Waste Plastics to 3D Printer Filament: An Overview on Industrial Applications

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ABSTRACT
Waste plastics have become a major threat to the environment and the inhabitants causing both land and water pollution. The incineration of waste plastics for energy generation results in air pollution that is more dangerous than disposing into landfills. Using 3D printing filament produced from recycled polymer materials (i.e., Polyethylene Terephthalate (PET) plastic bottles) could turn the waste plastic into re-usable additive manufacturing feedstock. This decreases the negative impact of waste plastics on our environment. The current applications for using recycled plastics in the design and fabrication of parts in additive manufacturing are highly laudable. 3D printing recycled filament through a step of manufacturing processes which include sorting, shredding, grinding, blending, melting, extruding, and spooling. This work aims to conduct a full assessment of the waste plastics recycling process for the production of 3D printing filament used for polymer-based part fabrication. This paper documents the review of the recent available literature on the production of filaments used for 3D printers from recycled polymer materials as the alternative way to reduce the harmful effect of waste plastics in the environment. Various conducted research works have shown that the application of 3D printed filament produced from recycled polymer materials has been widely utilized in medical, automotive, architecture, aerospace, food packaging, and engineering applications.

Keywords: 3D Printer, Filament Recycling, Waste Plastic Management, Mechanical Properties, Industrial Application

NOMENCLATURE
PET: Polyethylene terephthalate
ABS: Acrylonitrile butadiene styrene
PLA: Polylactic acid
rPET: Recycled polyethylene terephthalate
FFF: Fused filament fabrication
SPW: Solid plastic waste
PE: Polyethylene
HDPE: High density polyethylene
LDPE: Lowe density polyethylene
SLS: Selective laser sintering
PVC: Polyvinylchloride
WEEE: Waste of electrical and electronic equipment
PP: Polypropylene
PDA: Polydopamine
Mg: Magnesium
PC: Polycarbonate
PE: Polyesters
PA: Polyamide
FP: Fluoropolymers

1-INTRODUCTION

Additive manufacturing (AM), commonly known as 3D printing, can be described as a process for developing prototypes and functional components achieved by consolidation of material layer by layer [1]. Applications of AM technologies have been witnessed in the healthcare, oil and gas, automotive, architecture, power generation, food packaging industry, electronics, and aviation industries [2]. As a result of this, additive manufacturing technologies have experienced an extraordinary evolution and a large range of materials can be processed, thus creating opportunities for the reuse of recycled materials [3]. In additive manufacturing, diverse materials used for the fabrication of 3D parts include thermoplastics (as shown in Fig 1), metal, ceramics, and biochemical [4, 5].

Among all these materials, thermoplastic materials are a very important part of engineering materials. These thermoplastic materials include Acetals, Acrylics, Acrylonitrile Butadiene Styrene (ABS), Cellulosic, Fluoropolymers, Polyamides, Polycarbonate, Polyesters, Polyethylene, Polypropylene, Polylactic acid, Polystyrene, Polyvinylchloride. Table 1 presents an overview on types of solid plastic waste used for the production of recycled filament.

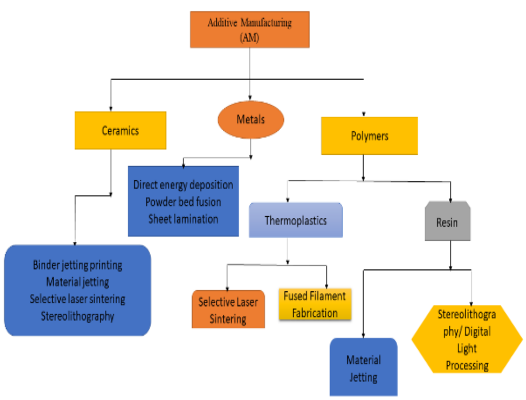


Fig. 1: 3D printing technology and material. Reprinted from Ref. [4**]**

Thermoplastic materials can be widely found in the most frequently used objects including safety helmets, drinking bottles, food containers, foam cups, disposable cups, bottles for milk and juice, automobiles, aircraft, electronic gadgets, and others. These thermoplastics are highly recyclable [15]. It is a material that is capable of withstanding heating and moulding processes [4].

