Al-Nahrain Journal for Engineering Sciences **NJES** 28(3)442-450, 2025
http://doi.org/10.29194/NJES.28030442

Utilizing Sustainable Recycled thermoplastic polymers in 3D Printing Filament

Bashar Dheyaa Hussein[1], Ghanim Sh. Sadiq[2]

Authors affiliations:
1) Department of Mechanical Engineering, Al-Nahrain University, Baghdad, Iraq
st.bashar.dh.hussein@ced.nahrainuniv.edu.iq

2*) Department of Mechanical Engineering, Al-Nahrain University, Baghdad, Iraq.
ghanim.s.sadiq@nahrainuniv.edu.iq

Paper History:

Received: 10th Nov. 2024

Revised: 26th Dec. 2024

Accepted: 8th Mar. 2025

Abstract

Over the last several years, additive manufacturing (AM), sometimes known as "3D printing", has seen remarkable expansion due to mechatronics and materials science advancements. Fused filament deposition (FDM) production is the predominant technology in additive manufacturing (AM) because of its cost-effectiveness in operational and material expenses. Nevertheless, the materials often used for this technique are pristine thermoplastics. Unsuccessful printing and throwaway prototypes generate a significant quantity of trash. Utilizing green and sustainable products is crucial to minimize the environmental effects. Recycled, bio-based, and mixed recycled materials provide a promising solution for 3D printing. The absence of comprehension about the interlayer adhesion process and material degradation in FDM printing has presented a significant obstacle for these environmentally friendly materials. This study comprehensively examines many materials used for FDM three-dimensional printing filaments, including recycled, bio-based, and mixed materials. The merits and drawbacks of thermoplastics and their composites were deliberated over. This evaluation is a comprehensive guide for engineers and researchers in selecting appropriate materials for three-dimensional printing. Three-dimensional printed objects have worse mechanical characteristics in comparison to injection molded materials.

Keywords: Polymer Recycle,3D Printing, Filament Production.

استخدام البوليمرات الحرارية البلاستيكية المعاد تدويرها بشكل مستدام في خيوط الطباعة ثلاثية الأبعاد

بشار ضياء حسين، غانم شاكر صادق

الخلاصة:

على مدى السنوات العديدة الماضية، شهدت التصنيع الإضافي (AM)، والمعروف أحيانًا باسم "الطباعة ثلاثية الأبعاد"، توسعًا ملحوظًا بسبب التقدم في الميكاترونيات وعلوم المواد. يعد إنتاج ترسب الخيوط المندمجة (FDM) التكنولوجيا السائدة في التصنيع الإضافي (AM) نظرًا لفعاليته من حيث التكلفة في النفقات التشغيلية والمواد. ومع ذلك، فإن المواد المستخدمة غالبًا لهذه التقنية هي مواد بلاستيكية حرارية نقية. تولد الطباعة غير الناجحة والنماذج الأولية التي يتم التخلص منها كمية كبيرة من القمامة. يعد استخدام المنتجات الخضراء والمستدامة أمرًا بالغ الأهمية لتقليل التأثيرات البيئية. توفر المواد المعاد تدويرها والمواد البيولوجية والمعاد تدويرها المختلطة حلاً واعدًا للطباعة ثلاثية الأبعاد. لقد شكل غياب الفهم حول عملية التصاق الطبقات وتدهور المواد في طباعة FDM عقبة كبيرة أمام هذه المواد الصديقة للبيئة. تدرس هذه الدراسة بشكل شامل العديد من المواد المستخدمة في خيوط الطباعة ثلاثية الأبعاد FDM، بما في ذلك المواد المعاد تدويرها والمواد البيولوجية والمختلطة. تمت مناقشة مزايا وعيوب المواد البلاستيكية الحرارية ومركباتها. يعد هذا التقييم دليلاً شاملاً للمهندسين والباحثين في اختيار المواد المناسبة للطباعة ثلاثية الأبعاد. تتمتع الأشياء المطبوعة ثلاثية الأبعاد بخصائص ميكانيكية أسوأ مقارنة بالمواد المصبوبة بالحقن.

