Recycled Polymer for FDM 3D Printing Filament Material: Circular Economy for Sustainability of Additive Manufacturing

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Abstract. Plastics have become the most popular and ubiquitous material in our daily lives and global plastic production has increased significantly. A large portion of the plastic is used to produce disposable packaging items, which are discarded and accumulated as post-consumer wastes both on the land and oceans. Distributive recycling of waste plastics through additive manufacturing became the most effective solution to overcome environmental pollution and reduce the use of fossil oils and gases. With the rise of additive manufacturing, the demand for polymers has increased exponentially and many scholars are concerned about how 3D printing filaments should be reproduced from recycled plastics. This review aimed to study the potentials of using recycled plastic for 3D printing filament to minimize environmental pollution and preserve material sustainability. The study revealed promising results for the use of recycled post-consumer plastic as a more sustainable and environmentally friendly 3D printing filament material. The impact of plastic degradation on their mechanical and thermal properties due to subsequent extrusion and contamination of plastics by impurities was also studied. Besides, the additive materials used to enhance mechanical properties and increase the molecular weight of recycled material are discussed. Finally, a conclusion is drawn and future research opportunities are also addressed.

Keywords: Additive manufacturing · 3D printing filament · Plastic waste · Plastic recycling

1 Introduction

Plastic has become the most popular material for humans after the production of phenol-formaldehyde resin through the polycondensation process from phenol and formaldehyde monomer units in 1909 [1]. In recent years, plastics become the most widely used material in several industrial sectors such as packaging, bags and containers, construction, furniture, transportation, automobiles, micro-devices, and biomedical components. This is due to their lightweight, durability, versatility, and low cost as compared to other materials [2–6]. Plastic production is increasing around the world due to its ability to replace metal, paper, wood, and glass in many engineering applications [4, 7–10].

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The world's annual plastic production was 1.5 million tons in 1950. It has increased significantly to 322 million tons in 2015, raised by over 500% in the last three decades, and is forecast to reach 850 million tons by the year 2050. The plastics industry is almost entirely dependent on nonrenewable oil and gas resources, which is not a sustainable option since these scarce resources will eventually run out. Plastic feedstock accounts for around 4% of global fossil oil and gas production, with another 3–4% used to provide energy for their production [4, 10–18].

Packaging and textile fibers account for the largest demand for plastics, accounting for approximately 80% of all synthetic polymers consumption [19]. Most plastics are non-biodegradable and poisonous to burn, so their widespread production and mismanaged use have a severe environmental effect and contaminate both the land and water. Landfilling and incineration, the most popular methods of disposing of plastic waste, both have the potential to damage the environment. Plastic incineration releases harmful substances into the atmosphere such as carbon dioxide, sulfur oxides, ashes, and dioxin. On the other hand, landfilling of plastic wastes occupy a lot of space and requires a long time to decompose because they are not often non-biodegradable. As a result, the linear economy paradigm (based on the "take–make–dispose of" model) has devastating effects on the environment, including depletion of natural resources, environmental pollution, and non-sustainable development [5, 6, 10, 12, 14, 18, 20–23].

To tackle environmental pollution, the circular economy (CE) concept overcomes environmental problems and ensures sustainability by addressing the contamination caused by plastic waste. Recycling is the best option in the circular economy for handling post-consumer plastics since it reduces the severe environmental impact of waste plastics and the use of petrochemical resources. The collection and transportation of low-density plastic waste to collection and reclamation centers, however, requires a significant amount of energy in traditional recycling. Separation and reconstruction require a substantial amount of labor and can have a significant impact on the environment. Distributed plastic recycling in which consumers recycle their waste saves energy for transportation and can reduce energy demand as compared to traditional recycling [12, 24–26].

One method of recycling is distributed recycling of plastics waste for additive manufacturing [26]. Additive manufacturing (AM), which is also known as 3D printing, is a process to make a 3D solid object from a 3D model through additive processes of successive layers of material under computer control [27–29]. 3D printing technology has progressed significantly in the processing of polymers in a variety of fields, including aerospace, unmanned aerial vehicles (UAVs), agriculture, biomedical, civil engineering, bioprinting, membrane technology, metal matrix composites, and food production [18].

The most popular 3D printing technology, fused deposition modeling (FDM), melts and extrudes thermoplastic filament via a temperature-controlled nozzle. The most commonly used filament materials acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA). With the rise of additive manufacturing technology, many scholars concern about how the filament material can be manufactured from recyclable plastic, which offers a viable solution and made it more environmentally friendly and sustainable [30, 31]. Different scholars investigate the possibility of utilizing recycled waste plastics as source material for 3d printing filament. For example, HDPE and ABS plastic wastes [21], PET bottles [9, 14, 32], polypropylene [5], PLA [23], and ABS [33] has been examined for 3D printing filaments material.

This study aimed to review the potentials of using recycled plastic wastes for 3D printing filament to minimize environmental pollution by waste plastics and preserve material sustainability in additive manufacturing. The study concerns the recycling potential of plastic wastes for 3D printing filament and it revealed that recycled plastic wastes can be utilized as a more sustainable and environmentally friendly material for 3D printing filament. This review also examines the degradation of the plastics during subsequent extrusions and contamination of the material by impurities can affect the mechanical properties of recycled polymer material. Besides, the additive materials used to enhance mechanical properties and increase the molecular weight of recycled material are discussed. This study is organized as follows: Plastic solid waste, its environmental effects, and management techniques are discussed in Sect. 2. Section 3 addresses additive manufacturing, the most commonly used thermoplastics for 3D printing filament material, and recycled polymers for 3D printing filament. Polymer degradation during subsequent extrusion and additives used to strengthen recycled polymer are also discussed. Also discussed. Section 4 addressed the conclusions and future research opportunities.

2 Plastic Solid Wastes and Its Management Techniques

2.1 Plastic Solid Wastes

Plastic is a synthetic organic chemical compound produced by polymerization of several monomers or repeating units. The majority of monomers used in plastic manufacturing are hydrocarbons extracted from fossil fuels such as coal and petroleum. Plastics' plasticity allows them to be formed, extruded and cast into different shapes and forms. Plastics are highly versatile materials that are used almost everywhere due to their lightweight, solid, durable, and flexible properties [1, 4, 34–37].

The high demand for plastic products, intense production, and unsustainable use and disposal results in the accumulation deposition of waste plastics in the environment. In recent years, the production of plastics has increased significantly. Packaging plastics are the most popular polymers, accounting for the majority of MSW. Post-consumer and industrial plastics, such as polyethylene terephthalate (PET), high-density polyethylene (HDPE), polypropylene (PP), polystyrene (PS), low-density polyethylene (LDPE), polycarbonate (PC), polyvinyl chloride (PVC), and others are the most common plastic solid wastes. The versatility and durability of plastics for diverse applications were anticipated, but the problems associated with the disposal of plastic debris were not [38–40].

2.2 Plastic Waste Environmental Pollution

The majority of plastic additives are poisonous chemicals that can cause environmental pollution and results in public health risks. Ingestion, inhalation, and skin touch are indeed the main ways that people are subjected to these additives. Indiscriminate plastic waste disposal results in environmental pollution, entanglement, and death of marine life, and clogging of drainage systems in towns and cities, etc. [37].

