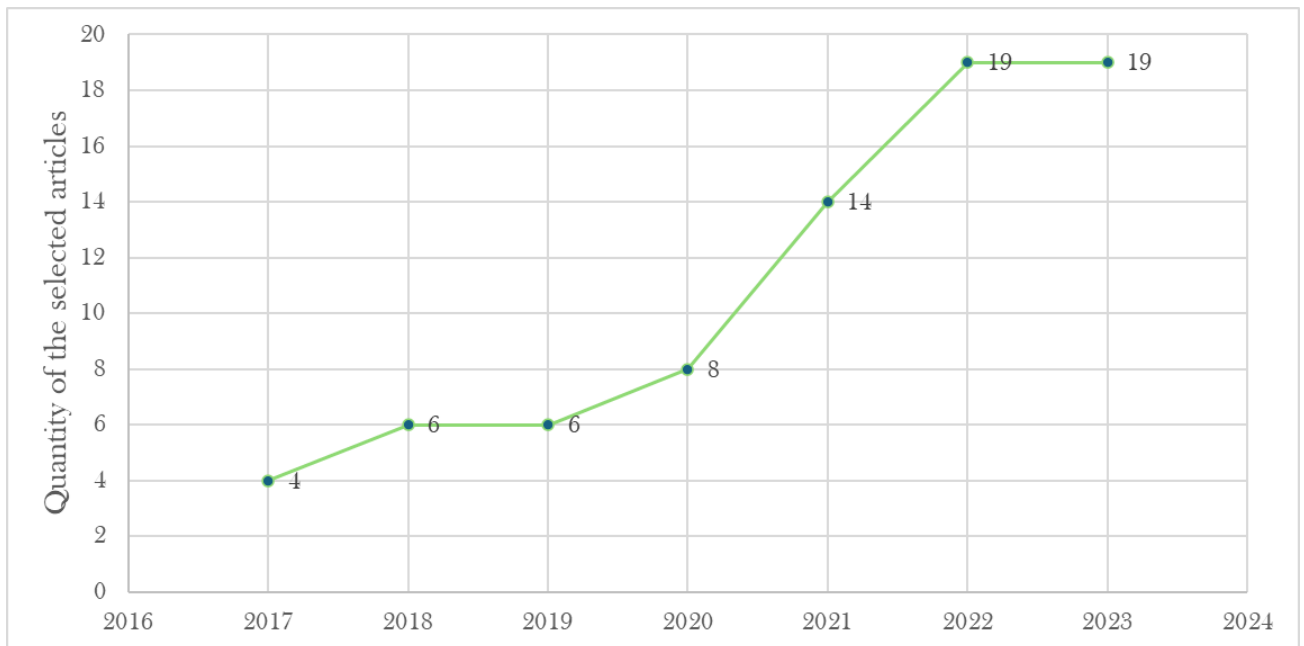


Figure 5. Distribution of the studies by year.

The flow chart presented in Fig.6 illustrate the general methodology employed in the studies for developing, testing, and characterizing their polymer blends. The process begins with the preparation of the materials, which includes the collection, sorting, cleaning, shredding, and grinding of the polymers. The subsequent step involves the compounding of these materials, which can be performed using various techniques such as twin-screw extrusion, single-screw extrusion, roll milling, batch mixing, or ultrasonic mixing. Once the blend is prepared, it is typically used to print objects, often for tensile testing purposes. Therefore, each study was systematically analyzed and categorized into two distinct applications: the production of new materials and non-production of new materials. Approximately 83% of the applications were related to the production of new materials. Among these, 42 utilized and evaluated the new material for 3D printing, focusing on the printing of a benchmark object (20), tensile testing specimens (27), or both (7). The evaluation of the different new materials were rated in Table A1 in the appendix with a scale going from 1 to 4: 1 when only the properties of the material are evaluated, 2 when the material is placed under a printable form (pellet or filament) 3 when we print the material as a test specimen and 4 when we print a real finished object with the material. Finally, the characterization of the material can be conducted both before and after the printing process to assess its properties and performance comprehensively.

Out of the 14 studies that did not focus on the development of new materials, 11 conducted printing. Six studies printed tensile test samples, four studies printed various objects, and one study printed both tensile test samples and objects. These studies focused on several key areas: comparing recycled plastics to their virgin counterparts [103], [104], [105], assessing the reprocess ability through multiple recycling cycles [54], [64], [106], [107], characterizing recycled plastics from sources such as glasses [108] and waste electrical and electronic equipment (WEEE) [109], and printer development.

In the review articles, three main AM technologies were identified, material extrusion, selective laser sintering (SLS) and digital light processing (DLP). From the material extrusion, 63% of the studies focused on fused filament fabrication (FFF/FDM), 7% of employed fused granular fabrication (FGF), and 1% on other technologies such as powder melt extrusion

(PME) and direct ink writing (DIW). 4% each used SLS and DLP (Fig.6.b). Additionally, 20% did not utilize additive manufacturing technologies but concentrated on the characterization of filaments (56%), compression molding (19%), hot pressing (19%), and injection molding (6%) samples for subsequent use in AM. Finally, only 4% of the reviewed papers were dedicated to technology development.

The various characterization methods employed in the reviewed studies revealed that mechanical characterization was the most prevalent, constituting 24% of the total. This was closely followed by thermal and morphological analyses, each accounting for 22%. Physicochemical characterization methods comprised 10%, while roughly 5% performed rheological tests. It was also found that the most commonly used materials were PLA, ABS, PP, PET, high density poly(ethylene) (HDPE) and polystyrene PS, as illustrated in Fig. 6.b.

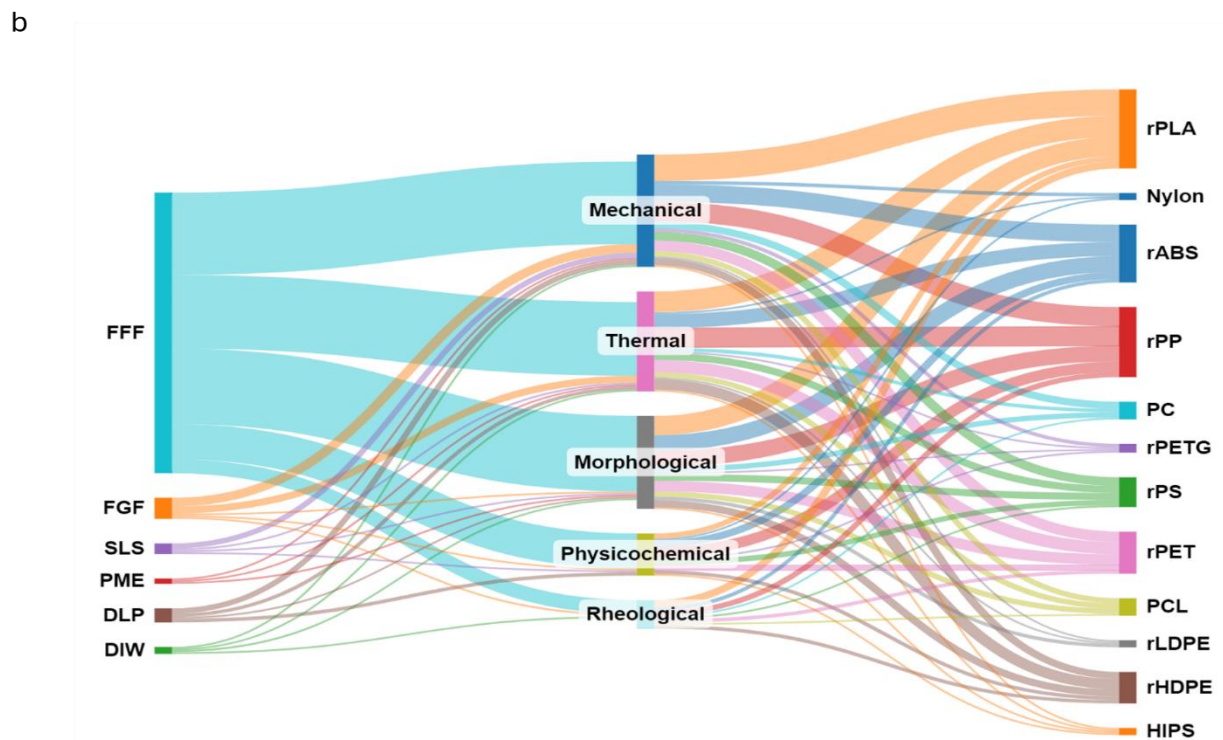
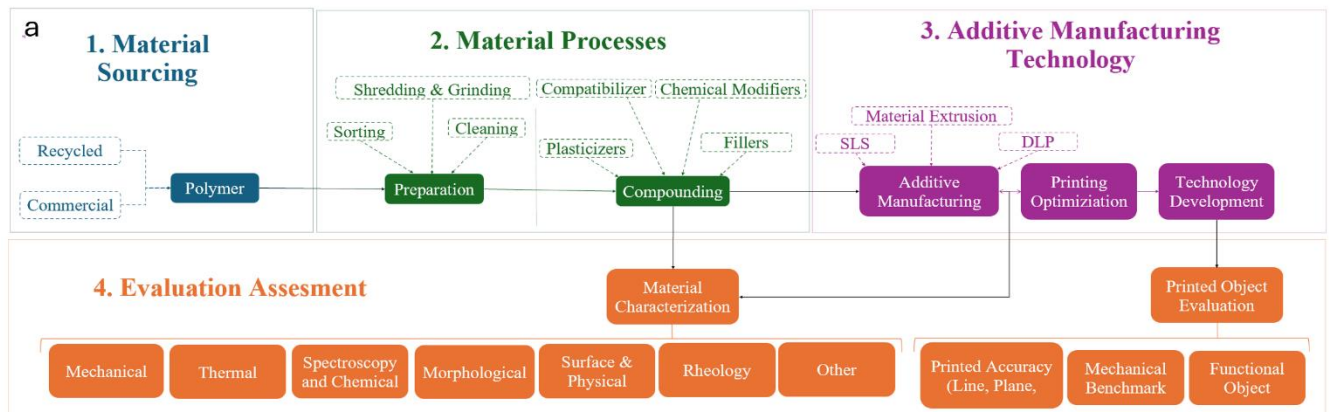


Figure 6. a) Flow chart showing the methodology employed in the articles, b) Technologies, methods to characterize, and materials used.

## 4.1 Innovations in Material Development

### 4.1.1 Enhancing Materials with Additives

The reviewed papers present innovative approaches for repurposing plastic waste by developing new materials and enhancing their properties with various additives Fig 7. These additives can be classified into three main categories: bio-sourced, polymer-based, and inorganic. In some cases, the fillers or additives themselves are recycled components, such as recycled carbon fiber [110], [111], glass fiber [112], cellulose [113], biocarbon [114], and corn husk [115].

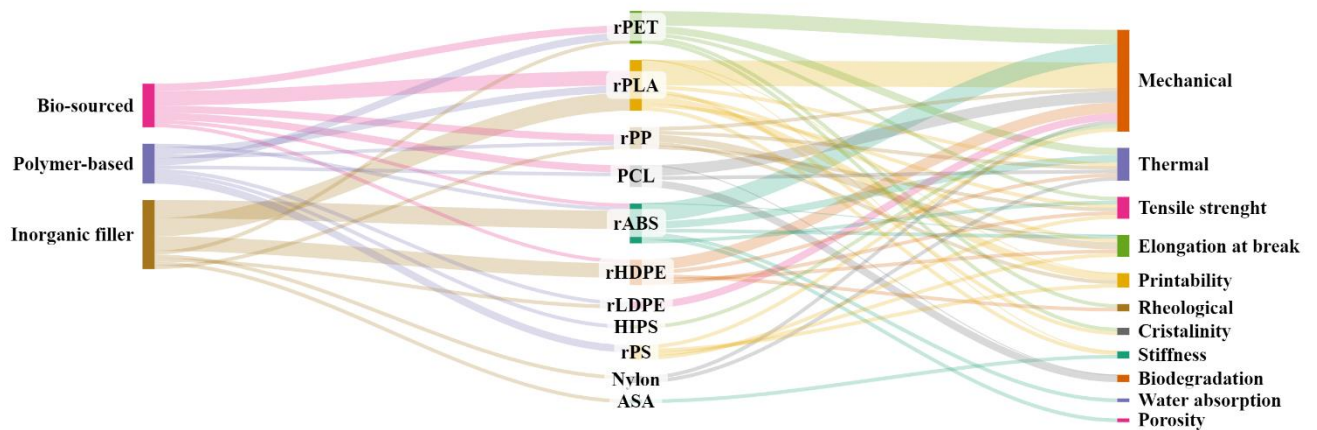


Figure 7. Sankey diagram of additives-material and characterization test relationship in the literature.

#### 4.1.1.1 Bio-sourced additives

The incorporation of bio-sourced additives has shown significant potential in enhancing the properties of recycled and virgin polymers, contributing to mechanical performance, biodegradability, and environmental sustainability. Table 2 presents various bio-sourced additives found in the literature and their enhancements to polymer matrices.

The production of biocarbon through the pyrolysis process of various food wastes has proven to be effective in filament production and in enhancing material properties acting as reinforcing agent. The use of biocarbon derived from spent coffee grounds combined with recycled water bottles and bale wrap has resulted in bio composites with enhanced mechanical thermal and rheological properties [116]. Similarly, Chong et al.,(2020) [114] explored the production of activated carbon (AC) from coconut fibers, which was then incorporated to recycled high density polyethylene rHDPE/PP. The blend enhanced the elongation at break of the composite material by the increased AC content. Despite neither study involving the actual printing of these filaments, they demonstrated an innovative approach to valorizing food waste alongside plastic waste for further 3D printing applications. Furthermore, the addition of biochar into recycled polyethylene terephthalate (rPET) has been shown to improve the mechanical, thermal, and dynamic properties of 3D printed parts, while also enhancing their crystallinity [117].

Another approach for the enhancement of properties using bio-sourced additives is the incorporation of the biopolymer cellulose. Studies showed improvements in the properties of PLA [105], [118], [119] and PP [113], while slightly lowering those from rABS, PS, and polyvinyl chloride (PVC) [119]. The incorporation of 5 wt% of microcrystalline cellulose (MCC) in PLA showed comparable properties of those of their injection-molded counterparts and slightly

increasing the elongation at break (5%), melt flow index (7%), and impact strength (7%) indicating a more ductile material and printability was also improved [118]. Contrarily, Hyvärinen and Kärk.,(2020) demonstrated that incorporating 10 wt% cellulose significantly reduced the tensile strength and Young's modulus of filaments made from rABS, PVC, and PS by approximately 60% and 50%, respectively, yet improve by 28% the mechanical properties of virgin PLA.

PLA has been widely blended with other different bio-sourced materials in order to improve its properties. For instance, the addition of birch fiber and polyethylene glycol (PETG ) [120], hydroxyapatite (HAP) and chitosan (CS) [121], and anchovy fishbone [122].

Other bio-sourced additives such, wool, collagen, and wood dust were likewise studied, showing enhanced mechanical properties [123], thermal stability [124], and biodegradability properties [125]. Furthermore, Hassan et al.,(2024) [126] presented a detailed review on the blending of biomass and plastic waste for use in 3D printing. This comprehensive analysis explored the various methods and benefits of integrating biomass with plastic waste, highlighting its potential to improve the sustainability and properties of 3D printed materials

These findings illustrate the diverse and beneficial impacts of bio-sourced additives on the development of sustainable and high-performance recycled polymer composites for additive manufacturing.

Table 2. Materials enhanced with bio-sourced additives.

Additive	Matrix Material	Weight Fraction	Main Findings	Reference
Biocarbon	rPET	0.50%	Improved mechanical, thermal, and rheological properties of bio composites	[116]
	Recycled HDPE/PP	10%	Enhanced elongation at break	[114]
	rPET	0.50%	Improved mechanical, thermal, dynamic properties, and crystallinity of 3D printed parts	[117]
Cellulose	PLA	5 wt% MCC	Comparable properties to injection-molded parts, enhanced printability and reduced warping	[118]
	rABS, rPS, rPVC	10 wt%	Reduced tensile strength and Young's modulus by 60% and 50%, respectively	[119]
	rPP	20 wt% CB, 10 wt% WF, 5 wt% WP	Improved mechanical and thermal properties	[113]
Wool	PCL	10%	Improved tensile strength and biodegradation capabilities	[123]
Collagen		20%	Maintained suitable mechanical properties while being biodegradable	[125]

Wood Dust	rABS	10%	Improved tensile strength and thermal stability	[124]
Birch Fiber & PEG	PLA	10% PEG	Decreased tensile strength and Young's modulus, slightly increased elongation at break	[120]
Hydroxyapatite & Chitosan	rPLA	10%	Significantly improved mechanical properties, suitable for biomedical scaffolds	[121]
Anchovy Fishbone Waste	PLA & Mater-bi	10%, 20%	Enhanced flexural modulus, good printability	[122]

#### 4.1.1.2 Polymeric-based additives

The blending of polymers or the incorporation of polymeric-based compatibilizer additives offer an alternative method to enhance material properties for the development of feedstock for AM.