Plastics are used everywhere, and knowing how to manage, dispose of and recycle them has become a very challenging task. A significant amount of plastic waste is not properly handled, either because of its urban waste nature [16-18] or because it is discharged into rivers [18]. Plastics have become part of our daily lives and it would be difficult to spend a single day without making use of plastics in any form. Despite these benefits, indiscriminate dumping of waste plastics has become the order of the day within our immediate environment. As a consequence of this, the indiscriminate dumping of waste plastics has constituted environmental damages to both land and aquatic habitats [19].

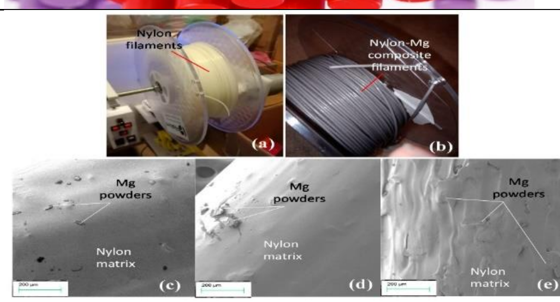
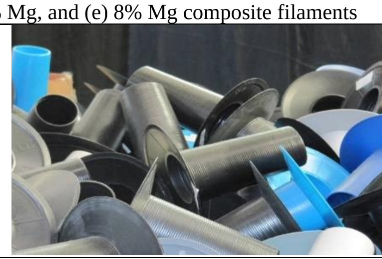
Plastic materials offer a variety of chemical and mechanical properties useful for a wide range of industrial applications [4]. Plastics are used in the manufacture of numerous products such as protective packaging, lightweight and safety components in cars, mobile phones, insulation materials in buildings, domestic appliances, furniture items, and medical devices, among others [10]. As of today, plastics are completely derived from petrochemicals produced from fossil oil and gas [4]. Plastics are less expensive, lightweight, and durable materials, which can readily be recycled into a variety of products that find their applications in a relevant industry [15 20]. Plastics are currently polluting to a high degree either by being disposed into landfills, ocean, or incinerated. Indiscriminate disposal of plastic as a waste in the environment and the health challenges it poses has become a major concern. Hence, there is a need for waste plastic recycling for 3D printing filament production. Recycling is one of the most important techniques employed to reduce the environmental impact caused by the indiscriminate disposal of waste plastic, as illustrated in Fig. 2. The retrieval of the waste from the environment reduces the waste, and recycling is a conversion technique to transform the waste into useful and functional products. Recycling methods can be categorized into three main groups namely mechanical recycling, chemical recycling, and incineration [21].

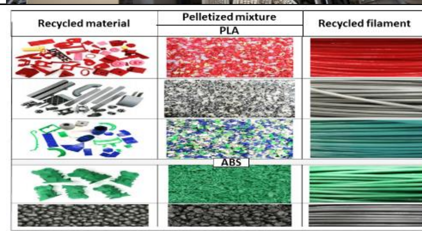
Among other waste management options, mechanical recycling of waste plastics has been regarded as one of the significant recycling methods that could provide more job opportunities than landfilling or incineration [22]. Recently, the conversion of waste plastics to 3D printing filaments has been explored by researchers. Peterson [23] utilized recycled filament for 3D printing for consumer goods. According to them, the current plastic mouthpieces on the market are not created using recycled plastics, so when they break, they only contribute to the plastic waste in landfills.

Therefore, this study focused on creating functional 3D printed mouthpieces from rPETG filament for the university of Arkansas Hogwild Band brass players to be used during performance [23].

Patti *et al.* [24] carried out assessment of recycled PLA based filament for 3D printing. This study focused on improving the sustainability aspects of the AM technology by examining the thermal and mechanical characteristics of recycled polymers, coming from waste products, in comparison with virgin matrices, for developing 3D printed parts.