Land Pollution - Plastic waste pollutes the terrestrial environment before making its way into the aquatic environment. Because of the deterioration of the plastics and the leaching of hazardous plastic additives into different environmental compartments, dumping plastics on the land leads to environmental pollution. Chlorinated plastics can leach harmful chemicals into the soil, which can then seep into groundwater or the natural marine ecosystems, thereby contaminating the environment [37].

Water Pollution - Plastic makes up about 80% of the debris found in the oceans. In 2012, it was reported that there were about 165 million tons of waste plastic in the oceans. Around 8 million tons of waste plastic is dumped into the ocean per year. After several years of decay in the ocean, harmful chemicals such as nonylphenol, dichlorodiphenyldichloroethylene (DDE), phenanthrene polystyrene, and bisphenol a (BPA) are released into the water, causing water pollution [37].

Plastic debris ingestion and entanglement of animals in waste plastics are frequently occurring events in the ocean. Plastics in the ocean break down into microplastics, which then find their way into food chains after being consumed by a variety of freshwater and marine organisms. Most aquatic species, such as microorganisms, sea turtles, seabirds, fish, and invertebrates, confuse plastic waste dumped into the ocean for food, ingesting it and reducing the animals' digestive capacity, resulting in hunger, malnutrition, and death. Entanglement with plastic products such as nets also hurt, injure, or even kill marine animals [37].

Air Pollution - It is one of the most serious environmental risks to public health, causing over 6 million deaths. When landfilled waste plastics decompose, carbon dioxide and methane are released into the atmosphere and contaminating it. Carbon dioxide is also emitted into the air when plastic products are burned, and this CO2 can absorb radiant heat and prevent it from leaving the earth, resulting in global warming. When plastics products are burned directly, contaminants such as dioxins, heavy metals, and furans are released into the air, posing health risks, especially respiratory problems [37].

2.3 Plastic Waste Management

Plastic waste management is critical for reducing the adverse effects of waste plastic on the environment. PSW management can, in general, reduce the accumulation of PSW in the environment and avoid environmental hazards. Improved plastic waste collection, processing, and disposal are needed to reduce global plastic debris and marine pollution. The most popular methods for managing plastic waste are disposal in a landfill, incineration, and recycling [37, 39, 41].

Landfilling - It is the conventional method of disposing of waste plastic in many countries; but, because most plastics take a long time to degrade, the discarded wastes have occupied the land for several years, and space for landfilling is becoming a major issue. Owing to the insufficient supply of oxygen in landfills, plastic waste on land can continue for several years. From a sustainability standpoint, one of the main disadvantages of landfills is that none of the material resources used to manufacture the plastic are recovered. Plastic waste in landfills also serves as a source of secondary contaminants such as benzenes, xylenes, benzene, toluene, ethyl, and trimethyl benzenes. Because of the types and amounts of hazardous chemicals present in landfills, and their potential for leaching, there is an increasing environmental and public health issue about the impact of landfills. If landfills are properly handled, environmental contamination and public health risks can be minimized [4, 37, 41].

Incineration - Plastic incineration is another method for disposing of waste plastics that avoids some of the disadvantages of landfilling in that it does not require a large amount of space and even allowing recovery of energy in the form of heat. Plastic incineration emits hazardous gases including halogenated chemicals and polyvinyl chloride, as well as furans, dioxins, and polychlorinated biphenyls (PCBs) to the environment. The air pollution produced by the noxious gases emitted into the atmosphere is a downside of the combustion of plastics. Plastics permanently damage the combustion heater of flue systems during incineration of plastic, and the chemicals released are harmful to both human health and the environment. Low molecular weight compounds can combust immediately into the air, polluting the environment [37, 41].

Recycling - Considering the extreme environmental consequences of landfilling and incineration, the preferred method of waste disposal is recycling. It eliminates the major environmental drawbacks of both incineration and landfill disposal of plastic. Recycling conserves money and energy, decreases pollutant emissions, decreases landfill consumption, creates jobs, and boosts local economies [24, 42]. Plastics recycling is a vital part of the global initiative to reduce the 8 million tons of waste plastic that enters the ocean each year. Regardless, from 1950 to 2015, roughly 9.5% of all plastic generated was recycled, while 12.5% was incinerated, and the remaining 78% was dumped in landfills [4, 37, 39, 41] as shown in the Fig. 1.

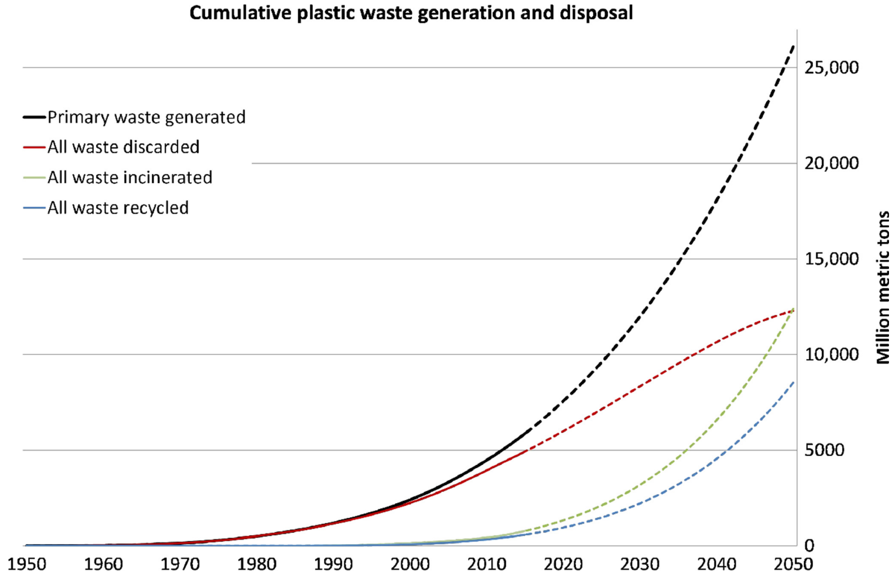

Fig. 1. Cumulative global plastic waste generation and disposal (in million metric tons). Solid lines show historical data from 1950 to 2015; dashed lines show projections of historical trends to 2050 [44].

Plastic recycling can be categorized into four: primary, secondary, tertiary, and quaternary recycling. Primary recycling is the mechanical reprocessing of plastics into the extrusion cycle to create a new product of the same material with similar properties. Secondary recycling is the mechanical recycling of plastics to create new items that replace virgin plastic or a portion of virgin plastic. As a result of this process, plastic degradation occurs, and the addition of various additives enhances the properties of the plastic and makes it suitable for new applications. Tertiary recycling, also known as chemical recycling, breaks down polymer chains into smaller molecules that can be used to make oils, new polymers, or other chemicals. Plastic waste is incinerated in quaternary recycling, and energy is recovered through the generation of heat and/or electricity. The most environmentally sustainable and cost-effective treatment approach tends to be primary recycling. However, since this process needs non-degraded, clean, and homogeneous plastic waste, it is limited. As a result, the majority of life cycle assessment studies are focused on secondary recycling, which is the second-best

Table 1. Plastic types, resin identification, their properties, and common uses [37].