الكلمات المفتاحية: إعادة تدوير البوليمر، الطباعة ثلاثية الأبعاد، إنتاج الخيوط

1.Introduction

Over the past few years, growing concerns about plastic waste contamination have prompted a shift towards circular economy models. These models enable the manufacturing of sustainable plastics, offering numerous socio-economic and environmental advantages. Extending material life and the materials' recovery at the end of their service life are fundamental aspects of this emerging

NJES is an **open access Journal** with **ISSN 2521-9154** and **eISSN 2521-9162**

economic paradigm [1]. Within this framework, it is imperative to prioritize creating effective recycling strategies for polymer-based materials. By continuously reusing waste and scraps, we can strive to eliminate the need for new resources and fully maximize the value of material waste [2]. According to a report on curbsides in the U.S., if the massive amount of recyclable materials produced, about 37.4 million tons, were effectively reused, it would have a significant positive impact. Specifically, it might decrease the United States emissions of greenhouse gases by a staggering 96 million metric tons of carbon dioxide equivalent. Additionally, it would conserve a yearly energy equivalent of 154 million barrels of oil and have the same effect as removing over 20 million cars from the road [3].

The push for sustainable development is driving Recent Developments in materials for three-dimensional printing technology. The thermoplastic materials most commonly utilized for fused filament/granular fabrication are polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) [4]. These materials are increasingly being sourced from recycled materials, a positive development. In addition to traditional 3D printing materials, new polymers and composite materials made from biological or cellulose sources were developed [5], [6]. It is crucial to prioritize the sustainable extraction of raw materials, particularly from renewable sources, to align with the principles of the circular economy. In addition, it is essential to consider every aspect of the process, including material processing, product design, production, usage, and post-use, to promote sustainability, including minimizing energy use, reducing processing steps, and minimizing waste production. There are a few options from a closed-loop perspective regarding the end-of-life stage: product remanufacturing, reuse, or recycling. Manufacturing practices prioritizing sustainability adhere to the 6R principles, which encompass reducing, remanufacturing, reusing, recovering, recycling, and redesigning [7].

3D printing technology has transformed the worldwide market for advanced items with sophisticated designs and exquisite details in industrial areas like construction and transportation [8]. The popularity of additive manufacturing (AM) using thermoplastic material has surged because of its cost-effectiveness and lack of need for extra equipment and molding [9]. Additive manufacturing (AM) or 3D printing is a method of combining materials to produce physical things based on a computer-aided design (CAD) process [10]. This technique can create objects with intricate geometries with little assistance, a task that is sometimes not feasible with conventional production machinery [11].

Out of the several 3D printing methods available, fused deposition modeling (FDM) has garnered significant attention because of its unique capability to construct completely operational components using multiple plastic materials [12]. Fused Deposition Modeling (FDM) is a 3D printing technique that involves heating and extruding thermoplastic filament to create individual layers, starting from the bottom and building up to the top. The affordability of the machinery and the simplicity of configuring the process variables to create accurate components have made this innovative technology a beneficial method for production in several sectors. Nevertheless, many issues are found with this technique. Enhancing geometric stability, component quality, and product qualities is crucial for the FDM process. Furthermore, the performance of three-dimensional printing is mainly determined by the qualities of the feedstock or filament [13]. A thorough comprehension of these characteristics is essential for a streamlined printing procedure. Multiple studies have shown the impact of processing settings on enhancing the mechanical characteristics of items produced using FDM printing [14]. While choosing and adjusting process variables impact the end product's qualities, the ensuing enhancements are not significant. Introducing fibers into thermoplastic material is a viable way to address these difficulties and attain the best mechanical and functional characteristics [15].

Several research studies have specifically examined the variables utilized to produce filaments with an ideal diameter and uniformity for the FDM process [16]. This understanding is crucial for the development of novel filament materials. However, achieving strong bonding between the fiber and the thermoplastic matrix in the FDM process takes much work. According to the literature, fiber additives coagulate readily, leading to clogged nozzles, non-uniformity, and porous filaments [17]. To achieve the excellent performance of the FDM product, it is necessary to optimize the characteristics of the filaments by carefully selecting the particle size and weight loading of the strengthened fiber. However, there is a need for more publications specifically examining the parametric analysis of filament creation. Investigating the optimal filament process variables is essential to producing robust fiber-matrix interactions and improving product quality.