Table 1. A highlight of different types of solid plastic waste (SPW) used in the production of recycled filament

S/N	Types of Plastics	Typical examples of waste plastic	Ref
1	Polyethylene Terephthalate (PET)		[6]
2	Polylactic acid (PLA)	 	[7 8]
3	Acrylonitrile Butadiene Styrene (ABS)		[9]
4	Selective Laser Sintering Waste Nylon Powders	 a) Extruded waste nylon filaments; (b) Mg composite filaments spools; and SEM imaging of surface topography for (c) 2% Mg, (d) 4% Mg, and (e) 8% Mg composite filaments	10
5	Polystyrene (PS)		11
6	Polyvinylchloride (PVC)		12

7	Waste of electrical and electronic equipment (WEEE)		13
8	**Recycled PLA and ABS filament.**		14

Sanchez *et al.* [25] investigated the mechanical, rheological and molecular properties of recycled PLA using open-source 3D printing. The feedstock material was prepared using a counter-rotating twin-screw extruder. In their study, they mentioned that the mechanical properties of the recycled material are slightly affected by the recycling process. This resulted to decrease of molecular weight of recycled material after the recycling process. It was pointed out that these decrease in molecular weight may be due to hydrolytic, radical degradation or residual catalyst that can promote transesterification during processing at high temperature [26-27].
In another investigation, Zander *et al.* [28] fabricated blends of recycled polypropylene with recycled PET and Polystyrene (PS). The addition of polypropylene served to increase the ductility of the blends, thereby improving the elongation at break. In a similar study, Zhao *et al.* [29] demonstrated that the tensile strength of the PLA can be further improved by coating the surface of the recycled PLA with bio-inspired polydopamine (PDA). In addition, Uddin *et al.* [10] investigated recycling of selective laser sintering (SLS) waste nylon into printable filaments, and parts reinforced with Mg particles. It was reported that Mg particles reinforced PLA filament could thus be added into selective laser sintering (SLS) waste nylon to print different lightweight surgical instruments and accessories of complex geometric shapes with required mechanical strength and stiffness. Oussai *et al.* [30] also developed 3D printing raw materials from plastic waste. Thirty (30) PET plastic bottles were turned into 3D printing filament. As reported in their study, water bottles were collected, cleaned (properly) and any external caps or seals were also removed, the bottles were then vacuum-sealed and heated to reduce their size, once cooled the bottles were cut into smaller chunks with a saw and a pair of scissors, after that, the pieces were shredded into tiny pieces, the pieces were then dried at a temperature of 160°C for 4 hours. The PET was then fed into a filament extruder, after multiple tests at different nozzle diameters and temperatures, the dried PET fed into the filament extruder produced PET filament. Because, disposable plastics have become one of the waste products that have constituted environmental pollution through the incineration process by releasing emission particles into the atmosphere which could result in various health implications such as respiratory, cardiovascular, and cancer effects [31]. Hence, there is a need to find an effective manufacturing process of converting plastic wastes into feedstock for the usefulness of industrial applications.

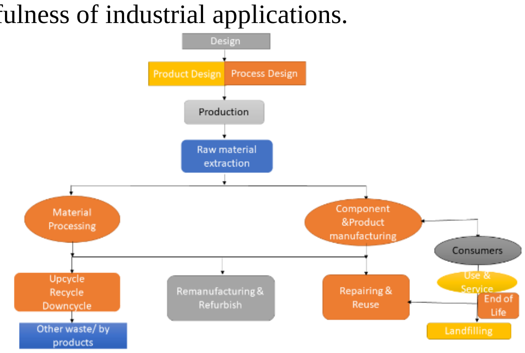


Fig. 2: Recycling scope for identifying sustainability benefits. Reprinted from Ref. [4]