Recycling Symbols	Plastics types	Properties	Common uses
1 PETE	PET	Clear, tough, solvent resistant, a barrier to gas and moisture, softens at 80 °C.	Soft drink and water bottles, containers, salad dressing, biscuit trays, and salad domes.
2 HDPE	HDPE	Hard to semi-flexible, resistant to chemicals and moisture, easily colored, processed, and formed	Shopping and freezer bags, buckets, detergent, shampoo, milk and juice bottles, etc.
3 PVC	PVC	Strong, tough, softens at 80 °C, Flexible, clear, elastic, can be solvent welded.	Fittings, plumbing pipes, blister packs, wall cladding, roof sheeting, garden hose,
4 LDPE	LDPE	Soft flexible, waxy surface, translucent, softens at 70 °C, scratches easily.	Refuse bags, mulch film, cling wrap, garbage bags, squeeze bottles.
5 PP	PP	Hard and translucent, soften at 140 °C, translucent, withstand solvents, versatile.	Microwave dishes, lunch boxes, packaging tape, garden furniture, and ice cream tubs
6 PS	PS	Clear, glassy rigid, opaque, semi-tough, affected by fat, acids, and solvents, but resistant to alkalis, salt solutions, low water absorption	Plastic cutlery, imitation glassware, toys, protective packaging, building, and food insulation
7 OTHER	Other like PC, ABS	Includes all resins and multi-materials (e.g. laminates) properties dependent on plastic or a combination of plastics.	Automotive and appliance components, computers, electronics, cooler bottles, packaging.

environmental solution and is favored over other management procedures in terms of reducing total energy consumption and greenhouse gas emissions [43].

Table 1 Summarizes the various forms of plastics, as well as their properties, resin identification codes, and common uses.

3 Polymers for FDM Additive Manufacturing

Additive manufacturing (AM), also known as 3D printing, is the process of making three-dimensional (3D) solid objects by laying down successive layers of material under computer control. It is distinguished from traditional machining techniques, which rely on material removal by milling, grinding, boring, cutting, and other methods [27, 45]. One of the fastest-growing industries is 3D printing. In comparison to 2016, the market is expected to rise by over 23% by 2021, reaching over 10 million USD. In recent years, 3D printing has gained a lot of popularity across a wide range of industries, with the aerospace, military, automotive, medical, and construction industries [24, 46].

There are now a large number of AM techniques available. Some techniques, such as selective laser sintering (SLS), selective laser melting (SLM), and fused deposition modeling (FDM), melt the material to make the layers, while others cure liquid materials using, such as stereolithography (SLA) [27, 47].

Among the various AM techniques, the FDM is a less expensive and simpler method that only involves a basic design and readily available raw materials. In FDM, a molten thermoplastic material is extruded from a temperature-controlled nozzle to create the layers of an object with a high degree of precision. The thermoplastics feedstock materials are suitable for functional prototypes, durable manufacturing equipment, and low-volume manufacturing components. Filaments for 3D printing are most commonly made in the extrusion process, which involves feeding a pellet or polymer powder into an extruder, where it is converted into a homogeneous material in the shape of a line with given parameters under the influence of temperature. Filaments made from recycled PLA or ABS are becoming more widely available.

3.1 Commonly Used Polymers for FDM Additive Manufacturing

Different materials may be used in FDM 3D printing technology depending on the working conditions. Thermoplastics, such as acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polycarbonate (PC), polyamides (nylon), polystyrene (PS), polyvinyl alcohol (PVA), high-impact polystyrene (HIPS), and various forms of polyethylene (PE), such as low-density polyethylene (LDPE), polyethylene terephthalate (PET) are used for 3D printing filament. Among these, the most commonly used filament materials are ABS and PLA [24, 30, 48].

Acrylonitrile-Butadiene-Styrene (ABS) - ABS is a carbon chain copolymer made up of polymerized acrylonitrile, butadiene, and styrene monomer units that are joined together to form a single polymer as shown in the figure below. These monomers contribute to the high impact strength and mechanical strength of this thermoplastic polymer, which makes it an opaque and strong thermoplastic appropriate for tough consumer goods. It has a wide range of processing properties, including the ability to be solid and stable at low temperatures while still being heat and chemical-resistant [8, 16, 32, 49].

Polylactic Acid (PLA) - PLA is a biodegradable thermoplastic made from sustainable (renewable) materials including cornstarch, sugar cane, tapioca roots, and potato starch. PLA is currently the most common 3D printing filament in the 3D printing world. It is more environmentally friendly as compared to other plastic materials. PLA is increasingly preferred over ABS due to its low toxicity, resistance to warping, and availability in glow-in-the-dark and translucent colors. The temperature range for printing is approximately 180 °C to 230 °C [8, 16, 32, 49].

3.2 Mechanical Recycling of Waste Plastic for 3D Printing Filament

The recent developments of open-source 3D material extrusion printers and extruders provide a new approach to plastic recycling with higher potential value-added products. In the conventional recycling process, the waste must be delivered to a recycling processing facility and then to a reclamation plant. After being recycled, the plastic is distributed a third time to the producers, who will use it to make new goods. Distributive recycling allows materials to be processed and used directly by the consumers. Since the distributive manufacturing case can be used and recycled locally, there is little to no need for shipping, allowing for substantial energy and cost savings [24, 50].

3D printing using recycled polymeric materials is a novel, rapidly emerging technology with the greatest degree of future viability. The mechanical recycling approach involved reprocessing post-consumer plastic products to produce new, similar, or different products. It is regarded as the easiest and most straightforward recycling process. The various activities involved are collecting, separating, and sorting, shredding, washing, and cleaning, drying, pelletizing, and extruding [8, 49, 51–53] as shown in Fig. 2.

Plastic waste collection involves collecting all types of plastics in one place for further treatment. After the materials have been collected in one place, the separation process begins, in which the plastic is sorted and separated using resin identification codes established by the Society of the Plastic Industry (SPI) as shown in Table 1. Since the sorting process affects the resin quality in part, the plastic must be sorted efficiently to prevent various plastic mixtures along the way [8, 49, 51, 54].

After sorting and separating, the plastic is normally washed with water, surfactants (detergents), and a sodium hydroxide (NaOH) solution to eliminate contaminants such as dust, grease, stickers, oil, and other pollutants. Depending on the post-processing conditions and level of contamination, the washing could be performed before or after the plastics are shredded and transformed into flakes. The shredding of the plastic involves grinding the sorted and gathered plastic into smaller-sized flakes. After shredding, the material is dried with enough heat in a drying machine to remove all moisture at the material's prescribed drying temperature.

