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CRITICAL REVIEW

Fused deposition modelling approach using 3D printing and recycled industrial materials for a sustainable environment: a review

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Abstract

According to research findings of many peer-reviewed studies, up to 90% of household items may be made of plastic. But nowadays, just a small portion of plastic waste is recycled. Plastic pyrolysis and polymer breakdown are environmentally hazardous. Processing is, therefore, necessary for recycling. Plastics are constantly being manufactured and require minimal processing, necessitating innovation. Plastic recycling is becoming a major issue for environmentalists and waste management professionals. Fused deposition modelling, or FDM, is one of the most popular types of additive manufacturing. It uses the melt extrusion process to deposit filaments of thermal polymers in a predetermined pattern. Using a computer-generated design, 3D printing, sometimes referred to as additive manufacturing, is a technique for building three-dimensional objects layer by layer. A 3D item is produced by the additive method of 3D printing, which involves building up layers of material. To make a three-dimensional object, FDM printers eject a thermoplastic filament that has been heated to its melting point layer by layer. 3D printing is a rapidly expanding industry and the market in this field has grown up to 23% by 2021. Several experiments on new 3D printing materials have been carried out to reduce pollution and the supply of plastic. Various additives have been investigated to increase recycled polymers' molecular weight and mechanical properties. The most frequent type of fibre found in that is thermoplastic fibre. In this instance, waste ABS (acrylonitrile butadiene styrene) plastic from industrial FDM printers was gathered and examined in a bustling open shop. In this review, we discussed the use of recyclable polymers in 3D printing for waste material management.

Keywords 3D printing · Fused deposition modelling (FDM) · Industrial materials · Recycling · Sustainable development

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1 Introduction

Plastics are non-biodegradable and contribute to increased pollution of the environment [1, 2]. Recycling these is the most beneficial option nowadays. Plastics degrade over a period ranging from 10 to 450 years [3]. Unfortunately, historical records show that recycling has been carried out via huge centralised factories that create goods of little economic value rather than individuals. Plastic recycling has emerged as one of the most important challenges in environmental preservation and waste management [4]. Rapid prototyping is made possible through 3D printing, which is also known as additive manufacturing (Fig. 1).

Metal powder recycling is feasible and profitable for businesses in terms of cost savings or revenue generation. It also helps to maintain a sustainable environment and society by reducing pollution and using less resources and energy. Industry has a huge capacity for additive manufacturing (AM), which forces the cost of the process to be brought down to, making it financially viable. Powder is frequently left behind after powder bed fusion (PDF) or 3D printing metallic items. By reducing the cost of the powder feedstock, which is just as crucial to the production of high-performance parts as the machine itself, reusing these in the manufacturing process will increase the sustainability of the process [5].

Fusion-based filament fabrication, or FDM 3D printing, is additive manufacturing (AM) technique used for material extrusion. FDM employs thermoplastic polymers in the form of filaments to manufacture parts layer by layer by precisely placing melted material in a specified direction. FDM is the most frequently used technology, with the greatest installed base of desktop and industrial-grade 3D printers worldwide.

A handful of the various additive manufacturing technologies developed include stereolithography, fused deposition modelling, selective laser sintering, and other free-form fabrication techniques [6]. Fused deposition modelling is one of the most widely used open-source technologies since commercial fused deposition modelling printers are tiny, affordable, and need little maintenance [7–11]. After being extruded, each layer is cooled and solidified before being used for further processing. In addition, additive manufacturing may be more environmentally friendly than conventional methods [12]. The advantages of additive manufacturing include lower material costs, the ability to customise components, and the ability to produce in various ways [13]. Life cycle analysis was used to evaluate the environmental effect of two distinct additive manufacturing machines (fused deposition modelling and polyjet) on that of a regular computer numerical control (CNC) milling machine using a life cycle analysis model (CNC milling machine) [14, 15]. According to the literature, the fused deposition modelling machine had the lowest environmental impact per component created [16, 17].

Removing considerable quantities of material in additive manufacturing is unnecessary since the products are created by stacking materials. It can minimise the amount of trash generated [18]. On the contrary, 3D printers may be used the same way traditional printers are in the office, resulting in a high rate of usage errors in the workplace. Aside from that, many users of commercial FDM printers are completely untrained in the 3D printing process (Table 1). Consequently, the actual quantity of material wasted may be more than the amount wasted under ideal operating conditions, with no human or printer errors [19]. FDM creates two types of waste materials in real-world situations: support material and prints that do not come out correctly. The printing direction and other variables may impact the amount of support material required [20–22].

The trash generated by fused deposition modelling raises environmental and economic issues [23]. When analysing the waste from fused deposition modelling, most research focuses primarily on creating support material. In other words, production under ideal conditions with no failures is the norm [24]. On the other hand, failure prints account for a significant portion of the material waste in the study's open shop [25]. For this reason, this article describes the results of a printing failure study done in an open shop with regular customers with varying degrees of printing expertise, followed by the future directions for decreasing material waste.

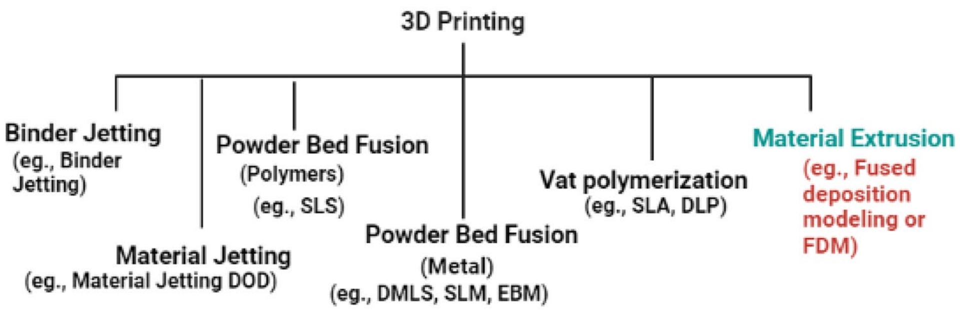


Fig. 1 There are several distinct kinds of 3D printing

Table 1 The primary variations between an industrial FDM machine and a conventional desktop one

Property	Industrial FDM	Desktop FDM
Typical accuracy	±0.15% (lower limit ±0.2 mm)	±1% (lower limit: ±1.0 mm)
Typically thick layers	0.18–0.5 mm	0.10–0.25 mm
The smallest wall thickness	1 mm	0.8–1 mm
Maximum construction envelope	Large (e.g. 900 × 600 × 900 mm)	Medium (e.g. 200 × 200 × 200 mm)
Relevant materials	Acrylonitrile butadiene styrene, PC, ULTEM	PLA, ABS, PETG
Supplementary materials	Water-soluble/break-away	Same as part (typically)
Capacities for production (per machine)	Low/medium	Low

2 Fused deposition modelling approach

Commercial fused deposition modelling printers generate the waste data considered. These printers may have less of an impact on the environment in the future. The purpose of additive manufacturing is to use just the essential materials to make the final product most efficiently [26]. As a consequence, less material and energy are used. Process time, energy usage, the main flow of workpiece materials, and the secondary flow of process catalysts should all be included in the environmental analysis for additive manufacturing processes [27]. Most studies on the environmental impact of additive manufacturing have focused on the amount of energy used [28–31]. Material waste in consumer operating settings has only been the subject of a few studies.

Two factors were evaluated while calculating the cost of constructing using fused deposition modelling: the quantity of material required to make a component and the amount of material utilised to construct the support. In certain cases, the material required for the support structure will vary based on the component [32]. Orientation of the printed component, in addition to printing time and part accuracy, may influence the surface roughness of the printed component's surface [33].

Although the failed printing resulted in a waste of materials, it did not specify how much material was used. It also provided a design guide for dimensioning and learning selective laser sintering components, but it did not specify how much material was wasted. Several online user manuals for commercial fused deposition modelling printers provide information on common problems and remedies [34]. The 16 most common fused deposition modelling difficulties are detailed in-depth, and a collection of potential solutions is included. The Print Quality Troubleshooting Guide compiled an extensive list of the most common 3D printing issues. In addition, it provided a print troubleshooting pictorial guide to identify and resolve issues for RepRap 3D printers by utilising a large collection of real-world images and print troubleshooting pictorial guide [35, 36]. These materials highlight the frequent faults that may occur in additive manufacturing. Nevertheless, the frequency and severity of such errors and the various human and machine interactions that may contribute to such errors have not been well examined.