2-RECYCLING MATERIALFOR 3D PRINTING FILAMENTS

The choice of material is the most important factor in making the 3D printing process more environmentally friendly. Polylactic acid (PLA), acrylonitrile butadiene styrene (ABS) and polyethylene terephthalate (PET) (Fig 3) have been used extensively to develop recycled filament for 3D printers [30]. PET is typically recycled from plastic bottles whereas ABS and PLA come from various sources such as car dashboards (ABS) and yogurt cups (PLA) [22]. The key to obtaining good quality recycled filament is to keep material input sources constant. This will ensure that the filament with minimal variation in its material properties [5]. Waste plastics can be recyclable and reusable [30], the most widely used are polyethylene terephthalate, used for synthetic fibers and water bottles), and second high-density polyethylene (HDPE), used for jugs, bottle caps, water pipes) [25]. The benefits of using waste plastic to produce recycled filament for 3D printers are:

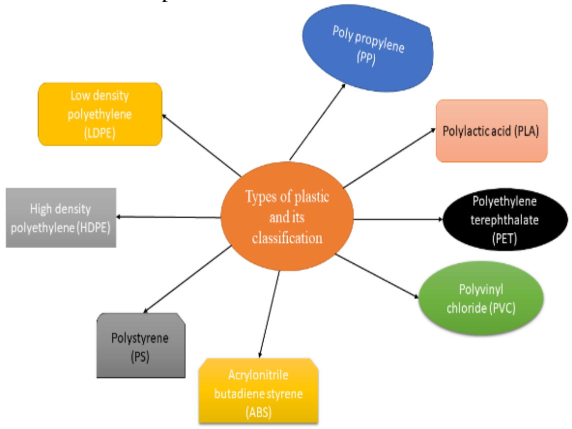


Fig. 3: Types of plastic and its classification. Reprinted from Ref. [31].

3-METHODS TO MANUFACTURE 3D FILAMENT FROM WASTE POLYMER MAERIALS

The process of recycling waste polymer material can be divided into three main groups namely mechanical recycling [32-34], chemical recycling [34], and energy recovery [35]. Among all these methods, both mechanical and chemical recycling have been widely utilized as one of the important techniques. The most common method for the recycling of thermoplastic polymers such as PET, PVC, PP, PE waste is mechanical recycling [36-38*]*.

Mechanical recycling

Mechanical recycling of plastics refers to the processing of plastics waste into secondary raw material or products without significantly changing the chemical structure of the material via mechanical processes (sorting, washing, dried, shredding, grinding, blending, melting, extruding, and spooling), thus producing recycled filaments that can be converted into 3D products.

Sorting: The plastic waste passes through extensive manual and/or automated mechanical sorting processes, designed to separate contaminated materials. The non-plastic contaminations such as metals, wood, paper, and others must be completely removed. Sorting technologies (including Near-infrared (NIR), X-rays, density, electrostatics, melting

transition to a circular economy where materials are reused as many times as possible;

- to end the toxic life cycle of throwaway products that end up in landfills or incinerators;
- to lower CO_2 production when creating recycled filament and a decrease of landfill usage; and,
- to reduce environmental impacts of accumulation of polymeric waste materials.

point, hydro cyclones, selective dissolution, and manual sorting) are used to determine the polymer type and also to recognize plastic-colored fractions [42].

Shredding: In a shredder, the cutting blade plays a vital role in the shredding process because it determines the size of shredded pieces [39]. After sorting, for mechanical recycling, the plastic recyclables are then shredded into smaller pieces called flakes. The flakes are then put forward for further processing in an extruder to produce pellets.

Grinding: After collecting PET plastic waste bottles, the next stage is grinding the bottles, in order to grind the material into pieces of small size, so as to achieve suitable feedstock for extruders.

Washing: Washing is a crucial step in the plastic recycling process since it removes some of the impurities that can impede the operation, or completely ruin a batch of recycled plastic

Drying: Moisture could cause loss of properties in the manufacture of filaments whose quality will be deteriorated if it is not properly dried. Drying of PET before extrusion has a major significant effect on flow behavior with the increase in viscosity for the dried rPET melt. Zande *et al.* [40] reported that pellets manufactured from solid plastic waste must be dried thoroughly before extrusion or a uniform filament diameter is difficult to attain due to the low viscosity of the extrudate. Due to the impact of moisture, 3D printing without drying the filament properly could result in voids in the printed layer and potentially a reduction in mechanical properties [40].