Most of the time, short or continuous fibres are used to reinforce FDM strands. These composites have the high strength-to-weight ratio, stiffness, and resistance to corrosion that can be achieved with fibre support[17]. Various reinforcing materials were incorporated into thermoplastic filaments, including carbon fiber, copper, graphene, and carbon nanotubes. Kevlar, glass, and Carbon are frequently utilized as high-performance fibers, while bamboo, wood, basalt, and flax are often employed as natural fibers in the FDM composites industry [18]. Both the matrix and fiber impact the performance and flaws of the filaments. This project highlights the value of recycling in lowering waste from certain thermoplastic materials and using them to create 3D printing threads while also using less energy. Melting temperatures and the material's mechanical characteristics, among other factors, can be used to determine the type of thermoplastic polymer used in the manufacturing of some parts in the fused deposition modeling process. The work also demonstrates the most significant types of thermoplastic polymers used, the difficulties that restrict the recycling process, and the advantages and disadvantages of recycled materials.

2.Plastic Waste Management

Plastics emerged in everyday situations almost a century ago. However, they have become essential materials due to their diverse qualities and wide range of uses in domestic, professional, recreational, and travel settings. Plastics are highly adaptable materials, allowing for nearly unlimited options in their use. Their indisputable benefit is their great mechanical strength, low density, lightweight nature, ease of production, and cost-effectiveness [19]. Due to their unique properties, plastic has been used in several industries, such as packaging, automotive, electrical, building, transit, medical, agriculture, and other sectors. Plastic, found everywhere, generates significant garbage, posing a substantial challenge for its management. In 2018, the worldwide output of plastics reached 359 million metric tons, with the European Union contributing 61.8 million metric tons. This quantity is projected to increase twofold throughout the next two decades [20]. Plastic garbage in several nations must be handled more adequately and end up in landfills. The availability of landfill space is limited, and the amount of plastic accumulated increases quickly each year. Stricter restrictions on waste management must be implemented to ensure the retrieval of materials and energy to comply with the demands of the circular economy initiative. Within the European Union, 75.1% of plastic trash underwent processing, with 32.5% recycled and 42.6% used for energy recovery. The remaining 24.9% are disposed of in landfills [21].

Multiple methods can be employed to manage plastic garbage growth. These include primary recycling (re-extrusion), mechanical recycling, chemical reuse, and energy-producing thermal processes including combustion, pyrolysis, and gasification[22]. Primary recycling enables the retrieval of uncontaminated polymer remnants that possess properties equivalent to those of the original material. This method may be used for unused leftovers in the manufacturing process, such as those in extrusion, often employed in many production facilities [23]. Secondary recycling also involves using resources that might include impurities or contaminants. The contaminants are eliminated throughout the conversion process after first shredding. The material undergoes a process of milling and granulation before being used in plastic processing. However, it is often inferior to materials used in primary recycling.

Chemical recycling involves using chemical processes to transform polymers into chemicals that may be used again for manufacturing, primarily by depolymerization procedures (solvolysis) [23]. Energy recovery methods from polymeric materials are the least ecologically advantageous choice. However, polymers have a substantial energy content and are highly efficient energy sources, with a calorific value comparable to fuel oil (average 42 MJ/kg) [24]. Nevertheless, it is essential to consistently oversee the discharge of substances from these procedures since they have the potential to produce several organic contaminants, including dioxins [25]. Microorganisms often cannot break down plastics because bacteria lack the necessary biological enzymes to break down these compounds [26].

Nevertheless, biodegradable materials that break down due to environmental factors are intentionally created, such as different kinds of polyesters like polylactide (PLA) or polycaprolactone (PCL) [26], which are used in the manufacturing of 3D printing filaments. The pyrolysis of plastics and the limited degradability of polymers create environmental risks that need their processing. Landfilling is a short-term remedy. Due to the ongoing and extensive manufacturing of plastics and the limited level of processing, a novel solution is required. The most effective waste management approach is to minimize garbage creation proactively. Regrettably, many variables, including convenience, consumer lifestyle, advantageous qualities, and lower manufacturing costs compared to glass and metal packaging, contribute to plastics' widespread presence and long-lasting nature in the environment. The concept of a waste-free economy remains theoretical and has yet to be implemented. Hence, there is a pressing want for cost-effective plastic processing technology. 3D printing with waste polymers is a promising solution that has the potential for widespread use in the future, in addition to the existing technologies.