2.1 Motivation and contribution

Fused filament fabrication and additive manufacturing (AM) are the most recent research horizons in fused deposition modelling printing [37]. In fused deposition modelling printing, the research hotspots are 'post-processing' and 'environmental effect.' This article may give insight into fused deposition modelling printing and important information for fused deposition modelling researchers to consider when analysing previous studies and advances [38].

2.2 Feasibility analysis

Figure 2 illustrates how a large institution counts waste by setting up two labelled collection bins in an open shop. Engineering students use the shop, which has 12 HP printers and 20 P3DP printers, to prototype their ideas for capstone projects and class assignments. On the other hand, printers continue to run after business hours to finish any incomplete printing tasks, with some 25 printers still active. As a result, using the device beyond operating hours is still possible. According to employees, the company expects daily visits from more than 300 people. The trash had to be emptied after 2 weeks. The acrylonitrile butadiene styrene (ABS) filament that was utilised to calculate the waste percentage at each interval was recorded. Mass balance was used to precisely weigh the support material and unsuccessful prints [34, 38].

By disassembling the components, it was feasible to distinguish between human and machine mistakes in each failure. We collated the staff knowledge, actual printer use patterns, and causes for dissatisfaction using the most recent FDM printer troubleshooting instructions. Two examples of 3D printer actions performed at the task and global levels of the process are shown in Figs. 3 and 4 [39]. These illustrations clarify that a failure could result from either human or mechanical fault. An activity flow

Fig. 2 FDM machines in an open shop made the waste. A shop has two labelled containers for measuring rubbish [34, 38] with permission from Springer Nature

chart for the printer's useful life shows the steps involved in acquiring, setting up, maintaining, and decommissioning the printer (Fig. 3). Success is independent of the number of individual print jobs. An activity diagram showing how to operate a printer at the unit level is shown in Fig. 4.

Information on what happened to material waste collection and sorting in various errors is provided. In addition, it offers suggestions for reducing the amount of waste produced by each kind of failure. In addition, it is emphasised that collecting has its limitations and challenges. Although the containers were labelled, some people persisted in throwing their waste in the wrong bins, despite the markings. As a result, all the garbage that had been gathered had been correctly scrutinised for any sorting errors. After sorting into the support bin, part builds were re-sorted into the failed bin. Throughout this period, there were a total of 20.11 kg of failed prints and 16.51 kg of support material produced. Figure 4 displays the variations in the mass of acrylonitrile butadiene styrene (ABS) during the study's time of 5 years. Material waste from failed building projects accounts for about 55% of total material waste [39].

It is calculated by dividing the number of rolls of filament consumed from inventory during each period by the percentage of wasted material. One kilogram is the weight of a single filament reel [40]. A total of 106 rolls of acrylonitrile butadiene styrene (ABS) filament were used throughout the experiment. A total of 106 kg of acrylonitrile butadiene styrene material was used for 3D printing in the open shop. In one collection cycle, the shop's inventory was monitored to determine the total quantity of material consumed. Ten weeks of combined inventory and waste monitoring data yielded 34.6% of the total material used for fused deposition modelling printing [41, 42].

Based on the assumption that all installed filament rolls were empty at the time of collection, these numbers represent the lowest feasible waste ratio. The average waste-to-materials ratio is 30.6%, according to the Environmental Protection Agency (EPA). An average of 5.2% is used to measure the standard deviation. The discarded pages accounted for 19.0% of all printed pages during the period under review. A controlled process experiment revealed that the total mass of material lost to failed structures was

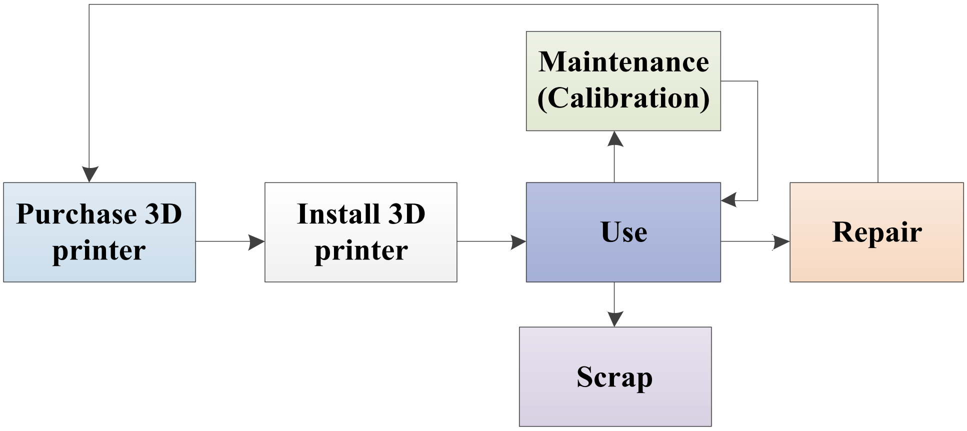
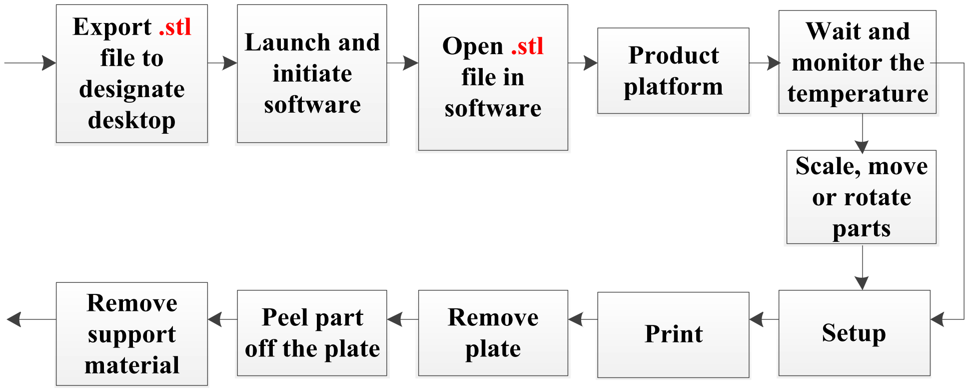


Fig. 3 Flow chart showing the activity diagrams that were utilised and this flow chart assists in evaluating how failures may be ascribed to human or machine mistakes [35]

Fig. 4 Software-based control flow chart might be useful when determining whether a failure may be attributed to human or machine error [35]



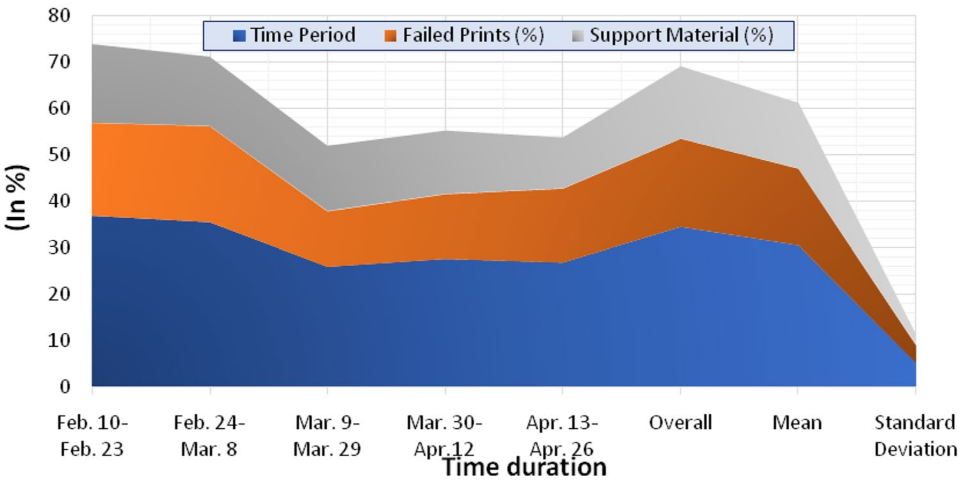
about 2.22 times more than the total material predicted in the controlled process experiment. Compared to perfect conditions, the total group of materials utilised was about 25% more than ideal conditions. The waste-to-materials ratio has changed through time, as seen in Fig. 5 [43].

