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Additive manufacturing for sustainability and circular economy: needs, challenges, and opportunities for 3D printing of recycled polymeric waste

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A B S T R A C T

Polymer-based product usage rapidly increases globally, leading to severe ecological, social, environmental, health, and economic impacts. There has been an international push for solutions to sustainable production, consumption, and end-of-life for plastics to combat these issues. Moreover, additive manufacturing (AM) or 3D printing (3DP) processes provide rapid fabrication of functional parts in lesser time, lower lead times, and lower research and development costs. Due to these reasons, these processes are now being utilized in different industrial sectors, including aerospace, automotive, biomedical, sports, food, electronics, and construction. The circular economy concept integrated with AM processes can deliver a synergic impact and a new life to discarded polymeric parts with distributed recycling and manufacturing. With the development and adoption of the proper techniques, AM can be used widely to reuse polymer wastes to turn them into valuable products. It can lead to much higher levels of reuse at very low cost and for targeted applications. Therefore, in this study, a comprehensive literature review is performed to outline guidelines and a circular economy model for AM of recycled polymers based on the reviewed literature. This study delivers insight into; different commodity polymers and their uses, challenges in polymer recycling, polymer recycling approaches, and a circular economy model for AM of recycled polymers.

1. Introduction

Polymers and their compounds are widely used to manufacture consumer goods and functional parts for industrial applications [1–3]. Polymers are non-biodegradable, which takes 10–450 years to degrade [4–6]; however, the widespread use of polymers globally has led to severe environmental hazards [7]. Since 1950, an astonishing 8.3 billion tonnes of plastic have been produced, with an average annual production of 360 million tonnes [8]. However, the lack of efficient waste management and recycling methods has resulted in discarded polymers entering ecosystems as microplastics, thus posing significant threats to ecosystems and organisms [9]. A total of 186 Mt of polymer waste was generated in 2019, out of total polymer waste of 368 Mt, with mismanaged polymer waste of 14% contribution from China and India [10]. Therefore, there has been a global emphasis on achieving sustainable production, consumption, and end-of-life solutions to address ecological, social, environmental, health, and economic impacts [11]. Recognizing this need, the European Union (EU) introduced a circular economy action plan in March 2020 to achieve the EU's 2050 climate neutrality target and tackle biodiversity loss [12]. Recycling or upcycling waste polymer could limit environmental degradation and pollution and provide sustainable and environmentally friendly prospects, but it remains a significant challenge due to several barriers [13–15]. These challenges hinder the re-utilization or recycling of polymers, such as chemical composition, polymer sorting, additives and coatings, contamination, and thermoset reprocessing [16].

In addition, among various industrial sectors such as transportation, energy, construction, agriculture, shelter, and manufacturing, the manufacturing sector contributes 25% of greenhouse gas (GHG) emissions worldwide [17]. Sustainable production and consumption approaches are crucial to address these environmental impacts caused by GHG emissions and waste generation [18]. In response to tackling GHG emissions associated

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with the manufacturing sector, the development and adaptation of additive manufacturing (AM) or 3D printing (3DP) processes have enabled decentralized manufacturing [19–21]. These processes provide rapid fabrication of functional parts in lesser time, lower lead times, and lower research and development costs [22–24]. Due to these reasons, these processes are now being utilized in different industrial sectors, including aerospace, automotive, biomedical, sports, food, electronics, and construction [25–29]. These processes employ linear processes where the material is used only once and discarded after use; however, with the flexibilities in the AM or 3DP processes, the waste polymer materials can be upcycled and reused to adopt a circular economy approach to deal with polymeric waste and for improved environmental sustainability [30–32].

The circular economy concept integrated with AM processes can deliver a synergic impact and a new life to discarded polymeric parts with distributed recycling and manufacturing. AM/3DP of recycled polymers is an alternative, distributed, inexpensive method of reusing such otherwise harmful waste. With the development and adoption of the proper techniques, AM can be used widely to reuse polymer wastes to turn into valuable products not only by companies but even by individuals at their homes and offices whenever, wherever, and whatever it fits valuable and advantageous. It can lead to much higher levels of reuse at very low cost and for targeted applications. Therefore, in this study, a comprehensive literature review is performed to outline guidelines and a circular economy model for additive manufacturing of recycled polymers based on the reviewed literature. This study delivers insight into; different commodity polymers and their uses, challenges in polymer recycling, polymer recycling approaches, and additive manufacturing of recycled polymers. The methodology adopted, aims and objectives, and outline of this study are reported in subsequent sections.

The specific objectives of this study are as follows:

- Understanding the polymer classes and challenges associated with the recycling process.
- Review the state-of-the-art polymer recycling techniques.
- Explore the utilization of recycled polymers for AM/3DP processes, associated challenges, and applications.
- Offer feedback on the reviewed literature and propose avenues for future research.
- Developing a circular economy model for additive manufacturing using recycled polymers.

This study outlines the classification of commodity polymers, challenges associated with polymer recycling, polymer recycling techniques, AM/3DP of recycled polymers, a circular economy model for additive manufacturing of recycled polymers, and future recommendations based on the state-of-the-art literature reviewed.

1.1. Methodology

A wide range of articles, review papers, magazines, and internationally reputed blogs were reviewed using different databases, i.e., Google Scholar, Springer, Scopus, Wiley, PubMed, MDPI, and Taylor & Francis. The literature was searched using keywords within the reported literature's title, abstract, and article keywords. The literature search used keywords such as polymer recycling, polymer waste, recycling, chemical, mechanical, additive manufacturing, sustainability, upcycling, and combinations of these keywords. Furthermore, the literature was filtered to select articles written and peer-reviewed in English. The primary source of the reviewed literature was original research or review articles; however, conference proceedings, book chapters, and theses were also considered. The gathered literature was further filtered to consider the most relevant studies by skimming the main text of the articles. The criterion was to include studies with up-to-date recycling techniques and recycled polymers used for additive manufacturing and exclude the articles where one of the above-mentioned themes is missing. An overview of the methodology adopted for this study is reported in Fig. 1.

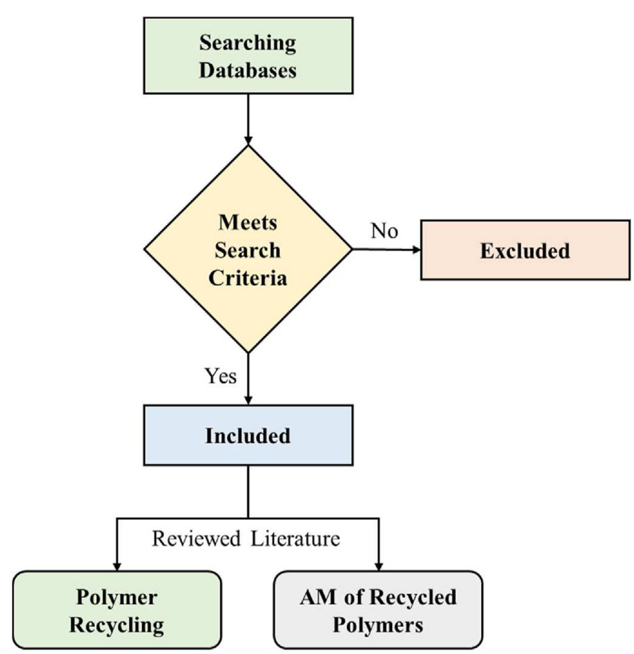


Fig. 1. Overview of methodology adopted for literature search.

2. Polymer classification, recycling, and challenges in polymer recycling

Polymers are used for several applications, including aerospace, automotive, medical, sports, and consumer goods [33]; however, being non-degradable by nature, they significantly burden the environment. Polymeric materials are primarily used to manufacture various products at the start of their lifecycle and discarded as waste after use. The waste disposal companies collect the polymer waste in segregated form or as general waste, depending on the geographical location. The polymer waste leaking into the environment and landfilling has caused tremendous challenges and poses a severe threat to life on Earth. However, polymer waste can undergo recycling at the end of its lifecycle, leading to upcycling and granting the waste a renewed lifecycle. In addition, raw material extraction and utilization can be reduced. The value addition to waste plastic to produce a higher-value product is called the upcycling of polymers [34]. Following, we discuss the classification of polymer waste and the challenges faced in their recycling process.

2.1. Polymer classification

Polymer waste is generated from different sources and forms, where the primary contribution arises from polymer packaging, bottles, and caps, manufactured using different polymeric materials. Based on the chemical composition of different polymers, they can be classified into seven categories [32], i.e., polyethylene terephthalate (PET), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polyvinyl chloride (PVC), polypropylene (PP), polystyrene (PS), and other plastics (ABS, Nylon, Polycarbonates) [35]. Table 1 reports the classification of polymers identified by the Society of Plastics Industry (SPI), their chemical compositions, and their uses. Besides this classification from the SPI, some emerging polymeric materials include polyesters, polyamides, and acrylic compounds. Among these categories, PP and PET contributed 46% of global polymer production in 2015, with 63.4% of these polymers utilized in the packaging industry [36]. Regarding recycling, PET (commonly used for water bottles) is the most recycled polymer, HDPE (widely used for shampoo bottles) is ranked second, while the rest of the polymers are rarely recycled.

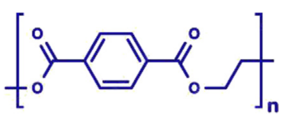
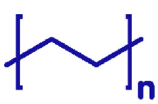
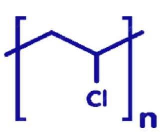
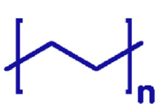
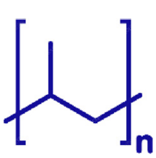
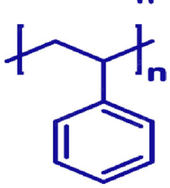
2.2. Polymer recycling techniques

Several polymer recycling strategies are reported in the literature and broadly classified into mechanical, chemical, and thermal recycling processes. These recycling techniques are discussed in the subsequent sections. Fig. 2 overviews different polymer recycling and upcycling approaches (mechanical, chemical, and thermal) and their resulting compounds.

2.2.1. Mechanical recycling

Mechanical recycling is a process by which polymers are recovered and reprocessed into new products [46]. The process involves several steps, including sorting, shredding, and melting the polymer [47]. The sorted polymer is first shredded into small pieces, then melted and extruded into pellets that can be used to manufacture new products. The sorting process is critical to the success of mechanical recycling, as it ensures that the recovered polymer is of consistent quality and can be effectively processed [48]. Several techniques are available for sorting polymers, including manual, automated, and optical. Manual sorting is often used for smaller volumes of material, while automated sorting using near-infrared spectroscopy (NIR) or X-ray fluorescence (XRF) is preferred for larger volumes [49]. Optical sorting using cameras and image analysis is also becoming more common. Once sorted, the polymer is shredded into small pieces using a granulator or similar equipment. The size of the shredded pieces depends on the intended use of the recycled polymer. The shredded polymer is then melted using heat and pressure, typically done in an extruder, a machine that uses a screw to transport the polymer through a heated barrel [50]. As the polymer is transported through the

Table 1
Polymer categories as per SPI, their chemical structures, uses, and recycling in the U.S.