Blending: is one of the most frequently used ways of mechanically recycling plastic waste. It is a process of blending recycled plastics with a similar type of virgin plastics or different types of recycled plastics in the melt processes with a view to enhancing the mechanical

Extruder: Extruders are the machines that provide the plastic recycling filament. The most widely used extruder, screw extruders, are divided into two groups: single screw and multi-screw extruders [41]. To mix different ingredients such as additives, fillers, and liquids, twin-screw extruders are more effective. Extrusion is a process used for creating a product (an extrudate) by forcing material through a die or an orifice to form a shape, or alternatively, an extruder is used to produce semi-finished or finished products. Fig. 4 and Fig.5presents a schematic representation of a single screw extruder.

Chemical recycling

Chemical recycling is a process that converts polymeric waste by changing its chemical structure to produce a substance that is used as raw materials for the manufacturing of new products. In chemical recycling, chemical processes are used to convert polymers into the original monomers [43].

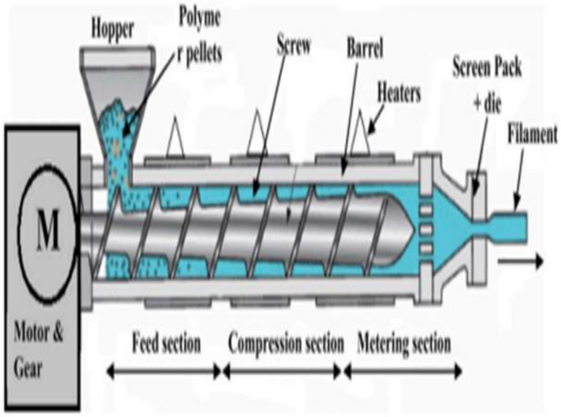


Fig. 4: Schematic representation of a single screw extruder. Reprinted from Ref. [42]

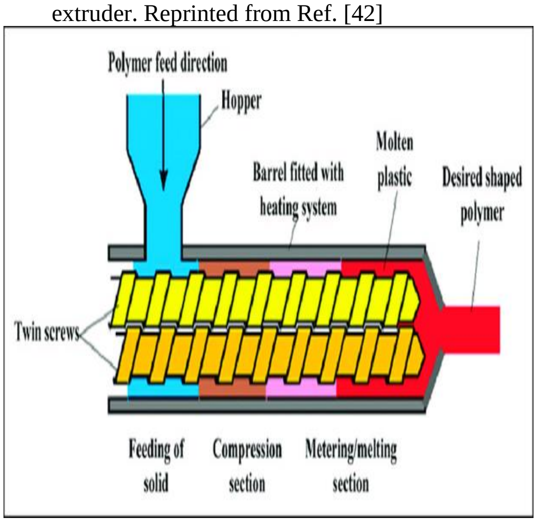


Fig. 5: Schematic representation of twin-screw extrusion system. Reprinted from Ref. [42]

Energy recovery

Energy recovery from waste is the conversion of non-recyclable waste materials into usable heat, electricity, or fuel through a variety of processes, including combustion, gasification, pyrolysis, anaerobic digestion, and landfill gas recovery. This process is often called waste to energy [44-45].

4- MECHANICAL PROPERTIES OF 3D PRINTED RECYCLED FILAMENT

There is currently little data available on the mechanical properties of recycled filament made of waste polymer material. Hence, it is necessary to document the mechanical properties of recycled filament produced from a waste polymer material and compared to commercially manufactured filament used for 3D printing (as illustrated in Tables 2&3). Table 4 consists of key published data conducted on the mechanical properties of the recycled filaments fabricated from the 3D printers. It presents the main findings of each article, considering the process conditions (such as layer thickness, extrusion temperature, preheating, infill density, among others), and the tensile strength and percentage elongation of recycled filament. As shown in Figure 5, the tensile strength-elongation relationship of the recycled filament produced from the waste polymer material such as PET, PETG, PLA/PDA, PLA exhibit a tensile strength of 200 MPa, 160 MPa, 53.24 MPa, 46.35 MPa respectively, while PETG, PLA/PDA recycled filament only indicate a significant amount of appreciable elongation of 27%, 12.79% respectively. This implies that the mechanical properties of PET or PETG samples that are 3D printed with the recycled filament have similar usable appropriate properties with those of the commercially manufactured 3D printing filament.