Throughout the year, users of the fused deposition modelling printers developed a stronger sense of self. The accumulation of knowledge and experience may cause a declining material waste ratio throughout time. Only over spring break at the institution under investigation did the total weight of unsuccessful prints fall below that of the supporting documentation. Only individuals who had been trained in the open shop were allowed to use the 3D printers there for the length of the suspension. The crew is in charge of keeping the 3D printers operational, and they frequently have more knowledge about them than the ordinary user. Therefore, the weight and quantity of failed prints may be much lower around spring break. The total number of failed prints during the analysed periods, broken down by failure type, is shown in Fig. 5. There were a lot of prints that failed because of calibration issues with the data. Printing components could fail if a printer's calibration has been applied incorrectly. People typically don not think much about the printing process.

Contrary to other sorts of failure that the printer can automatically detect, such as warping brought on by insufficient platform heating, printers may be unable to detect calibration issues. Non-transparent lids on UP small 3D printers assist prevent failures brought on by heat losses, but they also make it harder for users to tell when a failure has occurred. By doing this, failures brought on by heat losses are avoided. The printers utilise a significant amount of paper in the process and produce waste because they keep printing until the job is finished. Customers who monitor the printing status of each printer and identify any issues as soon as they arise can prevent significant amounts of material waste. If there are any problems with the product, customer support professionals need to be informed. The team may then start investigating the root of the issue after that. The staff will fix any calibration faults to prevent them in the future [44].

The platform heating system failure is the second type of failure. Platform pre-heating is necessary to prevent warping and enhance each individual component's adhesion to a printing platform [45, 46]. Pre-heating could take anywhere from a few minutes to several hours, depending on the temperature of the platform when the procedure started. It would take less time to warm up the platform if the printer had just

Fig. 5 During the investigation (2016), a total of 106 rolls of ABS filaments were utilised. As a result, 106 kg of materials was utilised in the open shop for 3D printing [35] (image permission of Springer Nature)



finished the previous job, saving time. On the other hand, if the printer has been idle for a long time, the pre-heating time will lengthen.

Consequently, users could easily keep track of the temperature of the platform. However, the PP3DP (polypropylene 3D printer) UP series of tiny printers do not have temperature sensors. As a result, beginners may have difficulty accurately controlling the pre-heating time [45]. Some users may even overlook the importance of pre-heating their devices. According to store employees who have seen it, the platform's warmth is considered the most common reason for client failure. It is possible to reduce platform heating waste by putting clear instructions in the open store during business hours. Apart from human mistakes and equipment failure, platform heating failure is common. The platform may be unable to reach the required temperature due to wear and tear on the printer, such as the inaccuracy of the temperature sensor. This is related to a number of other issues. As a result, printers must be checked regularly to ensure proper operation [44].

The quantity of material lost due to layer shifts, the printer stops, and skip layers may be reduced if a regular inspection and maintenance program is implemented. It is also possible to reduce filament waste by limiting the number of failures that need filament re-installation. Operators should also use care while removing filament for troubleshooting. There is currently no plan for inspections or maintenance in the open shop. Employees self-diagnose and self-correct printer issues in their spare time. Some damage may occur during removal, and user's education and training may assist in reducing the amount of discarded material [46].

To reduce the quantity of material lost due to physical and nonphysical issues, better design for additive manufacturing and a better overall structure may be necessary. Recently, the issue of plastic recycling has come to the top of the list of critical environmental protection and waste management issues that need to be addressed, and for a good reason [47]. Many uses for polymer materials have been identified in both everyday life and industry, demonstrating their versatility [48, 49]. The ongoing use of plastic wastes and their persistence and noxiousness when disposed of as garbage prompted the topic of plastic wastes to be raised. Polymeric materials can be reused, giving them a second chance at life and allowing for more efficient waste management in producing consumable products. For example, a tremendous increase occurs in the 3D printing business [50]. Many thermoplastic materials, including recycled materials, can be used to make printable filaments, which may then be printed. As an alternative to the current practice of collecting plastic waste and reprocessing it, papers on 3D printing filaments derived from recycled polymers are examined in this research. These researchers evaluated the influence of processing on the physicochemical and mechanical properties of thermoplastic polymers extensively used in the construction industry [51]. The researchers also examined commercially available filaments made from recyclable materials and equipment, allowing users to make their own filaments for 3D printing purposes.

2.3 Problems formulation and novelty

Focusing on long-term sustainability is crucial in the manufacturing business. Global climate mitigation has affected the industrial sector on a far larger scale. Increased resource utilisation has resulted in the depletion of raw materials for manufacturing. Additive production is a sophisticated manufacturing process that was developed in response to the deteriorating environment, economic imbalances, and inefficient production techniques for complex geometries [52]. Another aspect of sustainability to consider is the ability to recycle and reuse 3D printing materials. Given the high cost of materials in the metal 3D printing industry, this is a legitimate concern. Additionally, it saves resources by requiring fewer manufacturing steps. Fused deposition modelling (FDM) 3D printing uses thermoplastics as its primary material, increasing the total usage of plastic [53].

Fused filament fabrication (FFF) is the 3D printing method used in this investigation. The starting materials for this product are thermoplastic polymers in filaments [54]. A robotic nozzle uses molten filament from a heated source to build structures. Unfortunately, mineral oil is frequently used to develop these fossil-based polymers as nonrenewable materials. As a result, environmental sustainability suffers greatly due to this wasteful usage of resources [8]. Sustainable development has an obvious ecological component, and this research aims to discover ways to enhance that aspect. Furthermore, the longevity of FFM 3D-printing filaments may be extended in many ways [55].

The most popular filaments used in 3D printing are thermoplastic filaments. ABS and polylactic acid (PLA) plastics are the most extensively utilised in today's automobile sector. The remaining materials include polycarbonate (PC), polycaprolactone (PCL), polystyrene (PS), polyetheretherketone (PEEK), polyetherimide (PEI), and different polyethene (PE) varieties such as linear low-density polyethene (LLDPE), low-density polyethene (LDPE), and high-density polyethene (HDPE). These materials are frequently used to print various products, including vehicle components, medical equipment, prototypes, packaging, and children's toys [4].

Making 3D printing filament with a recycle bot (a domestic plastic extruder) and an open-source self-replicating 3D printer is a potential distributed recycling solution for PLA and ABS waste. Impurities in the computer waste that could affect filament consistency and obstruct the 3D printer nozzle were manually eliminated. The temperature was maintained above the glass transition point but below the breakdown of molecular structures for this experiment. The ABS material must be dried and crushed to avoid bubbles on the filament's surface [56].

3 Waste management in the plastic industry

Plastics have been used in our daily lives for less than 100 years, but they have many applications in our homes, workplaces, and on the road. Furthermore, because of their adaptability, plastics can be used in an almost infinite number of ways. The obvious advantages of high mechanical strength, low density, lightweight, ease of manufacture, and low cost are undeniable [57]. Plastics are used in various applications due to their properties, including packaging, the automobile industry, electricity generation, construction, transportation, medicine, and agriculture. However, extensive plastic use generates massive amounts of waste, and managing this waste is difficult. In 2018, 359 million metric tonnes of plastics were produced worldwide. This number is expected to double over the next 20 years.

Landfills are a common destination for plastic waste in many countries. Plastic waste is piling up in landfills at an alarming rate, and there is not enough room for it all. A more stringent approach to waste management is needed to support the circular economy's goal of recovering resources and reusing them. One hundred twenty-five percent of plastic garbage in landfills was processed in the EU (32.5% recycled, and 42.6% utilised for energy recovery). Re-extrusion, mechanical recycling, chemical reuse, and thermal processes that generate energy (combustion, pyrolysis, and gasification) are some methods available to cope with the ever-increasing amount of plastic waste. Primary recycling allows for the recovery of uncontaminated polymer remains with properties comparable to those of the original material to reduce waste. It may be used to dispose of waste materials from other parts of the production process, such as the extrusion process, which is utilised in most manufacturing facilities today [58].