3.Three-Dimensional Printer Filament

Three-dimensional printing is being used more and more to manufacture production parts (49%) and spare parts (32%), as well as to create prototypes (68%) quickly and proof of concepts (59%) in various industries such as consumer products, construction, electronics, medical, manufacturing, aerospace, and automotive [27]. In 2020, the worldwide three-dimensional printing market was valued at $15.8 billion and is projected to grow to $56.1 billion by 2026. Thermoplastic materials comprised around 27% of the market share, contributing to roughly 12% of the overall materials for the three-dimensional printing market. In 2020, thermoplastic materials were the second-largest category of three-dimensional printing materials, behind photopolymers [28].

Three-dimensional printing offers advantages such as creating intricate designs and quickly producing unique components without requiring specialized equipment or molds. Sustainability is inherent in three-dimensional printing because of its capacity to provide on-demand and localized production, resulting in decreased time to market and shorter supply chains. Three-dimensional printed components are often designed to be highly efficient and lightweight, resulting in a favorable effect on the environmental impact throughout the life cycle of a product [29]. An essential factor in the sustainability of three-dimensional printing is its capacity to minimize resource use and waste creation in manufacturing.

3.1 Three-dimensional Printer Filament Kinds

There are several categories of three-dimensional printer filament: [30], [31]:

1. The most utilized three-dimensional printing filaments are ABS (acrylonitrile butadiene styrene) and PLA (polylactic acid), considered standard plastic filaments. PLA is recognized for its excellent impact-resistance properties, whereas ABS is renowned for its toughness and lightweight nature.
2. Additional thermoplastic filaments include HIPS (high-impact polystyrene), ABS (acrylonitrile styrene acrylate), PVA (polyvinyl alcohol), PET (polyethylene terephthalate), and nylon (polyamide). The use of these filaments varies depending on their characteristics. For example, HIPS and PVA are frequently employed as support materials for dual-extrusion printers because of their solubility characteristics.
3. Filaments offer flexibility through a unique combination of rubber and rigid plastic characteristics. Several materials used in engineering applications are TPE, TPU, and amphora filament. Both TPE and TPU are commonly used for flexible designs.
4. Unique filaments: these utilize a base material, like PLA, and incorporate special additives to provide additional functionality. Some examples are sandstone, wood, silk, metal, and magnetic filaments. The choice of filaments will differ based on the desired appearance of the final product. For instance, achieving a silk-like finish is highly sought after in silk filaments.

3.2 Exotic Filaments

Exotic three-dimensional printing filaments are composite filaments consisting of a primary material augmented with additions, which provides unique mechanical characteristics and surface treatments.

4. Additive Manufacturing

Additive manufacturing (AM) combines materials to create components according to a digital model, often done by adding layers of material, as opposed to the traditional method of subtractive manufacturing, which involves removing material to create parts [32]. Additive manufacturing is the umbrella term that describes a collection of technologies that utilize a material deposition process for fast prototyping. This technique utilizes the incremental deposition of material in consecutive layers, enabling the straightforward fabrication of components with either primary or intricate geometries. It may be readily managed and handled by an operator if necessary. Although often linked to the incorporation of thermoplastic material, there are currently existing procedures capable of manufacturing metal components. The primary objective is to attain quality standards that enable the synthesis of human tissue. Furthermore, there are additional procedures that depend on this particular mode of manufacturing. This research primarily focuses on FDM technology, often known as Fused Deposition Molding [33].

4.1 Fused deposition modeling

Fused deposition modeling (FDM) is a widely used approach in three-dimensional printing and is considered the most prevalent method [34]. It is designed to utilize thermoplastic materials, which are substances capable of undergoing melting or softening when exposed to heat (at temps easily attainable by applying thermal energy) and returning to a solid form upon cooling [35]. The process starts by applying heat to the material in the extrusion head, causing the polymer to undergo a melting transformation. Subsequently, the substance is forced out and placed onto the surface at a specific rate and size. The fluctuation of these factors may impact the time of the print, as well as the thickness and accuracy of each layer, ultimately affecting the quality of the resulting component [36].

5. Polymer Recycling

The environment and the bottom line of a business may be greatly affected by plastic trash. Recycling has made it possible to save materials, make dumps last longer, and make less trash. Because thermoplastic can be recycled, it can be assumed that reusing it has positive effects in many areas of life. Polymer recycling can be broken down into three different types: mechanical, chemical, and energy (primary, secondary, and tertiary) where explained in Fig.1. The polymer is broken down chemically into monomers or hydrocarbons, which can then be used to make high-quality plastics or chemicals. Recycling plastic in an energetic way means using it as a fuel to make heat and electricity [37], [38].