The plastic flakes are extruded into pellets and then extruded in a filament extruder machine to produce 3D printing filament. The filament extrusion process is a continuous procedure in which shredded plastic flakes or pellets are fed into the heated barrel

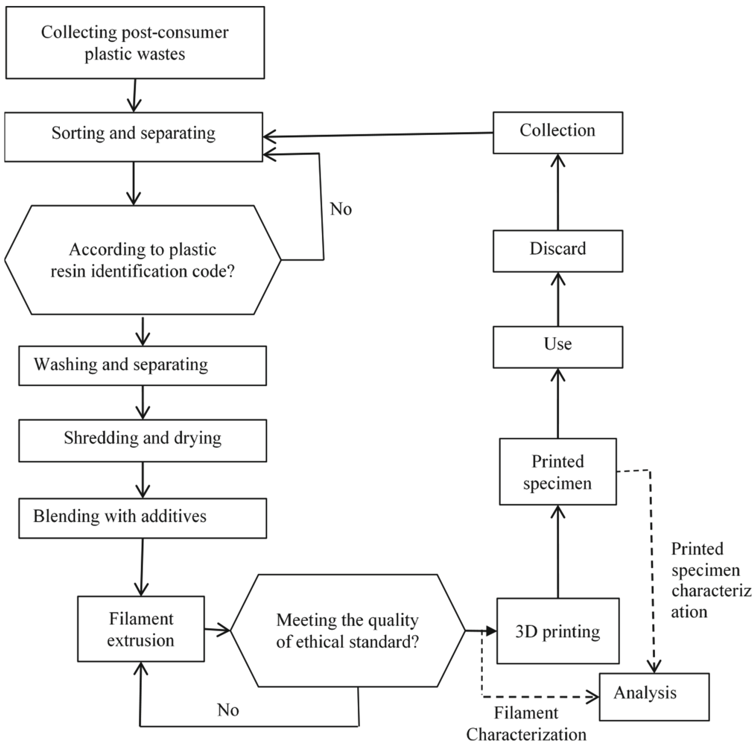

Fig. 2. Manufacture of recycled filament from postconsumer plastic waste materials.

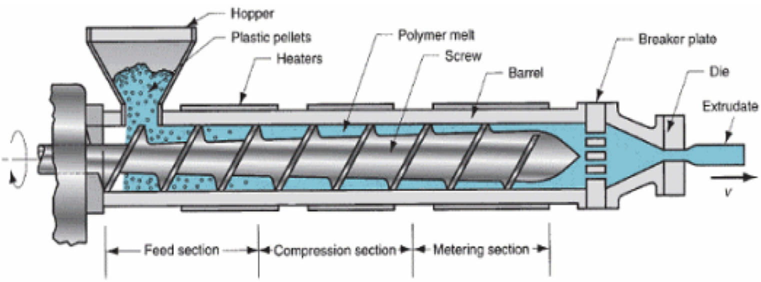

Fig. 3. Single screw plastic extruder [49].

of the extruder via a hopper as shown in Fig. 3. The material is carried through the barrel by a screw that rotates with a high torque motor. The pellets are heated, mixed, and compressed in the barrel before being squeezed out as a wire-shaped filament material through the die /nozzle. After that, the extruded filament is fully cooled and cut to the desired length before being rolled over the spool [8, 49, 55–58].

Plastic additives and virgin materials are mixed with recycled material and then extruded to modify its properties and avoid plastic degradation during extrusion.

Finally, using an FDM 3D printer, the prepared recycled filament is used to print a specimen. Finally, Mechanical, rheological, and thermal analysis are on the printed element [24].

3.3 Recycled Plastics for FDM Filament Material – State of the Art

Recycling post-consumer plastics for 3D printing filament will address the global issue of plastic waste while also making the manufacturing process more environmentally friendly. To resolve the problem of environmental pollution and to reduce the use of petroleum for plastic material, several attempts have been made to create 3D printing filament materials from recycled plastics.

Choudhary et al. [9] investigated the environmental and economic impacts from the recycling of PET plastic bottle waste with renewable and conventional sources of electricity in India by using three different scenarios. Scenario A uses virgin PET pellets with conventional electricity, scenario B uses waste PET bottle recycling with conventional electricity, and scenario C uses waste PET bottle recycling with solar electricity. The results indicate that scenario B has the greatest environmental effects, followed by scenarios C and A and it showed that renewable energy (solar electricity) should be used to recycle PET bottle waste for filament manufacturing. The study's drawback is that it is a region-specific environmental and economic impact experiment.

Ferrari et al. [14] examined the recycling of PET bottles collected at the beach. The influence of various processing conditions on the crystalline structure of 3D printed samples made from the extruded wire was investigated. Rheological studies were carried out to see whether there was any change in the viscosity of PET after several processing cycles. The degradation temperature decreased as the number of processing cycles increased, indicating a reduction in thermal stability. Tensile testing revealed a difference in mechanical properties due to high concentrations of the crystalline or amorphous phase in the tested sample.

Pinho et al. [18] investigated the properties of recycled 3D printed PLA polymer from food packages and ABS copolymers from car dashboards. The chemical, thermal, and mechanical properties, as well as surface roughness and wettability, were compared to characterize the 3D printing performance of the recycled and virgin polymers. PLA showed reductions in both tensile stress and flexural strength by 33% while recycled ABS showed no improvements in the mechanical properties of the specimens. The mean surface roughness of both recycled polymers was reduced by 55 to 65%.

Mohammed et al. [21] examined the recycling of HDPE and ABS plastic wastes into FDM 3D printing filaments to refine print parameters and create a range of demonstration models. The results show that the proposed supply chain can produce highly repeatable ABS and HDPE filaments with diameters of 1.74 $\pm$ 0.1 mm for ABS and 1.65 $\pm$ 0.1 mm for HDPE materials. Finally, producing usable filaments from waste plastics could be a feasible option for reducing the burden of increased landfill and use.

Lanzotti et al. [23] studied the 'mechanical properties of specimens printed with virgin and recycled PLA', as well as performing short-beam mechanical tests. One-time recycled (106.8 $\pm$ 9.0 MPa) and twice recycled (108.5 $\pm$ 9.9 MPa)) specimens had comparable short-beam strength to that of the virgin specimens (119.1 $\pm$ 6.6 MPa).

Leonard et al. [32] investigated recycled PET specification and extrusion parameters. Mechanical and thermal property test of recycled PET printed dog bone showed a melt flow index (2.85 g/10min), tensile strength (35.7 MPa), Young's modulus (2457 MPa), melting temperature (250 °C), and extruding temperature (250–260 °C) of recycled PET. These properties are comparable to commercial filaments within an appropriate range, allowing recycled PET to be used for 3D printing filament, and the results provide recycling parameters.

Herianto et al. [5] used the Taguchi and ANOVA methods to investigate the production of recycled Polypropylene filaments to optimize extrusion processing parameters. The results showed that an average filament diameter of 1.6 mm is produced at an extrusion speed of 40 rpm, a spooler speed of 4 rpm, and an extrusion temperature of 2000 C. However, since recycled PP 3D printing filaments have a rough and easily curved surface, further research is needed.