Secondary recycling involves materials that may have been polluted in the process and non-contaminated resources. These pollutants are removed from the environment before conversion by shredding. It is milled and granulated and utilised as a raw material for plastic manufacture; however, the quality of this material is often poorer than that of primary recycling. In depolymerisation activities (solvolysis), polymers are transformed into chemicals reused in manufacturing as part of the chemical recycling process [59]. Plastics as an energy source are the least environmentally friendly option, although their calorific value is equivalent to that of fuel oil (average 42 MJ/kg) and they are very efficient energy sources [60]. These types of operations can release dioxins and other organic contaminants into the environment. As a result, they must be closely supervised at all times [61]. Currently, bacteria have not yet evolved enzymes that allow for the biological breakdown of plastics, which is important [62]. Polylactic acid (PLA) and polycaprolactone (PCL) are two examples of biodegradable polyesters used to make 3D printing filaments that degrade when exposed to environmental factors. PLA and PCL are both polymers that degrade when exposed to environmental factors [63].

It is necessary to process them to deal with the pyrolysis of plastics and the absence of polymer degradation. The use of landfills is just a temporary solution. A new solution is required due to the continual production of plastics and the poor degree of processing already available. There is no question that the most effective strategy to manage waste is to prevent it from being created in the first place. Plastics are sadly more prevalent and persistent in the environment than glass and metal packaging due to various factors, including simplicity of use, consumer lifestyle, advantages of characteristics, and cheaper production costs. A waste-free economy is still only a notion when establishing one. There is an urgent need for cost-effective plastic processing solutions to meet this demand. An innovative and high-potential solution for 3D printing using waste polymers is also being explored and may be employed in the future.

4 Methods for separating, decontaminating, and purifying plastic materials

Pyrolysis occurs in the creation of hazardous compounds from municipal plastic waste (MPW), which comprises various types of plastics such as polyvinyl chloride (PVC) and polyethene terephthalate (PET) [64]. PVC is converted into HCl and chlorinated hydrocarbons such dichloromethane (CH_2Cl_2) and chloroform ($CHCl_3$). Without the proper gas emission control modules, these organic and inorganic chlorides have the potential to destroy pyrolysis equipment, taint other products, and pollute the air [65]. Additionally, oxidising (burning) these chlorinated hydrocarbons can produce more dangerous byproducts, including dioxins and furans [66]. When PET thermally decomposes, carbonic acids such as benzoic and terephthalic acids are produced. They are problematic for the pyrolysis plant because they cause pipework to corrode and become clogged [67] (terephthalic acid is solid at room temperature). Additionally, the mechanical or chemical recycling of PET is more fascinating than its pyrolysis (e.g. hydrolysis, methanolysis, glycolysis, ammonolysis, and aminolysis). The entire depolymerisation of PET results from chemical recycling [68]. As a result, before pyrolysis, mixed polymers must be separated.

High-performance polymers and plastic decontamination are areas of expertise for several technologies. Recovering value, maintaining material qualities, and lowering material costs are all benefits of plastic decontamination recycling methods, to eliminate the dangerous chemicals in recycled plastics that have restricted their use. This is the case with odours or other substances that modify their physical characteristics, including resistance. Removing additional materials that are restricted by plastics do not disappear through recycling. The target plastic resin is first isolated from a mixed waste stream before the solvent extraction process can begin. The separated resin is dissolved in one or more carefully chosen solvents to create a homogenised solution. Then, using a series of physical separation and chemically aided procedures, non-plastic impurities such as additives, colourants, odorants, and others are eliminated from this homogenised solution. The purified plastic is dissolved in the filtrate that is still present. The filtrate mixture is then added with a non-solvent, and the purified resin is re-precipitated and recovered. The result is a refined resin that can be utilised to create new plastic products. The entire procedure uses non-hazardous solvents that are recovered and recirculated while operating at a relatively low temperature and pressure [69].

5 Thermal treatment for recycled material extruded

Recyclable material undergoes thermal processing before being extruded. Catalytic pyrolysis was discussed by [70] in terms of the makeup of the pyrolytic oil and the effects of operating factors like temperature and retention time. One method for transforming plastic into a preliminary liquid product is pyrolysis. A thermochemical process called thermal pyrolysis can be carried out at a variety of temperatures (350–900 °C), unlike combustion, which calls for a wide spectrum of oxidising agents (350–900 °C). Different temperatures–low (400 °C), medium (400–600 °C), and high (> 600 °C)–can be used for pyrolysis (i.e., PET). The medium (400–600 °C) and high (> 600 °C) types are determined by the temperature level and residence period (Table 2). Pyrolysis and the intended products are defined by temperature and residence time [69].

6 3D printing using recycled polymers

In recent years, there has been a significant increase in the global production of plastic-based products. A further point to note is that Asia accounted for half of the 359 million tonnes of plastic generated in 2019, with Europe accounting for just 17% of the total. For virgin plastic production, just 1.3 billion barrels of the 1.3 billion barrels of oil generated annually throughout the globe are required [59]. Most polymers used in manufacturing do not degrade and may be present in the environment for hundreds of years after manufacturing [72]. Environmental pollution is a key source of worry that stems from this fact. According to research, it is possible to reuse up to 90% of plastics. Currently, plastic rubbish accounts for up to 80% of landfill waste, with just a tiny fraction of that waste being recycled. Plastics generated from HDPE, LDPE (low-density polyethene), PP (polypropylene), and PVC (polyvinyl chloride), which manufacturers frequently use, are the most serious source of concern. Their landfills are a source of greenhouse gas emissions, damage the environment, and potentially harm human health [73]. PLA-related trash has a substantially less global impact than other types of garbage since its natural origin has no major environmental impact. As a consequence of their mechanical limitations, manufacturers are hesitant to use this material more frequently. However, the fact that, after a few recycling cycles, the material loses its features presents the biggest problem in recycling. Apart from that, there has been a reduction in instability, which might harm human health [74].

The use of 3D printing technology allows for creating complex structures on a smaller scale. However, because of technological improvements, the increased usage of plastic has also been a source of worry. Even while 3D printing waste is not a major problem, data show that the technology itself may be used to decrease the amount of post-production waste created, according to the manufacturer [75]. Recycling polymeric materials for 3D printing includes a variety of steps such as selective material separation, decontamination and purification, grinding, extrusion, and remelting. This operation's logistical and financial aspects are the most challenging aspects of the whole process. According to the results, recycling resources provides no economic advantage, and the cost of a recycled product is defined by the market price of the filament used in its creation in the first place [76].

Table 2 Based on operational circumstances and intended products, pyrolysis procedures were modified from [69, 71]

Process	heating Rate	Residence time	Temperature (°C)	Major products
Slow carbonisation	Very low	Days	450–600	Charcoal
Slow pyrolysis	< 5 °C/s	10–60 min	450–600	Char, oil
Fast pyrolysis	10–200 °C/s	0.5–5 s	550–650	Oil
Flash pyrolysis	1000 °C/s	< 1 s	450–900	Oil, gas

7 Recyclability and material characteristics

During extrusion, polymers degrade due to shear stress, temperature, and oxygen exposure. Although both PLA and PE are vulnerable to these components, this process happens in both of them [77]. It is important to note that the polymer's physical properties significantly influence the quality of the extrusion products that may be generated. For example, polymers' viscosity, molecular weight, and breaking strength may be drastically changed by repeatedly extruding them at high temperatures. In addition, various factors, such as temperature and the amount of material extruded, may induce changes in the qualities of the material [78, 79]

Some non-biodegradable plastic (HDPE: high-density polyethylene) is frequently utilised in geomembranes, plastic lumber, corrosion-resistant pipes, and plastic bottles. Due to its extensive daily use, which accounts for a significant portion of the plastic solid waste produced, it can also be viewed as a significant supply of raw materials for the recycling sector. For its high strength to density ratio, HDPE is well-known. As a reinforcement, ZrO_2 increases tensile strength and hardness, and creates a special recyclable material that can survive high temperatures for an extended period of time. Zirconium's white crystalline oxide, ZrO_2, is also referred to as zirconia (not to be confused with zircon) [23, 24]. The mineral baddeleyite is the most prevalent naturally occurring form of it and has a monoclinic crystalline structure. Cubic zirconia, a dopant-stabilised cubic structured zirconia, is produced in a range of hues for usage as a gemstone and a diamond substitute. According to a survey of the literature, numerous researches have been published on the use of metallic, ceramic, and nonmetallic particles in 3D printing applications to strengthen the recycling and recovery properties of polymers (Fig. 6). According to certain studies, adding 25% graphene via chemical and mechanical means to recycled acrylonitrile butadiene styrene (ABS) polymer improves electrical and thermal conductivity [80].