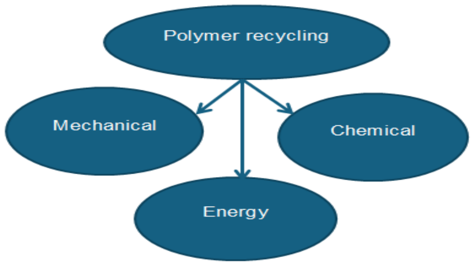


Figure (1): Type of polymer recycling

5.1 Mechanical Recycling

This kind of recycling is utilized in two distinct sectors: industrial (where the polymer is reprocessed to be reintroduced into the manufacturing cycle) and post-consumption (dealing with general garbage). The polymer must undergo the following stages for recycling [39], [40], and these stages were explained in Fig. 2:

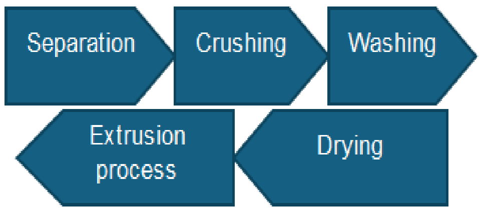


Figure (2): Stages of mechanical recycling

- Separation: the process of categorizing and reassembling various kinds of plastic based on their specific type;
- Crushing: the process of milling and reducing into smaller bits or grains.
- Washing: often using water to eliminate any impurities;
- Drying: removing moisture from the substance and reducing its volume.
- Extrusion is the last stage in which the material is melted, compressed, and forced out via a small opening.

5.2 Shredder

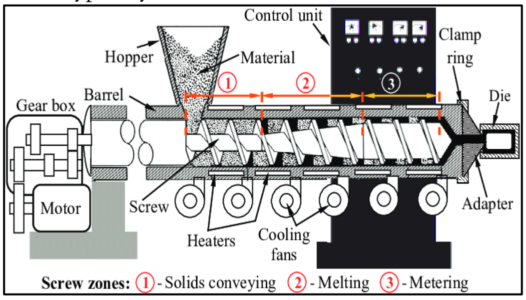
The shredder is a common component of equipment used in several sectors. Some machines are designed to pulverize paper, while others are intended for grinding plastics. There are even some machines that can grind an entire automobile. The properties of objects, whether they are functional or structural, obviously alter based on their functions. Nevertheless, even within the same sector of the business, such as plastic, the attributes of the shredder might vary. Shredders equipped with a rotating blade axle and fixed blade can efficiently cut through materials. For more challenging uses, such as larger manufacturing quantities, equipment with comparable but more demanding purposes may utilize a shredder equipped with two rows of movable blades. The shredding action is a consequence of the combination of three activities [41]:

- The cutting process refers to the actual mechanism used for cutting. Like a scissor mechanism, the mechanism's effectiveness relies on the blades' sharpness and the gap between subsequent ones.
- The tearing process refers to pulling a material apart and its capacity to create a separation, resulting in an initial fracture. This phenomenon is seen explicitly in plastics and rubbers.
- Fracture process: Some materials, such as glass, exhibit a very brittle fracture characteristic. Fractures often occur when the blades are inadequately honed or when there is excessive spacing between them. Particular attention should be given to this matter due to the potential hazard of ejecting tiny components from the machinery.

5.3 Extruder

Similar to the fact that there are shredders of all sizes and functions, there are also extruders that serve varied purposes, such as extruding filaments for three-dimensional printing or injecting polymers into a mold. The essential elements of an extruder Fig.3, include:

- The machine's frame provides support and guarantees the appropriate alignment of the spinning components.
- The threaded shaft is responsible for moving the material along the pipe.
- The tube also has a considerable impact on the transport of chemicals.
- Hopper: a receptacle where the raw material is introduced or loaded.
- The motor shaft is responsible for the rotating motion of the threaded shaft.
- Heating cells (resistors): used to generate heat and cause the material to melt.
- The matrix can have many configurations and affects the shape of the material section at the output.
- Typically, the motor utilized is electric.