For a single recycling cycle, Mohammed et al. [33] investigate the feasibility of using 100% recycled ABS for FDM 3D printing filament material and characterize the resulting improvements in printing quality and mechanical properties. According to the result, ABS can be recycled into consistent 3D printing filaments without the use of virgin material. The findings showed that waste ABS can be recycled and reprinted using 3D printing technology, which could open up new possibilities for long-term sustainability.

Table 2 summarizes various works of literature review on recycled post-consumer polymers for FDM 3D printing filament material.

Table 2. Recycled Filaments from plastic solid waste.

Material	Origin	Reference
PP	From household appliances, post-consumer electric devices, and automotive parts	[5]
ABS	Terluran GP-35 ABS, My 3D Media, Australia	[6]
HDPE	Detergent containers, Shampoo bottles, milk jars, cleaning agent bottles	[8]
HDPE	Post-consumer milk jug	[10]
ABS	Post-consumer ABS	[12]
PET	PET bottles from seaside	[14]
PLA	PLA type 4043D (Nature Works)	[17]
PLA, ABS	From food packages and car dashboards, respectively	[18]
PP	CIRCO® recycled PP	[59]
PLA	4032D type PLA (Nature Works)	[20]
ABS, HDPE	Waste milk cartons (HDPE) and failed/waste 3D prints (ABS)	[21]
PLA	Virgin and recycled PLA	[23]
PLA	Virgin and recycled PLA	[48]
HDPE	Fortum CIRCO® HDPE	[49]
PET	PET water bottles	[32]

(continued)

Table 2. (*continued*)

Material	Origin	Reference
HDPE	HDPE scraps	[52]
ABS	Failed 3D prints and support material	[33]
PET	Soda bottles water bottles, and salad containers	[60]
HDPE	HDPE bottles	[61]
PET	Water bottles	[62]
PET	Carbonated drink bottle and water bottles	[63]
PC	Clear PC regrind provided by McDonnough Plastics, Fenton, MI	[64]
HDPE	Milk bottles, shampoo bottles, detergent containers, and household bottles	[51]
PS	Polystyrene foam collected from an electrical appliance store	[65]
PS, ABS, PVC	Provided by Etelä-Karjalan Jätehuolto Oy and Destaclean Oy companies	[66]
HDPE	Filament purchased from Filaments.ca	[67]

3.4 Additives for Recycled Filament Manufacturing

The introduction of one or more additive materials significantly improves the properties of recycled materials Additives, such as polymer chain extensions and peroxide-based additives, have been extensively researched to increase the recycled polymer's molecular weight and boost its mechanical properties.

The effect of biopolymer lignin additive on the mechanical and thermal parameters of recycled PLA during the FDM process was investigated by Gkartzou et al. [68]. Ground PLA is combined with lignin in various weight ratios and extruded at temperatures ranging from 180 to 190 °C. In contrast to pure PLA samples, the addition of biopolymer lignin increases melting properties while decreasing tensile strength (18%) and Young's modulus (6%).

Tian et al. [69] investigated how 3D printed continuous carbon fiber reinforced (CFR) PLA composites could be recycled and remanufactured. The bending ability of remanufactured CFR thermoplastic composites specimens was 25% higher than that of original specimens. It was possible to achieve a material recovery rate of 100% for continuous carbon fiber and 73% for PLA matrix. Total energy consumption of 67.7 MJ/kg for recycling and 66 MJ/kg for remanufacturing processes was discovered and compared to traditional methods.

The mechanical and thermal efficiency of Biochar and recycled PET composite was investigated by Idrees et al. [70]. The addition of biochar (below 100 m) strengthened the composite's mechanical, thermal, and dynamic properties. In comparison to pure PET, a 0.5 wt% biochar infusion in the recycled PET increases the tensile strength (32%), and a polymer composite with a 5 wt% loading increases the tensile modulus (60%).

The effect of micronized rubber powder and styrene-ethylene-butadiene-styrene (SEBS) elastomer additives on the mechanical properties of recycled PET polymers was studied by Zander and Boelter [71]. In comparison with the pure recycled PET, the addition of 350% SEBS, 5wt% rubber, and over 550% maleic anhydride functionalized SEBS increased toughness (85%), however, there was no significant variance in tensile strength.

Pan et al. [72] investigated the physical and mechanical properties of recycled PP/HDPE plastics feedstock for filament extrusion after incorporating nanocrystalline powders of iron (Fe), chromium (Cr), silicon (Si), and aluminum (Al). As compared to the initial recycled filaments, the addition of a 1% mix of Fe–Si–Cr or Fe–Si–Al powder resulted in improved thermal stability, yield strength (375), and Young modulus (17%). This is due to improved interfacial adhesion between the polymer and the nano-metal powders which results in less crack formation.

Singh et al. [73] investigated the impact of adding SiC/Al2O3 reinforcement to recycled HDPE plastic waste base matrix with paraffin wax binding agent. To ensure uniform dispersion, a twin-screw extruder was used to prepare HDPE, SiC, and Al2O3 in various proportions. The results showed that the additives significantly increased the materials' mechanical strength while having a minor impact on the material's thermal properties.

Stoof and Pickering [74] investigated the impact of varying harakeke, hemp fiber, or recycled gypsum contents (0–50 wt%) in pre-consumer recycled polypropylene (PP) composite filaments. When compared to plain PP filament, the results showed that harakeke fiber (30 wt%), the most effective filament, improved tensile strength (74%) and Young's modulus (214%). In comparison to plain PP, 30 wt% harakeke filament had the least shrinkage of 0.34%, resulting in a net reduction of 84%.

3.5 Degradation of Polymers

Degradation of polymer is an irreversible process that causes a drastic change in the filament material's structure, resulting in the loss of properties. It's crucial to figure out how recycling affects the properties of polymers used in 3D printing. High temperatures present during the plastic recycling, and any shear stress, temperature, or oxygen present during extrusion degrade polymers. Multiple extrusion of polymeric materials has a significant impact on their properties, such as change of viscosity, a decrease of molecular weight, and mechanical property deterioration. The change of the polymer's physical properties has a major impact on the production of high-quality filament materials [16, 24].

Cruz et al. [17] studied the mechanical, rheological, and molecular properties of a recycled PLA filament material throughout five full recycling cycles. After 5 cycles, the mechanical experiment revealed a reduction in the strain at break (10.63%) and a decrease in molecular weights 26.73% and 46.91% after 3 and 5 extrusions cycles respectively. The material viscosity was also reduced from 2729.21 Pa.s during extrusion 1 to 219.85 Pa.s in extrusion 5. In comparison to the virgin value, the melt flow index was increased by around 6.05 times after 5 recycling cycles.

Mohammed et al. [6] investigate the changes in mechanical properties of ABS as it is manufactured using FDM 3D printing at various stages of recycling. As compared to virgin polymer, the recycled polymer had lower tensile and compressive strengths. The ultimate tensile strength of one-time recycled ABS was reduced by 26 to 32%, while two-time recycled ABS was reduced by 16 to 52%. The result also revealed several property changes of the polymer, including decreased melt flow, higher glass transition temperatures, and the production of carbonyl groups due to the thermal-oxidative degradation of both the SAN and butadiene ingredients of ABS.