7.1 Polymers for 3D printing on a commercial scale

The 3D printing business is one of the most quickly increasing industries in the world right now. It is estimated that the market will have risen by more than 23% by 2021, reaching a value of more than ten million dollars by that period [81]. Even though 3D printing has only been around for a few years, it has quickly become a popular trend in recent years. Because of its simplicity and low production costs, 3D printing is often employed in prototype and small-scale manufacturing applications. 3D printing has recently grown in various industries, including aerospace, military, automotive, medical, and construction [81]. Among the materials used in 3D printing, thermoplastic filaments account for the majority (98%) [82]. ABS and PLA are the two most often encountered polymers worldwide [77]. Polycaprolactone (PCL) and many polyethene (PE) variants, including low-density (LD), linear low-density, and high-density polyethene, are among the materials used (HD). Polycarbonate (PC), polystyrene (PS), polyetherimide (PEI), and polyetheretherketone (PEEK) are all included in this category (high-density PE). Printed products ranging from vehicle components to medical equipment to prototypes to packaging to miniature garden buildings to children's playthings are routinely produced utilising these sorts of materials, as are a broad range of other items. Unfortunately, even if the advantages of 3D printing exceed the technology's negatives, the process still creates much waste.

Furthermore, since prints may be used to construct components without machining or other equipment, many of them are destroyed after just a few applications. The waste management problem will only worsen as the number of thermoplastic prints increases with the development of additive technologies. Recycled plastic filaments might be a feasible replacement for virgin plastic filaments. Most 3D printing filaments are produced by extrusion, which includes putting a granulate or polymer powder into an extruder, which is then heated to homogenise the material into a line with precisely defined properties (standardised diameter, adapted to the size of the printer element). Many manufacturers now offer recycled PLA and ABS filaments for 3D printing applications. Unfortunately, very little is known about the mechanical properties of recycled filaments at this point. Despite this, they significantly influence the overall quality of printed items. Therefore, it would be beneficial to research the rates of recycled filaments and compare them to the rates of virgin material to enhance 3D printing technology in the future [77].

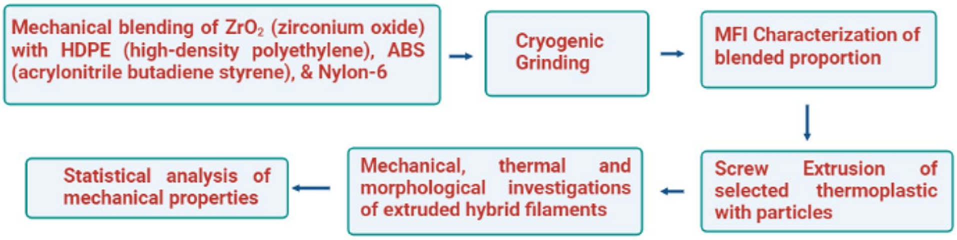


Fig. 6 The procedures needed to recycle thermoplastic waste

7.2 Polymer manufacturing additives

Many attempts have been made to develop a new generation of 3D printing materials to combat environmental pollution and replace the rapidly diminishing supply of post-petroleum plastics. Research and testing on recycled polymer additives that enhance molecular weight and improve mechanical properties have been carried out in great detail. It has been investigated if additives that extend polymer chains and peroxides that accelerate the formation of free radicals are beneficial (molecular weight increase, cross-linking agent). After being combined with lignin, PLA is extruded at temperatures between 180 and 190 °C. Compared to samples made entirely of PLA, the addition of biopolymer improves melting characteristics but lowers tensile strength by 18% and Young's modulus by around 6% [83]. In addition, carbon fibres were used in the construction of the vehicle. In comparison to the original material, the recycled material had a 25% higher bending strength than the original. Among the materials tested, CFR (carbon fibre reinforced) and PLA (polylactic acid) had recovery rates of 100% and 71%, respectively [84]. The polymer's properties were improved for the first time during this method. With the continual loss of physical properties in recycled polymers, it became clear that new adhesive reinforcement types would need to be investigated. As a result, dopamine was used in this experiment since most surfaces are easily absorbed and have a long half-life.

Additionally, this property may be coated with polymers to give them a unique appearance. It is necessary to mix the ground PLA into an ammonia-based dopamine solution for 4 h after it has been introduced. PLA is then dried and extruded as a result of this process. The mass dispersion of PLA containing dopamine starts at 200 °C, but the temperature of pure PLA is more than 320 °C. Aside from this improvement, the coating also increased the material's tensile strength by about 20% [85, 86].

The use of antioxidants and oxidising stabilisers may help enhance recycled plastics' properties. Hydroquinone and tropolone are examples of such medications. Hydroquinone has been found to maintain the stability of the PLA chain length during thermal processing, making it a more effective free radical scavenger than other chemicals. The material's mechanical properties were found to be similar to these results [87]. In the past, polyethene terephthalate (PET) and post-pyrolysis packaging waste were also used as 3D printing materials (biochar filament, 0.5 and 5% by weight). A significant increase in the strength of the composite was seen when comparing pure PET shred to the composite (between 32 and 60%) [88]. It has also been improved in terms of thermal and dimensional stability for mixed compounds. Unique 3D printing methods, such as utilising lignocellulose-based mats that may be 3D printed using recycled PET, have been investigated for their possible use in novel 3D printing processes [89]. According to the alignment of the fibres and the direction of matting (directional or oppositional), different results were obtained for the mechanical properties that were examined (for example, tensile strength value for directional 15.72 MPa and oppositional 2.5 MPa). The article suggested that mats may be suitable for use in additive manufacturing processes in the future.

An addition in the form of biocarbon was shown to enhance the regenerated material's mechanical characteristics significantly. Thermal treatment combined recycled PET bottles with biocarbon (100 m). The material's tensile strength was improved by 32% due to the inclusion of an extra component. The modulus of elasticity increased by nearly 60%, and the resistance to heat and oxidative conditions improved [88]. As well as reinforcing PLA, biocarbon may also be utilised to strengthen other materials. The stiffness of the samples was found to be enhanced by the additions in conjunction with natural additives (up to 8%) [90]. Recycled gypsum (0–50 wt.) and hemp or harakeke fibre filaments (0–50 wt.) were added individually during the formation of new mat types to boost the value of recycled polypropylene (PP). The greatest results were from harakeke fibber filaments (30 wt.; tensile strength 39 MPa, Young modulus 2.8 GPa). When printing procedures are used to print certain materials, they tend to lose some of their characteristics [80]. Recycled polymers might be improved by adding nanocrystalline powders of Fe, Si, Cr, and Al into the extrusion process of PP and HDPE filaments. When compared to the values of the base materials, adding 1% of a powder combination (Fe-Si-Cr or Fe-Si-Al) increased yield strength by 37% and young modulus by 17%. Metals also help prevent cracks from forming [91]. Recycled HDPE with an addition in SiC/Al_2O_3 showed a considerable increase in mechanical strength. Paraffin wax serves as a binding agent when HDPE waste is combined with reinforcing (SiC/Al_2O_3). A screw extruder is used to extrude the mixture. The material's thermal properties are marginally affected by the addition of the additive, while the material's mechanical strength is greatly improved. According to literature, zirconium oxide might be used to improve recycled HDPE in another investigation. A ball mill grinds the additive into the polymer after mechanical mixing [4]. At 190 °C, the filament is extruded. The coefficient of friction of the unreinforced material is 40% greater than that of the zirconium oxide-reinforced polymer. For low-temperature bearings, the novel polymer may serve as a construction material. It was tested if a stabilisation promoter, SEBS, could be added to the PET, PP, and PE combination used as a feedstock for 3D printing. The tensile strength of the mixes was lower than that of pure recycled PET (23 MPa for PP/PS mix, 19 MPa with SEBS addition) (35 MPa). In most instances, PP/PET was 50–50 weighted, although glass transition was moved to a higher temperature range in others [92]. The recycled material's characteristics were greatly enhanced by including an extra component or multiple components. To address the issue of restricted material reuse, this is a novel way.