Code	Polymer	Chemical structure	SPI symbol	Applications	Recycling scenario	Ref
1	PET		1 PETE	Beverage Bottles, Peanut-Butter Jars, Salad Domes, Water Bottles, Medicine Jars	The 5.3 million tons of this waste has an 18.5% rate. Bottles may have a second life as another bottle or polyester fiber in garments and furniture.	[37,38]
2	HDPE		2 HDPE	Milk, Shampoo, Detergent Bottles, Trash Bags	Around 9% of the six million tons is recycled, the second best in the US. Reused in bottles. Automotive components, pipes, and park benches.	[37,39]
3	PVC		3 V	Cosmetic Containers, Cling Film Wrap, Gift Cards, Plumbing Pipes, Cables	There is negligible US capacity to recycle 840,000 tons of this waste. Even if collected, almost all end up in landfills or incinerated.	[37,40]
4	LDPE		4 LDPE	Shopping Bags, Mailing Pouches, Shrink-Wrap, Sandwich Bags	At 8.6 million tons, the largest category by weight. Less than 5% recycled.	[37,41]
5	PP		5 PP	Yogurt Cups, Coffee Pods, Ice Cream Tubs	Less than 2% of 8.1 million tons a year make it through recycling.	[37,42]
6	PS		6 PS	Take-Out Containers, Plastic Utensils, Hot-Drink Cups, Coffee-Cup Lids	Almost all 2.3 million tons are dumped in a landfill or incinerated with US recycling at less than 1% of this waste.	[37,43]
7	Others		7 OTHER	Baby Bottles, Multimaterial Packaging	It includes other plastics, including bio-based food packaging. Hardly any of 90,000 tons is reused.	[37,44]

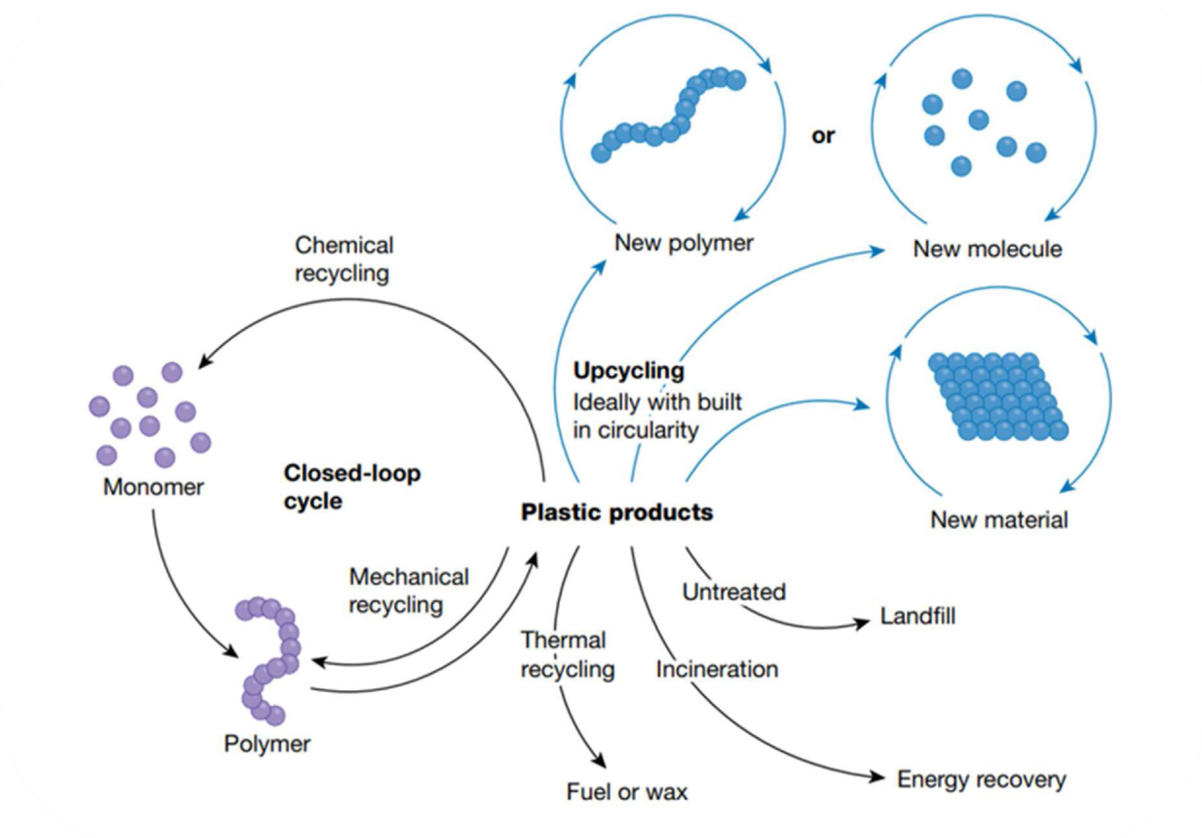


Fig. 2. An overview of closed-loop recycling and upcycling of polymer waste to different chemical compounds [45].

barrel, it is melted and mixed to ensure a consistent product. The molten polymer is then forced through a die to create specific size and shape pellets. The pellets are used to manufacture new products, such as plastic containers, toys, and automotive parts [51]. However, the quality of the recycled polymer may be lower than that of virgin polymer, as the process can result in the degradation of the polymer and contamination by impurities [52]. Therefore, the recycled polymer may need to be blended with virgin polymer to achieve the desired properties. Blending can also help to address any issues with color or other aesthetic qualities of the recycled material.

Mechanical recycling is a relatively simple and cost-effective process that can recycle a variety of polymers. It also has a low environmental impact, not involve using chemicals or other hazardous materials. However, the quality of the recycled polymer may be lower than that of virgin polymer, which can limit its use in certain applications [53,54]. Additionally, the process can result in the release of microplastics, which can be harmful to the environment and wildlife [55]. Despite these challenges, mechanical recycling remains essential for reducing waste and conserving resources [56,57]. Ongoing research and development are focused on improving the efficiency and effectiveness of the process and finding ways to address issues with the quality of recycled material [58]. New technologies, such as advanced sorting techniques and additive manufacturing processes, are also being developed further to enhance the potential of mechanical recycling [59].

2.2.2. Chemical recycling

Polymers are broken down into constituent monomers through a chemical reaction in the chemical recycling process, which can then be used to produce new polymer products [60]. This process involves several steps, including depolymerization, purification, and polymerization [61]. Depolymerization breaks down the polymer into its constituent monomers, which can be achieved through several methods, including pyrolysis, gasification, and hydrolysis, as shown in Fig. 2 [62–65]. Pyrolysis involves heating the polymer to high temperatures without oxygen, while gasification consists of converting the polymer into a gas through a chemical reaction [66]. Hydrolysis involves using water or other solvents to break down the polymer [67]. Once the polymer has been depolymerized, the resulting monomers are purified to remove any impurities that may have been produced during the depolymerization process, typically done using chromatography or distillation techniques [68]. The purified monomers can then be used to produce new polymer products through polymerization. Polymerization combines monomers to form a polymer, which can be achieved through several methods, including addition polymerization and condensation polymerization [69].

Chemical recycling can be used to recycle a wide range of polymers, including those that are difficult to recycle using other methods [70]. It also has the potential to produce a high-quality recycled polymer that is equivalent to or even better than virgin polymer [71]. However, some challenges are associated with chemical recycling, i.e., the process can be energy-intensive and require hazardous chemicals [72]. Additionally, the cost of the process can be high, particularly for smaller-scale operations. The depolymerization process may also affect the quality of the recycled polymer, which can produce impurities or degradation products [73]. Despite these challenges, chemical recycling remains essential for reducing waste and conserving resources. Ongoing research and development are focused on improving the efficiency and effectiveness of the process and finding ways to address issues with the quality of the recycled material. New technologies, such as enzymatic depolymerization and microwave-assisted pyrolysis, are also being developed further to enhance the potential of chemical recycling [74–76].

2.2.3. Thermal recycling

Thermal recycling, or thermal degradation, is a process by which polymers are broken down into constituent monomers or other chemicals through heat [77]. This process typically involves heating the polymer to high temperatures without oxygen, causing the polymer to break down into smaller molecules [78]. The resulting products can then be used to produce new polymer products and other chemicals, such as fuels and waxes [79]. Thermal recycling can be carried out using various methods, including fluidized bed reactors, rotary kilns, and microwave pyrolysis [80–82]. Thermal recycling can produce a high-quality recycled polymer equivalent to or even better than virgin polymer [83]. However, the process can be energy-intensive, require hazardous chemicals, and the quality of the recycled polymer may be affected by the thermal degradation process, which can produce impurities or degradation products [84]. There is also the issue of scaling up the process from laboratory to industrial scale, which can be complex and expensive. Ongoing research and development are focused on improving the efficiency and effectiveness of the process and finding ways to address issues with the quality of the recycled material. New technologies, such as catalytic pyrolysis and hybrid thermal-mechanical recycling, are also being developed to further enhance the potential of thermal recycling [85–88].

2.3. Polymer recycling challenges

Recycling polymers can provide sustainable and environmentally friendly prospects; however, several challenges that hinder the re-utilization or recycling of polymers are summarized in Fig. 3 and are discussed in subsequent sections.

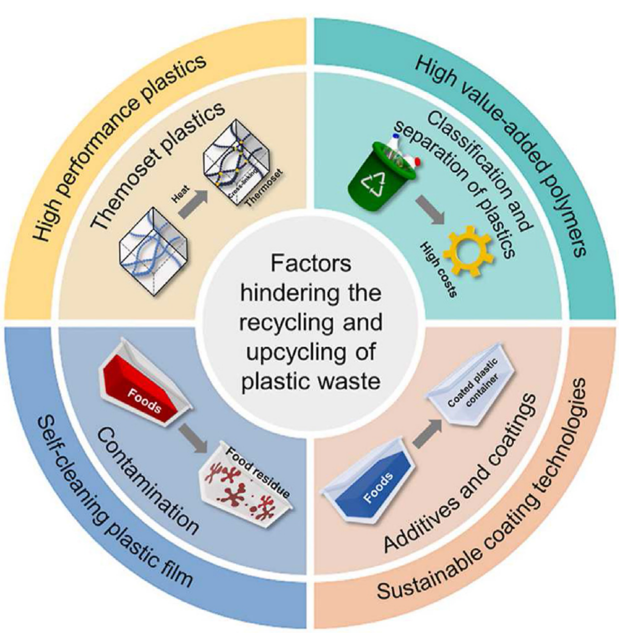


Fig. 3. Challenges in recycling of polymer waste (Reproduced under the terms of the CC-BY-NC-ND license from Reference [34], Copyright © 2023 The Authors. Published by Elsevier Ltd.).

2.3.1. Chemical composition

The chemical composition of polymers reflects the recyclability of any polymer type. LDPE, HPDE, PP, PS, and PVC are common commodity polymers that exhibit high mechanical strength up to 100 °C [89], and a significant portion of commodity polymers are olefin-based. Due to their chemical composition, olefin-based polymers are challenging to recycle chemically due to the strong C–C covalent bond among the polymer chains, requiring elevated temperatures and high-performance catalysts [90]. These polymers are produced at a low cost from shale gas; however, the recycling cost does not add value to recycled olefin-based polymers resulting in a recycling rate of <10% for these polymers [38,91]. In contrast, engineering plastics, like PET, ABS, and nylon, can retain their mechanical properties even above 100 °C [92]. PET polymer comprises ester-based chains (as shown in Table 1) that can be decomposed through the hydrolysis process; however, the overall plastic waste of PET contributes 10%, while olefin-based polymers account for >50%. Therefore, novel, low-cost, and effective recycling technologies are desired for olefin-based polymers.

2.3.2. Polymers sorting

Another challenge in recycling polymer waste is the segregation of different polymer types and associated cost, especially in the case of mechanical recycling [93]. The chemical industries use separation and purification processes to produce chemical products, which approach is equally applicable to recycling polymer waste. The recycling process varies for each polymer type; even the polymers with similar chemical structures (e.g., C–C bond in LDPE and PP) can not be melted together and are difficult to separate once mixed [94]. Generally, commercial products contain multiple polymer types within a single product [95]; therefore, polymer sorting is a significant challenge, and high-efficiency sorting techniques are desired [47].