In this context, Singh et al.,(2019) [127] investigated the mechanical and thermal properties of a blend comprising rABS, rPLA, and high-impact polystyrene (HIPS) for use in multi-material AM. The study demonstrated significant enhancements in the mechanical properties of the multi-material blend, with improvements of 60%, 14.3%, and 94.6% for rABS, rPLA, and rHIPS, respectively. These enhancements were attributed to the synergistic effect of combining polymers with varying mechanical properties, resulting in prototypes with superior load-bearing capabilities and improved structural integrity. Another study by Hu et al.,(2017) [128] incorporated 60 w% of a laboratory-made elastomer poly (lactate/butanediol/sebacate/itaconate) into PLA to create a thermoplastic vulcanizate aimed at improving the toughness and elasticity of PLA. The results showed enhanced mechanical properties, including tensile strength and Young's modulus. Additionally, the elongation at break improved to 314%, demonstrating a balance between strength and elasticity. Similarly, other studies showed the enhancement of mechanical properties by blending poly(3-hydroxybutyrate) (PHB) and poly( $\epsilon$ -caprolactone) (PCL)-based materials [129], expanded polystyrene (EPS) and glycerol and gypsum [130], PLA with aramid filaments [131], polyurea with ureido-cytosine quadruple hydrogen bonding [132], and synthetased isosorbide-based poly(aryletherketone) (PIEK) [133].

The blending of recycled materials with their virgin counter parts also showed enhancement in the mechanical properties and ensured thermal stability of ABS [134], PLA [103], [105], [118].

The potential of combining polymers and adding a polymer compatibilizer as third agent was explored through the utilization of the copolymer SEBS (Poly (styrene-block-ethene-co-butene-block-styrene) as a compatibilizer in various polymer blends, including rPET and rLDPE [116], [135], rPP, rPET, and rPS [113], as well as in enhancing rPET [136]. These investigations consistently demonstrate that SEBS is an effective compatibilizer for different polymer blends, significantly improving mechanical and thermal properties by enhancing compatibility and promoting better interfacial adhesion. Gupta et al.,(2021) [135] found that incorporating 5% SEBS into blends of rPET and rLLDPE significantly improved tensile strength, elongation at break, and impact resistance. This improvement was attributed to SEBS forming covalent bonds with rPET and creating a miscible phase with rLLDPE. In another study, Zander and Boelter.,(2021) [136] showed that the addition of 5 wt% SEBS with MA significantly increased the toughness of rPET by over 550%, achieving a value of 41.5 MPa compared to neat rPET. The elongation at break increased to 4.2%, demonstrating improved

ductility while maintaining the material's glass transition temperature and crystallinity. These findings indicate that SEBS-MA is a promising compatibilizer for enhancing the mechanical performance of rPET in 3D printing applications. Moreover, the effect of SEBS on rPP/rPET and rPP/rPS blends were examined [113]. It was found that SEBS improve tensile strength and elongation to failure in rPP/rPET blends, facilitating better interfacial adhesion and reducing phase separation. The impacts on rPP/rPS blends were less pronounced, however, with only moderate improvements in tensile strength. These findings underscore the potential of SEBS in developing high-performance, sustainable materials for advanced manufacturing applications, particularly in additive manufacturing and 3D printing. SEBS's ability to enhance mechanical properties, improve ductility, and maintain thermal stability makes it a valuable component in the development of next-generation polymer composites.

Table 3. Polymer based additives.

Additive	Matrix Material	Weight Fraction	Main Findings	Reference
Multi-material Blends	rABS, PLA, HIPS	N/A	Improved mechanical properties, significant enhancements	[127]
	PLA and Laboratory-made elastomer (PLBSI)	60 wt%	Improved toughness, elasticity, and stiffness	[128]
	Poly(3-hydroxybutyrate) and Poly( $\epsilon$ -caprolactone)	40%	Enhanced mechanical and thermal properties	[129]
Glycerol & Gypsum	EPS	2 wt% Glycerol, 10 wt% Gypsum	Improved tensile strength, elongation at break, and printability	[130]
Ureido-cytosine	Polyurea	20 wt%	Improved stiffness, balance between strength and flexibility	[132]
Aramid filaments	PLA	40%	Increased tensile strength and ductility	[131]
SEBS	rPET, rLDPE,	5%	Improved tensile strength, elongation at break, and impact resistance	[116], [135]
	rPET	5%	Increasing of the toughness	[136]
	rPP, rPS	5%	Improved tensile strength and elongation to failure	[113]

#### 4.1.1.3 Inorganic fillers

The integration of inorganic additives into recycled polymer matrices presents another promising avenue for enhancing mechanical and thermal properties, as evidenced by various studies. They are especially useful in applications requiring high performance, such as engineering and industrial components. These additives help reduce warpage and improve the overall dimensional accuracy of printed parts. For instance, glass fibers (GF), and carbon fibers (CF), are particularly noteworthy for their ability to significantly improve the performance of composite materials. Schirmeister et al.,(2021) [137] demonstrated that incorporating GF and nanophase-separated rubber into a PP matrix results in composites that helped to address the

warpage issue and have comparable mechanical properties to the injected. Rahimizadeh et al., (2019) [112] and Tolcha and Woldemichael(2023) [138], highlighted the benefits of adding GF to PLA and rHDPE/rPET composites, respectively, noting improvements in specific stiffness and tensile strength. These enhancements often come with trade-offs, such as increased brittleness and reduced elongation, underscoring the need for careful balance in additive content to maintain desirable mechanical properties [112]. Furthermore, the effectiveness of CF in reinforcing recycle polymers has revealed substantial improvements in tensile strength and young modulus [111], [139], and elastic modulus [140]. Blends from CF/Nylon and GF/Nylon printing waste have shown increased tensile strength to 65Mpa and lower degradation temperature [141].

The incorporation of fly ash (FA) captured from coal-fired power plants into HDPE [142], [143] and ABS [144] was investigated in three distinct studies. All the studies focused on creating filaments with varying percentages of FA added to the HDPE and ABS matrices. The addition of 2% FA to ABS did not significantly impact the thermal nor the mechanical properties. Conversely, in the study involving HDPE, higher FA content resulted in increased thermal stability and flexural modulus; however, the flexural strength decreased with increasing cenosphere content due to poor adhesion between the cenospheres and the HDPE matrix. The optimization of extrusion parameters, such as temperature and speed, was crucial for achieving uniform dispersion and minimizing void content in the filaments. Both studies underscore the potential of using industrial waste materials in 3D printing to enhance sustainability, despite employing different approaches and materials. In other study, Singh et al., (2018) [143] investigated the recycling potential of HDPE foam filaments filled with 40 wt.% FA cenospheres. The results demonstrated a uniform dispersion of cenospheres and consistent performance across multiple extrusion cycles. The study found that both the modulus and yield strength of the blend increased with strain rate and repeated extrusion cycles, indicating a promising potential for recycling without significant loss in mechanical properties.

Reinforced by adding various fillers, rABS has enhanced its mechanical and thermal properties. The addition of 2.5 wt% and 5.0 wt% of recycled carbon black rCB increased tensile strength and elastic modulus while also affecting surface roughness, water absorptivity, and density [145]. Chawla et al.,(2023, 2022) [124], [146] found that adding 10 wt.% iron (Fe) powder to rABS significantly improved tensile strength and ductility for 3D printing, with lower porosity enhancing thermal capacity. Singh et al.,(2019) [147] studied ABS reinforced with bakelite (BAK), silicon carbide (SiC), and aluminum oxide (Al<sub>2</sub>O<sub>3</sub>), finding that a blend of 70% ABS, 10% BAK, 10% Al<sub>2</sub>O<sub>3</sub>, and 10% SiC exhibited superior flexural strength, thermal stability, and dispersion compared to other compositions.

Recycled PLA have also been enhanced with different fillers such as, titanium dioxide (TiO<sub>2</sub>) nanoparticles [148],and silica-sand [149]. Likewise, other materials were enhanced with various fillers. For instance, rLDPE with SiC and Al<sub>2</sub>O<sub>3</sub> ceramic particles [150], ASA with stamp sand[151], and thermoplastic with iron slag powder, alumina and zirconia [152], as seen in Table 4.

Table 4. Materials blended with inorganic fillers.

Additive	Matrix Material	Weight Fraction	Main Findings	Reference
	PP	25%, 30%	Improved bed adhesion.	[137]

r-Glass fiber	PLA	5%, 10%, 15%, 20%, 25%.	Improved stiffness and young modulus	[112]
	rHDPE, rPET	15%, 30%	Increment of tensile strength.	[138]
r-Glass fiber and carbon fiber	rNylon,	20%, 40%, 50%, 60%, 80%	Enhanced mechanical properties, and thermal stability	[141]
r-Carbon fiber	PLA	5%, 10%	rCF have comparable mechanical properties with vCF	[140]
	rHDPE	11.2%, 18.9%, 29.5%	Higher CF content increment in the yield strength, tensile strength, and modulus	[139]
	ABS	50%	Improvement in tensile strength	[111]
r-Fly Ash	rHDPE	20%,40%, 60%	Higher cenosphere content, increased the rheological properties and flexural modulus. 3D printed specimens showed comparable results with the literature	[142]
		40%	Increased thermal stability, flexural modulus, and consistent performance across extrusion cycles	[143]
	rABS	2%,	Low addition of FA did not differ from pure ABS, however lower the elongation at break.	[144]
r-Carbon Black	rABS	2.5 wt%, 5 wt%	Improved tensile strength, elastic modulus, surface roughness, and water absorptivity	[145]
r-Iron Powder		10 wt%	Enhanced mechanical properties and reduced porosity	[124], [146]
r-Silicon Carbide & Aluminum Oxide		10% SiC, 10% Al <sub>2</sub> O <sub>3</sub>	Improved mechanical properties, enhanced thermal stability	[150]

r-Silica-Sand	rPLA	10 wt%	Enhanced mechanical properties	[149]
Titanium Dioxide	vPLA, rPLA	7%	Improved tensile strength, thermal stability, and crystallinity	[148]
r-SiC & Al <sub>2</sub> O <sub>3</sub>	LDPE	20%	Improved mechanical properties and durability	[150]
r-Iron slag, alumina and zirconia	Thermoplastic	60 wt%	Enhanced porosity and mechanical strength	[152]
Stamp Sand	ASA	40%	Increased stiffness, suitable for outdoor applications	[151]

#### 4.1.2. Multi-material blends from waste stream

The studies reviewed highlight the significant advancements and potential of recycling and upcycling various waste materials for 3D printing applications. Collectively, these studies emphasize the importance of innovative recycling techniques and material optimization to develop high-performance, sustainable composites for additive manufacturing. Ariel et al.,(2022) [115] prepared filaments from post-consumer EPS packaging blended with corn husk fibers, demonstrating the potential for recycling and repurposing waste streams for 3D printing applications. Further research is needed to enhance the material properties and printability of these recycled composites. Chu et al.,(2022) [153] focused on developing recycled polymer blend filaments from post-consumer EPS and single-use PP containers. Their findings indicated that the optimal blend ratio of rPS to rPP was 50/50, achieving a tensile strength of 32 MPa. A higher rPP content improved ductility and interlayer adhesion due to lower melt viscosity, resulting in fewer voids and better interlayer coalescence. Increasing the printing temperature, however, caused thermal degradation, reducing tensile strength. The study also highlighted that increasing the rPP content enhanced melt flow and crystallinity, but led to warping in the printed specimens. Turku et al.,(2018) [154] investigate the feasibility of using rPS, rABS, and rPVC as feedstock for 3D printing filaments.

Recycling single-use face masks directly did not possess the rheological characteristics necessary for 3D printing. To address this, Battegazzore et al.,(2022) [155] mixed the recycled material with 30 wt% and 50 wt% commercial PP, resulting in higher stiffness and similar tensile strength compared to commercial 3D printing materials. In contrast, Zabihi et al.,(2024) [156] employed a more effective upcycling method by blending reclaimed PP from masks with vegetable oil and 30% glass fiber. This approach achieved significant improvements in mechanical properties, with a 33% increase in tensile strength and a 55% increase in strain compared to untreated reclaimed PP. While ref [155] blended recycled materials with commercial polymers to achieve desirable properties, ref [156] demonstrate the efficacy, long term cost-benefit of chemical modifications and the incorporation of organic and inorganic reinforcing agents to enhance mechanical performance. Both studies provide valuable insights into the recycling and upcycling of single-use face masks, addressing the environmental concerns associated with PP waste.

The potential of rPET and rHDPE blends in enhancing the performance of 3D printing filaments was explored. Tolcha and Woldemichael., (2023) [138] demonstrated that incorporating short glass fibers significantly improves the mechanical and thermal properties

of 3D printing filaments, thereby making them suitable for more demanding 3D printing applications [157], focused on an 80:20 blend, modified through three distinct methods: compatibilization with maleic anhydride, surface functionalization of PET with sodium dodecyl sulphate, and a novel hybrid approach combining both methods. Their findings revealed that these modified blends, particularly those incorporating both compatibilization and surface functionalization techniques, exhibit enhanced thermal, mechanical, and morphological properties. Finally, Suescun Gonzalez et al.,(2024) [82] examined the technical feasibility and cost analysis of using mixed rPET and rHDPE for large-scale 3D printing. Their study demonstrated significant cost reductions and technical feasibility through the DRAM approach, though they noted that further exploration is needed to address quality issues in printed outputs.

The studies by Toncheva et al.,(2021) [158] and Laoutid et al.,(2022) [129] highlights the versatile applications of recycled tire rubber (TR) in different polymer matrices through advanced manufacturing techniques. Ref [158] utilized STL to integrate TR into polyamide 12 (PA12) and thermoplastic polyurethane (TPU), observing that up to 30 wt% TR in PA12 resulted in a tensile strength of 23.5 MPa and enhanced impact resistance. However, TPU composites with 20 wt% TR, despite achieving a tensile strength of 31 MPa, suffered from high porosity, which negatively impacted their mechanical properties. While ref [129] added TR in ABS and thermoplastic polyolefin (TPO) composites for 3D printing. They found that ABS composites with 15 wt.% GTR experienced reductions in impact resistance and Young's modulus, with minimal elongation at break.

Lastly, Nur Nazira Alias et al., (2024) [159] focused on HDPE and PP blends with recycled flexible plastic (RF), demonstrating enhanced thermal stability and ductility, making them suitable for 3D printing applications. He et al.,(2020) [160] conducted a comprehensive study to explore the microscopic morphology, rheological behavior, and mechanical properties of rABS and poly(butylene terephthalate) (PBT) blends, employing styrene-acrylonitrile-glycidyl methacrylate (SAG) as a compatibilizer. The investigation revealed that both the mixing scheme and the amount of SAG significantly influenced the mechanical properties of the blends

#### 4.1.3 Material characterization

Transitioning from waste to multi-material products requires thorough material characterization to ensure performance meets application standards. As shown in Fig. 8, various techniques have been used across studies. Mechanical testing was the most common due to its simplicity and informative output, followed by morphological and thermal analyses to assess homogeneity, stability, and printability (e.g., fusion and glass transition temperatures). Techniques such as scanning electron microscopy (SEM), atomic force microscopy (AFM), and micro-computed tomography ( $\mu$ -CT) are used for morphology, while scanning calorimetry (DSC) and thermogravimetric analysis (TGA) assess thermal behavior. dynamic mechanical analysis (DMA) further evaluates viscoelastic and rheological properties.

Rheological testing, crucial for 3D printing, includes Melt flow index (MFI) for flow behavior and capillary rheology for simulating printing shear rates. For complex waste streams, chemical identification through FTIR, Raman spectroscopy, or X-ray diffraction (XRD) is essential to detect polymer types and interactions. FTIR is especially useful for rapid sorting of mixed waste. Some studies also focused on optimizing printing parameters to improve mechanical performance and flowability, with specific characterizations depending on the application.