The properties of filament material are degraded by the introduction of impurities into the material during recycling. During injection molding, Torres et al. [75] investigated thermomechanical degradation of post-consumer PET bottles versus virgin PET. In comparison to virgin PET, contaminants and residual moisture promote crystallization of the recycled PET. The intrinsic viscosity and molecular weight are reduced as a result of this. Due to differences in crystallinity, impurities in recycled PET, and the virgin and recycled materials' thermal and mechanical backgrounds, Virgin PET bottles were ductile (>200% elongation at break), while post-consumer PET bottles were brittle (less than 10% elongation at break).

4 Conclusion and Future Outlook

Plastics have become extremely common in recent years owing to low production costs, lightweight, durable, and high strength. Due to the high demand for plastics and its intensive production, the amount of waste plastic disposal is increasing which needs environmentally friendly plastic waste valorization methods. Plastics are not vulnerable to biodegradation and the decomposition of plastic wastes after several years results in environmental pollution. The most common methods for plastic waste disposal are incineration and landfilling which result in severe environmental impact. In the circular economy concept, distributed recycling of plastic waste is an effective method to treat post-consumer plastics to overcome environmental pollution and create a plastic waste-free environmental sustainability. One method of distributed recycling of plastic is to recycling of plastic waste for 3D printing filament.

In this review, the potential of using recycled post-consumer plastics for 3D printing filament material was discussed. The study shows promising results for the use of post-consumer recycled polymers as source materials for 3D printing filament material. Using recycled plastic wastes for FDM feedstock reduces CO_2 emission, energy consumption, and material costs.

Many researchers have explored the possibility of using recycled polymers to make 3D printing filaments, but there is a lack of performance testing for these filaments in the literature, so further research on the mechanical property range and limitations of recycled filament is needed. The effect of FDM process parameters on recycled polymer-based products and the bonding between printed recycled polymer layers should be also further investigated. These activities would almost certainly expand the use of recycled filament and the applications for which it can be used.

In comparison to commercial 3D printing filaments, recycled 3D printing filaments will have lower mechanical properties. With each subsequent recycling phase, the mechanical properties of plastics deteriorate. To improve the mechanical properties of the recycled plastic material, recycled plastics must be blended with virgin material and additives (plasticizers, chain extenders, etc.). Further research is required to determine which materials can be mixed and which materials need additives to be used in material extrusion AM applications. More research on blends of virgin and recycled materials, as well as additives, is required to allow for several more processing cycles of post-consumer plastics without degradation of properties.

References

1. Chen, S., Liu, Z., Jiang, S., Hou, H.: Carbonization: a feasible route for reutilization of plastic wastes. Sci. Total Environ. **710**, 136250 (2020). https://doi.org/10.1016/j.scitotenv.2019.136250
2. Al-Salem, S.M., Lettieri, P., Baeyens, J.: Recycling and recovery routes of plastic solid waste (PSW): a review. Waste Manag. **29**(10), 2625–2643 (2009). https://doi.org/10.1016/j.wasman.2009.06.004
3. Hahladakis, J.N., Iacovidou, E.: Closing the loop on plastic packaging materials: what is quality and how does it affect their circularity? Sci. Total Environ. **630**, 1394–1400 (2018). https://doi.org/10.1016/j.scitotenv.2018.02.330
4. Hopewell, J., Dvorak, R., Kosior, E.: Plastics recycling: challenges and opportunities. Philos. Trans. R. Soc. B Biol. Sci. **364**(1526), 2115–2126 (2009). https://doi.org/10.1098/rstb.2008.0311
5. Atsani, S.I., Mastrisiswadi, H.: Recycled polypropylene filament for 3D printer: extrusion process parameter optimization. In: IOP Conference Series: Materials Science and Engineering, vol. 722, no. 1 (2020). https://doi.org/10.1088/1757-899X/722/1/012022
6. Mohammed, M.I., Wilson, D., Gomez-Kervin, E., Tang, B., Wang, J.: Investigation of closed-loop manufacturing with acrylonitrile butadiene styrene over multiple generations using additive manufacturing. ACS Sustain. Chem. Eng. **7**(16), 13955–13969 (2019). https://doi.org/10.1021/acssuschemeng.9b02368
7. Arena, U., Mastellone, M.L., Perugini, F.: Life cycle assessment of a plastic packaging recycling system. Int. J. Life Cycle Assess. **8**(2), 92–98 (2003). https://doi.org/10.1007/BF02978432
8. Hamod, H.: Suitability of recycled HDPE for 3D printing filament: plastics technology (December 2014)
9. Choudhary, K., Sangwan, K.S., Goyal, D.: Environment and economic impacts assessment of PET waste recycling with conventional and renewable sources of energy. Procedia CIRP **80**, 422–427 (2019). https://doi.org/10.1016/j.procir.2019.01.096
10. Kreiger, M.A., Mulder, M.L., Glover, A.G., Pearce, J.M.: Life cycle analysis of distributed recycling of post-consumer high density polyethylene for 3-D printing filament. J. Clean. Prod. **70**, 90–96 (2014). https://doi.org/10.1016/j.jclepro.2014.02.009
11. Lebreton, L.C., Greer, S.D., Borrero, J.C.: Numerical modelling of floating debris in the world’s oceans. Mar. Pollut. Bull. **64**(3), 653–661 (2012). https://doi.org/10.1016/j.marpolbul.2011.10.027
12. Zhong, S., Pearce, J.M.: Tightening the loop on the circular economy: coupled distributed recycling and manufacturing with recyclebot and RepRap 3-D printing. Resour. Conserv. Recycl. **128**, 48–58 (2018). https://doi.org/10.1016/j.resconrec.2017.09.023
13. Thompson, R.C., Moore, C.J., Saal, F.S.V., Swan, S.H.: Plastics, the environment and human health: current consensus and future trends. Philos. Trans. R. Soc. B Biol. Sci. **364**(1526), 2153–2166 (2009). https://doi.org/10.1098/rstb.2009.0053
14. Ferrari, F., Corcione, C.E., Montagna, F., Maffezzoli, A.: 3D printing of polymer waste for improving people’s awareness about marine litter. Polymers (Basel) **12**(8), 1738 (2020). https://doi.org/10.3390/POLYM12081738