2.3.3. Additives and coatings

Polymers commonly contain additives, such as reinforcing content, plasticizing agents, pigments, and antioxidants, making it difficult to recover the base polymer due to polymers' low molecular diffusion rate [96,97]. The polymers form strong van der Waals forces with organic additives and coatings, adding up significant energy and costs required for recycling [98]. Recyclability is also reduced if the coating material is not recyclable; for instance, a thermoset polymer coating on a thermoplastic polymer must be removed and separated for recycling. Secondly, dyes are used to produce colored polymers, degrading the commercial value of recycled polymers [99]. Decolorization is possible; however, it requires significant resources. Although researchers have reported electrochemical degradation methods, mostly at lab-scale, are challenging to up-scale and are expansive [100]. Therefore, novel and low-cost techniques to remove additives and coatings are desired to cope with this significant challenge in polymer recycling.

2.3.4. Contamination

Food packaging waste contributes 26% of the polymer waste generated [101], which needs to be cleaned of contamination before recycling. The cleaning process is crucial despite the recycling process (mechanical or chemical) to be used, which is typically performed using hot/cold water and detergents or corrosive chemicals. However, the cleaning process adds up the drying and wastewater treatment costs. In addition, the removal of food-derived pollutants is challenging; for instance, caustic cleaning can not eradicate the odor components [102]. Therefore, a significant proportion of polymer waste (i.e., food packaging) faces poor recycling efficiency.

2.3.5. Thermoset reprocessing

Another challenge in polymer waste recycling is reprocessing thermoset plastics, as these materials do not melt or dissolve [103]. Thermoplastic materials are unsuitable for applications desiring higher temperatures (i.e., electronics substrates, aircraft and automobile components, etc.) due to their high coefficient of thermal expansion (CTE) [104]. Thermoset polymers are used alternatively for such applications, as they provide higher dimensional stability under elevated temperatures and better mechanical and chemical resistant properties. However, recovery of thermoset polymers and removing any additives is highly challenging; for instance, in the case of metals usage (gold, silver, copper, palladium, tantalum) in printed circuits [105]. These metals must be removed from the polymer before recycling, which can not be achieved through a simple heating/cooling process [106]. Therefore, advanced extraction processes recover metals from thermosets, which require toxic chemicals and release hazardous gases to the environment [106].

3. Additive manufacturing of recycled polymers

Numerous studies have reported using recycled polymers for additive manufacturing (AM) processes, specifically material extrusion (ME). These polymers include polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polypropylene (PP), polyethylene terephthalate (PET), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polystyrene (PS), high-impact polystyrene (HIPS), nylon-6, and polyamide-12 (PA12). Table 2 summarizes reported studies where the fused filament fabrication (FFF) process is utilized for recycled polymeric materials.

3.1. Degradation of mechanical properties

Mechanical properties of the functional parts are of prime concern in structural applications [121]; however, these properties degrade when the material is recycled [122]. Therefore, several researchers have explored the impact of recycling cycles on the degradation of the mechanical properties of recycled polymers. Sanchez et al. [107] proposed a methodology to evaluate the decentralized recycling integrated with distributed manufacturing (i.e., AM or 3DP), as shown in Fig. 4. Furthermore, the proposed roadmap was applied to recycle and reuse PLA material for the FFF process and to evaluate the impact of physio-chemical degradation on the mechanical properties of 3D-printed parts. An improvement in elastic modulus was observed for the additively manufactured recycled PLA material due to a reduction in viscosity during recycling. However, a reduction in the rest of the mechanical properties (i.e., tensile strength and strain) was notable. Likewise, Tanney et al. [108] also investigated the effect of recycling on the degradation of PLA material used for the FFF process. The impact of adding virgin polymer pellets to recycled material was also examined on the mechanical properties. The cyclic heating during the recycling process significantly affected the mechanical properties; however, adding virgin pellets assisted in recovering the mechanical performance of 3D-printed samples.

3.2. Composites mechanical properties

Another approach to improve the mechanical properties of polymers is to reinforce them with suitable particulates and fibers [123–125]. The degraded mechanical properties of recycled polymers can be improved by adding reinforcement. Using this technique, Singh et al. [114,115] synthesized thermosetting waste polymer and SiC/Al_2O_3 reinforced recycled ABS polymer composites to investigate their mechanical performance. Fixed bakelite concentration (10%) and varying recycled ABS and ceramic (SiC/Al_2O_3) content were selected for investigation. Tensile testing coupons were fabricated via the FFF process for mechanical testing (Fig. 5).

Table 2
A summary of recycled polymers utilized in AM processes.

Polymer	Reinforcement	3D Printer	Summary	Ref.
PLA	–	Mondrian & FoldaRap	• Detailed methodology for recycling polymers. • Implementation of PLA material as a case study. • Degradation of mechanical properties with recycling.	[107]
PLA	–	Monoprice Maker Select	• Recycling of PLA and impact of adding virgin pellets. • Degradation of mechanical properties with recycling. • Improvement in mechanical properties by adding virgin pellets.	[108]
HDPE	Wood Dust	Robotic Arm & Delta	• Recycling polymer to develop eco-composites. • Investigations on dimensional accuracy of 3DP parts. • Comparable dimensional control with ABS parts.	[109]
HDPE	SiC/Al_2O_3	Stratasys U-print	• Recycled HDPE composites with different contents. • Mechanical testing of filaments for FDM. • Wear properties investigation of cylindrical pins.	[110,111]
HDPE/LDPE	Al_2O_3	Accucraft	• Machinability assessment of recycled composites. • Adding reinforcement improved thermal stability and surface characteristics.	[112,113]
ABS	Bakelite/SiC/Al_2O_3	–	• Waste thermosetting polymer and ceramic-reinforced ABS composites. • Evaluation of mechanical performance.	[114,115]
ABS	MnO_2, $ZnCl_2$, NH_4Cl, Graphite	Accucraft	• Use of recycled ABS to fabricate dry cells. • ESD consisted of at least 40% recycled polymer by weight. • Improved thermal stability and mechanical properties of 3D-printed dry cell.	[116]
PET	Cellulose Fibers	–	• Utilization of textile-derived cellulose fibers. • Thermomechanical and microscopic analysis of feedstock filament. • Toughening effect of reinforcement to PET.	[117]
PET	Biochar	Hyrel 30M	• Incorporation of biochar into recycled PET. • Filament preparation for the FFF process. • 32% increase in tensile strength for 0.5 wt% biochar content. • 60% increase in tensile modulus for 5 wt% biochar loading.	[118]
PET	Rubber Powder	Lulzbot Taz 6	• Rubber powder inclusion to recycled PET. • Significant improvement in toughness with different content of rubber and elastomers. • Tensile strength was unaffected.	[119]
PP	Gypsum, Hemp, and Harakeke Fiber	–	• Reinforcement of natural fibers and recycled gypsum to PP. • Mechanical performance of composite filaments and shrinkage of 3DP parts. • Improvement in mechanical properties and lower shrinkage.	[120]

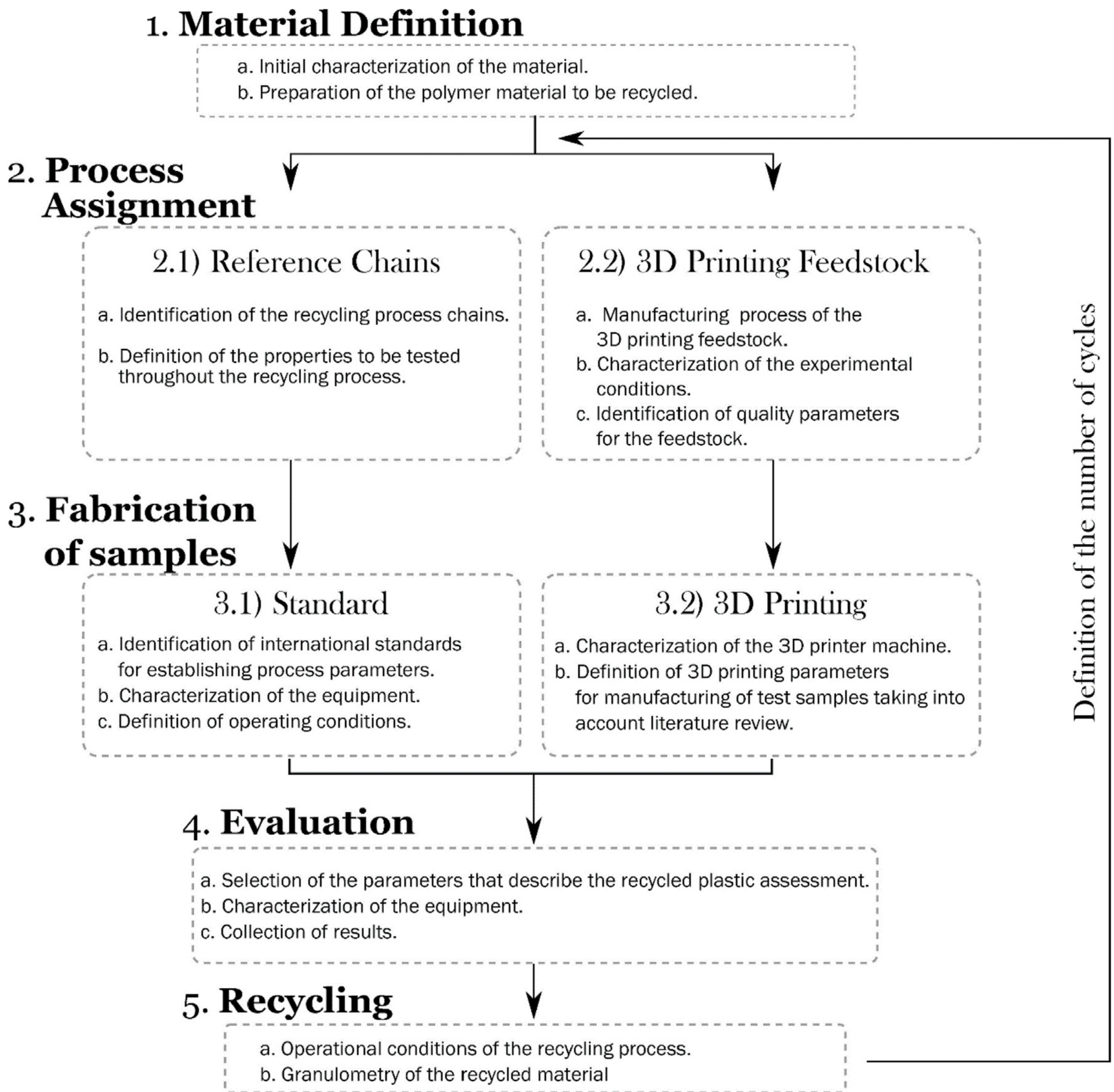


Fig. 4. Proposed methodology for evaluation of recycled polymers for AM process (Adapted from reference [107], Copyright © 2017 Elsevier B.V.).

The mechanical performance of 3D-printed composite samples was comparable with virgin ABS properties.