8 Recommended applications and perspectives for the future

Plants have become increasingly popular over the last years with low production costs, lightweight, durability, and strength. This is particularly true for consumers. Furthermore, they have a lengthy shelf life, are detrimental to the environment, and are non-biodegradable in nature [93]. Plastics have been extensively used throughout the last 50 years due to their durability, versatility, and low production costs, among other factors [56]. It is estimated that by 2050, the world will manufacture about 320 million of magnesium per year, which is predicted to climb to 850 million Mg by 2050. In the preceding 30 years, the production of plastics has increased by a factor of five.

Additionally, there is an increasing problem with plastic waste, which necessitates the development of environmentally beneficial methods of using waste plastic in production. In typical recycling, low-density plastics are collected and separated from higher density plastics. Because the movement of products can pollute the environment, so there is need to remove it. In addition, Recyclebot's distributed recycling technique is more environmentally friendly since it makes filament for 3D printing out of recycled plastic wastes derived from the users' trash. Using rubbish as a resource to manufacture valuable items at the place of genesis is a revolutionary method of recycling that can transform the world [56]. Different types of plastic garbage may be recycled in a variety of ways. Plastics may be recycled in various ways, including chemical, mechanical, energy, and re-extrusion recycling. Palletisation and extrusion are two of the most effective methods [93]. The market impacts the need for plastic recycling [80].

On the other hand, typical recycling has considerable drawbacks, such as rubbish disposal and polluting the environment. 3D printing for closed-loop recycling might be a realistic alternative in the future [74, 75]. Personalised products may be created via 3D printing, also known as additive manufacturing (AM) [85]. Thermoplastics that are utilised as feedstock for AM may be recovered via the process [80]. Some possible uses include medicine, food, construction materials, toys, and other things [86]. Combining recycled polymers' thermal, mechanical, and tribological properties is feasible by fabricating composites that incorporate a polymeric matrix reinforced by fibre, ceramics, metal, or glass, among other materials [94].

When printing operations, such as print speed, melting temperature, melt pressure, and nozzle size, are modified and standardised, accuracy improves. The mechanical properties of an FDM-printed item might vary substantially depending on the printing circumstances. Optimising the processing of each composite polymer is required to provide consistent prints and reduce waste from failed prints and support materials. Appropriate material for layer-by-layer building must have low melting temperatures and viscosity and solidify fast after extrusion to prevent clogging the nozzle. Increased melt viscosity may impair the material's printability due to the fillers used in biocomposite polymers [95]. When the printing direction raster angle is zero, printed goods' anisotropic behaviour and mechanical characteristics improve. Print speed is also important to guarantee that the extruded material cools enough before applying the next layer without distortion. However, the layer must not cool down too rapidly to prevent future layers from adhering [96].

9 Conclusions

As a result of their incapacity to disintegrate, when plastics degrade, they damage the ecosystem in which they occur. According to the literature studies, recycling has proven to be the most successful technique for maximising the value of post-consumer plastics. Plastics deteriorate over 10 to 450 years, depending on the material. Historic practices included utilising large, centralised enterprises that create low-value commodities for recycling purposes. The high cost of transportation is a contributing cause to this situation. Desktop 3D printing permits manufacturing complex plastic things at the user's location rather than in a factory. This sector's value is projected to increase dramatically in the next few years. Consumers may create their items out of recycled materials, which is the basic premise of the initiative and saving money in various ways, including reducing spending on commercial plastic products and lowering environmental expenses. Additionally, we have seen in various articles many alternative applications for various needs during the present coronavirus epidemic. For example, through 3D printing, it may be possible to create visors that protect the eyes against coronavirus infection. For example, 3D printing enables manufacturers to adjust fast to their production processes in response to changing market needs.

Non-biodegradable materials have mostly replaced biodegradable materials in 3DP applications due to their superior mechanical and physical properties. Because of their exceptional physical properties, some materials, such as acrylonitrile butadiene styrene (ABS), are used as replacement parts or prototypes in the manufacturing industry. ABS is a high melting point thermoplastic polymer. On the other hand, these materials are not environmentally friendly, necessitating the urgent search for more biodegradable alternatives. Although certain filaments have been produced using bio-based fillers such as plant-based to give the printed item a wood-like look and feel, this is not always the case. Therefore, materials that are both environmentally friendly and cost-effective are urgently required. This paper aims to look at the utility of reusable and biodegradable materials for FDM, focusing on the sustainability of materials used in extrusion-based 3D printing that might be utilised as biomaterials for consumer prototypes and other applications.

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Data availability All data and information are mentioned in the manuscript.

Declarations

Ethics approval The submitted work is original, not published or submitted elsewhere in any form or language.

Consent to participate Consent was obtained from all individual participants included in the study.

Consent to publish The author confirms that the work described has not been published before and is not under consideration for publication elsewhere. All co-authors have approved the work.

Conflict of interest The author declares no competing interests.

References

1. Rahman MH, Bhoi PR (2021) An overview of non-biodegradable bioplastics. J Clean Prod 294:126218
2. Wei X-F, Bohlén M, Lindblad C, Hedenqvist M, Hakonen A (2021) Microplastics generated from a biodegradable plastic in freshwater and seawater. Water Res 198:117123
3. Antelava A, Jablonska N, Constantinou A, Manos G, Salaudeen SA, Dutta A, Al-Salem SM (2021) Energy Potential of Plastic waste valorization: a short comparative assessment of pyrolysis versus gasification. Energy Fuels 35:3558–3571
4. Mikula K, Skrzypczak D, Izydorczyk G, Warchoł J, Moustakas K, Chojnacka K, Witek-Krowiak A (2021) 3D printing filament as a second life of waste plastics—a review. Environ Sci Pollut Res 28:12321–12333
5. Gorji NE, O'connor R, Brabazon D (2021) XPS, SEM, AFM, and nano-indentation characterization for powder recycling within additive manufacturing process. IOP Conf Ser Mater Sci Eng IOP Publishing 12025
6. Belka M, Bączek T (2021) Additive manufacturing and related technologies–the source of chemically active materials in separation science. TrAC Trends Anal Chem 142:116322
7. Baca D, Ahmad R (2020) The impact on the mechanical properties of multi-material polymers fabricated with a single mixing nozzle and multi-nozzle systems via fused deposition modeling. Int J Adv Manuf Technol 106:4509–4520. https://doi.org/10.1007/s00170-020-04937-3
8. Suárez L, Domínguez M (2020) Sustainability and environmental impact of fused deposition modelling (FDM) technologies. Int J Adv Manuf Technol 106:1267–1279. https://doi.org/10.1007/s00170-019-04676-0
9. Camposeco-Negrete C (2020) Optimization of printing parameters in fused deposition modeling for improving part quality and process sustainability. Int J Adv Manuf Technol 108:2131–2147. https://doi.org/10.1007/s00170-020-05555-9
10. Liu Z, Wang Y, Wu B, Cui C, Guo Y, Yan C (2019) A critical review of fused deposition modeling 3D printing technology in manufacturing polylactic acid parts. Int J Adv Manuf Technol 102:2877–2889. https://doi.org/10.1007/s00170-019-03332-x
11. Lebedev SM, Gefle OS, Amitov ET, Zhuravlev DV, Berchuk DY, Mikutskiy EA (2018) Mechanical properties of PLA-based composites for fused deposition modeling technology. Int J Adv Manuf Technol 97:511–518. https://doi.org/10.1007/s00170-018-1953-6
12. Mustapha KB, Metwalli KM (2021) A review of fused deposition modelling for 3D printing of smart polymeric materials and composites. Eur Polym J 156:110591
13. Bandyopadhyay A, Traxel KD, Lang M, Juhasz M, Eliaz N, Bose S (2022) Alloy design via additive manufacturing: advantages, challenges, applications and perspectives. Mater Today
14. Panda BN, Shankhwar K, Garg A, Jian Z (2017) Performance evaluation of warping characteristic of fused deposition modelling process. Int J Adv Manuf Technol 88:1799–1811. https://doi.org/10.1007/s00170-016-8914-8
15. Sehhat MH, Mahdianikhotbesara A, Yadegari F (2022) Impact of temperature and material variation on mechanical properties of parts fabricated with fused deposition modeling (FDM) additive manufacturing. Int J Adv Manuf Technol 120:4791–4801. https://doi.org/10.1007/s00170-022-09043-0
16. Boulaala M, Elmessaoudi D, Buj-Corral I, El Mesbahi J, Ezbakhe O, Astito A, El Mrabet M, El Mesbahi A (2020) Towards design of mechanical part and electronic control of multi-material/multicolor fused deposition modeling 3D printing. Int J Adv Manuf Technol 110:45–55. https://doi.org/10.1007/s00170-020-05847-0
17. Raoufi K, Haapala KR, Etheridge T, Manoharan S, Paul BK (2022) Cost and environmental impact assessment of stainless steel microscale chemical reactor components using conventional and additive manufacturing processes. J Manuf Syst 62:202–217
18. Jawadand S, Randive K (2021) A sustainable approach to transforming mining waste into value-added products. Innov Sustain Min Springer 1–20
19. Kerekes TW, Lim H, Joe WY, Yun GJ (2019) Characterization of process–deformation/damage property relationship of fused deposition modeling (FDM) 3D-printed specimens. Addit Manuf 25:532–544
20. Zhang X, Fan W, Liu T (2020) Fused deposition modeling 3D printing of polyamide-based composites and its applications. Compos Commun 21:100413
21. Lin S, Xia L, Ma G, Zhou S, Xie YM (2019) A maze-like path generation scheme for fused deposition modeling. Int J Adv Manuf Technol 104:1509–1519. https://doi.org/10.1007/s00170-019-03986-7
22. Li G, Zhao J, Jiang J, Jiang H, Wu W, Tang M (2018) Ultrasonic strengthening improves tensile mechanical performance of