15. World Plastics Production 1950–2015. https://committee.iso.org/files/live/sites/tc61/files/ThePlasticIndustryBerlinAug2016-Copy.pdf. Accessed 23 Dec 2020
16. Pakkanen, J., Manfredi, D., Minetola, P., Iuliano, L.: About the use of recycled or biodegradable filaments for sustainability of 3D printing: state of the art and research opportunities. Smart Innov. Syst. Technol. **68**, 776–785 (2017). https://doi.org/10.1007/978-3-319-57078-5_73
17. Cruz, F., Lanza, S., Boudaoud, H., Hoppe, S., Camargo, M.: Polymer recycling and additive manufacturing in an open source context: optimization of processes and methods. In: Proceedings - 26th Annual International Solid Freeform Fabrication Symposium - An Additive Manufacturing Conference, SFF 2015, pp. 1591–1600 (2020)
18. Pinho, A.C., Amaro, A.M., Piedade, A.P.: 3D printing goes greener: study of the properties of post-consumer recycled polymers for the manufacturing of engineering components. Waste Manag. **118**, 426–434 (2020). https://doi.org/10.1016/j.wasman.2020.09.003
19. Snowdon, M.R., Abdelwahab, M., Mohanty, A.K., Misra, M.: Mechanical optimization of virgin and recycled poly (ethylene terephthalate) biocomposites with sustainable biocarbon through a factorial design. Results Mater. **5**, 100060 (2020). https://doi.org/10.1016/j.rinma.2020.100060
20. Zhao, P., Rao, C., Gu, F., Sharmin, N., Fu, J.: Close-looped recycling of polylactic acid used in 3D printing: an experimental investigation and life cycle assessment. J. Clean. Prod. **197**, 1046–1055 (2018). https://doi.org/10.1016/j.jclepro.2018.06.275
21. Mohammed, M.I., Mohan, M., Das, A., Gibson, I.: A low carbon footprint approach to the reconstitution of plastics into 3D-printer filament for enhanced waste reduction, pp. 234–241 (2017). https://doi.org/10.18502/keg.v2i2.621
22. Dontsov, Y.V., Panin, S.V., Buslovich, D.G., Berto, F.: Taguchi optimization of parameters for feedstock fabrication and FDM manufacturing of wear-resistant UHMWPE-based composites. Materials (Basel) **13**(12), 1–26 (2020). https://doi.org/10.3390/ma13122718
23. Lanzotti, A., Martorelli, M., Maietta, S., Gerbino, S., Penta, F., Gloria, A.: A comparison between mechanical properties of specimens 3D printed with virgin and recycled PLA. Procedia CIRP **79**, 143–146 (2019). https://doi.org/10.1016/j.procir.2019.02.030
24. Mikula, K., et al.: 3D printing filament as a second life of waste plastics—a review. Environ. Sci. Pollut. Res. **28**(10), 12321–12333 (2020). https://doi.org/10.1007/s11356-020-10657-8
25. Cruz Sanchez, F.A., Boudaoud, H., Camargo, M., Pearce, J.M.: Plastic recycling in additive manufacturing: a systematic literature review and opportunities for the circular economy. J. Clean. Prod. **264**, 121602 (2020). https://doi.org/10.1016/j.jclepro.2020.121602
26. Woern, A.L., McCaslin, J.R., Pringle, A.M., Pearce, J.M.: RepRapable Recyclebot: open source 3-D printable extruder for converting plastic to 3-D printing filament. HardwareX **4**, e00026 (2018). https://doi.org/10.1016/j.ohx.2018.e00026
27. Gokhare, V.G.: A review paper on 3D-printing aspects and various processes used in the 3D-printing. Int. J. Eng. Res. Technol. **6**(06), 953–958 (2017)
28. Nale, S., Kalbande, A.G.: A review on 3D printing technology. Int. J. Innov. Emerg. Res. Eng. **5**(7), 2001–2004 (2020)
29. Saiyam Jain, U.S.: 3D printing. Int. J. Eng. Res. Technol. **578**, 1–14 (2020). http://www.globalview.gr/2016/06/30/62949/
30. Sai, P.C., Yeole, S.: Fused deposition modeling – insights. In: Proceedings of the International Conference on Advances in Design and Manufacturing (December 2014). https://doi.org/10.1201/9780203910795.ch8
31. Osswald, T.A., Puentes, J., Kattinger, J.: Fused filament fabrication melting model. Addit. Manuf. **22**, 51–59 (2018). https://doi.org/10.1016/j.addma.2018.04.030

32. Leonard Mutiva, B., Byiringiro, J.B., Eng, R., Peter Muchiri, S.N.: A study on suitability of recycled polyethylene terephthalate for 3D printing filament. IOSR J. Mech. Civ. Eng. **15**(2), 4–9 (2017). https://doi.org/10.9790/1684-1502030409
33. Mohammed, M.I., Das, A., Gomez-Kervin, E., Wilson, D., Gibson, I.: Ecoprinting: investigating the use of 100% recycled acrylonitrile butadiene styrene (ABS) for additive manufacturing. In: 28th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference, SFF 2017, pp. 532–542 (2020)
34. Whitacre, D.M.: Reviews of Environmental Contamination and Toxicology. Springer, Heidelberg (2012). https://doi.org/10.1007/978-1-4614-3137-4
35. Thompson, R.C., Swan, S.H., Moore, C.J., Vom Saal, F.S.: Our plastic age. Philos. Trans. R. Soc. B Biol. Sci. **364**(1526), 1973–1976 (2009). https://doi.org/10.1098/rstb.2009.0054
36. Proshad, R., Kormoker, T., Islam, M.S., Haque, M.A., Rahman, M.M., Mithu, M.M.R.: Toxic effects of plastic on human health and environment: a consequences of health risk assessment in Bangladesh. Int. J. Heal. **6**(1), 1 (2017). https://doi.org/10.14419/ijh.v6i1.8655
37. Alabi, O.A., Ologbonjaye, K.I., Awosolu, O., Alalade, O.E.: Public and environmental health effects of plastic wastes disposal: a review. J. Toxicol. Risk Assess.**5**(2), 1–13 (2019). https://doi.org/10.23937/2572-4061.1510021
38. Ghosh, S.K.: Plastics in municipal solid waste: what, where, how and when? Waste Manag. Res. **37**(11), 1061–1062 (2019). https://doi.org/10.1177/0734242X19880656
39. Antelava, A., et al.: Plastic solid waste (PSW) in the context of life cycle assessment (LCA) and sustainable management. Environ. Manag. **64**(2), 230–244 (2019). https://doi.org/10.1007/s00267-019-01178-3
40. Ismail, B., Sc, F.B., Yassin, E.E.: Management of PET plastic bottles waste through recycling in Khartoum State. Sudan Academy of Science. Engineering, Research and Industrial Council, p. 90 (2010). https://inis.iaea.org/collection/NCLCollectionStore/_Public/44/007/44007611.pdf
41. Webb, H.K., Arnott, J., Crawford, R.J., Ivanova, E.P.: Plastic degradation and its environmental implications with special reference to poly(ethylene terephthalate). Polymers (Basel) **5**(1), 1–18 (2013). https://doi.org/10.3390/polym5010001
42. Prata, J.C., et al.: Solutions and integrated strategies for the control and mitigation of plastic and microplastic pollution. Int. J. Environ. Res. Public Health **16**(13), 1–19 (2019). https://doi.org/10.3390/ijerph16132411
43. Maris, J., Bourdon, S., Brossard, J., Cauret, L.: Mechanical recycling: compatibilization of mixed thermoplastic wastes. Polym. Degrad. Stab. **147**, 245–266 (2017). https://doi.org/10.1016/j.polymdegradstab.2017.11.001
44. Geyer, R., Jambeck, J.R., Law, K.L.: Production, use, and fate of all plastics ever made, pp. 25–29 (2017)
45. Gopinathan, J., Noh, I.: Recent trends in bioinks for 3D printing. Biomater. Res. **22**(1), 4–7 (2018). https://doi.org/10.1186/s40824-018-0122-1
46. Shah, J., Snider, B., Clarke, T., Kozutsky, S., Lacki, M., Hosseini, A.: Large-scale 3D printers for additive manufacturing: design considerations and challenges. Int. J. Adv. Manuf. Technol. **104**(9–12), 3679–3693 (2019). https://doi.org/10.1007/s00170-019-04074-6
47. Sciaky: Additive manufacturing (2014)
48. Anderson, I.: Mechanical properties of specimens 3D printed with virgin and recycled polylactic acid. 3D Print. Addit. Manuf. **4**(2), 110–115 (2017). https://doi.org/10.1089/3dp.2016.0054
49. Angatkina, K.: Recycling of HDPE from MSW waste to 3D printing filaments (2018)