Likewise, Carrete et al. [117] utilized textile-derived cellulose fibers for reinforcement to recycled PET water bottles. Filament feedstock for the 3DP process was produced via melt compounding followed by thermomechanical and microscopic analysis. A toughening effect of cellulose reinforcement was observed on recycled PET. Idrees et al. [118] incorporated recycled PET with

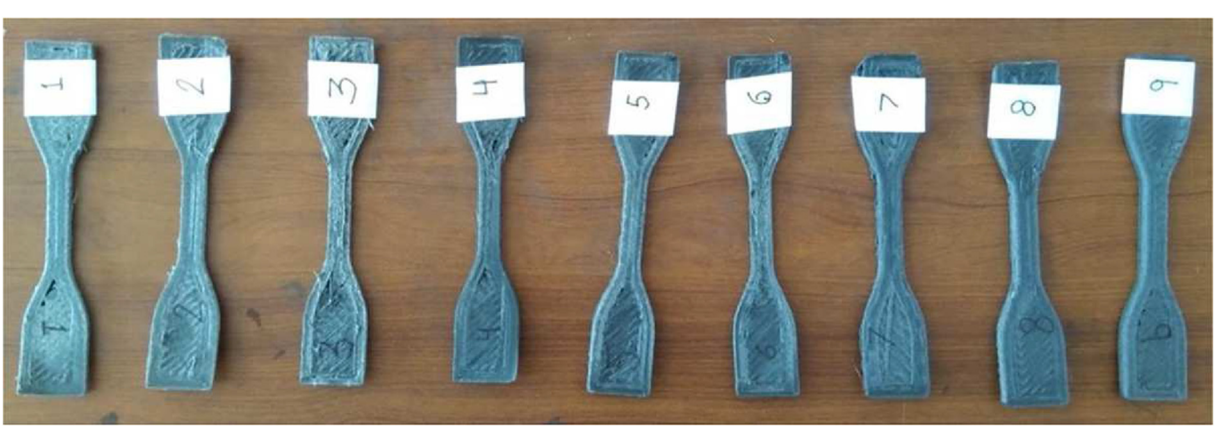


Fig. 5. Ceramic and bakelite reinforced recycled ABS 3D-printed samples (Adapted from reference [114], Copyright © 2021, © SAGE Publications).

biochar produced via pyrolysis of packaging waste for the 3DP process. PET/biochar composite filaments were produced to fabricate specimens for thermal, mechanical, and textural properties. The results revealed a 32% improvement in tensile strength and 60% in tensile modulus for 0.5 wt% and 5 wt% of biochar content to PET, respectively. Zander and Boelter [119] used micronized rubber from tire scrap and styrene-ethylene-butadiene-styrene (SEBS) elastomers to reinforce recycled PET. The influence of adding rubber powder and SEBS on the mechanical and thermal properties of resulting composites was evaluated. The results revealed an extraordinary improvement in the toughness of PET composites, while tensile strength remained unaffected. Stoof and Pickering [120] investigated using hemp, harakeke fibers, and recycled gypsum in recycled PP. Filament feedstock material was prepared with varying reinforcement of different additives to recycled PP. Improved strength and stiffness were achieved for 30 wt% inclusion of harakeke fiber, followed by the mechanical performance of hemp fiber inclusion. However, improved stiffness and dimensional control were observed in gypsum reinforcement. A similar trend of improved mechanical properties was reported for 3D-printed parts.

3.3. Final part characteristics (dimensional accuracy)

The precision and accuracy of 3D-printed parts are crucial for fabricating functional components [126]. The 3DP process should provide adequate dimensional accuracy for the proper functionality of 3D-printed structures. The 3DP processing of recycled polymers is crucial due to variations in their thermomechanical properties during recycling. Horta et al. [109] developed eco-composites through recycled HDPE reinforced with wood dust for large-scale material extrusion 3D printer. The effect of different processing parameters on dimensional accuracy of 3D-printed parts was evaluated manufactured at different scale 3D printers and compared with ABS 3D-printed structures. The recycled HDPE/wood dust composites revealed a comparable dimensional control to ABS parts; therefore, the large-scale AM route was feasible for recycled polymeric composites.

3.4. Rapid tooling & prototyping

AM processes are widely used for rapid tooling and prototyping applications [127–129]; therefore, efforts have been made to evaluate recycled polymers and their composites for such applications. For instance, Singh et al. [110,111] developed recycled HDPE-based composites with varying reinforcing content of SiC/Al_2O_3. The resulting polymer composites were used to produce filament feedstock for the FFF process. The filament feedstock was tested mechanically to evaluate the mechanical performance of different HDPE/SiC/Al_2O_3 composites. Finally, functional prototypes (cylindrical pins) were fabricated and evaluated for their wear properties (Fig. 6). SiC/Al_2O_3 reinforced HDPE revealed improved mechanical and wear performance than un-reinforced HDPE, which could be used for decentralized additively manufactured rapid tooling applications. Adding to their previous work, Bedi et al. [112,113] examined the machinability of recycled HDPE and LDPE and explored the rapid tooling applications of recycled HDPE with Al_2O_3 reinforcement. From experimental results, the primary recycled LDPE was the most suitable choice from a machinability perspective.

3.5. Recycled plastic for energy storage device

Additively manufactured polymers and their composites are widely adopted for several applications, such as electronics, construction, aerospace, and automotive [130–134]. Properly selecting targeted applications for reused polymers can open up unlimited opportunities. For example, Singh et al. [116] utilized recycled ABS polymer reinforced with different compounds (i.e., MnO_2, $ZnCl_2$, NH_4Cl, and Graphite) to fabricate an in-house energy storage device (ESD) via the FFF process. Three of the four zones of the dry cell comprised were fabricated using different reinforcing contents to ABS, while casted zinc metal was used for the fourth zone. Fig. 7(a) presents different zones of the dry cell, while sand-casted zinc plate and 3D-printed discs are reported in Fig. 7(b) and (c), respectively. The final dry cell assembly consisted of at least 40% by weight of recycled ABS and revealed the voltage potential as per commercial dry cell. The thermos-mechanical characterization results also endorsed the better thermal stability and mechanical performance of 3D-printed ESD.

4. Additive manufacturing for sustainability and circular economy: proposed model

Based on the above discussion and reported literature, it is evident that a circular economy model implemented in the additive manufacturing of polymers can support sustainability. A circular economy model is proposed, as reported in Fig. 8, for future research to implement and adopt to meet sustainable development goals (SDGs) and environmental sustainability. The proposed model is divided into five stages, from the procurement of virgin polymers to the end-of-life stage, and these stages are discussed as follows:

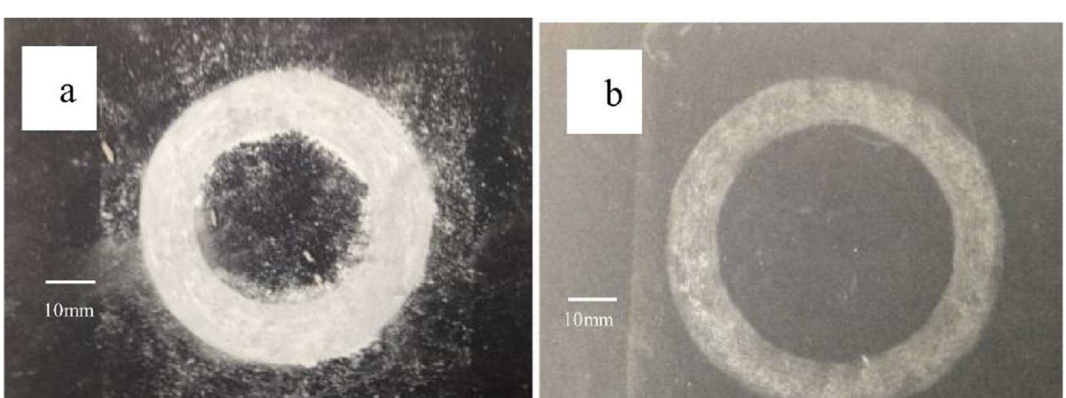


Fig. 6. Wear performance of cylindrical pins (at 10 N load) (a) Recycled HDPE un-reinforced (b) SiC/Al_2O_3 reinforced HDPE (Adapted from reference [110], Copyright © 2018 Elsevier Ltd.).

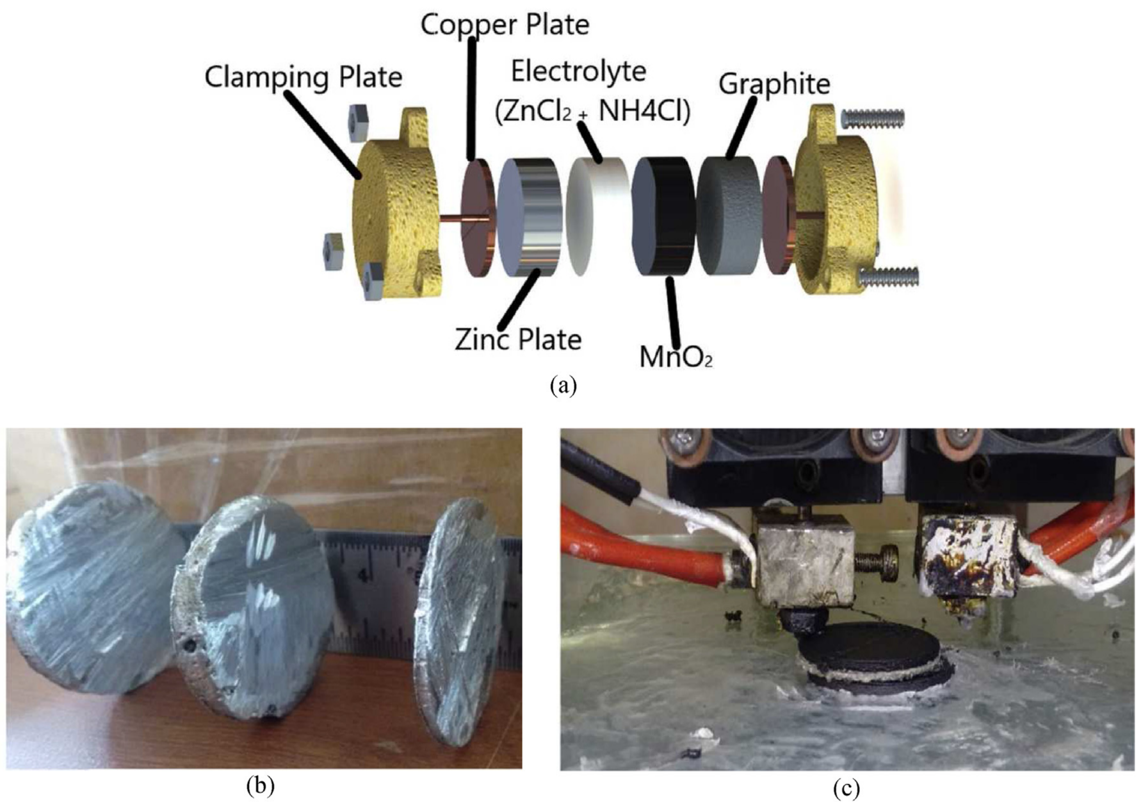


Fig. 7. Design and fabrication of ESD using recycled ABS polymer (a) Different zone of dry cell (b) Sand casted zinc plate (c) 3D-Printed ABS-based discs (Adapted from reference [116], Copyright © 2018 Elsevier Ltd.).