According to data published by Anderson [46], it was reported that the recycled samples exhibit similar properties to the virgin filament. Tensile yield strength is reported to decrease from 40.3 MPa to 35.9 MPa, tensile modulus decreased from 4258 MPa to 4032 MPa. Shear yield strength increased from 33.0 to 35.3 MPa.

Few previous research studies have been carried out to determine the mechanical properties of recycled filaments (as indicated in Table 5) developed from different categories of waste plastic materials such as PET, ABS, PLA, and among others.

It was concluded that recycling waste plastic materials into usable filaments can be used to produce parts with similar properties to parts manufactured with virgin filament (as presented in Tables 2&3). Table 3 presents a list of published literature on the production of recycled filament.

Table 2. Tensile properties of virgin PET compared with recycled PET 3D printed specimens. Reprinted from Ref. [47].

Property	Virgin PET	Recycled PET
Average tensile yield strength (MPa)	34.871	29.742
Standard deviation	1593	2778

Average tensile modulus of elasticity (MPa)	3670	3346
Standard deviation	224	413

Table 3: Short-beam strength reported as mean value ± standard deviation. Reprinted from Ref. [48].

PLA filament	Short-beam strength (MPa)
Virgin	119.1 ± 6.6
One time-recycled	106.8 ± 9.0
Twice recycled	108.5 ± 9.9
Three times recycled	75.0 ± 16.2

Table 4. Mechanical properties of recycled filament fabricated from 3D printers

S/N	Recycled Polymer materials	Ultimate Tensile strength (UTS) (MPa)	Elongation (EL) %	Ref
1	rPET	200	2.40	[49]
2	rPETG	160	27	[49]
3	rPLA	46.35	9.05	[29]
4	rPLA with PDA coating	53.24	12.79	[29]
5	rPLA	37.829	-	[50]

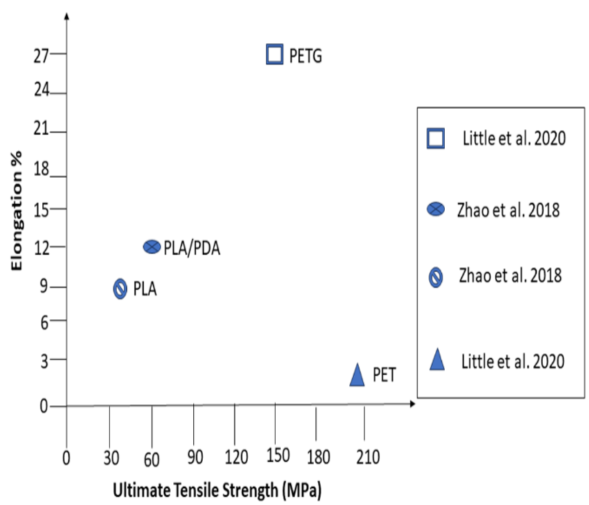


Fig. 6: The ultimate tensile strength – elongation relationship of selected recycled filaments. Reprinted from Ref. [29], [49-50].

5- BARRIERS TO RECYCLING WASTE PLASTICS

Some studies have reported that there is a loss of properties during the recycling of waste polymer material while melting [25]. The decrease in properties of the recycled filament is due to different cooling methods after filament extrusion affected the filament crystallinity. More so, it has become a major challenge to obtain filament of the same diameter with rPET due to the relatively low viscosity of the extrudate. This reduces the molecular weight, and breaking strength of the recycled filament [46]. In the various conducted research works, it has been discovered that recycled filaments, made of waste polymer materials, have low mechanical properties and increased warpage as compared to those commonly used in three-dimensional (3D) printing [54]. Additionally, there were printing difficulties with the recycled filament, where it would clog the extrusion nozzle at times while none occurred with the virgin filament. Clogging may have occurred due to impurities since filtering was not used in the re-extrusion process [46]. Sanchez *et al.* [25] examined the effect of the degradation of the material's mechanical and rheological properties after some cycles of multiple extrusion and printing processes. In their study, the feedstock material was prepared using a counter-rotating twin-screw extruder. It was concluded that the mechanical properties of the recycled material are slightly affected by the recycling process [25].