50. Zander, N.E.: Recycled polymer feedstocks for material extrusion additive manufacturing. In: Polymer-Based Additive Manufacturing: Recent Developments, Part 3 - Recycled Polymer Feedstocks for Material Extrusion Additive Manufacturing (2019). https://doi.org/10.1021/bk-2019-1315.ch003
51. Chong, S., Pan, G.-T., Khalid, M., Yang, T.-K., Hung, S.-T., Huang, C.-M.: Physical characterization and pre-assessment of recycled high-density polyethylene as 3D printing material. J. Polym. Environ. **25**(2), 136–145 (2016). https://doi.org/10.1007/s10924-016-0793-4
52. Baechler, C., Devuono, M., Pearce, J.M.: Distributed recycling of waste polymer into RepRap feedstock. Rapid Prototyp. J. **19**(2), 118–125 (2013). https://doi.org/10.1108/13552541311302978
53. Braanker, G.B., Flohil, J.J., Tokaya, G.E.: Developing a plastics recycling add-on for the RepRap 3D printer. Delft Univ. Technol. **42**, 8–20 (2010)
54. Gu, F., Guo, J., Zhang, W., Summers, P.A., Hall, P.: From waste plastics to industrial raw materials: a life cycle assessment of mechanical plastic recycling practice based on a real-world case study. Sci. Total Environ. **601–602**, 1192–1207 (2017). https://doi.org/10.1016/j.scitotenv.2017.05.278
55. Albi, E., Kozel, K., Ventoza, D., Wilmoth, R.: AKABOT: 3D printing filament extruder (2014)
56. Wankhade, M.H., Bahaley, S.G.: Design and development of plastic filament extruder for 3D printing. IRA-Int. J. Technol. Eng. **10**(03), 23–40 (2018)
57. Nassar, M.A., Elfarahaty, M., Ibrahim, S., Hassan, Y.: Design of 3D filament extruder for Fused Deposition Modeling (FDM) additive manufacturing. Int. Des. J. **9**(4), 55–62 (2019)
58. Raza, S.M., Singh, D.: Experimental investigation on filament extrusion using recycled materials (2020)
59. Iunolainen, E.: Suitability of recycled PP for 3D PRINTING FILAMENT, p. 48 (2017)
60. Zander, N.E., Gillan, M., Lambeth, R.H.: Recycled polyethylene terephthalate as a new FFF feedstock material. Addit. Manuf. **21**, 174–182 (2018). https://doi.org/10.1016/j.addma.2018.03.007
61. Arendra, A., Akhmad, S., Hidayat, K., Prasnowo, M.A.: Development of low cost recycled HDPE filament extruder for 3D printing filament, pp. 2–8 (2019). https://doi.org/10.4108/eai.18-7-2019.2288536
62. Little, H.A., Tanikella, N.G., Reich, M.J., Fiedler, M.J., Snabes, S.L., Pearce, J.M.: Towards distributed recycling with additive manufacturing of PET flake feedstocks. Materials (Basel) **13**, 4273 (2020)
63. Nwogu, C., Anthony, O.C.: Characterization of recycled polyethylene terephthalate powder for 3D printing feedstock. Int. J. Adv. Sci. Eng. Technol. **6**, 8844 (2019)
64. Bhadeshia, H.K.D.H.: Mechanical properties and applications of recycled polycarbonate particle material extrusion-based additive manufacturing. Mater. Sci. Technol. (U. K.) **32**(7), 615–616 (2016). https://doi.org/10.1080/02670836.2016.1197523
65. You, A., Be, M.A.Y., In, I.: Preparation and characterisation of 3D printer filament from post-used Styrofoam. In: AIP Conference Proceedings, vol. 2233, p. 020022 (May 2020)
66. Turku, I., Kasala, S., Kärki, T.: Characterization of polystyrene wastes as potential extruded feedstock filament for 3D printing. Recycling **3**(4), 57 (2018). https://doi.org/10.3390/recycling3040057
67. Wampol, C.: Additive Manufacturing with High Density Polyethylene : Mechanical Properties Evaluation. South Dakota State Univ. Open PRAIRIE Open Public Res. Access Institutional Repository and Information Exchange (2018)

68. Gkartzou, E., Koumoulos, E.P., Charitidis, C.A.: Production and 3D printing processing of bio-based thermoplastic filament. Manuf. Rev. **4**, 1 (2017). https://doi.org/10.1051/mfreview/2016020
69. Tian, X., Liu, T., Wang, Q., Dilmurat, A., Li, D., Ziegmann, G.: Recycling and remanufacturing of 3D printed continuous carbon fiber reinforced PLA composites. J. Clean. Prod. **142**, 1609–1618 (2017). https://doi.org/10.1016/j.jclepro.2016.11.139
70. Idrees, M., Jeelani, S., Rangari, V.: Three-dimensional-printed sustainable biochar-recycled PET composites. ACS Sustain. Chem. Eng. **6**(11), 13940–13948 (2018). https://doi.org/10.1021/acssuschemeng.8b02283
71. Zander, N.E.: Rubber toughened recycled polyethylene terephthalate for material extrusion additive manufacturing (2020). https://doi.org/10.1002/pi.6079
72. Pan, G.T., Chong, S., Tsai, H.J., Lu, W.H., Yang, T.C.K.: The effects of iron, silicon, chromium, and aluminium additions on the physical and mechanical properties of recycled 3D printing filaments. Adv. Polym. Technol. **37**(4), 1176–1184 (2018). https://doi.org/10.1002/adv.21777
73. Singh, N., Singh, R., Ahuja, I.P.S.: Recycling of polymer waste with SiC/Al2O3 reinforcement for rapid tooling applications. Mater. Today Commun. **15**, 124–127 (2018). https://doi.org/10.1016/j.mtcomm.2018.02.008
74. Stoof, D., Pickering, K.: Sustainable composite fused deposition modelling filament using recycled pre-consumer polypropylene. Compos. Part B **135**, 110–118 (2018). https://doi.org/10.1016/j.compositesb.2017.10.005
75. Torres, N., Robin, J.J., Boutevin, B.: Study of thermal and mechanical properties of virgin and recycled poly (ethylene terephthalate) before and after injection molding. Eur. Polym. J. **36**, 2075–2080 (2000)