fused deposition modeling 3D printing. Int J Adv Manuf Technol 96:2747–2755. https://doi.org/10.1007/s00170-018-1789-0

23. Hongyao S, Xiaoxiang Y, Jianzhong F (2018) Research on the flexible support platform for fused deposition modeling. Int J Adv Manuf Technol 97:3205–3221. https://doi.org/10.1007/s00170-018-2046-2
24. Dumpa N, Butreddy A, Wang H, Komanduri N, Bandari S, Repka MA (2021) 3D printing in personalized drug delivery: an overview of hot-melt extrusion-based fused deposition modeling. Int J Pharm 600:120501
25. Zou S, Xiao J, Ding T, Duan Z, Zhang Q (2021) Printability and advantages of 3D printing mortar with 100% recycled sand. Constr Build Mater 273:121699
26. Javaid M, Haleem A, Singh RP, Suman R, Rab S (2021) Role of additive manufacturing applications towards environmental sustainability. Adv Ind Eng Polym Res 4:312–322
27. Liu G, Zhang X, Chen X, He Y, Cheng L, Huo M, Yin J, Hao F, Chen S, Wang P (2021) Additive manufacturing of structural materials. Mater Sci Eng R Reports 145:100596
28. Peng T, Kellens K, Tang R, Chen C, Chen G (2018) Sustainability of additive manufacturing: an overview on its energy demand and environmental impact. Addit Manuf 21:694–704
29. Le Bourhis F, Kerbrat O, Hascoet J-Y, Mognol P (2013) Sustainable manufacturing: evaluation and modeling of environmental impacts in additive manufacturing. Int J Adv Manuf Technol 69:1927–1939
30. Kerbrat O, Bourhis FL, Mognol P, Hascoët J-Y (2016) Environmental impact assessment studies in additive manufacturing. Handb Sustain Addit Manuf Springer 31–63
31. Rejeski D, Zhao F, Huang Y (2018) Research needs and recommendations on environmental implications of additive manufacturing. Addit Manuf 19:21–28
32. Mohamed OA, Masood SH, Bhowmik JL (2015) Optimization of fused deposition modeling process parameters: a review of current research and future prospects. Adv Manuf 3:42–53
33. Arnold C, Monsees D, Hey J, Schweyen R (2019) Surface quality of 3D-printed models as a function of various printing parameters. Materials (Basel) 12:1970
34. Huang J, Chen Q, Jiang H, Zou B, Li L, Liu J, Yu H (2020) A survey of design methods for material extrusion polymer 3D printing. Virtual Phys Prototyp 15:148–162
35. Song R, Telenko C (2016) Material waste of commercial FDM printers under realistic conditions. Int Solid Freeform Fabr Symp. University of Texas at Austin
36. Bell C (2014) Maintaining and troubleshooting your 3D printer. Springer
37. Go J, Schiffres SN, Stevens AG, Hart AJ (2017) Rate limits of additive manufacturing by fused filament fabrication and guidelines for high-throughput system design. Addit Manuf 16:1–11
38. Valerga AP, Batista M, Fernandez-Vidal SR, Gamez AJ (2019) Impact of chemical post-processing in fused deposition modelling (FDM) on polylactic acid (PLA) surface quality and structure. Polymers (Basel) 11:566
39. Ajayi SO, Oyedele LO, Akinade OO, Bilal M, Alaka HA, Owolabi HA, Kadiri KO (2017) Attributes of design for construction waste minimization: a case study of waste-to-energy project. Renew Sustain Energy Rev 73:1333–1341
40. Albi E, Kozel K, Ventoza D, Wilmoth R (2014) Akabot: 3d printing filament extruder
41. Aziz HA, Abu Amr SS, Vesilind PA, Wang LK, Hung Y-T (2021) Introduction to solid waste management. Solid Waste Eng Manag Springer 1–84
42. Dul S, Fambri L, Pegoretti A (2016) Fused deposition modelling with ABS–graphene nanocomposites. Compos Part A Appl Sci Manuf 85:181–191
43. Song R, Telenko C (2017) Material and energy loss due to human and machine error in commercial FDM printers. J Clean Prod 148:895–904
44. Tan Q, Ren Z, Cai T, Li C, Zheng T, Li S, Xiong J (2015) Wireless passive temperature sensor realized on multilayer HTCC tapes for harsh environment. J Sensors
45. Song R (2019) Towards automated guidance for helping novices design for sustainable additive manufacturing and CNC machining
46. Petsiuk AL, Pearce JM (2020) Open source computer vision-based layer-wise 3D printing analysis. Addit Manuf 36:101473
47. Tabelin CB, Park I, Phengsaart T, Jeon S, Villacorte-Tabelin M, Alonzo D, Yoo K, Ito M, Hiroyoshi N (2021) Copper and critical metals production from porphyry ores and E-wastes: a review of resource availability, processing/recycling challenges, socio-environmental aspects, and sustainability issues. Resour Conserv Recycl 170:105610
48. Jadoun S, Yáñez J, Mansilla HD, Riaz U, Chauhan NPS (2022) Conducting polymers/zinc oxide-based photocatalysts for environmental remediation: a review. Environ Chem Lett. https://doi.org/10.1007/s10311-022-01398-w
49. Jadoun S, Riaz U, Budhiraja V (2020) Biodegradable conducting polymeric materials for biomedical applications: a review. Med Devices Sens. https://doi.org/10.1002/mds3.10141
50. Verma R, Vinoda KS, Papireddy M, Gowda ANS (2016) Toxic pollutants from plastic waste-a review. Procedia Environ Sci 35:701–708
51. Lanzotti A, Martorelli M, Maietta S, Gerbino S, Penta F, Gloria A (2019) A comparison between mechanical properties of specimens 3D printed with virgin and recycled PLA. Procedia Cirp 79:143–146
52. Keshavamurthy R, Tambrallimath V, Ugrasen G, Girish DP (2021) Sustainable product development by fused deposition modelling process. Fused Depos Model Based 3D Print Springer 213–225
53. Ngo TD, Kashani A, Imbalzano G, Nguyen KTQ, Hui D (2018) Additive manufacturing (3D printing): a review of materials, methods, applications and challenges. Compos Part B Eng 143:172–196
54. Wickramasinghe S, Do T, Tran P (2020) FDM-based 3D printing of polymer and associated composite: a review on mechanical properties, defects and treatments. Polymers (Basel) 12:1529
55. Schneevogt H, Stelzner K, Yilmaz B, Abali BE, Klunker A, Völlmecke C (2021) Sustainability in additive manufacturing: exploring the mechanical potential of recycled PET filaments. Compos Adv Mater 30:26349833211000064
56. Zhong S, Pearce JM (2018) 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
57. Mwanza BG, Mbohwa C (2017) Drivers to sustainable plastic solid waste recycling: a review. Procedia Manuf 8:649–656
58. Singh R, Singh J, Singh S (2016) Investigation for dimensional accuracy of AMC prepared by FDM assisted investment casting using nylon-6 waste based reinforced filament. Measurement 78:253–259
59. Singh N, Hui D, Singh R, Ahuja IPS, Feo L, Fraternali F (2017) Recycling of plastic solid waste: a state of art review and future applications. Compos Part B Eng 115:409–422
60. Kumar S, Panda AK, Singh RK (2011) A review on tertiary recycling of high-density polyethylene to fuel. Resour Conserv Recycl 55:893–910
61. Ragaert K, Delva L, Van Geem K (2017) Mechanical and chemical recycling of solid plastic waste. Waste Manag 69:24–58
62. Snyder JC, Stimpson CK, Thole KA, Mongillo DJ (2015) Build direction effects on microchannel tolerance and surface roughness. J Mech Des 137