Table 5. List of published literature on the production of recycled filament

S/N	Recycled polymer materials	Types of recycling process	Research summary	Ref
1	Polyethylene Terephthalate Powder (PET)	Mechanical recycling	The two grades of PET bottles i.e., grade one which is designated PET1 with intrinsic viscosity values ranging from 0.78-0.80 (used for water bottles), and grade two which is designated PET2 with intrinsic viscosity values ranging from 0.80-0.85 (used for carbonated drinks bottles) were crushed separately. Experimental results show that both PET1 and PET2 have very good flow properties. Also, comparison with other 3D printing plastics like ABS, PLA, PVA, Nylon, and HDPE shows that PET powder is suitable for 3D printing.	51
2	Polyethylene Terephthalate Powder (PET)	Mechanical recycling	The recycled PET from bottles and packaging into material extrusion printing filament and evaluated the chemical, thermal, and mechanical properties as well as crystallinity. Tensile strength was found to be comparable to commercial filaments such as ABS and polycarbonate PC-ABS.	40
3	Polylactic acid (PLA)	Mechanical recycling	The mechanical properties of recycled PLA and PDA/PLA were investigated by tensile tests. It was reported that the tensile strength of the PLA can be improved by coating the surface of the recycled PLA with bio-inspired PDA.	29
4	Waste of electrical and electronic equipment (WEEE)	Mechanical recycling	The thirteen selected WEEE plastic samples were washed, reduced to < 4 mm, and extruded in filament with the proper diameter. The polymeric heterogeneity and the presence of foreign materials in some samples were the main critical issues highlighted during the extrusion. The suitable filaments were used to print test objects with different geometries.	13
5	Polystyrene (PS), acrylonitrile butadiene styrene (ABS), and polyvinylchloride (PVC)	Mechanical recycling	Filament fracture micrograph analysis detected heterogeneous morphology in the case of PVC, while PS and ABS showed regular microstructures.	52
6	Selective Laser Sintering Waste Nylon Powders	Mechanical recycling	Waste SLS nylon powders were then reinforced with Mg powders to improve further mechanical properties of the filaments. Due to enhanced mechanical properties and printability, it is imperative to say that the prints made of waste SLS nylon combined with Mg particles can be potentially used in many applications, including as medical components in healthcare and hospitals. Further, salvaging SLS waste nylon into FFF printing could be a viable route to support a circular economy and sustainability in future additive manufacturing.	10
7	Polyethylene Terephthalate (PET)	Mechanical recycling	This study showed a wide disparity in the physical properties of rPET depending on the source and particle shape (flake or pellet) and indicated a large area for future work both in material characterization as well as the processing and machine design to make rPET from water bottles a common feedstock.	49
8	Polylactic acid (PLA)	Mechanical recycling	The results from this work suggest that mechanical recycling of 3D printing PLA wastes is feasible from a material properties point of view. The mechanical recycling process leads to an increase of the crystallinity and a decrease of the	53

			intrinsic viscosity of the formulations, particularly in the sample based on blends of different 3D-PLA wastes. Also, the thermal analysis results point out that the recycled PLA crystallizes more easily than the sample recycled from a single PLA grade.	
9	Polyethylene Terephthalate (PET)	Mechanical recycling	Recycled PET is a suitable material for fused filament fabrication (FFF) printing, provided the material is properly cleaned and dried. Rheological data showed drying of the recycled polyethylene terephthalate led to an increase in the polymer's viscosity. It was concluded that filament from recycled polyethylene terephthalate has the capability for replacing commercial filament in printing a diverse range of plastic parts.	40

Mechanical properties

The previous studies reported that recycling of polymer reduces the mechanical strength as well as adhesion strength [55-56]. According to Zander *et al.* [40], the use of additives such as nucleation agents, dopamine [29], oxidizing stabilizers (Hydroquinone and tropolone) [57], cellulose, biocarbon [58], and chain extenders, or fillers such as toughening agents, may further be used to improve the mechanical properties of the rPET filaments. The properties of products printed with recycled feedstocks have become a major concern as compared to the products printed from commercial filaments [59].