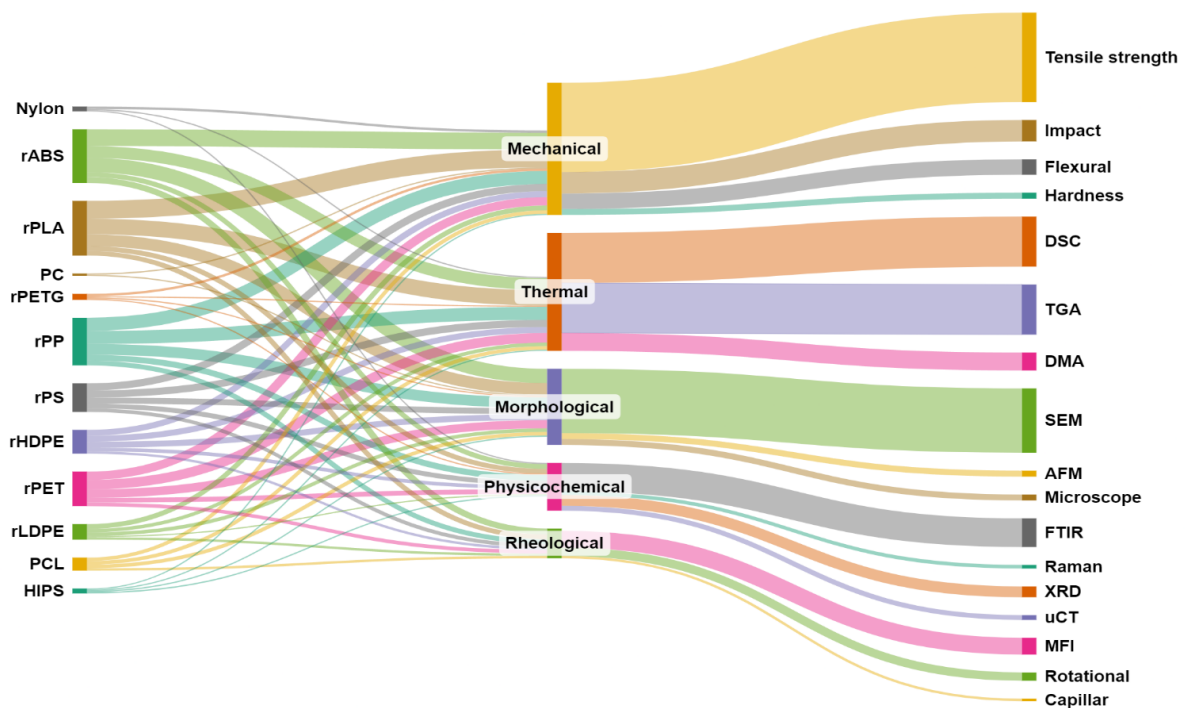


Figure 8. Sankey diagram of the main characterization methods used in the literature.

## 4.2 3D printing with recycled materials

Among the technical studies reviewed, the use of filaments was well established, with 51 studies employing FFF or FDM technology. The use of granules and powders for material extrusion, however, is gaining traction as a viable technology for recycling waste that eliminates a melt/solidification cycle to improve the lifetime of the material as well as cost. It remains in its infancy, with only 7 studies using FGF and PME. Additionally, 6 studies have adopted SLS and DLP technologies, using powders and resins, respectively.

and even elements in furniture and construction. Despite this growing interest, their use remains limited by technical challenges such as inconsistent mechanical performance, limited printability, and variability in material composition. Studying these materials is therefore essential not only for improving their processing and performance but also for enabling scalable, sustainable solutions in decentralized manufacturing models like DRAM. This review seeks to identify these limitations and explore research gaps that hinder the effective application of recycled polymer blends and multi-material systems in 3D printing.

In the printing phase, two critical steps are the quality assessment of the printed parts and the optimization of printing parameters. Quality assessment ensures that the printed parts meet the desired specifications and standards, while parameter optimization fine-tunes the printing process to enhance performance, accuracy, and material properties.

### 4.2.1 Quality assessment of 3DP recycled materials

The primary objective of this step is to print a benchmark artifact [161], which facilitates the evaluation of both the technology and material capabilities, illustrating printability and identifying challenges. These artifacts serve as a standardized test piece that helps in assessing the performance of the material under specific printing conditions, ensuring a comprehensive understanding of its mechanical properties, process optimization needs, and

overall suitability for intended applications. The literature has shown three main benchmark categories, mechanical, geometrical benchmark, and functional objects [162].

The most used method is the mechanical benchmark, which tests the mechanical properties of the material, typically designed according to standards such as ISO or ASTM. These benchmarks evaluate properties like tensile strength, compressive strength, elasticity, and impact resistance, ensuring that the material meets specific performance criteria. Mechanical properties have been conducted to validate the suitability of the materials [54], [108], [163], [164], [165], [166].

To evaluate printing accuracy, different geometrical benchmarks can be employed. Cubes are commonly printed due to their simplicity and rapid manufacturing, providing valuable information on visual and dimensional accuracy [115], [150], [152], [156]. Depending on the application, the printed objects can be varied. For instance, to demonstrate the shape memory effects, different shapes and structures such as, star shapes [167], [168], and scaffolds [169] were used. These designs were selected to effectively showcase the shape memory properties (smart materials that can return to a predefined shape when exposed to specific external stimuli, such as heat or stress) of the respective materials, as illustrated in Fig. 9. Other objects such as animals [109], [122], [170], decorative items [106], [171], cylinders [172] and multilayer meshes [173] are utilized to demonstrate the materials' adaptability in customizing structures for specific applications.

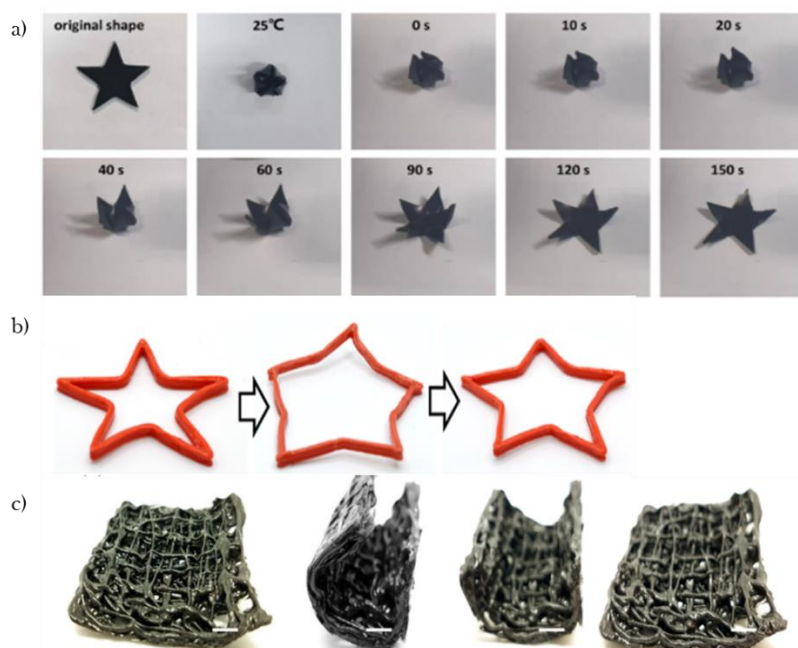


Figure 9. Shape memory of printing objects, a) PLA/Fe<sub>3</sub>O<sub>4</sub> [167], b) PCL/TPU [168], c) PolyTMPAC [169].

Some reviewed articles highlight the printing of functional objects for various applications. This has the advantage of making useful items rather than contributing to waste for research itself and demonstrate utility of the materials. For example, Romani et al.,(2023) [75] valorized blends of granular rABS and PC by printing sports equipment (shin guards), furniture components (coat hanger joints), and construction materials (bricks) Fig.10a. Garwacki et al.,(2024) [174] assessed different blends of recycled PETG with PET and additives by printing mounting bearings Fig.10.b. Seggiani et al.,( 2018) [125] also turned PCL and HC blends into pot plants, using material extrusion fabrication Fig.10.d. Chao and Liao., (2023) [106]

developed a method for mechanically recycling photo-cured thermosetting acrylic resin from dental models using DLP printing. This process involved grinding, milling, roll milling, and printing, successfully producing dental models through multiple recycling cycles without loss of mechanical properties or printability Fig.10.c. Lastly, utilizing a composite of AC and rPP a 3D-printed gas mask was developed [175] Fig.10.e.

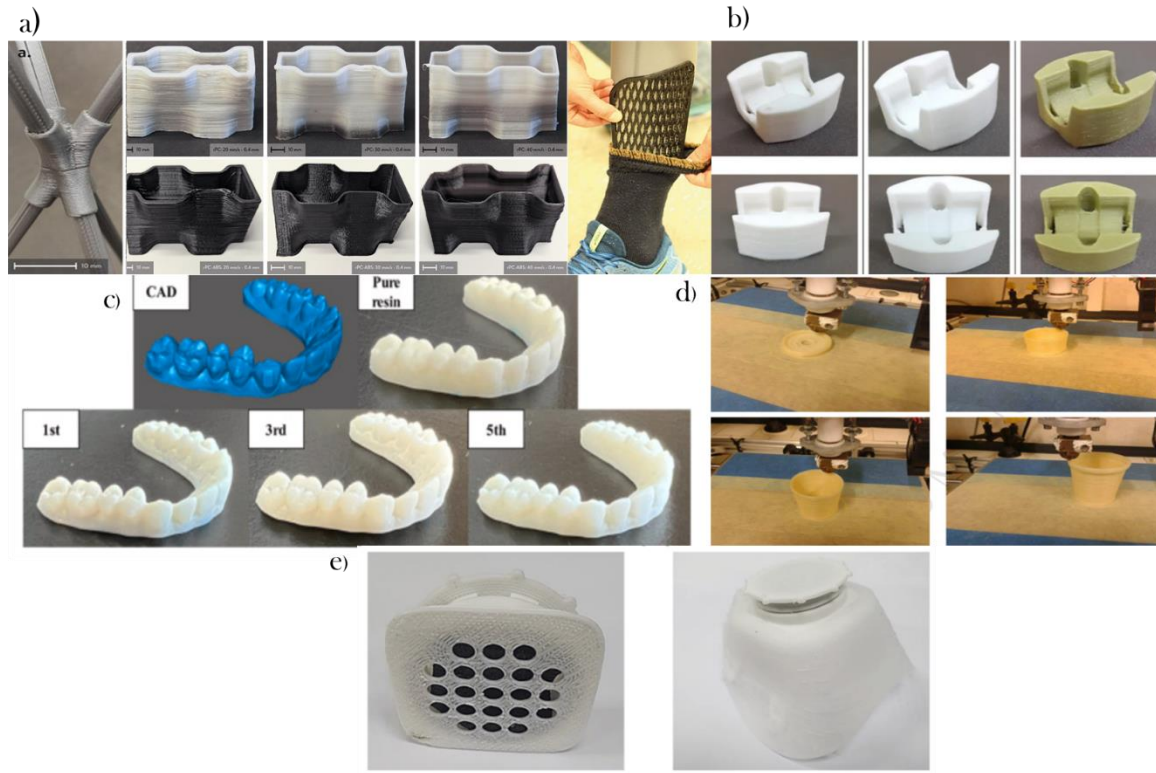


Figure 10. Different functional objects printed with multi-material plastic waste as test prints.

#### 4.2.2 Optimization of 3D Printing Processes

Optimization of 3D printing processes is crucial for maximizing the performance and reliability of recycled materials. Recent studies have highlighted the significant impact of printing parameters on the mechanical properties and overall quality of 3D-printed parts. These parameters include print direction [164], speed [75], [103], infill density [134], [176], bed temperature [177], and extrusion rate [120], [178]. Effective optimization of these factors can lead to significant improvements in the quality and functionality of parts made from recycled polymers. For instance, the printing direction, speed, and temperature can scientifically influence the layer adhesion, surface finish, and mechanical properties, while the infill profoundly influences the internal structure and overall strength of the printed part. The density of the infill determines not only the weight and material usage but also the mechanical properties of the final product. The study by de la Torre-Gamarra et al., (2023) [176] focused on 3D printing thick  $\text{LiCoO}_2$  electrodes for Li-ion batteries using highly filled thermoplastic filaments. The study aimed to create easily recyclable, all-ceramic electrodes designed in a coin-type geometry. Maintaining a 100% infill density and experimenting with various infill patterns was crucial to ensuring the structural integrity and performance of the printed electrodes Fig.11.a.

Extrusion rate, on the other hand, can influence the layer adhesion, print quality, and material performance of the printed objects. Yap et al.,(2021) [178] explored the rPS/LDPE blend,

observing that higher printing temperatures and increased LDPE content improved layer adhesion due to lower viscosity. Increasing the extrusion rate from 100% to 120% further enhanced adhesion, reducing air gaps and improving overall print quality. Ref [120] highlighted the importance of optimizing extrusion parameters when producing filaments with natural fibers. They identified issues with extrusion screw length, which caused blending inefficiencies and diameter variations, leading to increased raw material consumption. The study suggested that an improved extrusion and blending system could produce a more homogeneous blend, enhancing filament quality.

Material optimization in 3D printing involves selecting and refining the materials used to ensure they meet the desired performance standards, especially when using recycled polymers. This process is crucial for enhancing the mechanical properties, sustainability, and overall quality of 3D-printed parts [179] utilized the Elimination and Choice Expressing the Reality (ELECTRE) method to systematically evaluate and rank materials from both virgin and recycled polymer resins. This multi-criteria decision-making technique considered key properties such as tensile strength, melting point, glass transition temperature, MFI, and coefficient of thermal expansion. Further emphasizing the importance of material optimization, ref [137] demonstrated that digitally tuning the glass fiber orientation by adjusting printing directions layer-by-layer or within a single-layer (Fig. 11), during the FFF process in PP composites resulted in stable mechanical properties across various printing speeds. The Catalloy-PP-GF composites exhibited significantly reduced warpage, comparable to amorphous thermoplastics like ABS, and enhanced mechanical properties in the 0° printing direction. Similarly, Arrigo et al., (2022) [180] focused on optimizing rPP for 3D printing by blending rPP with first-use PP filled with 20 wt% talc (PPT), the study aimed to achieve suitable rheological and mechanical properties for FFF processes. They used the Taguchi method where an orthogonal array was designed to consider temperature profile, feed rate, and screw speed. The results demonstrated that with proper material and process optimization, rPP-based formulations could achieve mechanical properties comparable to virgin PP filaments, supporting the sustainable manufacturing of high-quality 3D-printed parts from recycled materials Fig.11.b,c.

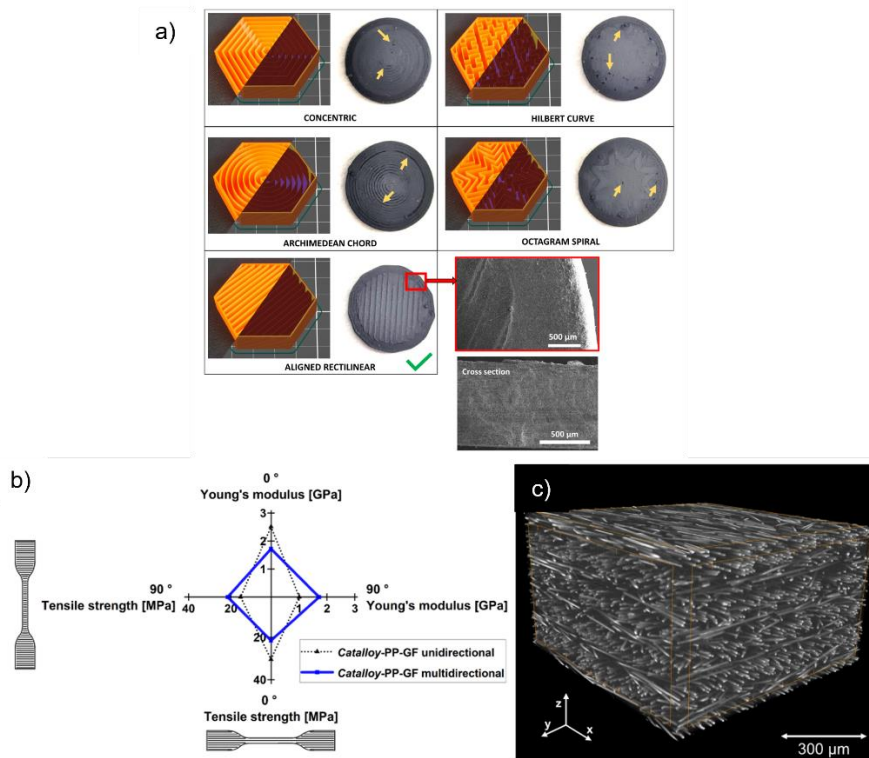


Figure 11. a) Different infill patterns of coin-type electrodes [176], b) Printing direction of the catalloy-PP-GF composite. c)  $\mu$ -CT image of catalloy-PP-GF [180].

The optimization of 3D printing parameters, such as infill density, bed temperature, and extrusion rate, has been shown to significantly enhance the performance and quality of parts made from recycled materials. Studies highlight that precise adjustments lead to improved tensile strength, reduced warpage, and better overall mechanical properties. These findings confirm that recycled polymers can be effectively used in additive manufacturing to produce high-quality, functional products when optimal printing conditions are employed.