Figure(3):Extruder components [42]

The extruder process begins with introducing the pre-crushed material in minute fragments. The material should be introduced into the hopper and, with the force of gravity, descend into the throat - a hole located at one end of the tube that is in line with the bottom of the hopper. Here, the material touches the threaded conveyor shaft. The shaft and tube inner surface frictional stresses pull the polymer to the opposite end. Material is slowly heated from the back of the tube (where it enters the machine) to the front (where it is discharged) along the course. Extrusion screw temperatures approach 275 celsius [23].

6. Challenges and Opportunities

Recycled-based PLA, ABS, PET, HDPE, PP, and PS have been identified as suitable materials for producing three-dimensional FDM filaments. PLA, ABS, and their composites are the most frequently utilized filaments in commercial applications, primarily because they are inexpensive and readily accessible. On the other hand, materials that are typically difficult to utilize in three-dimensional printing, including PET, HDPE, PP, PS, recycled materials, and their composites, can be significantly improved by implementing specific processing techniques. Plasticisers, compatibilizers, additives, coating for surface modification, low-temp plasma treatment, heating before layering, and chemical vapor treatment are used. Nevertheless, several concerns persist concerning 3D printed components, including subpar mechanical characteristics, inadequate interlayer adhesion, insufficient fiber concentration in composites, the production of voids, and heightened water absorption. Therefore, more research should be undertaken to address these constraints. In order to enhance the mechanical characteristics of three-dimensional printed components, further surface characterization using atomic force microscopy (AFM) is necessary. This technology will help us better understand the molecular orientation and provide chemical cross-linking solutions. Further work is needed to explore the possibilities of creating self-healing materials during printing. In order to facilitate the use of recycled materials in three-dimensional printing, it is necessary to create clear material categories and criteria for producing filaments. Cold plasma treatment, which does not include heating, may effectively enhance the surface quality and dimensional precision of FDM products. In addition, nylon, also known as polyamide, and thermoplastic elastomers, such as thermoplastic polyurethane (TPU) and thermoplastic elastomer (TPE), are appropriate materials for 3D printing. Nevertheless, more research must be undertaken using recycled or composite materials derived from nylon and thermoplastic elastomers[43].Furthermore, there is a need to research using recycled high-performance polymers such as thermoplastic polyurethane (TPU) to produce three-dimensional filaments. Thermosetting photopolymers comprise 50% of the three-dimensional printing materials industry. Consequently, it is essential to do more study on recyclable thermosets [44].

7. Recycle Materials Used in Three-dimensional Printer Filaments

Three-dimensional printing filaments are available in various materials, including sandstone, ceramic, wood, metal, carbon fiber, silk, and thermoplastics. The choice of materials is contingent upon the final print's specific application and desired characteristics. Recycling scheme for 3D printing materials are expressed in Fig.4,[45].

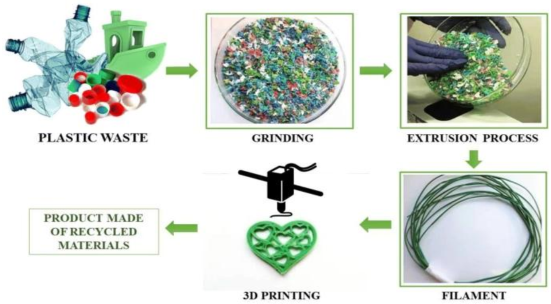


Figure (4): Recycling scheme for 3D printing materials

The following are examples of commonly used materials:

7.1 polylactic acid (PLA)

The "favorite" substance in the environment is polylactic acid. is a recyclable and biodegradable thermoplastic made from plant starch and other renewable materials [46]. The extrusion temperature of this semi-crystalline thermoplastic ranges from 160˚C to 220˚C [47]. It is regarded as an eco-friendly substance that is low-cost to produce, biodegradable, and biocompatible, and has good processability [48]. It is a very tough, stiff substance that is hard to bend. It is an inappropriate material to withstand impacts due to its extreme hardness [49]. Due to the friction involved in the operations, the material has low machinability, low resilience to high temperatures, and low friction. For fittings or parts that are subjected to significant mechanical or thermal strains, it is not advised [50], [51].