According to Mikula *et al.* [58], a significant improvement of the mechanical properties of the recycled material was exhibited in the presence of an additive in the form of biocarbon. It was reported that the presence of polydopamine (PDA) in PLA improved the tensile strength of the fabricated specimens by enhancing the bonding strength [55]. This result was demonstrated in their study that the average ultimate tensile strength increases from 46.35 ± 1.08 MPa to 53.24 ± 1.85 MPa after coating with PDA [55].

In addition, more quality research works are required to be performed to comprehend how recycled polymer material should be processed or to determine which materials could or should be mixed, and which materials required additives or processing aids to make them viable for AM applications [55]. To improve the quality of recycled filaments, more research works are required to be conducted in the area of recycling to explore additives that may boost processing cycles of engineering-grade polymers without degradation in properties. The addition of reinforcing materials can further lead to parts with tailored properties and reduced distortion as discussed by Zander *et al* .[54]

Babagowda *et al.* [50] investigated the effect of mechanical properties of PLA filament which was blended with recycled PLA materials. Tensile and flexural or bending tests were carried out to determine the mechanical response characteristics of the printed specimen. The following conclusions were drawn from their study;

The optimized process parameters for accomplishing larger tensile strength were 0.1mm layer thickness, 10% additives in PLA.

ii. The optimized process parameters for achieving larger flexural strength were 0.1mm layer thickness, 20% additives in PLA.

Environmental concern

One of the major limitations of printing products with recycled filament is the possible release of air emissions such as volatile organic compounds and ultrafine particles emissions [61-62] [63]. When fabricating parts layer by layer at high temperatures using 3D printers both gases and particles are emitted into the environment [32, 46]. Hence, there have been some reports of higher particle emissions with recycled filaments [46]. During the 3D printing process, releasing of emission particles into the environment can be mitigated by employing enclosed desktop 3D printers with HEPA filters [61]. To maintain a toxic-free environment for printing with recycled filament, it is important to have proper ventilation in the fabrication laboratory while fabricating the parts [62].

6- CONCLUSION AND RECOMMENDATIONS

3D printing filament is the most commonly used consumable resource for printing plastic-based parts. Due to the properties of plastics such as lightweight, easy to manufacture, corrosion resistance, resistance to shock, ductility, electrically and thermally insulative, chemical resistance, and others. Waste plastics are the promising candidates for the recycled filament used for 3D printing applications, it reduces the production cost of the 3D process and mitigates the harmful effects of waste plastic on the environment. However, this review has discussed the various common barriers to recycling waste plastic which can only be mitigated by the use of additives such as nucleation agents, dopamine, oxidizing stabilizers (hydroquinone and tropolone), cellulose, biocarbon, and chain extenders, or fillers such as toughening agents, to further improve the mechanical properties of the recycled filaments.

Recommendation

Further investigations are required to improve the mechanical properties of recycled filaments made of waste plastic with the use of appropriate additives to achieve similar properties to parts manufactured with virgin polymer.

The issues of nozzle clogging while printing with recycled filament has to be properly addressed.

More investigations are needed to be carried out to ascertain how recycled polymer material can be processed or mixed, and which material required additives or processing aids to make them viable for AM applications.

More investigations are needed to control the effect of moisture in the recycled filament. 3D printing without drying the filament properly could result to voids in the printed road and potentially a loss in mechanical properties. This issue needs to be properly addressed.

7-ETHICS ISSUES

The authors of this paper declare that research involving human or animal subjects was conducted with due regard to relevant ethical standards and guidelines.

8-CONFLICT OF INTEREST

The authors declare no conflict of interest.

9-AUTHORS' CONTRIBUTIONS

All authors equally helped to write this manuscript.

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