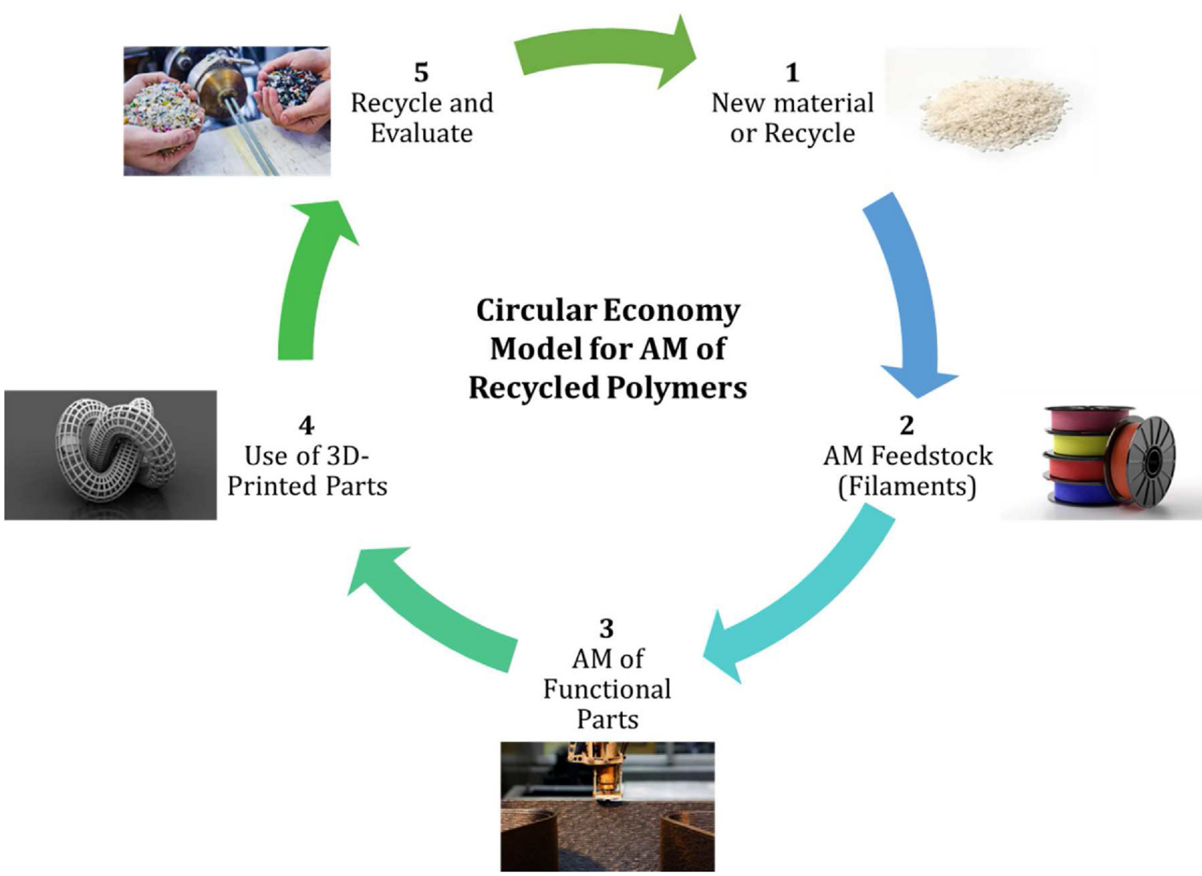


Fig. 8. Proposed circular economy model for additive manufacturing of recycled polymers.

- **New Material or Recycled Materials**: Conventionally, the preparation for AM/3DP process (specifically the FFF/FDM process) starts at this stage, where a virgin material is adopted for preparing feedstock material for 3DP. The use of virgin materials should be minimized at this stage to reduce the environmental impact of degradation of natural resources and landfilling or damping at end-of-life. The recycled materials may undergo degradation depending upon the recycling cycles; however, adding suitable reinforcement (natural/synthetic) will assist in recovering the recycled polymeric material properties.
- **AM Feedstock (Filaments)**: Filament production is the next step in AM process, where polymeric material is fed to an extruder to produce continuous filaments for the FFF process. The filament production facilities can first be decentralized at research lab scales and then expanded to commercial applications to produce FFF feedstock material from recycled polymers and their composites. Decentralizing such facilities is vital to minimize the logistics costs associated with transporting raw materials, AM feedstock, and waste collection.
- **AM of Functional Parts**: The recycled polymeric materials can be used to fabricate functional components, as discussed in the previous sections. The proper choice of application is vital at this stage to make the AM of recycled polymers efficient, effective, and sustainable. The design of functional parts is vital for the proper functioning of 3D-printed parts, along with the optimum selection of material properties and FFF processing parameters. Using numerical modeling and simulation tools to predict the efficiency of the 3DP process may further promote sustainable utilization of materials and resources to produce desired resolution, dimensional accuracy, precision, and performance of 3D-printed parts.
- **Use of 3D-Printed Parts**: The proper functionality of 3D-printed parts manufactured using recycled polymers is vital. Therefore, selecting the suitable material and appropriate reinforcement is crucial in the design phase. Predicting 3D-printed structure response to external stimuli may further enhance the sustainability of the overall process. The numerical modeling and simulation tools should be explored, adopted, and improved to cater to the physio-chemical degradation of polymers caused by the recycling process.
- **Recycle and Evaluate**: At the end of life, the polymeric functional components should undergo sorting and evaluation of physical, mechanical, and chemical properties. The significant degradation of these properties may require the addition of virgin polymers to regain their properties. Secondly, recycled polymers may be reconsidered for applications where these properties are insignificant (such as toys, decoration, etc.). The recycled polymers can undergo a new lifecycle at this stage, and the cycle continues.

Besides the proposed model, initiating the recycling approach at lab scales is recommended, as the research and development results in significant polymeric waste produced using AM process, including failed 3D-prints and 3DP process waste (i.e., support structures), discarded samples, and tested samples. The segregation of polymeric waste is straightforward at this scale and can be performed manually. The AM processes are mainly used for low-volume and high-customization parts; therefore, the in-house recycling facilities can be used for sorting, recycling, and reusing polymeric waste.

AM/3DP drives the circular economy by revolutionizing production paradigms. Its precise layering process minimizes material waste while utilizing recycled polymers as feedstock enhances sustainability. Its localized, on-demand production model reduces transportation and resource-intensive manufacturing, aligning with circular economy principles. Moreover, the technology promotes longevity and repairability through easy design modifications, extending product lifecycles and diverting items from premature disposal. AM's integration fosters resource efficiency, waste reduction, and durable products, contributing to a more sustainable and regenerative economic model.

5. Conclusions and future recommendations

In conclusion, plastic waste management stands out as one of the most pressing environmental challenges humanity is facing today. Although mechanical recycling is an effective and sustainable approach to recycling plastic waste, it has certain limitations, such as the restricted range of polymers that can be recycled and the potential degradation of the molecular weight of polymers. On the other hand, chemical recycling holds great promise as an alternative method that can convert plastic waste into valuable feedstock materials to produce fuels and monomers. However, chemical recycling demands a higher level of expertise, investment, and energy consumption, which could lead to increased emissions compared to mechanical recycling. Adopting advanced recycling methods, such as chemical recycling, can substantially decrease energy consumption, save billions of dollars, and promote a more sustainable future. Despite the challenges, there is mounting industrial interest in developing and implementing innovative solutions to tackle plastic waste management. Governments, industries, and individuals must work collaboratively and take concrete measures to reduce plastic waste generation, boost recycling, and transition towards a circular economy. AM/3DP of recycled polymers is an alternative, distributed, inexpensive method of reusing such otherwise harmful waste. With the development and adoption of the appropriate techniques, AM can be used widely to reuse polymer wastes to turn into valuable products not only by companies but even by individuals at their homes and offices whenever, wherever, and whatever it fits advantageous. It can lead to much higher levels of reuse at very low cost and for targeted applications. Collaborative efforts are desired by research institutes, industries, and government officials to promote sustainability with local waste collection, sorting, recycling, and decentralized manufacturing to meet local needs in terms of commodity plastic-based consumer goods.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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References

[1] S.M. Mousavi, S.A. Hashemi, M.Y. Kalashgrani, N. Omidifar, S. Bahrani, N. Vijayakameswara Rao, A. Babapoor, A. Gholami, W.-H. Chiang, Bioactive graphene quantum dots based polymer composite for biomedical applications, Polymers (Basel) 14 (2022), https://doi.org/10.3390/polym14030617.
[2] P. Jagadeesh, M. Puttegowda, O.P. Oladijo, C.W. Lai, S. Gorbatyuk, D. Matykiewicz, S.M. Rangappa, S. Siengchin, A comprehensive review on polymer composites in railway applications, Polym. Compos. 43 (2022) 1238–1251, https://doi.org/10.1002/pc.26478.