### 4.3 Technology development

Advancements in technology are essential for overcoming challenges in 3D printing and expanding the use of diverse materials. Different industries require materials with specific properties, and technological progress allows for the customization of these materials to meet unique requirements, enhancing performance and efficiency. Sustainability is increasingly emphasized, driving the need for eco-friendly materials [181]. Innovative technologies can facilitate the development of biodegradable or recyclable materials, significantly reducing environmental impact. Furthermore, advanced technology can streamline production processes, lowering costs and making high-performance materials more accessible and affordable.

Whyman et al., (2018) [182] designed and developed a pellet extrusion system for 3D printing biopolymers. Unlike conventional filament extrusion systems, this system allows the printing of materials in pellet form, expanding the range of usable materials, including biopolymers and material blends. The system includes a feed hopper, an extrusion screw, and temperature control and cooling systems. Tests demonstrated that the system can print with consistency and mechanical quality comparable to commercial 3D printers using filaments Fig. 13a. Miao et al., (2024) [168] designed, developed, and tested an open-source powder material extrusion 3D printer Fig. 13b. The printer was developed to allow the direct printing of powdered materials, which is particularly useful for materials that are thermally unstable or difficult to

process in filament form. The printer demonstrated the ability to print a wide range of materials, including recycled plastics, polymer composites, and functional polymers with special properties such as phosphorescence and ferromagnetism. The article highlights the accessibility and versatility advantages of this system compared to commercial printers. Both articles address significant advancements in 3D printing by expanding capabilities beyond traditional filaments. Ref [182] focuses on creating a pellet extrusion system designed for biopolymers, providing a robust and adaptable solution for materials that cannot be easily shaped into filaments. The second introduces an open-source printer that allows direct extrusion of powdered materials, which is especially advantageous for materials presenting thermal instabilities or those difficult to process in filament form. This approach demonstrates considerable versatility by enabling the printing of recycled plastics and functional polymers with unique properties.

Formela and Eyigöz., (2024) [183] conducted a review on the application of planetary roller extruders (PREs), showcasing their ability to handle complex mixtures while enhancing energy efficiency and material properties. This review underscores the potential of PREs to significantly improve the quality and performance of recycled polymer blends, making them more suitable for additive manufacturing applications. The study highlights the versatility and effectiveness of PREs in processing recycled materials, which can lead to more sustainable and high-performance 3D printing solutions.

The advancement in technology presents significant opportunities for the recycling and upcycling of multi-material plastic waste. However, further research is necessary to fully harness these opportunities and optimize processes for better efficiency and material properties.

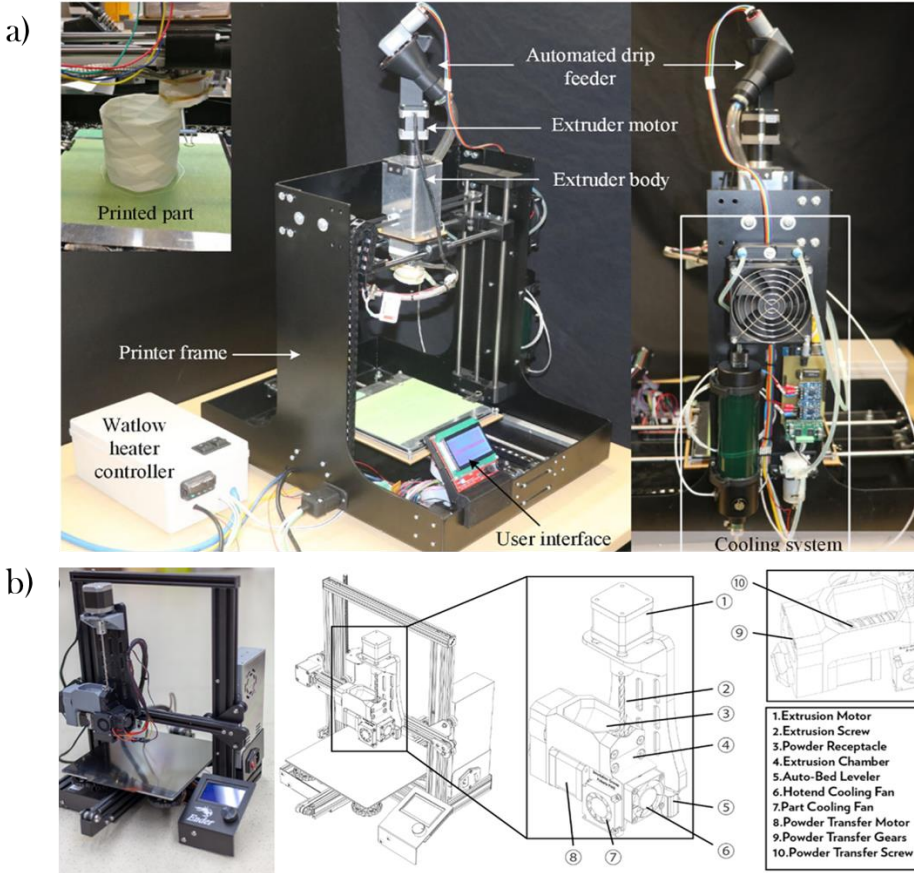


Figure 13. a) Custom biopolymer pellet printer [182], b) PME printer [168]

## 4.4 Reprocessing materials in multiple cycles

The concept of reprocessing and multiple cycle analysis is crucial for understanding how many times a material can be recycled without losing its properties, which is essential for implementing DRAM as an efficient and sustainable recycling process.

While the assessment of multiple recycling cycles for mono-materials has been widely studied [184], [185], [186], [187], [188], [189], [190], [191], the reprocessability of multi-material systems remains significantly underexplored. In this review, only five articles addressing this topic were identified. Nur-A-Tomal et al., (2020) [54] demonstrated that waste children's toys made of ABS could be recycled up to ten times without significant degradation in physical, chemical, and mechanical properties, however, a slightly darker color of the samples was observed. This finding suggested a viable path for sustainable reuse of toys in 3D printing applications. Kozlovsky et al.,(2018) [177] explored the mechanical properties of reused nylon feedstock for powder-bed additive manufacturing, noting that initial reprocessing stages influenced ultimate tensile strength, but had minimal impact on elongation at break, indicating potential for recycling in manufacturing settings.

Plavec et al., (2022) [107] analyzed the recyclability of a biodegradable PLA/PHB blend known as NONOILEN. They conducted nine cycles following two different processing streams. The study showed that while multiple cycles led to material degradation affecting viscosity, no significant impacts on the strength were identified. Hlaváčiková et al.,(2024) [192], examined the use of regranulate from PLA and PHB blends, finding that the mechanical and thermal properties remained comparable to virgin materials despite multiple processing cycles. This suggests the viability of using regranulation in producing sustainable 3D printing materials. Lastly, Papatheodorou et al., (2023) [64] focused on the printability and biological performance of recycled Tritan Copolyester TX1501 and PA12 composites. Their study found that TX1501 maintained printability and surface quality after ten recycling cycles, while PA12 experienced significant issues affecting its performance.

Although few articles have studied reprocessing of materials, these studies underline the potential for multiple reprocessing cycles in maintaining material properties, thus contributing to a circular economy in plastic manufacturing. However, it is important to also consider factors such as the addition of fillers in composites. The goal should not only be to create higher-performing materials but also to develop more sustainable ones.

## 5. Discussion

Over the past decade, significant progress has been made in repurposing waste materials for additive manufacturing. This systematic review underscores the growing interest and significant advancements in the field of 3D printing with recycled multi-materials.

The obtained results clearly show that the creation and development of new materials using recycled additives or recycled plastic derived from waste streams, including 3D printing waste, have become a central subject of research. These efforts aim to address the decrement of the recycled material properties inherent in the degradation issues that reduce the molecular weight and break the polymer chains that occur during each processing cycle [19], [193]. Efforts have primarily aimed to enhance the properties of these recycled materials to make them more suitable for various 3D printing applications. Despite significant advancements in properties enhancement, the ultimate end-use of these developed materials remains unclear in many studies. While researchers have focused extensively on improving mechanical and thermal properties, there is often a lack of clarity regarding the real purpose or practical application of these materials. Although some articles demonstrate the use of blended materials in functional objects, the common trend is the printing of samples primarily for mechanical properties evaluation, rather than showcasing the materials' utility in real-world

applications. Future research should integrate considerations of the end-of-life phase and the practical applications of these materials to ensure sustainability and functionality.

It is also important to highlight the scarcity of studies focused on polymer–polymer blends, which underscores the technical challenges associated with achieving compatible mixtures. This gap reveals a critical need for further research aimed at improving blend performance for 3D applications, particularly given that a significant share of plastic consumption and waste involves mixed polymers. In fact, many everyday products are composed of multiple polymers, complicating their recycling. For example, water bottles are typically made of PET with caps composed of HDPE or PP; milk bottles often use HDPE with PP caps; meat packaging trays are commonly PET with multilayered sealing films; and yogurt pots frequently made of PS illustrate the material diversity prevalent in food packaging. Consequently, the packaging sector is the primary sectors consuming plastics in the EU (39.1%) [4], and generates substantial volumes of these multi-polymer blends. However, current recycling systems are not equipped to manage effectively.

Another challenge arises as not all blends exhibit the same properties, thus comprehensive characterization is essential to inform appropriate recycling strategies. Therefore, a considerable portion of the research has been dedicated to the comprehensive characterization of new materials. Scholars have employed various techniques to assess mechanical, thermal, morphological, and rheological properties. Mechanical characterization is frequently employed to evaluate properties such as tensile strength, modulus de young, and elongation at break. Thermal analysis was focused on the thermal stability of the new materials, while morphological assessment indicates the homogeneity between the multi-material blends. Although, FTIR is effective in identifying polymer types and, in some cases, detecting additives or contaminants, yet few articles focused in those area. similarly, rheological properties are crucial for the understanding flow behavior of the materials during the printing process. Accessible methods such as the open-source Melt Flow Index (MFI) [185] offer valuable insights into material performance under low shear rates; however, this type of characterization remains less employed in the current literature.

Despite these extensive characterization efforts, there remains a significant gap in studies that evaluate the materials over multiple recycling cycles to assess long-term degradation and sustainability. Additionally, the lack of comprehensive life cycle assessment (LCA) limits the understanding of these materials' durability, environmental impact over extended periods and multiple uses. LCAs are crucial for evaluating and quantifying the environmental impact of materials and processes. They aid in decision-making aimed at reducing environmental impact from the material's cradle to grave by considering factors such as resource consumption, energy use, emissions, and waste generation [39], [194]. Without these assessments, it is challenging to determine whether the environmental benefits of using recycled multi-materials outweigh the potential drawbacks associated with their production and use. Moreover, economic assessments are equally important to ensure that the production and application of these recycled materials are cost-effective and scalable for additive manufacturing. According to Graziosi et al.,(2024) [181], achieving sustainability in additive manufacturing (AM) requires focusing on three main areas: the use of recycled or rapidly renewable raw materials, the development of energy-efficient printers that facilitate material reuse and minimize waste, and the optimization of part design to reduce manufacturing impacts and improve the product lifetime and end-of life. While existing reviews address the first area and some progress has been made in improving technology, part design remains underexplored. More studies in these areas should be prioritized in future research to further enhance sustainability in AM. Additionally, should focus on long-term performance, degradation behavior, and the overall lifecycle of the materials.

On the other hand, the revalorization and printing processes have predominantly focused on creating filaments or using filaments, solidifying material extrusion as a preferred method. Although, SLS and DLP technologies were also used, interestingly, out of the seven additive manufacturing technologies, only these three were utilized. Further research and development in other types of AM could enhance the efficiency and applicability of these emerging technologies for sustainable manufacturing. While the manufacturing of medium-sized objects has facilitated the assessment of mechanical properties, the use of large-scale printers and the repurposing high quantities of materials into larger, functional objects remains underexplored. Developing and utilizing large-scale printers capable of processing recycled multi-materials could significantly enhance the practicality and impact of this field of research. Additionally, the creation of material blends typically involves preliminary processes before actual printing. Utilizing printers capable of processing materials in pellet, granule, or powder form can help reduce one degradation cycle and presents a potential for innovation by enabling the printer itself to act as a blender, allowing for simultaneous blending and printing. Exploring this integration could open new avenues for efficiently utilizing recycled materials in additive manufacturing.

## 5.2 Challenges and opportunities

### 5.2.1 Challenges

The implementation of recycled multi-materials in the 3D printing field presents several significant challenges related to material compatibility, processing, technological limitations, and regulatory frameworks that must be addressed to advance the field. One of the primary issues is ensuring the uniform dispersion of additives or other polymers within a polymer matrix, which is often compromised due to the inherent heterogeneity in mixing different materials [142], [154]. This poor dispersion can lead to material degradation, resulting in brittleness and lower rheological properties [107], [115]. Additionally, the compatibility of these materials with existing 3D printers poses another hurdle, as many printers are not designed to handle certain types of recycled materials, necessitating modifications or technological improvements [168], [182]. Integrating technologies such as Arduino (open-source electronics platform), sensors, and digital twins can facilitate the precise handling of the extrusion process, reducing issues like under-extrusion and warping. Furthermore, the establishment of standards and regulations to guide the characterization and sustainable production of filaments is crucial for the broader adoption of recycled materials in 3D printing [195]. Finally, ensuring repeatability and optimizing printing parameters are essential for the consistent and reliable use of recycled multi-materials.

### 5.2.2 Opportunities

In the rush to find alternatives for effectively recycling and revalorizing multi-material plastic waste, and the new adoption of AM as a process to achieve this, DRAM [81], [196] has emerged as a promising method to transform recycled plastics from communities into products manufactured via AM. This perspective opens several opportunities. Firstly, innovation in printing and extrusion technologies is necessary to handle a wider range of recycled materials effectively. Following this, optimizing extrusion processes and printing technologies is crucial to ensure the quality and consistency of printed products.

Furthermore, the development of standards and methodologies that ensure the ethical formulation of new materials is imperative. Future research should focus on developing and adopting standardized characterization techniques tailored specifically for recycled materials. These standards will enable better comparison and validation of findings across different studies, facilitating the advancement of knowledge in this field.

The understanding of the environmental impact, energy consumption, and emissions throughout the production, usage, and end-of-life phases of produced materials should be included in the studies [197]. Additionally, bridging the gap between material development and real-world application will provide a clearer picture of the practical utility and sustainability of these materials. Developing scalable and economically viable recycling processes is crucial for the widespread adoption of recycled materials in additive manufacturing. This involves creating integrated workflows that can efficiently blend and process recycled polymers while maintaining consistent quality.

Future research should also explore the development and application of bio-compostable materials in additive manufacturing. Ensuring these materials can decompose naturally without harming the environment will be a significant step towards sustainability.

## 6. Conclusions

In this article, a systematic literature review was conducted with the objective of assess the current state of recycling multi-material blends into 3D printing. The review revealed that researchers are predominantly focused on developing new materials with polymer matrices and various additives (bio-sourced, organic and inorganic fillers), often sourced from recycled materials. The primary goal of these studies is to enhance the properties of these materials for use in 3D printing applications, with mechanical tests are commonly used to characterize these novel materials. Researchers have demonstrated significant improvements in load-bearing capabilities, toughness, elasticity, and printability. The printing, optimization of parameters, the re-processability of the materials, and the development of the technology were also studied. Studies underscore the value of multi-material 3D printing in developing sustainable, high-performance composite materials, paving the way for innovative applications in engineering, medical, and construction fields.

Despite this progress, ongoing research and innovation are essential to address existing challenges and fully realize the potential of recycling multi-material polymer blends through additive manufacturing. The integration of recycled materials in 3D printing holds great promise for sustainable manufacturing practices, contributing to environmental sustainability and resource optimization. Thus, this review highlights the need to expand research in three main directions: 1) end-use applications, 2) comprehensive biodegradability, cost and environmental assessments, and 3) development and design of printers.