63. Jadoun S, (2019) Polylactide (PLA) based nanocomposites for applications in antibacterial/microbial and biomedical engineering. Biocompos Biomed VI
64. Jadoun S, Jangid NK, (2019) Polyvinyl alcohol (PVA) based nanocomposites for biomedical and tissue engineering applications. Biocompos Biomed VI
65. Arjang S, Motahari K, Saidi M (2018) Experimental and modeling study of organic chloride compounds removal from naphtha fraction of contaminated crude oil using sintered γ-Al2O3 nanoparticles: equilibrium, kinetic, and thermodynamic analysis. Energy Fuels 32:4025–4039
66. Lee K-H (2007) Pyrolysis of municipal plastic wastes separated by difference of specific gravity. J Anal Appl Pyrolysis 79:362–367
67. Muhammad C, Onwudili JA, Williams PT (2015) Thermal degradation of real-world waste plastics and simulated mixed plastics in a two-stage pyrolysis–catalysis reactor for fuel production. Energy Fuels 29:2601–2609
68. Yoshioka T, Handa T, Grause G, Lei Z, Inomata H, Mizoguchi T (2005) Effects of metal oxides on the pyrolysis of poly (ethylene terephthalate). J Anal Appl Pyrolysis 73:139–144
69. Belbessai S, Azara A, Abatzoglou N (2022) Recent advances in the decontamination and upgrading of waste plastic pyrolysis products: an overview. Processes 10:733
70. Miandad R, Barakat MA, Aburiazaiza AS, Rehan M, Nizami AS (2016) Catalytic pyrolysis of plastic waste: a review. Process Saf Environ Prot 102:822–838
71. Gao F (2010) Pyrolysis of waste plastics into fuels
72. Gu L, Ozbakkaloglu T (2016) Use of recycled plastics in concrete: a critical review. Waste Manag 51:19–42
73. Aboulkas A, El Bouadili A (2010) Thermal degradation behaviors of polyethylene and polypropylene. Part I: Pyrolysis kinetics and mechanisms. Energy Convers Manag 51:1363–1369
74. Lithner D, Larsson Å, Dave G (2011) Environmental and health hazard ranking and assessment of plastic polymers based on chemical composition. Sci Total Environ 409:3309–3324
75. Sanchez FAC, Boudaoud H, Hoppe S, Camargo M (2017) Polymer recycling in an open-source additive manufacturing context: mechanical issues. Addit Manuf 17:87–105
76. Hopewell J, Dvorak R, Kosior E (2009) Plastics recycling: challenges and opportunities. Philos Trans R Soc B Biol Sci 364:2115–2126
77. Anderson I (2017) Mechanical properties of specimens 3D printed with virgin and recycled polylactic acid, 3D Print. Addit Manuf 4:110–115
78. Jadoun S, Riaz U, Budhiraja V (2021) Biodegradable conducting polymeric materials for biomedical applications: a review Med Devices Sens 4:e10141. https://doi.org/10.1002/mds3.10141
79. Zander NE, Gillan M, Burckhard Z, Gardea F (2019) Recycled polypropylene blends as novel 3D printing materials. Addit Manuf 25:122–130
80. Singh R, Kumar R, Tiwari S, Vishwakarma S, Kakkar S, Rajora V, Bhatoa S (2021) On secondary recycling of ZrO2-reinforced HDPE filament prepared from domestic waste for possible 3-D printing of bearings. J Thermoplast Compos Mater 34:1254–1272
81. Shah AA, Hasan F, Hameed A, Ahmed S (2008) Biological degradation of plastics: a comprehensive review. Biotechnol Adv 26:246–265
82. Jadoun S, (2019) Cellulose based nanocomposites for biomedical and pharmaceutical applications. Biocompos Biomed VI
83. Gkartzou E, Koumoulos EP, Charitidis CA (2017) Production and 3D printing processing of bio-based thermoplastic filament. Manuf Rev 4:1
84. Telenko C, Seepersad CC (2012) A comparison of the energy efficiency of selective laser sintering and injection molding of nylon parts. Rapid Prototyp J
85. Zhao P, Rao C, Gu F, Sharmin N, Fu J (2018) Close-looped recycling of polylactic acid used in 3D printing: an experimental investigation and life cycle assessment. J Clean Prod 197:1046–1055
86. Zhao XG, Hwang K-J, Lee D, Kim T, Kim N (2018) Enhanced mechanical properties of self-polymerized polydopamine-coated recycled PLA filament used in 3D printing. Appl Surf Sci 441:381–387
87. Pillin I, Montrelay N, Bourmaud A, Grohens Y (2008) Effect of thermo-mechanical cycles on the physico-chemical properties of poly (lactic acid). Polym Degrad Stab 93:321–328
88. Idrees M, Jeelani S, Rangari V (2018) Three-dimensional-printed sustainable biochar-recycled PET composites. ACS Sustain Chem Eng 6:13940–13948
89. Tian X, Liu T, Wang Q, Dilmurat A, Li D, Ziegmann G (2017) Recycling and remanufacturing of 3D printed continuous carbon fiber reinforced PLA composites. J Clean Prod 142:1609–1618
90. Notta-Cuvier D, Odent J, Delille R, Murariu M, Lauro F, Raquez J-M, Bennani B, Dubois P (2014) Tailoring polylactide (PLA) properties for automotive applications: effect of addition of designed additives on main mechanical properties. Polym Test 36:1–9
91. Pan G, Chong S, Tsai H, Lu W, Yang TC (2018) The effects of iron, silicon, chromium, and aluminum additions on the physical and mechanical properties of recycled 3D printing filaments. Adv Polym Technol 37:1176–1184
92. Xu F, Loh HT, Wong YS (1999) Considerations and selection of optimal orientation for different rapid prototyping systems. Rapid Prototyp J
93. Shah J, Snider B, Clarke T, Kozutsky S, Lacki M, Hosseini A (2019) Large-scale 3D printers for additive manufacturing: design considerations and challenges. Int J Adv Manuf Technol 104:3679–3693
94. Boparai KS, Singh R, Fabbrocino F, Fraternali F (2016) Thermal characterization of recycled polymer for additive manufacturing applications. Compos Part B Eng 106:42–47
95. Jadoun S, Anna Dilfi KF (2021) Silver nanoparticles with natural polymers. Polym Nanocompos Based Silver Nanoparticles Synth Charact Appl 139–157
96. Rett JP, Traore YL, Ho EA (2021) Sustainable materials for fused deposition modeling 3D printing applications. Adv Eng Mater 23:2001472