[3] R.P. Chaudhary, C. Parameswaran, M. Idrees, A.S. Rasaki, C. Liu, Z. Chen, P. Colombo, Additive manufacturing of polymer-derived ceramics: materials, technologies, properties and potential applications, Prog. Mater. Sci. 128 (2022) 100969, https://doi.org/10.1016/j.pmatsci.2022.100969.
[4] M.H. Rahman, P.R. Bhoi, An overview of non-biodegradable bioplastics, J. Clean. Prod. 294 (2021) 126218, https://doi.org/10.1016/j.jclepro.2021.126218.
[5] X.-F. Wei, M. Bohlén, C. Lindblad, M. Hedenqvist, A. Hakonen, Microplastics generated from a biodegradable plastic in freshwater and seawater, Water Res. 198 (2021) 117123, https://doi.org/10.1016/j.watres.2021.117123.
[6] A. Antelava, N. Jablonska, A. Constantinou, G. Manos, S.A. Salaudeen, A. Dutta, S.M. Al-Salem, Energy potential of plastic waste valorization: a short comparative assessment of pyrolysis versus gasification, Energy Fuels 35 (2021) 3558−3571, https://doi.org/10.1021/acs.energyfuels.0c04017.
[7] N.J. Beaumont, M. Aanesen, M.C. Austen, T. Börger, J.R. Clark, M. Cole, T. Hooper, P.K. Lindeque, C. Pascoe, K.J. Wyles, Global ecological, social and economic impacts of marine plastic, Mar. Pollut. Bull. 142 (2019) 189−195, https://doi.org/10.1016/j.marpolbul.2019.03.022.
[8] S. Walker, R. Rothman, Life cycle assessment of bio-based and fossil-based plastic: a review, J. Clean. Prod. 261 (2020) 121158, https://doi.org/10.1016/j.jclepro.2020.121158.
[9] G. Everaert, M. De Rijcke, B. Lonneville, C.R. Janssen, T. Backhaus, J. Mees, E. van Sebille, A.A. Koelmans, A.I. Catarino, M.B. Vandegehuchte, Risks of floating microplastic in the global ocean, Environ. Pollut. 267 (2020) 115499, https://doi.org/10.1016/j.envpol.2020.115499.
[10] H. Ritchie, M. Roser, Plastic Pollution, 2018, pp. 1−40. https://ourworldindata.org/plastic-pollution. (Accessed 15 July 2023).
[11] T.E. Gomes, M.S. Cadete, J. Dias-de-Oliveira, V. Neto, Controlling the properties of parts 3D printed from recycled thermoplastics: a review of current practices, Polym. Degrad. Stab. 196 (2022), https://doi.org/10.1016/j.polymdegradstab.2022.109850.
[12] European Commission, Circular economy action plan (n.d.), https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en. (Accessed 27 February 2023).
[13] S.C. Dertinger, N. Gallup, N.G. Tanikella, M. Grasso, S. Vahid, P.J.S. Foot, J.M. Pearce, Technical pathways for distributed recycling of polymer composites for distributed manufacturing: windshield wiper blades, Resour. Conserv. Recycl. 157 (2020) 104810, https://doi.org/10.1016/j.resconrec.2020.104810.
[14] X. Tian, T. Liu, Q. Wang, A. Dilmurat, D. Li, G. Ziegmann, Recycling and remanufacturing of 3D printed continuous carbon fiber reinforced PLA composites, J. Clean. Prod. 142 (2017) 1609−1618, https://doi.org/10.1016/j.jclepro.2016.11.139.
[15] A.K. Cress, J. Huynh, E.H. Anderson, R. O'neill, Y. Schneider, Ö. Keleş, Effect of recycling on the mechanical behavior and structure of additively manufactured acrylonitrile butadiene styrene (ABS), J. Clean. Prod. 279 (2021) 123689, https://doi.org/10.1016/j.jclepro.2020.123689.
[16] M.K. Singh, A.K. Mohanty, M. Misra, Upcycling of waste polyolefins in natural fiber and sustainable filler-based biocomposites: a study on recent developments and future perspectives, Compos. B Eng. 263 (2023) 110852, https://doi.org/10.1016/j.compositesb.2023.110852.
[17] World Economic Forum, Why industry needs a reset − and how to do it. https://www.weforum.org/agenda/2020/09/why-industry-needs-a-reset-and-how-to-do-it/, 2020. (Accessed 22 March 2023).
[18] M.N. Rojas-Valencia, E. Aquino, Recycling of construction wastes for manufacturing sustainable bricks, Proc. Inst. Civ. Eng.: Constr. Mater. 172 (2019) 29−36, https://doi.org/10.1680/jcoma.16.00046.
[19] H. Ikram, A. Al Rashid, M. Koç, Additive manufacturing of smart polymeric composites: literature review and future perspectives, Polym. Compos. (2022), https://doi.org/10.1002/pc.26948.
[20] A. Al Rashid, S.A. Khan, S.G. Al-Ghamdi, M. Koç, Additive manufacturing: technology, applications, markets, and opportunities for the built environment, Autom. Constr. 118 (2020) 103268, https://doi.org/10.1016/j.autcon.2020.103268.
[21] A. Al Rashid, W. Ahmed, M.Y. Khalid, M. Koç, Vat photopolymerization of polymers and polymer composites: processes and applications, Addit. Manuf. 47 (2021) 102279, https://doi.org/10.1016/J.ADDMA.2021.102279.
[22] R. Kumar, M. Kumar, J.S. Chohan, The role of additive manufacturing for biomedical applications: a critical review, J. Manuf. Process. 64 (2021) 828−850, https://doi.org/10.1016/j.jmapro.2021.02.022.
[23] A.C. De Leon, Q. Chen, N.B. Palaganas, J.O. Palaganas, J. Manapat, R.C. Advincula, High performance polymer nanocomposites for additive manufacturing applications, React. Funct. Polym. 103 (2016) 141−155, https://doi.org/10.1016/j.reactfunctpolym.2016.04.010.
[24] F. Krujatz, A. Lode, J. Seidel, T. Bley, M. Gelinsky, J. Steingroewer, Additive biotech—chances, challenges, and recent applications of additive manufacturing technologies in biotechnology, N. Biotechnol. 39 (2017) 222−231, https://doi.org/10.1016/j.nbt.2017.09.001.
[25] H. Ikram, A. Al Rashid, M. Koç, Synthesis and characterization of hematite (α-Fe2O3) reinforced polylactic acid (PLA) nanocomposites for biomedical applications, Compos. C: Open Access 9 (2022), https://doi.org/10.1016/j.jcomc.2022.100331.
[26] R. Imran, A. Al Rashid, M. Koç, Review on computational modeling for the property, process, product and performance (PPPP) characteristics of additively manufactured porous magnesium implants, Bioprinting 28 (2022) e00236, https://doi.org/10.1016/j.bprint.2022.e00236.
[27] B. Yilmaz, A. Al Rashid, Y. Ait, Z. Evis, M. Koç, Bioprinting: a review of processes, materials and applications, Bioprinting 23 (2021) e00148, https://doi.org/10.1016/j.bprint.2021.e00148.
[28] A. Paolini, S. Kollmannsberger, E. Rank, Additive manufacturing in construction: a review on processes, applications, and digital planning methods, Addit. Manuf. 30 (2019) 100894, https://doi.org/10.1016/j.addma.2019.100894.
[29] A. Camposeo, L. Persano, M. Farsari, D. Pisignano, Additive manufacturing: applications and directions in photonics and optoelectronics, Adv. Opt. Mater. 7 (2019), https://doi.org/10.1002/adom.201800419.
[30] A.E. Schwarz, T.N. Ligthart, D. Godoi Bizarro, P. De Wild, B. Vreugdenhil, T. van Harmelen, Plastic recycling in a circular economy; determining environmental performance through an LCA matrix model approach, Waste Manag. 121 (2021) 331−342, https://doi.org/10.1016/j.wasman.2020.12.020.
[31] H.A. Colorado, E.I.G. Velásquez, S.N. Monteiro, Sustainability of additive manufacturing: the circular economy of materials and environmental perspectives, J. Mater. Res. Technol. 9 (2020) 8221−8234, https://doi.org/10.1016/j.jmrt.2020.04.062.
[32] F.A. Cruz Sanchez, H. Boudaoud, M. Camargo, J.M. Pearce, Plastic recycling in additive manufacturing: a systematic literature review and opportunities for the circular economy, J. Clean. Prod. 264 (2020) 121602, https://doi.org/10.1016/j.jclepro.2020.121602.
[33] A. Al Rashid, S.A. Khan, S.G. Al-ghamdi, M. Koc, Additive manufacturing of polymer nanocomposites: needs and challenges in materials, processes, and applications, J. Mater. Res. Technol. 14 (2021) 910−941, https://doi.org/10.1016/j.jmrt.2021.07.016.
[34] H. Jung, G. Shin, H. Kwak, L.T. Hao, J. Jegal, H.J. Kim, H. Jeon, J. Park, D.X. Oh, Review of polymer technologies for improving the recycling and upcycling efficiency of plastic waste, Chemosphere 320 (2023) 138089, https://doi.org/10.1016/j.chemosphere.2023.138089.
[35] H. Wu, H. Mehrabi, P. Karagiannidis, N. Naveed, Additive manufacturing of recycled plastics: strategies towards a more sustainable future, J. Clean. Prod. 335 (2022), https://doi.org/10.1016/j.jclepro.2021.130236.
[36] J.C.C. Yeo, J.K. Muiruri, W. Thitsartarn, Z. Li, C. He, Recent advances in the development of biodegradable PHB-based toughening materials: approaches, advantages and applications, Mater. Sci. Eng. C 92 (2018) 1092−1116, https://doi.org/10.1016/j.msec.2017.11.006.
[37] Greenpeace, The Hard Truth About Recycling, Greenpeace Company Reports. (n.d.), https://www.greenpeace.org/usa/. (Accessed 15 March 2023).
[38] T. Thiounn, R.C. Smith, Advances and approaches for chemical recycling of plastic waste, J. Polym. Sci. 58 (2020) 1347−1364, https://doi.org/10.1002/pol.20190261.
[39] S. Kumar, M.R. Ramesh, M. Doddamani, Recycling potential of MWCNTs/HDPE nanocomposite filament: 3D printing and mechanical characterization, J. Mater. Cycles Waste Manag. 25 (2023) 1168−1178, https://doi.org/10.1007/s10163-023-01607-w.
[40] J.V. Manopanta-Aigaje, D. Peralta-Zurita, Thermal-mechanical properties of recycled PVC used in Schrader valve caps In: M. Botto-Tobar, O.S. Gómez, R. Rosero Miranda, A. Díaz Cadena, W. Luna-Encalada (Eds.), Trends in Artificial Intelligence and Computer Engineering, ICAETT 2022. Lecture Notes in Networks and Systems, Springer Nature Switzerland 619, 2023, pp. 497−509. https://doi.org/10.1007/978-3-031-25942-5_39.
[41] C. Samorì, W. Pitacco, M. Vagnoni, E. Catelli, T. Colloricchio, C. Gualandi, L. Mantovani, A. Mezzi, G. Sciutto, P. Galletti, Recycling of multilayer packaging waste with sustainable solvents, Resour. Conserv. Recycl. 190 (2023) 106832, https://doi.org/10.1016/j.resconrec.2022.106832.
[42] P. Gijsman, R. Fiorio, Long term thermo-oxidative degradation and stabilization of polypropylene (PP) and the implications for its recyclability, Polym. Degrad. Stab. 208 (2023) 110260, https://doi.org/10.1016/j.polymdegradstab.2023.110260.
[43] F. Tahmasebi, S.H. Jafari, S.M.F. Farnia, SbB-g-GMA copolymer as a dual functional reactive compatibilizer and impact modifier for potential recycling of PET and PS via melt blending approach, J. Polym. Environ. (2023), https://doi.org/10.1007/s10924-023-02803-3.
[44] E. Naderi Kalali, S. Lotfian, M. Entezar Shabestari, S. Khayatzadeh, C. Zhao, H. Yazdani Nezhad, A critical review of the current progress of plastic waste recycling technology in structural materials, Curr. Opin. Green Sustain. Chem. 40 (2023) 100763, https://doi.org/10.1016/j.cogsc.2023.100763.
[45] Andere Basterretxea, Want to know more about plastic upcycling? Polykey (2022). https://polykey.eu/want-to-know-more-about-plastic-upcycling-2/. (Accessed 22 March 2023).
[46] Z.O.G. Schyns, M.P. Shaver, Mechanical recycling of packaging plastics: a review, Macromol. Rapid Commun. 42 (2021) 2000415, https://doi.org/10.1002/marc.202000415.
[47] J.-P. Lange, Managing plastic waste−sorting, recycling, disposal, and product redesign, ACS Sustain. Chem. Eng. 9 (2021) 15722−15738, https://doi.org/10.1021/acssuschemeng.1c05013.
[48] N. Taneepanichskul, D. Purkiss, M. Miodownik, A review of sorting and separating technologies suitable for compostable and biodegradable plastic packaging, Front. Sustain. 3 (2022), https://doi.org/10.3389/frsus.2022.901885.
[49] C. Araujo-Andrade, E. Bugnicourt, L. Philippet, L. Rodriguez-Turienzo, D. Nettleton, L. Hoffmann, M. Schlummer, Review on the photonic techniques suitable for automatic monitoring of the composition of multi-materials wastes in view of their posterior recycling, Waste Manag. Res. 39 (2021) 631−651, https://doi.org/10.1177/0734242X21997908.