### **Declaration of competing**

The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

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### **References**

- [1] I. F. Kyriakidis, N. Kladovasilakis, E. M. Pechlivani, and K. Tsongas, "Mechanical Performance of Recycled 3D Printed Sustainable Polymer-Based Composites: A Literature Review," *Journal of Composites Science*, vol. 8, no. 6, Art. no. 6, Jun. 2024, doi: 10.3390/jcs8060215.
- [2] G. Maitlo *et al.*, "Plastic Waste Recycling, Applications, and Future Prospects for a Sustainable Environment," *Sustainability*, vol. 14, no. 18, Art. no. 18, Jan. 2022, doi: 10.3390/su141811637.
- [3] S. Ghosh, J. K. Sinha, S. Ghosh, K. Vashisth, S. Han, and R. Bhaskar, "Microplastics as an Emerging Threat to the Global Environment and Human Health," *Sustainability*, vol. 15, no. 14, Art. no. 14, Jan. 2023, doi: 10.3390/su151410821.
- [4] P. Europe, "Plastics - the facts 2022," Plastics Europe. Accessed: Sep. 05, 2024. [Online]. Available: <https://plasticseurope.org/fr/knowledge-hub/plastics-the-facts-2022/>
- [5] G. Gregory, "Circular Claims Fall Flat Again - Greenpeace USA." Accessed: Jul. 30, 2024. [Online]. Available: <https://www.greenpeace.org/usa/reports/circular-claims-fall-flat-again/>, <https://www.greenpeace.org/usa/reports/circular-claims-fall-flat-again/>
- [6] L. K. Ncube, A. U. Ude, E. N. Ogunmuyiwa, R. Zulkifli, and I. N. Beas, "An Overview of Plastic Waste Generation and Management in Food Packaging Industries," *Recycling*, vol. 6, no. 1, Art. no. 1, Mar. 2021, doi: 10.3390/recycling6010012.
- [7] OECD, *Global Plastics Outlook: Economic Drivers, Environmental Impacts and Policy Options*. Paris: Organisation for Economic Co-operation and Development, 2022. Accessed: Sep. 05, 2024. [Online]. Available: [https://www.oecd-ilibrary.org/environment/global-plastics-outlook\\_de747aef-en](https://www.oecd-ilibrary.org/environment/global-plastics-outlook_de747aef-en)
- [8] B. D. Vogt, K. K. Stokes, and S. K. Kumar, "Why is Recycling of Postconsumer Plastics so Challenging?," *ACS Appl. Polym. Mater.*, vol. 3, no. 9, pp. 4325–4346, Sep. 2021, doi: 10.1021/acsapm.1c00648.
- [9] L. Gui, "Recycling Infrastructure Development under Extended Producer Responsibility in Developing Economies," *Production and Operations Management*, vol. 29, no. 8, pp. 1858–1877, Aug. 2020, doi: 10.1111/poms.13202.
- [10] P. Thakur, "Welfare Effects of International Trade in Waste," Sep. 12, 2022, *Rochester, NY*: 4216639. doi: 10.2139/ssrn.4216639.
- [11] T. Hayashi, "Plastic Recycling Policy in China and the Waste Plastic Trade," in *Empirical Research on Environmental Policies in China: China Towards Decarbonization and Recycle Economy*, K. Fujikawa, Ed., Singapore: Springer Nature, 2023, pp. 37–54. doi: 10.1007/978-981-99-5957-0\_3.
- [12] B. Li and Y. Mu, "Impact of China's National Sword Policy on Waste Import Margins: A Difference-in-Differences Approach," *Sustainability*, vol. 16, no. 2, Art. no. 2, Jan. 2024, doi: 10.3390/su16020776.
- [13] W. Grzebieniarz, D. Biswas, S. Roy, and E. Jamróz, "Advances in biopolymer-based multi-layer film preparations and food packaging applications," *Food Packaging and Shelf Life*, vol. 35, p. 101033, Mar. 2023, doi: 10.1016/j.fpsl.2023.101033.
- [14] M. Roosen *et al.*, "Detailed Analysis of the Composition of Selected Plastic Packaging Waste Products and Its Implications for Mechanical and Thermochemical Recycling," *Environ. Sci. Technol.*, vol. 54, no. 20, pp. 13282–13293, Oct. 2020, doi: 10.1021/acs.est.0c03371.
- [15] G. E. Viacava, M. R. Ansorena, and N. E. Marcovich, "Chapter 18 - Multilayered films for food packaging," in *Nanostructured Materials for Food Packaging Applications*, J. Jacob, I. Cacciotti, and S. Thomas, Eds., in *Micro and Nano Technologies*, Elsevier, 2024, pp. 447–475. doi: 10.1016/B978-0-323-99525-2.00011-6.
- [16] C. T. de M. Soares, M. Ek, E. Östmark, M. Gällstedt, and S. Karlsson, "Recycling of multi-material multilayer plastic packaging: Current trends and future scenarios," *Resources, Conservation and Recycling*, vol. 176, p. 105905, Jan. 2022, doi: 10.1016/j.resconrec.2021.105905.

- [17] E. U. Thoden van Velzen, S. Chu, F. Alvarado Chacon, M. T. Brouwer, and K. Molenveld, "The impact of impurities on the mechanical properties of recycled polyethylene," *Packaging Technology and Science*, vol. 34, no. 4, pp. 219–228, 2021, doi: 10.1002/pts.2551.
- [18] F. Vilaplana and S. Karlsson, "Quality Concepts for the Improved Use of Recycled Polymeric Materials: A Review," *Macromolecular Materials and Engineering*, vol. 293, no. 4, pp. 274–297, 2008, doi: 10.1002/mame.200700393.
- [19] J. Zhou, T.-G. Hsu, and J. Wang, "Mechanochemical Degradation and Recycling of Synthetic Polymers," *Angewandte Chemie*, vol. 135, no. 27, p. e202300768, 2023, doi: 10.1002/ange.202300768.
- [20] R. Chandra and R. Rustgi, "Biodegradable polymers," *Progress in Polymer Science*, vol. 23, no. 7, pp. 1273–1335, Nov. 1998, doi: 10.1016/S0079-6700(97)00039-7.
- [21] R. Rendón-Villalobos *et al.*, "The Role of Biopolymers in Obtaining Environmentally Friendly Materials," in *Composites from Renewable and Sustainable Materials*, IntechOpen, 2016. doi: 10.5772/65265.
- [22] M. K. Akkapeddi, B. Van Buskirk, C. D. Mason, S. S. Chung, and X. Swamikannu, "Performance blends based on recycled polymers," *Polymer Engineering & Science*, vol. 35, no. 1, pp. 72–78, 1995, doi: 10.1002/pen.760350110.
- [23] M. K. Eriksen, J. D. Christiansen, A. E. Daugaard, and T. F. Astrup, "Closing the loop for PET, PE and PP waste from households: Influence of material properties and product design for plastic recycling," *Waste Management*, vol. 96, pp. 75–85, Aug. 2019, doi: 10.1016/j.wasman.2019.07.005.
- [24] J. Maris, S. Bourdon, J.-M. Brossard, L. Cauret, L. Fontaine, and V. Montembault, "Mechanical recycling: Compatibilization of mixed thermoplastic wastes," *Polymer Degradation and Stability*, vol. 147, pp. 245–266, Jan. 2018, doi: 10.1016/j.polymdegradstab.2017.11.001.
- [25] M. Nechifor, F. Tanasă, C.-A. Teacă, and M. Zănoagă, "Compatibilization strategies toward new polymer materials from re-/up-cycled plastics," *International Journal of Polymer Analysis and Characterization*, vol. 23, no. 8, pp. 740–757, Jan. 2018, doi: 10.1080/1023666X.2018.1509493.
- [26] M. Pracella, L. Rolla, D. Chionna, and A. Galeski, "Compatibilization and properties of poly(ethylene terephthalate)/polyethylene blends based on recycled materials," *Macromolecular Chemistry and Physics*, vol. 203, no. 10–11, pp. 1473–1485, 2002, doi: 10.1002/1521-3935(200207)203:10/11<1473::AID-MACP1473>3.0.CO;2-4.
- [27] L. A. Utracki, "Compatibilization of Polymer Blends," *The Canadian Journal of Chemical Engineering*, vol. 80, no. 6, pp. 1008–1016, 2002, doi: 10.1002/cjce.5450800601.
- [28] K. Nomura *et al.*, "Multiblock Copolymers for Recycling Polyethylene–Poly(ethylene terephthalate) Mixed Waste," *ACS Appl. Mater. Interfaces*, vol. 12, no. 8, pp. 9726–9735, Feb. 2020, doi: 10.1021/acsami.9b20242.
- [29] Y. Wang *et al.*, "Morphologies, structures, and properties on blends of triblock copolymers and linear low-density polyethylene," *Journal of Polymer Engineering*, vol. 44, no. 1, pp. 23–33, Jan. 2024, doi: 10.1515/polyeng-2023-0167.
- [30] H. Inoya, Y. Wei Leong, W. Klinklai, Y. Takai, and H. Hamada, "Compatibilization of recycled poly(ethylene terephthalate) and polypropylene blends: Effect of compatibilization on blend toughness, dispersion of minor phase, and thermal stability," *Journal of Applied Polymer Science*, vol. 124, no. 6, pp. 5260–5269, 2012, doi: 10.1002/app.34385.
- [31] R. Navarro, F. Parres, J. E. Crespo, S. Sánchez-Caballero, and M. A. Sellés, "COMPATIBILIZATION OF POSTCONSUMER PET/HDPE BLENDS.," p. 2, 2020.
- [32] N. Miskolczi, P. Kucharczyk, V. Sedlarik, and H. Szakacs, "Plastic waste minimization: Compatibilization of polypropylene/polyamide 6 blends by polyalkenyl-poly-maleic-

- anhydride-based agents,” *Journal of Applied Polymer Science*, vol. 129, no. 5, pp. 3028–3037, 2013, doi: 10.1002/app.38724.
- [33] P. Raffa, M.-B. Coltelli, and V. Castelvetro, “Expanding the application field of post-consumer poly(ethylene terephthalate) through structural modification by reactive blending,” *Journal of Applied Polymer Science*, vol. 131, no. 19, 2014, doi: 10.1002/app.40881.
- [34] N. N. Fomina and V. G. Khozhin, “Compatibilization of polymer mixtures during processing of waste products from thermoplastics,” *Nanobuild*, vol. 13, no. 4, pp. 229–236, Aug. 2021, doi: 10.15828/2075-8545-2021-13-4-229-236.
- [35] M. Pracella and D. Chionna, “Functionalization of Styrene-Olefin Block Copolymers by Melt Radical Grafting of Glycidyl Methacrylate and Reactive Blending with PET,” *Macromolecular Symposia*, vol. 218, no. 1, pp. 173–182, 2004, doi: 10.1002/masy.200451418.
- [36] F. P. L. Mantia, V. Titone, A. Milazzo, M. Ceraulo, and L. Botta, “Morphology, Rheological and Mechanical Properties of Isotropic and Anisotropic PP/rPET/GnP Nanocomposite Samples,” *Nanomaterials*, vol. 11, no. 11, Art. no. 11, Nov. 2021, doi: 10.3390/nano11113058.
- [37] O. Kaymakci and N. Uyanik, “In-situ Microfibrillar Recycled PET/Glass Fiber/PP Hybrid Thermoplastic Composites,” *Mater. Plast.*, vol. 57, no. 4, pp. 309–316, Jan. 2021, doi: 10.37358/MP.20.4.5429.
- [38] S. C. Dertinger *et al.*, “Technical pathways for distributed recycling of polymer composites for distributed manufacturing: Windshield wiper blades,” *Resources, Conservation and Recycling*, vol. 157, p. 104810, Jun. 2020, doi: 10.1016/j.resconrec.2020.104810.
- [39] M. A. Kreiger, M. L. Mulder, A. G. Glover, and J. M. Pearce, “Life cycle analysis of distributed recycling of post-consumer high density polyethylene for 3-D printing filament,” *Journal of Cleaner Production*, vol. 70, pp. 90–96, May 2014, doi: 10.1016/j.jclepro.2014.02.009.
- [40] P. Santander, F. A. Cruz Sanchez, H. Boudaoud, and M. Camargo, “Closed loop supply chain network for local and distributed plastic recycling for 3D printing: a MILP-based optimization approach,” *Resources, Conservation and Recycling*, vol. 154, p. 104531, Mar. 2020, doi: 10.1016/j.resconrec.2019.104531.
- [41] F. A. Cruz Sanchez, H. Boudaoud, M. Camargo, and J. M. Pearce, “Plastic recycling in additive manufacturing: A systematic literature review and opportunities for the circular economy,” *Journal of Cleaner Production*, vol. 264, p. 121602, Aug. 2020, doi: 10.1016/j.jclepro.2020.121602.
- [42] M. Huang and A. K. Schlarb, “Polypropylene/poly(ethylene terephthalate) microfibrillar reinforced composites manufactured by fused filament fabrication,” *Journal of Applied Polymer Science*, vol. 138, no. 23, p. 50557, 2021, doi: 10.1002/app.50557.
- [43] A. Petsiuk, B. Lavu, R. Dick, and J. M. Pearce, “Waste Plastic Direct Extrusion Hangprinter,” *Inventions*, vol. 7, no. 3, Art. no. 3, Sep. 2022, doi: 10.3390/inventions7030070.
- [44] M. J. Reich, A. L. Woern, N. G. Tanikella, and J. M. Pearce, “Mechanical Properties and Applications of Recycled Polycarbonate Particle Material Extrusion-Based Additive Manufacturing,” *Materials*, vol. 12, no. 10, Art. no. 10, Jan. 2019, doi: 10.3390/ma12101642.
- [45] S. Zhong and J. M. Pearce, “Tightening the loop on the circular economy: Coupled distributed recycling and manufacturing with recyclebot and RepRap 3-D printing,” *Resources, Conservation and Recycling*, vol. 128, pp. 48–58, Jan. 2018, doi: 10.1016/j.resconrec.2017.09.023.

- [46] E. E. Petersen and J. Pearce, "Emergence of Home Manufacturing in the Developed World: Return on Investment for Open-Source 3-D Printers," *Technologies*, vol. 5, no. 1, Art. no. 1, Mar. 2017, doi: 10.3390/technologies5010007.
- [47] B. T. Wittbrodt *et al.*, "Life-cycle economic analysis of distributed manufacturing with open-source 3-D printers," *Mechatronics*, vol. 23, no. 6, pp. 713–726, Sep. 2013, doi: 10.1016/j.mechatronics.2013.06.002.
- [48] J. M. Pearce, "Building Research Equipment with Free, Open-Source Hardware," *Science*, vol. 337, no. 6100, pp. 1303–1304, Sep. 2012, doi: 10.1126/science.1228183.
- [49] J. M. Pearce, *Open-Source Lab: How to Build Your Own Hardware and Reduce Research Costs*. Elsevier, 2013.
- [50] M. F. Coakley *et al.*, "The NIH 3D Print Exchange: A Public Resource for Bioscientific and Biomedical 3D Prints," *3D Printing and Additive Manufacturing*, vol. 1, no. 3, pp. 137–140, Sep. 2014, doi: 10.1089/3dp.2014.1503.
- [51] M. Coakley and D. E. Hurt, "3D Printing in the Laboratory: Maximize Time and Funds with Customized and Open-Source Labware," *J Lab Autom.*, vol. 21, no. 4, pp. 489–495, Aug. 2016, doi: 10.1177/2211068216649578.
- [52] D. J. Byard, A. L. Woern, R. B. Oakley, M. J. Fiedler, S. L. Snabes, and J. M. Pearce, "Green fab lab applications of large-area waste polymer-based additive manufacturing," *Additive Manufacturing*, vol. 27, pp. 515–525, May 2019, doi: 10.1016/j.addma.2019.03.006.
- [53] N. Gallup, J. K. Bow, and J. M. Pearce, "Economic Potential for Distributed Manufacturing of Adaptive Aids for Arthritis Patients in the U.S.," *Geriatrics*, vol. 3, no. 4, Art. no. 4, Dec. 2018, doi: 10.3390/geriatrics3040089.
- [54] M. S. Nur-A-Tomal, F. Pahlevani, and V. Sahajwalla, "Direct transformation of waste children's toys to high quality products using 3D printing: A waste-to-wealth and sustainable approach," *Journal of Cleaner Production*, vol. 267, p. 122188, Sep. 2020, doi: 10.1016/j.jclepro.2020.122188.
- [55] E. E. Petersen and J. Pearce, "Emergence of Home Manufacturing in the Developed World: Return on Investment for Open-Source 3-D Printers," *Technologies*, vol. 5, no. 1, Art. no. 1, Mar. 2017, doi: 10.3390/technologies5010007.
- [56] J. Pearce and J.-Y. Qian, "Economic Impact of DIY Home Manufacturing of Consumer Products with Low-cost 3D Printing from Free and Open Source Designs," *European Journal of Social Impact and Circular Economy*, vol. 3, no. 2, Art. no. 2, Jul. 2022, doi: 10.13135/2704-9906/6508.
- [57] H. A. Little, N. G. Tanikella, M. J. Reich, M. J. Fiedler, S. L. Snabes, and J. M. Pearce, "Towards Distributed Recycling with Additive Manufacturing of PET Flake Feedstocks," *Materials*, vol. 13, no. 19, Art. no. 19, Jan. 2020, doi: 10.3390/ma13194273.
- [58] N. E. Zander, M. Gillan, and R. H. Lambeth, "Recycled polyethylene terephthalate as a new FFF feedstock material," *Additive Manufacturing*, vol. 21, pp. 174–182, May 2018, doi: 10.1016/j.addma.2018.03.007.
- [59] A. Alexandre, F. A. Cruz Sanchez, H. Boudaoud, M. Camargo, and J. M. Pearce, "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 Printing and Additive Manufacturing*, vol. 7, no. 5, pp. 237–247, Oct. 2020, doi: 10.1089/3dp.2019.0195.
- [60] F. A. Cruz Sanchez, H. Boudaoud, S. Hoppe, and M. Camargo, "Polymer recycling in an open-source additive manufacturing context: Mechanical issues," *Additive Manufacturing*, vol. 17, pp. 87–105, Oct. 2017, doi: 10.1016/j.addma.2017.05.013.
- [61] M. I. Mohammed, D. Wilson, E. Gomez-Kervin, C. Vidler, L. Rosson, and J. Long, "The Recycling of E-Waste ABS Plastics by Melt Extrusion and 3D Printing Using Solar Powered Devices as a Transformative Tool for Humanitarian Aid," 2018, Accessed: Jul. 28, 2024. [Online]. Available: <https://hdl.handle.net/2152/90080>

- [62] S. Oberloier, N. G. Whisman, and J. M. Pearce, "Finding Ideal Parameters for Recycled Material Fused Particle Fabrication-Based 3D Printing Using an Open Source Software Implementation of Particle Swarm Optimization," *3D Printing and Additive Manufacturing*, Apr. 2022, doi: 10.1089/3dp.2022.0012.
- [63] A. Romani and M. Levi, "Large-Format Material Extrusion Additive Manufacturing for Circular Economy Practices: A Focus on Product Applications with Materials from Recycled Plastics and Biomass Waste," *Sustainability*, vol. 16, no. 18, Art. no. 18, Jan. 2024, doi: 10.3390/su16187966.
- [64] A. Papatheodorou, I. Gavalas, D. Ntenekou, and A. Karatza, "The Influence of Thermoplastic Composite Recycling on the Additive Manufacturing Process and In-Use Phase as Candidate Materials for Wearable Devices Applications," *Polymers*, vol. 15, no. 18, p. 3775, Sep. 2023, doi: 10.3390/polym15183775.
- [65] K. Ragaert, L. Delva, and K. Van Geem, "Mechanical and chemical recycling of solid plastic waste," *Waste Management*, vol. 69, pp. 24–58, Nov. 2017, doi: 10.1016/j.wasman.2017.07.044.
- [66] A. P. Siddaway, A. M. Wood, and L. V. Hedges, "How to Do a Systematic Review: A Best Practice Guide for Conducting and Reporting Narrative Reviews, Meta-Analyses, and Meta-Syntheses," *Annual Review of Psychology*, vol. 70, no. 1, pp. 747–770, 2019, doi: 10.1146/annurev-psych-010418-102803.
- [67] N. Singh, D. Hui, R. Singh, I. P. S. Ahuja, L. Feo, and F. Fraternali, "Recycling of plastic solid waste: A state of art review and future applications," *Composites Part B: Engineering*, vol. 115, pp. 409–422, Apr. 2017, doi: 10.1016/j.compositesb.2016.09.013.
- [68] S. B. Borrelle *et al.*, "Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution," *Science*, vol. 369, no. 6510, pp. 1515–1518, Sep. 2020, doi: 10.1126/science.aba3656.
- [69] R. Geyer, "Chapter 2 - Production, use, and fate of synthetic polymers," in *Plastic Waste and Recycling*, T. M. Letcher, Ed., Academic Press, 2020, pp. 13–32. doi: 10.1016/B978-0-12-817880-5.00002-5.
- [70] I. Antonopoulos, G. Faraca, and D. Tonini, "Recycling of post-consumer plastic packaging waste in the EU: Recovery rates, material flows, and barriers," *Waste Management*, vol. 126, pp. 694–705, May 2021, doi: 10.1016/j.wasman.2021.04.002.
- [71] K. Ragaert, S. Hubo, L. Delva, L. Veelaert, and E. Du Bois, "Upcycling of contaminated post-industrial polypropylene waste: A design from recycling case study," *Polymer Engineering & Science*, vol. 58, no. 4, pp. 528–534, 2018, doi: 10.1002/pen.24764.
- [72] I. A. Ignatyev, W. Thielemans, and B. Vander Beke, "Recycling of Polymers: A Review," *ChemSusChem*, vol. 7, no. 6, pp. 1579–1593, Jun. 2014, doi: 10.1002/cssc.201300898.
- [73] A. Kassab, D. Al Nabhani, P. Mohanty, C. Pannier, and G. Y. Ayoub, "Advancing Plastic Recycling: Challenges and Opportunities in the Integration of 3D Printing and Distributed Recycling for a Circular Economy," *Polymers*, vol. 15, no. 19, Art. no. 19, Jan. 2023, doi: 10.3390/polym15193881.
- [74] M. Paramatti, A. Romani, G. Pugliese, and M. Levi, "PLA Feedstock Filled with Spent Coffee Grounds for New Product Applications with Large-Format Material Extrusion Additive Manufacturing," *ACS Omega*, vol. 9, no. 6, pp. 6423–6431, Feb. 2024, doi: 10.1021/acsomega.3c05669.
- [75] A. Romani, M. Levi, and J. M. Pearce, "Recycled Polycarbonate and Polycarbonate/Acrylonitrile Butadiene Styrene Feedstocks for Circular Economy Product Applications with Fused Granular Fabrication-Based Additive Manufacturing," Jul. 12, 2023, *Rochester, NY*: 4508039. doi: 10.2139/ssrn.4508039.
- [76] T. Kuclourya, R. Monroy, and E. Cuan-Urquizo, "Scientometric analysis and critical review of fused deposition modeling in the plastic recycling context | Elsevier Enhanced Reader." Accessed: Feb. 15, 2023. [Online]. Available: <https://reader.elsevier.com/reader/sd/pii/S2772912522000082?token=4FF666D00D3E7>

- 904E2199DF96E96257B9E9964B1DD8E156A1FE66235ADAF79EC63393C9918D66FE41823045B5D257BD&originRegion=eu-west-1&originCreation=20230215094650
- [77] D. Lee, Y. Lee, K. Lee, Y. Ko, and N. Kim, "Development and Evaluation of a Distributed Recycling System for Making Filaments Reused in Three-Dimensional Printers," *Journal of Manufacturing Science and Engineering*, vol. 141, no. 2, décembre 2018, doi: 10.1115/1.4041747.
- [78] M. Sauerwein and E. L. Doubrovski, "Local and recyclable materials for additive manufacturing: 3D printing with mussel shells," *Materials Today Communications*, vol. 15, pp. 214–217, Jun. 2018, doi: 10.1016/j.mtcomm.2018.02.028.
- [79] M. I. Mohammed, A. Das, E. Gomez-Kervin, D. Wilson, and I. Gibson, "EcoPrinting: Investigating the Use of 100% Recycled Acrylonitrile Butadiene Styrene (ABS) for Additive Manufacturing," University of Texas at Austin, 2017. Accessed: Feb. 21, 2023. [Online]. Available: <https://repositories.lib.utexas.edu/handle/2152/89859>
- [80] C. Caceres-Mendoza, P. Santander-Tapia, F. A. Cruz Sanchez, N. Troussier, M. Camargo, and H. Boudaoud, "Life cycle assessment of filament production in distributed plastic recycling via additive manufacturing," *Cleaner Waste Systems*, vol. 5, p. 100100, Aug. 2023, doi: 10.1016/j.clwas.2023.100100.
- [81] M. Kreiger, G. C. Anzalone, M. L. Mulder, A. Glover, and J. M. Pearce, "Distributed Recycling of Post-Consumer Plastic Waste in Rural Areas," *MRS Online Proceedings Library (OPL)*, vol. 1492, pp. 91–96, Jan. 2013, doi: 10.1557/opl.2013.258.
- [82] C. Suescun Gonzalez, F. A. Cruz Sanchez, H. Boudaoud, C. Nouvel, and J. M. Pearce, "Multi-material distributed recycling via material extrusion: recycled high density polyethylene and poly (ethylene terephthalate) mixture," *Polymer Engineering & Science*, vol. n/a, no. n/a, 2024, doi: 10.1002/pen.26643.
- [83] M. H. Al Maamori, S. A. Habeeb, and M. A. Moslem, "Enhancing the physical properties of recycled low-density polyethylene and virgin low-density polyethylene blend using octanoate starch," *Progress in Rubber, Plastics and Recycling Technology*, p. 14777606241239065, Mar. 2024, doi: 10.1177/14777606241239065.
- [84] J. Zhang, V. Hirschberg, and D. Rodrigue, "Blending Recycled High-Density Polyethylene HDPE (rHDPE) with Virgin (vHDPE) as an Effective Approach to Improve the Mechanical Properties," *Recycling*, vol. 8, no. 1, Art. no. 1, Feb. 2023, doi: 10.3390/recycling8010002.
- [85] T. O. Azeez, "Thermoplastic Recycling: Properties, Modifications, and Applications," in *Thermosoftening Plastics*, IntechOpen, 2019. doi: 10.5772/intechopen.81614.
- [86] Renewable carbon, "RCI Position Paper on Chemical and Physical Recycling (PDF)," Renewable Carbon Publications. Accessed: Sep. 05, 2024. [Online]. Available: <https://renewable-carbon.eu/publications/product/rci-position-paper-on-chemical-and-physical-recycling/>
- [87] J. Parameswaranpillai, S. Thomas, and Y. Grohens, "Polymer Blends: State of the Art, New Challenges, and Opportunities," in *Characterization of Polymer Blends*, John Wiley & Sons, Ltd, 2014, pp. 1–6. doi: 10.1002/9783527645602.ch01.
- [88] D. R. Paul and J. W. Barlow, "Polymer Blends," *Journal of Macromolecular Science, Part C*, vol. 18, no. 1, pp. 109–168, Jan. 1980, doi: 10.1080/00222358008080917.
- [89] U. Riaz and S. M. Ashraf, "Characterization of Polymer Blends with FTIR Spectroscopy," in *Characterization of Polymer Blends*, John Wiley & Sons, Ltd, 2014, pp. 625–678. doi: 10.1002/9783527645602.ch20.
- [90] A. Verberckmoes *et al.*, "Morphological analysis of mechanically recycled blends of high density polyethylene and polypropylene with strong difference in melt flow index," *Polymer*, vol. 300, p. 126999, Apr. 2024, doi: 10.1016/j.polymer.2024.126999.
- [91] G. Kotzev, S. Djoumalisky, M. Krasteva, M. Iliev, E. Pérez, and M. L. Cerrada, "Effect of Sample Configuration on the Morphology of Foamed LDPE/PP Blends Injection Molded by a Gas Counterpressure Process," *Macromolecular Materials and Engineering*, vol. 292, no. 6, pp. 769–779, 2007, doi: 10.1002/mame.200700030.

- [92] W. Zhang, S. Deodhar, and D. Yao, "Geometrical Confining Effects in Compression Molding of Co-continuous Polymer Blends," *Ann Biomed Eng*, vol. 38, no. 6, pp. 1954–1964, Jun. 2010, doi: 10.1007/s10439-010-0026-2.
- [93] L.-T. Lee, M.-C. Wu, C.-T. Yang, and C.-W. Li, "Studies of inherent mixing and physical properties for green polymer blends comprising natural polyphenol and biodegradable polymer with aliphatic-aromatic backbone," *J Polym Res*, vol. 23, no. 12, p. 255, Nov. 2016, doi: 10.1007/s10965-016-1153-8.
- [94] L. A. Utracki and C. A. Wilkie, Eds., *Polymer Blends Handbook*. Dordrecht: Springer Netherlands, 2014. doi: 10.1007/978-94-007-6064-6.
- [95] A. Ghosh, "Performance modifying techniques for recycled thermoplastics," *Resources, Conservation and Recycling*, vol. 175, p. 105887, Dec. 2021, doi: 10.1016/j.resconrec.2021.105887.
- [96] R. N. Jagtap, K. K. Wadgaonkar, and L. B. Mehta, "Influence of Ethylene-Methacrylic Acid Copolymer on Thermo-mechanical, Morphological and Rheological Properties of Recycled PET/SEBS Blend," *Fibers Polym*, vol. 20, no. 7, pp. 1323–1332, Jul. 2019, doi: 10.1007/s12221-019-8318-0.
- [97] S. J. Lee, S. J. Yoon, and I.-Y. Jeon, "Graphene/Polymer Nanocomposites: Preparation, Mechanical Properties, and Application," *Polymers*, vol. 14, no. 21, Art. no. 21, Jan. 2022, doi: 10.3390/polym14214733.
- [98] M. Entezam, H. A. Khonakdar, and A. A. Yousefi, "On the Flame Resistance Behavior of PP/PET Blends in the Presence of Nanoclay and a Halogen-Free Flame Retardant," *Macromolecular Materials and Engineering*, vol. 298, no. 10, pp. 1074–1084, 2013, doi: 10.1002/mame.201200195.
- [99] A. Hellati, D. Benachour, M. E. Cagiao, S. Boufassa, and F. J. Baltá Calleja, "Role of a compatibilizer in the structure and micromechanical properties of recycled poly(ethylene terephthalate)/polyolefin blends with clay," *Journal of Applied Polymer Science*, vol. 118, no. 3, pp. 1278–1287, 2010, doi: 10.1002/app.32090.
- [100] R. Cardinaels, "Chapter 8 - Compatibilization of polymer blends by Janus particles," in *Compatibilization of Polymer Blends*, A. A.r. and S. Thomas, Eds., Elsevier, 2020, pp. 249–275. doi: 10.1016/B978-0-12-816006-0.00008-6.
- [101] B. Dairi, H. Djidjelli, A. Boukerrou, S. Migneault, and A. Koubaa, "Morphological, mechanical, and physical properties of composites made with wood flour-reinforced polypropylene/recycled poly(ethylene terephthalate) blends," *Polymer Composites*, vol. 38, no. 8, pp. 1749–1755, 2017, doi: 10.1002/pc.23745.
- [102] R. S. Chen, S. Ahmad, S. Gan, and M. A. Tarawneh, "High loading rice husk green composites: Dimensional stability, tensile behavior and prediction, and combustion properties," *Journal of Thermoplastic Composite Materials*, vol. 33, no. 7, pp. 882–897, Jul. 2020, doi: 10.1177/0892705718815536.
- [103] M. Bremer, L. Janoschek, D. Kaschta, N. Schneider, and M. Wahl, "Influence of plastic recycling—a feasibility study for additive manufacturing using glycol modified polyethylene terephthalate (PETG)," *SN Appl. Sci.*, vol. 4, no. 5, p. 156, May 2022, doi: 10.1007/s42452-022-05039-3.
- [104] V. Mishra, C. K. Ror, S. Negi, S. Kar, and L. N. Borah, "3D printing with recycled ABS resin: Effect of blending and printing temperature," *Materials Chemistry and Physics*, vol. 309, p. 128317, Nov. 2023, doi: 10.1016/j.matchemphys.2023.128317.
- [105] A. K. Pal *et al.*, "3D PRINTING SUSTAINABLE BIOCOMPOSITES FROM RECYCLED PLA AND MICRO-CRYSTALLINE CELLULOSE," 2021.
- [106] W.-C. Chao and Y.-C. Liao, "Cost-effective recycled resin for digital light processing 3D printing," *Journal of Cleaner Production*, vol. 388, p. 136013, Feb. 2023, doi: 10.1016/j.jclepro.2023.136013.
- [107] R. Plavec *et al.*, "Influence of Multiple Thermomechanical Processing of 3D Filaments Based on Polylactic Acid and Polyhydroxybutyrate on Their Rheological and Utility