[50] L. Trossaert, M. De Vel, L. Cardon, M. Edeleva, Lifting the sustainability of modified pet-based multilayer packaging material with enhanced mechanical recycling potential and processing, Polymers (Basel) 14 (2022), https://doi.org/10.3390/polym14010196.
[51] H. Mangold, B. von Vacano, The frontier of plastics recycling: rethinking waste as a resource for high-value applications, Macromol. Chem. Phys. 223 (2022) 2100488, https://doi.org/10.1002/macp.202100488.
[52] G.A. Vincent, T.A. de Bruijn, S. Wijskamp, M.I. Abdul Rasheed, M. van Drongelen, R. Akkerman, Shredding and sieving thermoplastic composite scrap: method development and analyses of the fibre length distributions, Compos. B Eng. 176 (2019) 107197, https://doi.org/10.1016/j.compositesb.2019.107197.
[53] N.C. Farias, I. Major, D. Devine, M. Brennan Fournet, R. Pezzoli, S. Farshbaf Taghinezhad, M. Hesabi, Multiple recycling of a PLA/PHB biopolymer blend for sustainable packaging applications: rheology-morphology, thermal, and mechanical performance analysis, Polym. Eng. Sci. 62 (2022) 1764–1774, https://doi.org/10.1002/pen.25962.
[54] G. Colucci, O. Ostrovskaya, A. Frache, B. Martorana, C. Badini, The effect of mechanical recycling on the microstructure and properties of PA66 composites reinforced with carbon fibers, J. Appl. Polym. Sci. 132 (2015), https://doi.org/10.1002/app.42275.
[55] G. Suzuki, N. Uchida, L.H. Tuyen, K. Tanaka, H. Matsukami, T. Kunisue, S. Takahashi, P.H. Viet, H. Kuramochi, M. Osako, Mechanical recycling of plastic waste as a point source of microplastic pollution, Environ. Pollut. 303 (2022) 119114, https://doi.org/10.1016/j.envpol.2022.119114.
[56] L. Delva, S. Hubo, L. Cardon, K. Ragaert, On the role of flame retardants in mechanical recycling of solid plastic waste, Waste Manag. 82 (2018) 198–206, https://doi.org/10.1016/j.wasman.2018.10.030.
[57] T. Chen, C.D. Mansfield, L. Ju, D.G. Baird, The influence of mechanical recycling on the properties of thermotropic liquid crystalline polymer and long glass fiber reinforced polypropylene, Compos. B Eng. 200 (2020) 108316, https://doi.org/10.1016/j.compositesb.2020.108316.
[58] M.Y. Khalid, Z.U. Arif, M. Hossain, R. Umer, Recycling of wind turbine blades through modern recycling technologies: a road to zero waste, Renew. Energy Focus 44 (2023) 373–389, https://doi.org/10.1016/j.ref.2023.02.001.
[59] M. Mohammed, D. Wilson, E. Gomez-Kervin, A. Petsiuk, R. Dick, J.M. Pearce, Sustainability and feasibility assessment of distributed E-waste recycling using additive manufacturing in a Bi-continental context, Addit. Manuf. 50 (2022) 102548, https://doi.org/10.1016/j.addma.2021.102548.
[60] P. Jagadeesh, S. Mavinkere Rangappa, S. Siengchin, M. Puttegowda, S.M.K. Thiagamani, G. Rajeshkumar, M. Hemath Kumar, O.P. Oladijo, V. Fiore, M.M. Moure Cuadrado, Sustainable recycling technologies for thermoplastic polymers and their composites: a review of the state of the art, Polym. Compos. 43 (2022) 5831–5862, https://doi.org/10.1002/pc.27000.
[61] Circular Asia, Chemical Recycling, 2023. https://www.circulareconomyasia.org/chemical-recycling/. (Accessed 22 March 2023).
[62] Y. Liu, Z. Yu, B. Wang, P. Li, J. Zhu, S. Ma, Closed-loop chemical recycling of thermosetting polymers and their applications: a review, Green Chem. 24 (2022) 5691–5708, https://doi.org/10.1039/D2GC00368F.
[63] R. Yang, G. Xu, B. Dong, H. Hou, Q. Wang, A “polymer to polymer” chemical recycling of PLA plastics by the “DE–RE polymerization” strategy, Macromolecules 55 (2022) 1726–1735, https://doi.org/10.1021/acs.macromol.1c02085.
[64] P. Quicker, M. Seitz, J. Vogel, Chemical recycling: a critical assessment of potential process approaches, Waste Manag. Res. 40 (2022) 1494–1504, https://doi.org/10.1177/0734242X221084044.
[65] S.R. Nicholson, J.E. Rorrer, A. Singh, M.O. Konev, N.A. Rorrer, A.C. Carpenter, A.J. Jacobsen, Y. Román-Leshkov, G.T. Beckham, The critical role of process analysis in chemical recycling and upcycling of waste plastics, Annu. Rev. Chem. Biomol. Eng. 13 (2022) 301–324, https://doi.org/10.1146/annurev-chembioeng-100521-085846.
[66] A. Inayat, A. Fasolini, F. Basile, D. Fridrichova, P. Lestinsky, Chemical recycling of waste polystyrene by thermo-catalytic pyrolysis: a description for different feedstocks, catalysts and operation modes, Polym. Degrad. Stab. 201 (2022) 109981, https://doi.org/10.1016/j.polymdegradstab.2022.109981.
[67] J. Demarteau, A.R. Epstein, P.R. Christensen, M. Abubekerov, H. Wang, S.J. Teat, T.J. Seguin, C.W. Chan, C.D. Scown, T.P. Russell, J.D. Keasling, K.A. Persson, B.A. Helms, Circularity in mixed-plastic chemical recycling enabled by variable rates of polydiketoenamine hydrolysis, Sci. Adv. 8 (2022) eabp8823, https://doi.org/10.1126/sciadv.abp8823.
[68] H. Hu, Q. Xu, L. Sun, R. Zhu, T. Gao, Y. He, B. Ma, J. Yu, X. Wang, [1]Rapid hydrolysis of waste and scrap PA6 textiles to ε-caprolactam, ACS Appl. Polym. Mater. 5 (2023) 751–763, https://doi.org/10.1021/acsapm.2c01744.
[69] F. Di Bisceglie, F. Quartinello, R. Vielnascher, G.M. Guebitz, A. Pellis, Cutinase-catalyzed polyester-polyurethane degradation: elucidation of the hydrolysis mechanism, Polymers (Basel) 14 (2022), https://doi.org/10.3390/polym14030411.
[70] K. Ghosal, C. Nayak, Recent advances in chemical recycling of polyethylene terephthalate waste into value added products for sustainable coating solutions-hope vs. hype, Mater. Adv. 3 (2022) 1974–1992, https://doi.org/10.1039/d1ma01112j.
[71] Y. Deng, Q. Zhang, D.H. Qu, H. Tian, B.L. Feringa, A chemically recyclable crosslinked polymer network enabled by orthogonal dynamic covalent chemistry, Angew. Chem. Int. Ed. 61 (2022), https://doi.org/10.1002/anie.202209100.
[72] N.A. Tarazona, R. Machatschek, J. Balcucho, J.L. Castro-Mayorga, J.F. Saldarriaga, A. Lendlein, Opportunities and challenges for integrating the development of sustainable polymer materials within an international circular (bio)economy concept, MRS Energy Sustain. 9 (2022) 28–34, https://doi.org/10.1557/s43581-021-00015-7.
[73] V.G. Zuin, K. Kümmerer, Chemistry and materials science for a sustainable circular polymeric economy, Nat. Rev. Mater. 7 (2022) 76–78, https://doi.org/10.1038/s41578-022-00415-2.
[74] A.C. Chang, A. Patel, S. Perry, Y. V Soong, C. Ayafor, H.-W. Wong, D. Xie, M.J. Sobkowicz, Understanding consequences and tradeoffs of melt processing as a pretreatment for enzymatic depolymerization of poly(ethylene terephthalate), Macromol. Rapid Commun. 43 (2022) 2100929, https://doi.org/10.1002/marc.202100929.
[75] A. Patel, A.C. Chang, S. Perry, Y.-H. V Soong, C. Ayafor, H.-W. Wong, D. Xie, M.J. Sobkowicz, Melt processing pretreatment effects on enzymatic depolymerization of poly(ethylene terephthalate), ACS Sustain. Chem. Eng. 10 (2022) 13619–13628, https://doi.org/10.1021/acssuschemeng.2c03142.
[76] S. Fan, Y. Zhang, T. Liu, W. Fu, B. Li, Microwave-assisted pyrolysis of polystyrene for aviation oil production, J. Anal. Appl. Pyrolysis 162 (2022) 105425, https://doi.org/10.1016/j.jaap.2021.105425.
[77] P. Yan, W. Zhao, S.J. Tonkin, J.M. Chalker, T.L. Schiller, T. Hasell, Stretchable and durable inverse vulcanized polymers with chemical and thermal recycling, Chem. Mater. 34 (2022) 1167–1178, https://doi.org/10.1021/acs.chemmater.1c03662.
[78] R.M. Gonçalves, A. Martinho, J.P. Oliveira, Recycling of reinforced glass fibers waste: current status, Materials 15 (2022), https://doi.org/10.3390/ma15041596.
[79] N. Zhao, Q. Wu, X. Zhang, T. Yang, D. Li, X. Zhang, C. Ma, R. Liu, L. Xin, M. He, Chemical vapor deposition growth of single-walled carbon nanotubes from plastic polymers, Carbon N Y 187 (2022) 29–34, https://doi.org/10.1016/j.carbon.2021.10.067.
[80] O. V Chub, N. Saadatkhah, J.-L. Dubois, G.S. Patience, Fluidized bed poly(-methyl methacrylate) thermolysis to methyl methacrylate followed by catalytic hydrolysis to methacrylic acid, Appl. Catal. A Gen. 638 (2022) 118637, https://doi.org/10.1016/j.apcata.2022.118637.
[81] A.J. Bowles, Á. Nievas, G.D. Fowler, Consecutive recovery of recovered carbon black and limonene from waste tyres by thermal pyrolysis in a rotary kiln, Sustain. Chem. Pharm. 32 (2023) 100972, https://doi.org/10.1016/j.scp.2023.100972.
[82] Y. Ren, L. Xu, X. Shang, Z. Shen, R. Fu, W. Li, L. Guo, Evaluation of mechanical properties and pyrolysis products of carbon fibers recycled by microwave pyrolysis, ACS Omega 7 (2022) 13529–13537, https://doi.org/10.1021/acsomega.1c06652.
[83] J. Qureshi, A review of recycling methods for fibre reinforced polymer composites, Sustainability 14 (2022), https://doi.org/10.3390/su142416855.
[84] I. Dedieu, S. Peyron, N. Gontard, C. Aouf, The thermo-mechanical recyclability potential of biodegradable biopolyesters: perspectives and limits for food packaging application, Polym. Test. 111 (2022) 107620, https://doi.org/10.1016/j.polymertesting.2022.107620.
[85] M.A. Charitopoulou, S.D. Stefanidis, A.A. Lappas, D.S. Achilias, Catalytic pyrolysis of polymers with brominated flame-retardants originating in waste electric and electronic equipment (WEEE) using various catalysts, Sustain. Chem. Pharm. 26 (2022) 100612, https://doi.org/10.1016/j.scp.2022.100612.
[86] Y. Yu, B. Gao, Y. Liu, X.B. Lu, Efficient and selective chemical recycling of CO2-based alicyclic polycarbonates via catalytic pyrolysis, Angew. Chem. Int. Ed. (2022), https://doi.org/10.1002/anie.202204492.
[87] D. Jubinville, G. Chen, T.H. Mekonnen, Simulated thermo-mechanical recycling of high-density polyethylene for the fabrication of hemp hurd plastic composites, Polym. Degrad. Stab. (2023) 110342, https://doi.org/10.1016/j.polymdegradstab.2023.110342.
[88] P. du Maire, M. Deckert, M. Johlitz, A. Öchsner, Thermo-mechanical recycling of climbing ropes: a case study on a closed loop process for PA6, Appl. Res. (2022) e202200091, https://doi.org/10.1002/appl.202200091 n/a.
[89] H. Vieyra, J.M. Molina-Romero, J. de D. Calderón-Nájera, A. Santana-Díaz, Engineering, recyclable, and biodegradable plastics in the automotive industry: a review, Polymers (Basel) 14 (2022), https://doi.org/10.3390/polym14163412.
[90] G. Celik, R.M. Kennedy, R.A. Hackler, M. Ferrandon, A. Tennakoon, S. Patnaik, A.M. LaPointe, S.C. Ammal, A. Heyden, F.A. Perras, M. Pruski, S.L. Scott, K.R. Poeppelmeier, A.D. Sadow, M. Delferro, Upcycling single-use polyethylene into high-quality liquid products, ACS Cent. Sci. 5 (2019) 1795–1803, https://doi.org/10.1021/acscentsci.9b00722.
[91] U.S. Chaudhari, Y. Lin, V.S. Thompson, R.M. Handler, J.M. Pearce, G. Caneba, P. Muhuri, D. Watkins, D.R. Shonnard, Systems analysis approach to polyethylene terephthalate and olefin plastics supply chains in the circular economy: a review of data sets and models, ACS Sustain. Chem. Eng. 9 (2021) 7403–7421, https://doi.org/10.1021/acssuschemeng.0c08622.
[92] S.-A. Park, H. Jeon, H. Kim, S.-H. Shin, S. Choy, D.S. Hwang, J.M. Koo, J. Jegal, S.Y. Hwang, J. Park, D.X. Oh, Sustainable and recyclable super engineering thermoplastic from biorenewable monomer, Nat. Commun. 10 (2019) 2601, https://doi.org/10.1038/s41467-019-10582-6.
[93] D. Pan, F. Su, C. Liu, Z. Guo, Research progress for plastic waste management and manufacture of value-added products, Adv. Compos. Hybrid Mater. 3 (2020) 443–461, https://doi.org/10.1007/s42114-020-00190-0.
[94] C. Aumnate, N. Rudolph, M. Sarmadi, Recycling of polypropylene/polyethylene blends: effect of chain structure on the crystallization behaviors, Polymers (Basel) 11 (2019), https://doi.org/10.3390/polym11091456.