- Properties,” *Polymers*, vol. 14, no. 10, Art. no. 10, Jan. 2022, doi: 10.3390/polym14101947.
- [108] S. Bhagia *et al.*, “3D printing of a recycled copolyester of terephthalic acid, cyclohexanedimethanol and tetramethylcyclobutanediol,” *Polymer Testing*, vol. 118, p. 107916, Jan. 2023, doi: 10.1016/j.polymertesting.2022.107916.
- [109] L. Cafiero *et al.*, “Characterization of WEEE plastics and their potential valorisation through the production of 3D printing filaments,” *Journal of Environmental Chemical Engineering*, vol. 9, no. 4, p. 105532, Aug. 2021, doi: 10.1016/j.jece.2021.105532.
- [110] P. Ghabezi, O. Sam-Daliri, T. Flanagan, M. Walls, and N. M. Harrison, “Circular economy innovation: A deep investigation on 3D printing of industrial waste polypropylene and carbon fibre composites,” *Resources, Conservation and Recycling*, vol. 206, p. 107667, Jul. 2024, doi: 10.1016/j.resconrec.2024.107667.
- [111] M. Morsidi, P. T. Mativenga, and M. Fahad, “Fused Deposition Modelling Filament with Recyclate Fibre Reinforcement,” *Procedia CIRP*, vol. 85, pp. 353–358, Jan. 2019, doi: 10.1016/j.procir.2019.09.026.
- [112] A. Rahimizadeh, J. Kalman, R. Henri, K. Fayazbakhsh, and L. Lessard, “Recycled Glass Fiber Composites from Wind Turbine Waste for 3D Printing Feedstock: Effects of Fiber Content and Interface on Mechanical Performance,” *Materials*, vol. 12, no. 23, p. 3929, Nov. 2019, doi: 10.3390/ma12233929.
- [113] N. E. Zander, M. Gillan, Z. Burckhard, and F. Gardea, “Recycled polypropylene blends as novel 3D printing materials,” *Additive Manufacturing*, vol. 25, pp. 122–130, Jan. 2019, doi: 10.1016/j.addma.2018.11.009.
- [114] S. Chong *et al.*, “Evaluation of the physico-mechanical properties of activated-carbon enhanced recycled polyethylene/polypropylene 3D printing filament,” *Sādhanā*, vol. 45, no. 1, p. 57, Feb. 2020, doi: 10.1007/s12046-020-1294-7.
- [115] J. J. Ariel Leong, S. C. Koay, M. Y. Chan, H. L. Choo, K. Y. Tshai, and T. K. Ong, “Composite Filament Made from Post-used Styrofoam and Corn Husk Fiber for Fuse Deposition Modeling,” *Journal of Natural Fibers*, vol. 19, no. 13, pp. 7033–7048, Dec. 2022, doi: 10.1080/15440478.2021.1941488.
- [116] A. Gupta, A. K. Mohanty, and M. Misra, “Biocarbon from spent coffee ground and their sustainable biocomposites with recycled water bottle and bale wrap: A new life for waste plastics and waste food residues for industrial uses,” *Composites Part A: Applied Science and Manufacturing*, vol. 154, p. 106759, Mar. 2022, doi: 10.1016/j.compositesa.2021.106759.
- [117] M. Idrees, S. Jeelani, and V. Rangari, “Three-Dimensional-Printed Sustainable Biochar-Recycled PET Composites,” *ACS Sustainable Chem. Eng.*, vol. 6, no. 11, pp. 13940–13948, Nov. 2018, doi: 10.1021/acssuschemeng.8b02283.
- [118] E. O. Cisneros-López *et al.*, “Recycled poly(lactic acid)-based 3D printed sustainable biocomposites: a comparative study with injection molding,” *Materials Today Sustainability*, vol. 7–8, p. 100027, Mar. 2020, doi: 10.1016/j.mtsust.2019.100027.
- [119] M. Hyvärinen and T. Kärki, “Tensile Properties of Cellulose-Filled Recycled Thermoplastic Composite Filaments for 3D Printing,” *KEM*, vol. 841, pp. 87–93, May 2020, doi: 10.4028/www.scientific.net/KEM.841.87.
- [120] M. Rafiee *et al.*, “Exploring the possibilities of FDM filaments comprising natural fiber-reinforced biocomposites for additive manufacturing,” *AIMS Materials Science*, vol. 8, no. 4, pp. 524–537, 2021, doi: 10.3934/matsci.2021032.
- [121] R. Singh, A. Barwar, R. Kumar, and V. Kumar, “On mechanically recycled PLA-HAP-CS-based filaments for 3D printing of smart biomedical scaffolds,” *J Braz. Soc. Mech. Sci. Eng.*, vol. 44, no. 9, p. 416, Sep. 2022, doi: 10.1007/s40430-022-03727-0.
- [122] R. Scaffaro, M. C. Citarrella, A. Catania, and L. Settanni, “Green composites based on biodegradable polymers and anchovy (*Engraulis Encrasicolus*) waste suitable for 3D

- printing applications,” *Composites Science and Technology*, vol. 230, p. 109768, Nov. 2022, doi: 10.1016/j.compscitech.2022.109768.
- [123] A. N. M. A. Haque and M. Naebe, “Material Extrusion of Wool Waste/Polycaprolactone with Improved Tensile Strength and Biodegradation,” *Polymers*, vol. 15, no. 16, p. 3439, Aug. 2023, doi: 10.3390/polym15163439.
- [124] K. Chawla, J. Singh, and R. Singh, “On chemical assisted blending of secondary recycled ABS with bakelite and wood dust for fused filament fabrication,” *Advances in Materials and Processing Technologies*, vol. 9, no. 1, pp. 116–137, Jan. 2023, doi: 10.1080/2374068X.2022.2085955.
- [125] M. Seggiani *et al.*, “Polycaprolactone-collagen hydrolysate thermoplastic blends: Processability and biodegradability/compostability,” *Polymer Degradation and Stability*, vol. 150, pp. 13–24, Apr. 2018, doi: 10.1016/j.polymdegradstab.2018.02.001.
- [126] M. Hassan, A. K. Mohanty, and M. Misra, “3D printing in upcycling plastic and biomass waste to sustainable polymer blends and composites: A review,” *Materials & Design*, vol. 237, p. 112558, Jan. 2024, doi: 10.1016/j.matdes.2023.112558.
- [127] R. Singh, R. Kumar, I. Farina, F. Colangelo, L. Feo, and F. Fraternali, “Multi-Material Additive Manufacturing of Sustainable Innovative Materials and Structures,” *Polymers*, vol. 11, no. 1, p. 62, Jan. 2019, doi: 10.3390/polym11010062.
- [128] X. Hu, H. Kang, Y. Li, Y. Geng, R. Wang, and L. Zhang, “Preparation, morphology and superior performances of biobased thermoplastic elastomer by in situ dynamical vulcanization for 3D-printed materials,” *Polymer*, vol. 108, pp. 11–20, Jan. 2017, doi: 10.1016/j.polymer.2016.11.045.
- [129] F. Laoutid, H. Lenoir, A. Molins Santaularia, A. Toncheva, T. Schouw, and P. Dubois, “Impact-Resistant Poly(3-Hydroxybutyrate)/Poly( $\epsilon$ -Caprolactone)-Based Materials, through Reactive Melt Processing, for Compression-Molding and 3D-Printing Applications,” *Materials*, vol. 15, no. 22, p. 8233, Nov. 2022, doi: 10.3390/ma15228233.
- [130] S. S. Bartolomei, F. L. F. Da Silva, E. A. B. De Moura, and H. Wiebeck, “Recycling Expanded Polystyrene with a Biodegradable Solvent to Manufacture 3D Printed Prototypes and Finishing Materials for Construction,” *J Polym Environ*, vol. 30, no. 9, pp. 3701–3717, Sep. 2022, doi: 10.1007/s10924-022-02465-7.
- [131] A. Rimkus, M. M. Farh, and V. Gribniak, “Continuously Reinforced Polymeric Composite for Additive Manufacturing—Development and Efficiency Analysis,” *Polymers*, vol. 14, no. 17, p. 3471, Aug. 2022, doi: 10.3390/polym14173471.
- [132] X. Chen *et al.*, “Quadruple Hydrogen Bonding Supramolecular Elastomers for Melt Extrusion Additive Manufacturing,” *ACS Appl. Mater. Interfaces*, vol. 12, no. 28, pp. 32006–32016, Jul. 2020, doi: 10.1021/acsami.0c08958.
- [133] X. Gao, H. Wang, S. Luan, and G. Zhou, “Synthesis and 3D-printing of isosorbide-based poly(aryletherketone) for carbon neutral manufacturing,” *Chemical Engineering Journal*, vol. 477, p. 146968, Dec. 2023, doi: 10.1016/j.cej.2023.146968.
- [134] V. Mishra, S. Negi, and S. Kar, “FDM-based additive manufacturing of recycled thermoplastics and associated composites,” *J Mater Cycles Waste Manag*, Jan. 2023, doi: 10.1007/s10163-022-01588-2.
- [135] A. Gupta, M. Misra, and A. K. Mohanty, “Novel sustainable materials from waste plastics: compatibilized blend from discarded bale wrap and plastic bottles,” *RSC Advances*, vol. 11, no. 15, pp. 8594–8605, 2021, doi: 10.1039/D1RA00254F.
- [136] N. E. Zander and Z. R. Boelter, “Rubber toughened recycled polyethylene terephthalate for material extrusion additive manufacturing,” *Polymer International*, vol. 70, no. 6, pp. 742–748, 2021, doi: 10.1002/pi.6079.
- [137] C. G. Schirmeister *et al.*, “Low Warpage Nanophase-Separated Polypropylene/Olefinic Elastomer Reactor Blend Composites with Digitally Tuned Glass Fiber Orientation by Extrusion-Based Additive Manufacturing,” *ACS Appl. Polym. Mater.*, vol. 3, no. 4, pp. 2070–2081, Apr. 2021, doi: 10.1021/acsapm.1c00119.

- [138] D. A. Tolcha and D. E. Woldemichael, "Development and characterization of short glass fiber reinforced-waste plastic composite filaments for 3D printing applications," *Heliyon*, vol. 9, no. 11, p. e22333, Nov. 2023, doi: 10.1016/j.heliyon.2023.e22333.
- [139] A. Borkar, A. Hendlmeier, Z. Simon, J. D. Randall, F. Stojcevski, and L. C. Henderson, "A comparison of mechanical properties of recycled high-density polyethylene/waste carbon fiber via injection molding and 3D printing," *Polymer Composites*, vol. 43, no. 4, pp. 2408–2418, Apr. 2022, doi: 10.1002/pc.26550.
- [140] N. Giani, L. Mazzocchetti, T. Benelli, F. Picchioni, and L. Giorgini, "Towards sustainability in 3D printing of thermoplastic composites: Evaluation of recycled carbon fibers as reinforcing agent for FDM filament production and 3D printing," *Composites Part A: Applied Science and Manufacturing*, vol. 159, p. 107002, Aug. 2022, doi: 10.1016/j.compositesa.2022.107002.
- [141] N. Al-Mazrouei, A. H. Al-Marzouqi, and W. Ahmed, "Characterization and Sustainability Potential of Recycling 3D-Printed Nylon Composite Wastes," *Sustainability*, vol. 14, no. 17, Art. no. 17, Jan. 2022, doi: 10.3390/su141710458.
- [142] M. Doddamani and N. Gupta, "26 - 3D printing of fly ash-based syntactic foams," in *Handbook of Fly Ash*, K. K. Kar, Ed., Butterworth-Heinemann, 2022, pp. 793–818. doi: 10.1016/B978-0-12-817686-3.00022-0.
- [143] A. K. Singh, B. Patil, N. Hoffmann, B. Saltonstall, M. Doddamani, and N. Gupta, "Additive Manufacturing of Syntactic Foams: Part 1: Development, Properties, and Recycling Potential of Filaments," *JOM*, vol. 70, no. 3, pp. 303–309, Mar. 2018, doi: 10.1007/s11837-017-2734-7.
- [144] A. Alduais, F. Kazanç, G. Bayram, and S. Özerinç, "ABS-Fly Ash Composite Filaments for Fused Deposition Modeling," in *Recent Advances in Manufacturing Processes and Systems*, H. K. Dave, U. S. Dixit, and D. Nedelcu, Eds., Singapore: Springer Nature, 2022, pp. 85–95. doi: 10.1007/978-981-16-7787-8\_7.
- [145] M. F. Saad *et al.*, "Parametric study on producing Fused Deposition Modelling filament made of recovered carbon black reinforced Acrylonitrile Butadiene Styrene plastics," *J. Phys.: Conf. Ser.*, vol. 2643, no. 1, p. 012011, Nov. 2023, doi: 10.1088/1742-6596/2643/1/012011.
- [146] K. Chawla, R. Singh, J. Singh, and H. Mehta, "Investigations on mechanical properties of secondary recycled ABS reinforced with Fe powder for 3D printing applications," *Materials Today: Proceedings*, vol. 50, pp. 2450–2454, 2022, doi: 10.1016/j.matpr.2021.10.291.
- [147] R. Singh, I. Singh, and R. Kumar, "Mechanical and morphological investigations of 3D printed recycled ABS reinforced with bakelite–SiC–Al<sub>2</sub>O<sub>3</sub>," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, vol. 233, no. 17, pp. 5933–5944, Sep. 2019, doi: 10.1177/0954406219860163.
- [148] S. Bergaliyeva *et al.*, "Thermal and Mechanical Properties of Reprocessed Polylactide/Titanium Dioxide Nanocomposites for Material Extrusion Additive Manufacturing," *Polymers*, vol. 15, no. 16, p. 3458, Aug. 2023, doi: 10.3390/polym15163458.
- [149] W. Ahmed, S. Siraj, and A. H. Al-Marzouqi, "3D Printing PLA Waste to Produce Ceramic Based Particulate Reinforced Composite Using Abundant Silica-Sand: Mechanical Properties Characterization," *Polymers*, vol. 12, no. 11, Art. no. 11, Nov. 2020, doi: 10.3390/polym12112579.
- [150] N. Singh, R. Singh, I. P. S. Ahuja, I. Farina, and F. Fraternali, "Metal matrix composite from recycled materials by using additive manufacturing assisted investment casting," *Composite Structures*, vol. 207, pp. 129–135, Jan. 2019, doi: 10.1016/j.compstruct.2018.09.072.
- [151] T. K. Meyer, N. G. Tanikella, M. J. Reich, and J. M. Pearce, "Potential of distributed recycling from hybrid manufacturing of 3-D printing and injection molding of stamp sand

- and acrylonitrile styrene acrylate waste composite,” *Sustainable Materials and Technologies*, vol. 25, p. e00169, Sep. 2020, doi: 10.1016/j.susmat.2020.e00169.
- [152] H. Kim and S. Lee, “Printability and physical properties of iron slag powder composites using material extrusion-based 3D printing,” *J. Iron Steel Res. Int.*, vol. 28, no. 1, pp. 111–121, Jan. 2021, doi: 10.1007/s42243-020-00475-0.
- [153] J. S. Chu, S. C. Koay, M. Y. Chan, H. L. Choo, and T. K. Ong, “Recycled plastic filament made from post-consumer expanded polystyrene and polypropylene for fused filament fabrication,” *Polymer Engineering & Sci*, vol. 62, no. 11, pp. 3786–3795, Nov. 2022, doi: 10.1002/pen.26144.
- [154] I. Turku, S. Kasala, and T. Kärki, “Characterization of Polystyrene Wastes as Potential Extruded Feedstock Filament for 3D Printing,” *Recycling*, vol. 3, no. 4, Art. no. 4, Dec. 2018, doi: 10.3390/recycling3040057.
- [155] D. Battegazzore, F. Cravero, G. Bernagozzi, and A. Frache, “Designing a 3D printable polypropylene-based material from after use recycled disposable masks,” *Materials Today Communications*, vol. 32, p. 103997, Aug. 2022, doi: 10.1016/j.mtcomm.2022.103997.
- [156] O. Zabihi *et al.*, “Mechanical upcycling of single-use face mask waste into high-performance composites: An ecofriendly approach with cost-benefit analysis,” *Science of The Total Environment*, vol. 919, p. 170469, Apr. 2024, doi: 10.1016/j.scitotenv.2024.170469.
- [157] A. Ragab, R. Elazhary, S. Schmauder, and A. Ramzy, “Plastic Waste Valorization for Fused Deposition Modeling Feedstock: A Case Study on Recycled Polyethylene Terephthalate/High-Density Polyethylene Sustainability,” *Sustainability*, vol. 15, no. 18, Art. no. 18, Jan. 2023, doi: 10.3390/su151813291.
- [158] A. Toncheva, L. Brison, P. Dubois, and F. Laoutid, “Recycled Tire Rubber in Additive Manufacturing: Selective Laser Sintering for Polymer-Ground Rubber Composites,” *Applied Sciences*, vol. 11, no. 18, p. 8778, Sep. 2021, doi: 10.3390/app11188778.
- [159] Nur Nazira Alias, Ireana Yusra Abdul Fatah, Yew Been Seok, Sharifah Hanis Yasmin Sayid Abdullah, Amir Hussain Bhat, and Saiful Bahri Mohd Diah, “Material Characterizations of the Polymers Reinforced with Recycled Flexible Plastic Blends as Filament for 3D Printing,” *ARASET*, vol. 37, no. 1, pp. 1–15, Jan. 2024, doi: 10.37934/araset.37.1.115.
- [160] H. He *et al.*, “Microscopic morphology, rheological behavior, and mechanical properties of polymers: Recycled acrylonitrile-butadiene-styrene/polybutylene terephthalate blends,” *J of Applied Polymer Sci*, vol. 137, no. 4, p. 48310, Jan. 2020, doi: 10.1002/app.48310.
- [161] M. Ciotti, G. Campana, and M. Mele, “A review of the accuracy of thermoplastic polymeric parts fabricated by additive manufacturing,” *Rapid Prototyping Journal*, vol. 28, no. 2, pp. 358–389, Jan. 2022, doi: 10.1108/RPJ-11-2020-0295.
- [162] V. M. Rivas Santos, A. Thompson, D. Sims-Waterhouse, I. Maskery, P. Woolliams, and R. Leach, “Design and characterisation of an additive manufacturing benchmarking artefact following a design-for-metrology approach,” *Additive Manufacturing*, vol. 32, p. 100964, Mar. 2020, doi: 10.1016/j.addma.2019.100964.
- [163] J. Domingues, T. Marques, A. Mateus, P. Carreira, and C. Malça, “An Additive Manufacturing Solution to Produce Big Green Parts from Tires and Recycled Plastics,” *Procedia Manufacturing*, vol. 12, pp. 242–248, Jan. 2017, doi: 10.1016/j.promfg.2017.08.028.
- [164] J. C. E. Mertens *et al.*, “Analysis of thermal history effects on mechanical anisotropy of 3D-printed polymer matrix composites via in situ X-ray tomography,” *J Mater Sci*, vol. 52, no. 20, pp. 12185–12206, Oct. 2017, doi: 10.1007/s10853-017-1339-4.
- [165] A. Moure Abelenda and F. Aiouache, “Microfactory for Valorization of E-waste Plastics (Acrylonitrile-Butadiene-Styrene, Polycarbonate, and Polypropylene) on Additive Manufacturing Sector,” Mar. 30, 2023. doi: 10.20944/preprints202303.0516.v1.

- [166] T. Prasopdee, T. Pannoppa, P. Porbun, P. Luangchuang, P. Promoppatum, and Y. Nakaramontri, "Effect of the thermoplastic types and ratios for the 3D printed thermoplastic natural rubber vulcanizates: Mechanical, dynamical, thermal, printed-structural properties," *Industrial Crops and Products*, vol. 203, p. 117238, Nov. 2023, doi: 10.1016/j.indcrop.2023.117238.
- [167] S. He *et al.*, "Polyurethanes Based on Polylactic Acid for 3D Printing and Shape-Memory Applications," *Biomacromolecules*, vol. 23, no. 10, pp. 4192–4202, Oct. 2022, doi: 10.1021/acs.biomac.2c00662.
- [168] X. Miao, K. C. H. Chin, and A. J. Boydston, "Design, testing, and application of an open-source powder material extrusion 3D printer," *Additive Manufacturing*, vol. 81, p. 104014, Feb. 2024, doi: 10.1016/j.addma.2024.104014.
- [169] S. Brooks, Z. Cartwright, D. Merckle, and A. C. Weems, "4D Aliphatic photopolymer polycarbonates as direct ink writing of biodegradable, conductive graphite-composite materials," *Polymer Composites*, vol. 42, no. 10, pp. 5134–5143, 2021, doi: 10.1002/pc.26211.
- [170] J. Casado, O. Konuray, G. Benet, X. Fernández-Francos, J. M. Morancho, and X. Ramis, "Optimization and Testing of Hybrid 3D Printing Vitrimer Resins," *Polymers*, vol. 14, no. 23, p. 5102, Nov. 2022, doi: 10.3390/polym14235102.
- [171] G. Zhu *et al.*, "Universal approach for developing reprocessible and reprintable plant oil-based resins for digital light processing 3D printing," *Chemical Engineering Journal*, vol. 475, p. 146080, Nov. 2023, doi: 10.1016/j.cej.2023.146080.
- [172] F. A. Kucherov, E. G. Gordeev, A. S. Kashin, and V. P. Ananikov, "Three-Dimensional Printing with Biomass-Derived PEF for Carbon-Neutral Manufacturing," *Angew Chem Int Ed Engl*, vol. 56, no. 50, pp. 15931–15935, Dec. 2017, doi: 10.1002/anie.201708528.
- [173] P. Qu, C. Lv, Y. Qi, L. Bai, and J. Zheng, "A Highly Stretchable, Self-Healing Elastomer with Rate Sensing Capability Based on a Dynamic Dual Network," *ACS Appl. Mater. Interfaces*, vol. 13, no. 7, pp. 9043–9052, Feb. 2021, doi: 10.1021/acsami.1c00282.
- [174] M. Garwacki, I. Cudnik, D. Dziadowiec, P. Szymczak, and J. Andrzejewski, "The Development of Sustainable Polyethylene Terephthalate Glycol-Based (PETG) Blends for Additive Manufacturing Processing—The Use of Multilayered Foil Waste as the Blend Component," *Materials*, vol. 17, no. 5, Art. no. 5, Jan. 2024, doi: 10.3390/ma17051083.
- [175] J. B. Park, S. H. An, J. W. Jung, and J. U. Lee, "Three-Dimensional Printing of Recycled Polypropylene and Activated Carbon Coatings for Harmful Gas Adsorption and Antibacterial Properties," *Polymers*, vol. 15, no. 5, p. 1173, Feb. 2023, doi: 10.3390/polym15051173.
- [176] C. de la Torre-Gamarra, M. D. García-Suelto, D. del Rio Santos, B. Levenfeld, and A. Varez, "3D-printing of easily recyclable all-ceramic thick LiCoO<sub>2</sub> electrodes with enhanced areal capacity for Li-ion batteries using a highly filled thermoplastic filament," *Journal of Colloid and Interface Science*, vol. 642, pp. 351–363, Jul. 2023, doi: 10.1016/j.jcis.2023.03.117.
- [177] K. Kozlovsky, J. Schiltz, T. Kreider, M. Kumar, and S. Schmid, "Mechanical Properties of Reused Nylon Feedstock for Powder-bed Additive Manufacturing in Orthopedics," *Procedia Manufacturing*, vol. 26, pp. 826–833, 2018, doi: 10.1016/j.promfg.2018.07.103.
- [178] E. P. Yap, S. C. Koay, M. Y. Chan, H. L. Choo, T. K. Ong, and K. Y. Tshai, "Recycling Polymer Blend made from Post-used Styrofoam and Polyethylene for Fuse Deposition Modelling," *J. Phys.: Conf. Ser.*, vol. 2120, no. 1, p. 012021, Dec. 2021, doi: 10.1088/1742-6596/2120/1/012021.
- [179] M. K. J. E. Exconde, J. A. A. Co, J. Z. Manapat, and E. R. Magdaluyo, "Materials Selection of 3D Printing Filament and Utilization of Recycled Polyethylene Terephthalate (PET) in a Redesigned Breadboard," *Procedia CIRP*, vol. 84, pp. 28–32, 2019, doi: 10.1016/j.procir.2019.04.337.

- [180] R. Arrigo, D. Battezzato, G. Bernagozzi, F. Cravero, D. N. Ribero Pedraza, and A. Frache, "Recycled PP for 3D Printing: Material and Processing Optimization through Design of Experiment," *Applied Sciences*, vol. 12, no. 21, p. 10840, Oct. 2022, doi: 10.3390/app122110840.
- [181] S. Graziosi *et al.*, "A vision for sustainable additive manufacturing," *Nat Sustain*, Apr. 2024, doi: 10.1038/s41893-024-01313-x.
- [182] S. Whyman, K. M. Arif, and J. Potgieter, "Design and development of an extrusion system for 3D printing biopolymer pellets," *Int J Adv Manuf Technol*, vol. 96, no. 9, pp. 3417–3428, Jun. 2018, doi: 10.1007/s00170-018-1843-y.
- [183] K. Formela and B. Eyigöz, "Planetary roller extruders in the sustainable development of polymer blends and composites – Past, present and future. | Express Polymer Letters | EBSCOhost." Accessed: May 05, 2024. [Online]. Available: <https://openurl.ebsco.com/contentitem/doi:10.3144%2Fexpresspolymlett.2024.32?sid=ebsco:plink:crawler&id=ebsco:doi:10.3144%2Fexpresspolymlett.2024.32>
- [184] A. Romani, L. Perusin, M. Ciurnelli, and M. Levi, "Characterization of PLA feedstock after multiple recycling processes for large-format material extrusion additive manufacturing," *Materials Today Sustainability*, vol. 25, p. 100636, Mar. 2024, doi: 10.1016/j.mtsust.2023.100636.
- [185] I. Papa, A. E. Hassanin, P. Russo, and A. Langella, "Comparison between conventional and additive processing of polylactic acid subjected to multiple recycling and lauroyl peroxide addition," *Prog Addit Manuf*, vol. 10, no. 4, pp. 2991–3001, Apr. 2025, doi: 10.1007/s40964-024-00799-3.
- [186] P. D. Fabbro *et al.*, "Influence of machine type and consecutive closed-loop recycling on macroscopic properties for fused filament fabrication of acrylonitrile-butadiene-styrene parts," *Rapid Prototyping Journal*, vol. 27, no. 2, pp. 268–277, Dec. 2020, doi: 10.1108/RPJ-03-2020-0060.
- [187] N. Vidakis *et al.*, "Sustainable Additive Manufacturing: Mechanical Response of Polyethylene Terephthalate Glycol over Multiple Recycling Processes," *Materials*, vol. 14, no. 5, Art. no. 5, Jan. 2021, doi: 10.3390/ma14051162.
- [188] N. Vidakis *et al.*, "Sustainable Additive Manufacturing: Mechanical Response of Polyamide 12 over Multiple Recycling Processes," *Materials*, vol. 14, no. 2, Art. no. 2, Jan. 2021, doi: 10.3390/ma14020466.
- [189] N. Vidakis, M. Petousis, and A. Maniadi, "Sustainable Additive Manufacturing: Mechanical Response of High-Density Polyethylene over Multiple Recycling Processes," *Recycling*, vol. 6, no. 1, Art. no. 1, Mar. 2021, doi: 10.3390/recycling6010004.
- [190] N. Vidakis, M. Petousis, N. Mountakis, C. N. David, D. Sagris, and S. C. Das, "Thermomechanical response of thermoplastic polyurethane used in MEX additive manufacturing over repetitive mechanical recycling courses," *Polymer Degradation and Stability*, vol. 207, p. 110232, Jan. 2023, doi: 10.1016/j.polymdegradstab.2022.110232.
- [191] F. A. Cruz Sanchez, H. Boudaoud, M. Camargo, and J. M. Pearce, "Plastic recycling in additive manufacturing: A systematic literature review and opportunities for the circular economy," *Journal of Cleaner Production*, vol. 264, p. 121602, Aug. 2020, doi: 10.1016/j.jclepro.2020.121602.
- [192] S. Hlaváčiková *et al.*, "The possibility of using the regranulate of a biodegradable polymer blend based on polylactic acid and polyhydroxybutyrate in FDM 3D printing technology," *Results in Materials*, vol. 21, p. 100511, Mar. 2024, doi: 10.1016/j.rinma.2023.100511.
- [193] J. Shojaeiarani, D. S. Bajwa, C. Rehovsky, S. G. Bajwa, and G. Vahidi, "Deterioration in the Physico-Mechanical and Thermal Properties of Biopolymers Due to Reprocessing," *Polymers*, vol. 11, no. 1, Art. no. 1, Jan. 2019, doi: 10.3390/polym11010058.
- [194] P. Kerdlap, A. R. Purnama, J. S. C. Low, D. Z. L. Tan, C. Y. Barlow, and S. Ramakrishna, "Environmental evaluation of distributed versus centralized plastic waste recycling:

- Integrating life cycle assessment and agent-based modeling,” *Procedia CIRP*, vol. 90, pp. 689–694, Jan. 2020, doi: 10.1016/j.procir.2020.01.083.
- [195] S. Feeley, B. Wijnen, and J. Pearce, “Evaluation of Potential Fair Trade Standards for an Ethical 3-D Printing Filament,” *Journal of Sustainable Development*, vol. 7, no. 5, Art. no. 5, Sep. 2014, doi: 10.5539/jsd.v7n5p1.
- [196] S. C. Dertinger *et al.*, “Technical pathways for distributed recycling of polymer composites for distributed manufacturing: Windshield wiper blades,” *Resources, Conservation and Recycling*, vol. 157, p. 104810, Jun. 2020, doi: 10.1016/j.resconrec.2020.104810.
- [197] A. Z. Naser, F. Defersha, E. Pei, Y. F. Zhao, and S. Yang, “Toward automated life cycle assessment for additive manufacturing: A systematic review of influential parameters and framework design,” *Sustainable Production and Consumption*, vol. 41, pp. 253–274, Oct. 2023, doi: 10.1016/j.spc.2023.08.009.

Table A1. Primary studies considered in the literature review

Reference	Type of Polymer material		Type of additives if used		Interest	Technology used							Specimen used for characterization					
	Commercial	Recycle	Fillers	Polymer-based		No AM used	ME				SL S	DL P	3D printing Tensile	3d printing object	Filament	conventional injection	compression moulding	Hot press
	Commercial	Recycle	Fillers	Polymer-based		No AM	FFF/FDM	FGF	PM E	DI W	SL S	DL P	3D printing Tensile	3d printing object	Filament	conventional injection	compression moulding	Hot press
(Morsidi et al., 2019)	x	x	x		2	x									x			
(Saad et al., 2023)	x	x	x		2	x									x			
(Singh et al., 2022)	x	x	x		2	x									x			
(Wiśniewska et al., 2023)	x	x	x		1	x											x	
(Arrigo et al., 2022)	x	x	x		3		x						x				x	
(Bartolomei et al., 2022)	x	x	x		3		x						x			x		
(Pal et al., 2021)	x	x	x		3		x						x			x		
(Haque and Naebe, 2023)	x	x	x		3		x						x					
(Alduais et al., 2022)	x	x	x		3		x						x					
(Rimkus et al., 2022)	x	x	x		3		x						x					
(Battezzore et al., 2022)	x	x	x		3		x						x					x
(Schirmeister et al., 2021)	x	x	x		4		x						x	x		x		
(Idrees et al., 2018)	x	x	x		3		x						x	x				
(Qu et al., 2021)	x	x	x		4		x							x				x
(Seggiani et al., 2018)	x	x	x		4		x							x				
(Kim and Lee, 2021)	x	x	x		4		x							x				

(Scaffaro et al., 2022)	x	x	x		4		x							x				
(Doddamani and Gupta, 2022)	x	x	x		4		x							x				
(Papatheodorou et al., 2023)	x	x	x		3		x							x				
(Domingues et al., 2017)	x	x	x		3			x					x					
(Bergaliyeva et al., 2023)	x	x	x		3			x					x					
(Miao et al., 2024)	x	x	x		4				x					x				
(Brooks et al., 2021)	x	x	x		4					x				x				
(Toncheva et al., 2021)	x	x	x		4						x		x	x				
(Casado et al., 2022)	x	x	x	x	4							x	x	x				x
(Cisneros-López et al., 2020)	x	x	x	x	3		x						x					x
(Garwacki et al., 2024)	x	x	x	x	4		x							x				x
(Laoutid et al., 2021, p. 3)	x	x		x	3		x						x					x
(Zander et al., 2019a)	x	x		x	3		x						x					x
(Yap et al., 2021)	x	x		x	3		x						x					
(X. Chen et al., 2020)	x	x		x	4		x						x	x				x
(Hlaváčiková et al., 2024)	x	x		x	3		x						x					
(Romani et al., 2023)	x	x		x	4			x						x				x
(Zhu et al., 2023)	x	x		x	4								x					x
(He et al., 2020)	x	x		x	1	x												x
(Mishra et al., 2023c)	x	x			2	x												x
(Nur Nazira Alias et al., 2024)	x	x			2	x												x
(Moure Abelenda and Aiouache, 2023)	x	x			3		x							x				
(Mishra et al., 2023b)	x	x			3		x							x				
(Giani et al., 2022)	x	x			3		x							x				

(Kozlovsky et al., 2018)	x	x			3						x		x					
(R. Singh et al., 2019a)	x	x			3			x					x					
(Bremer et al., 2022)	x	x			3			x					x					
(Chao and Liao, 2023)	x	x			4						x			x				
(Prasopdee et al., 2023)	x		x		4			x						x				
(Singh et al., 2018)	x		x		2	x											x	
(Whyman et al., 2018)	x		x		4				x					x				
(Mertens et al., 2017)	x		x		3						x		x					
(Laoutid et al., 2022)	x		x	x	4			x					x	x				
(Hu et al., 2017)	x			x	4			x					x	x				x
(Gao et al., 2023)	x			x	3			x					x					
(He et al., 2022)	x				4			x						x				
(de la Torre-Gamarra et al., 2023)	x				4			x						x				
(Ahmed et al., 2020)		x	x		2	x											x	
(Chong et al., 2020)		x	x		2	x											x	
(Chawla et al., 2022)		x	x		2	x											x	
(Chawla et al., 2023)		x	x		2	x											x	
(Gupta et al., 2021)		x	x		1	x												x
(N. Singh et al., 2019)		x	x		4			x						x				x
(Kumar et al., 2022)		x	x		3			x						x				
(Ariel Leong et al., 2022)		x	x		4			x						x				
(Al-Mazrouei et al., 2022)		x	x		3			x					x					x
(Meyer et al., 2020)		x	x		3			x					x				x	
(Tolcha and Woldemichael, 2023)		x	x		3			x					x					
(Ragab et al., 2023)		x	x		3			x					x					