[95] M. Roosen, N. Mys, M. Kusenberg, P. Billen, A. Dumoulin, J. Dewulf, K.M. Van Geem, K. Ragaert, S. De Meester, Detailed analysis of the composition of selected plastic packaging waste products and its implications for mechanical and thermochemical recycling, Environ. Sci. Technol. 54 (2020) 13282–13293, https://doi.org/10.1021/acs.est.0c03371.
[96] S. Wagner, M. Schlummer, Legacy additives in a circular economy of plastics: current dilemma, policy analysis, and emerging countermeasures, Resour. Conserv. Recycl. 158 (2020) 104800, https://doi.org/10.1016/j.resconrec.2020.104800.
[97] B.D. Vogt, K.K. Stokes, S.K. Kumar, Why is recycling of postconsumer plastics so challenging? ACS Appl. Polym. Mater. 3 (2021) 4325–4346, https://doi.org/10.1021/acsapm.1c00648.
[98] R. Cherrington, J. Marshall, A.T. Alexander, V. Goodship, Exploring the circular economy through coatings in transport, Sustain. Prod. Consum. 32 (2022) 136–146, https://doi.org/10.1016/j.spc.2022.04.016.
[99] A.M. Ferreira, I. Sucena, V. Otero, E.M. Angelin, M.J. Melo, J.A.P. Coutinho, Pretreatment of plastic waste: removal of colorants from HDPE using biosolvents, Molecules 27 (2022), https://doi.org/10.3390/molecules27010098.
[100] J. Huang, D. Yan, H. Dong, F. Li, X. Lu, J. Xin, Removal of trace amount impurities in glycolytic monomer of polyethylene terephthalate by recrystallization, J. Environ. Chem. Eng. 9 (2021) 106277, https://doi.org/10.1016/j.jece.2021.106277.
[101] O. Drzyzga, A. Prieto, Plastic waste management, a matter for the 'community', Microb. Biotechnol. 12 (2019) 66–68, https://doi.org/10.1111/1751-7915.13328.
[102] M. Weber Macena, R. Carvalho, L.P. Cruz-Lopes, R.P.F. Guiné, Plastic food packaging: perceptions and attitudes of Portuguese consumers about environmental impact and recycling, Sustainability 13 (2021), https://doi.org/10.3390/su13179953.
[103] B. Geueke, K. Groh, J. Muncke, Food packaging in the circular economy: overview of chemical safety aspects for commonly used materials, J. Clean. Prod. 193 (2018) 491–505, https://doi.org/10.1016/j.jclepro.2018.05.005.
[104] W. Post, A. Susa, R. Blaauw, K. Molenveld, R.J.I. Knoop, A review on the potential and limitations of recyclable thermosets for structural applications, Polym. Rev. 60 (2020) 359–388, https://doi.org/10.1080/15583724.2019.1673406.
[105] X. Ji, M. Yang, A. Wan, S. Yu, Z. Yao, Bioleaching of typical electronic waste-printed circuit boards (WPCBs): a short review, Int. J. Environ. Res. Public Health 19 (2022), https://doi.org/10.3390/ijerph19127508.
[106] Z. Chen, M. Yang, Q. Shi, X. Kuang, H.J. Qi, T. Wang, Recycling waste circuit board efficiently and environmentally friendly through small-molecule assisted dissolution, Sci. Rep. 9 (2019) 17902, https://doi.org/10.1038/s41598-019-54045-w.
[107] F.A. Cruz Sanchez, H. Boudaoud, S. Hoppe, M. Camargo, Polymer recycling in an open-source additive manufacturing context: mechanical issues, Addit. Manuf. 17 (2017) 87–105, https://doi.org/10.1016/j.addma.2017.05.013.
[108] D. Tanney, N.A. Meisel, J. Moore, Investigating material degradation through the recycling of PLA in additively manufactured parts, in: Solid Freeform Fabrication 2017: Proceedings of 28th Annual International Solid Freeform Fabrication Symposium - an Additive Manufacturing Conference, 2017, pp. 519–531.
[109] J.F. Horta, F.J.P. Simões, A. Mateus, Large scale additive manufacturing of eco-composites, Int. J. Mater. Form. 11 (2018) 375–380, https://doi.org/10.1007/s12289-017-1364-5.
[110] N. Singh, R. Singh, I.P.S. Ahuja, Recycling of polymer waste with SiC/Al2O3 reinforcement for rapid tooling applications, Mater. Today Commun. 15 (2018) 124–127, https://doi.org/10.1016/j.mtcomm.2018.02.008.
[111] N. Singh, R. Singh, I.P.S. Ahuja, Thermomechanical investigations of SiC and Al2O3–reinforced HDPE, J. Thermoplast. Compos. Mater. 32 (2019) 1347–1360, https://doi.org/10.1177/0892705718796544.
[112] P. Bedi, R. Singh, I.P.S. Ahuja, Investigations for machinability of primary recycled thermoplastics with secondary recycled rapid tooling, Sādhanā 44 (2019) 210, https://doi.org/10.1007/s12046-019-1190-1.
[113] P. Bedi, R. Singh, I.P.S. Ahuja, Investigations for tool life of 3D printed HDPE and LDPE composite based rapid tooling for thermoplastics machining applications, Eng. Res. Express 1 (2019), https://doi.org/10.1088/2631-8695/ab29ab.
[114] R. Singh, R. Kumar, I. Singh, Investigations on 3D printed thermosetting and ceramic-reinforced recycled thermoplastic-based functional prototypes, J. Thermoplast. Compos. Mater. 34 (2021) 1103–1122, https://doi.org/10.1177/0892705719864623.
[115] R. Singh, I. Singh, R. Kumar, Mechanical and morphological investigations of 3D printed recycled ABS reinforced with bakelite–SiC–Al2O3, Proc. Inst. Mech. Eng. C J. Mech. Eng. Sci. 233 (2019) 5933–5944, https://doi.org/10.1177/0954406219860163.
[116] R. Singh, H. Singh, I. Farina, F. Colangelo, F. Fraternali, On the additive manufacturing of an energy storage device from recycled material, Compos. B Eng. 156 (2019) 259–265, https://doi.org/10.1016/j.compositesb.2018.08.080.
[117] I.A. Carrete, P.A. Quiñonez, D. Bermudez, D.A. Roberson, Incorporating textile-derived cellulose fibers for the strengthening of recycled polyethylene terephthalate for 3D printing feedstock materials, J. Polym. Environ. 29 (2021) 662–671, https://doi.org/10.1007/s10924-020-01900-x.
[118] M. Idrees, S. Jeelani, V. Rangari, Three-dimensional-printed sustainable biochar-recycled PET composites, ACS Sustain. Chem. Eng. 6 (2018) 13940–13948, https://doi.org/10.1021/acssuschemeng.8b02283.
[119] N.E. Zander, Z.R. Boelter, Rubber toughened recycled polyethylene terephthalate for material extrusion additive manufacturing, Polym. Int. 70 (2021) 742–748, https://doi.org/10.1002/pi.6079.
[120] D. Stoof, K. Pickering, Sustainable composite fused deposition modelling filament using recycled pre-consumer polypropylene, Compos. B Eng. 135 (2018) 110–118, https://doi.org/10.1016/j.compositesb.2017.10.005.
[121] A. al Rashid, H. Ikram, M. Koç, Additive manufacturing and mechanical performance of carbon fiber reinforced Polyamide-6 composites, Mater. Today Proc. 62 (2022) 6359–6363, https://doi.org/10.1016/j.matpr.2022.03.339.
[122] H.N. Salwa, S.M. Sapuan, M.T. Mastura, M.Y.M. Zuhri, R.A. Ilyas, Life cycle assessment (LCA) of recycled polymer composites, in: Recycling of Plastics, Metals, and Their Composites, CRC Press, 2021, pp. 487–501, https://doi.org/10.1201/9781003148760-27.
[123] M.Y. Khalid, A. Al Rashid, Z.U. Arif, W. Ahmed, H. Arshad, A.A. Zaidi, Natural fiber reinforced composites: sustainable materials for emerging applications, Results Eng. 11 (2021) 100263, https://doi.org/10.1016/j.rineng.2021.100263.
[124] A. Al Rashid, M.Y. Khalid, R. Imran, U. Ali, M. Koc, Utilization of banana fiber-reinforced hybrid composites in the sports industry, Materials 13 (2020) 3167, https://doi.org/10.3390/ma13143167.
[125] A. Al Rashid, M. Koç, Fused filament fabrication process: a review of numerical simulation techniques, Polymers 13 (20) (2021) 3534, https://doi.org/10.3390/polym13203534.
[126] A. Al Rashid, S. Abdul Qadir, M. Koç, Microscopic analysis on dimensional capability of fused filament fabrication three-dimensional printing process, J. Elastomers Plast. 0 (2021) 009524432110472, https://doi.org/10.1177/00952443211047263.
[127] T. Srivatsan, T. Sudarshan, Additive Manufacturing: Innovations, Advances, and Applications, CRC Press, 2015, https://doi.org/10.1201/b22510.
[128] M.B. Mawale, A.M. Kuthe, S.W. Dahake, Additive layered manufacturing: state-of-the-art applications in product innovation, Concurr. Eng. Res. Appl. 24 (2016) 94–102, https://doi.org/10.1177/1063293X15613111.
[129] A. Mitchell, U. Lafont, M. Hołyńska, C. Semprimoschnig, Additive manufacturing — a review of 4D printing and future applications, Addit. Manuf. 24 (2018) 606–626, https://doi.org/10.1016/j.addma.2018.10.038.
[130] J.C. Najmon, S. Raeisi, A. Tovar, Review of Additive Manufacturing Technologies and Applications in the Aerospace Industry, Elsevier Inc., 2019, https://doi.org/10.1016/b978-0-12-814062-8.00002-9.
[131] T. Tom, S.P. Sreenilayam, D. Brabazon, J.P. Jose, B. Joseph, K. Madanan, S. Thomas, Additive manufacturing in the biomedical field-recent research developments, Results Eng. 16 (2022) 100661, https://doi.org/10.1016/j.rineng.2022.100661.
[132] Z.U. Arif, M.Y. Khalid, A. Zolfagharian, M. Bodaghi, 4D bioprinting of smart polymers for biomedical applications: recent progress, challenges, and future perspectives, React. Funct. Polym. 179 (2022), https://doi.org/10.1016/j.reactfunctpolym.2022.105374.
[133] B.G. Thiam, A. El Magri, H.R. Vanaei, S. Vaudreuil, 3D printed and conventional membranes-a review, Polymers (Basel) 14 (2022), https://doi.org/10.3390/polym14051023.
[134] S. Gaidar, V. Samusenkov, S. Strigin, R. Martínez-García, Application of polyfunctional nanomaterials for 3D printing, Polym. Compos. 43 (2022) 3116–3123, https://doi.org/10.1002/pc.26604.