7.2 Acrylonitrile Butadiene Styrene (ABS)

One of the earliest materials used in FDM and one of the most widely used now is ABS (acrylonitrile butadiene styrene). It is a well-known amorphous copolymer with excellent mechanical qualities, including high stiffness, toughness, impact strength, and heat resistance. ABS requires a hot printing bed with an extrusion temperature between 215 and 250 degrees Celsius. Additionally, when printing, ABS experiences warping and shrinking issues [52].The industry makes extensive use of this petroleum-based thermoplastic due to its extended service life, high stiffness, and resilience to impact and temperature. In contrast to PLA, for instance, this material is more flexible. If a fitting is required, this could be practical [53].

7.3 Polyethylene Terephthalate (PET)

The semi-crystalline thermoplastic polyethylene terephthalate (PET) has an extrusion temperature between 212°C and 235°C. PET prints odorlessly, is recyclable, and is quite durable. Impact strength, excellent tensile strength, and thermal stability are among this material's favorable attributes [54], [55]. PET is not frequently used for FDM printing due to its low crystallinity, high melting temperature, and water absorption. Furthermore, compared to PLA, it is more likely to have brittle failure. PET filaments that are currently available include glycol-modified PET (PET-G) and recycled PET. PET-G is an amorphous plastic that has less brittleness because cyclohexane dimethanol is used in place of the ethylene glycol chain. Compared to PET, PET-G is more flexible, biocompatible, long-lasting, recyclable, and easier to work with when using 3D printing filament [56], [57].

7.4 High density polyethylene (HDPE)

Is frequently found in homes (such as in milk and detergent bottles) and is a desirable plastic waste feedstock for filament extrusion because it is stronger and more ductile than low-density polyethylene and polyethylene terephthalate [58]. Between 180 and 190˚C, the extrusion temperatures were regulated.It is lightweight, pliable, resistant to chemicals, non-absorbent, and simple to color and mold. When the temperature drops significantly, HDPE material has a tendency to distort, curl up, or shrink. The bottom layers, which have a lower temperature, will probably shrink when the object is printed layer by layer by FFF 3D printers, giving rise to deformed or curled shapes. When printing with HDPE, adhesion is another issue because it only sticks to hot HDPE [59], [60].

7.5 Polypropylene (PP)

In a variety of environmental settings, this compound exhibits exceptional resistance to fatigue and stress cracking [61]. Additionally, it is incredibly flexible and retains its impact and flexural strength even after numerous cycles of thermal reprocessing. The material's elliptical shape for filaments is caused by its wide diameter range, limited resistance to low temperatures, high susceptibility to UV radiation, warping, and poor layer adhesion. Its printing temperature ranges from 210 to 230 ˚C [62], [63].

7.6 High Impact Polystyrene (HIPS)

HIPS has a high level of impact resistance, much like ABS. However, it is simple to construct and a biodegradable substance. 190˚C to 210˚C is the extrusion temperature for 3D printing filament [64], [65]. An increasingly popular polymer in additive manufacturing is high-impact polystyrene (HIPS). Because of its excellent dimensional stability, affordability, and simplicity in processing and coloring, it is frequently utilized in prototyping [66]. Similar to ABS, HIPS is quickly produced, biodegradable, and has exceptional impact strength. When using a 3D printer to create HIPS, a heated print bed is necessary [67], [68].

8. Conclusion

Plastics resist biodegradation, and their disintegration leads to further environmental pollution. Recycling has been identified as the most beneficial approach to enhance the value of post-consumer plastics while aligning with the principles of a circular economy. The degradation process of plastics ranges from 10 to 450 years. Historically, recycling was carried out using extensive centralized facilities that create low-value commodities, which refers to the exorbitant expenses associated with transportation. Three-dimensional printing facilitates many methodologies. Desktop three-dimensional printing enables the production of intricate plastic objects at home rather than in a factory. It is projected that the value of this industry will see significant growth in the following years. The concept involves enabling consumers to manufacture things directly using recycled resources, which offers many cost reductions: Engaging in environmentally friendly practices and purchasing commercial plastic items helps to implement a circular economy.

References

[1] K. A. Iyer, L. Zhang, and J. M. Torkelson, "Direct use of natural antioxidant-rich agro-wastes as thermal stabilizer for polymer: Processing and recycling," ACS Sustain. Chem. Eng., vol. 4, no. 3, pp. 881-889, 2016. DOI:10.1021/acssuschemeng.5b01283

[2] F. A. C. Sanchez, H. Boudaoud, M. Camargo, and J. M. Pearce, "Plastic recycling in additive manufacturing: A systematic literature review and opportunities for the circular economy," J. Clean. Prod., vol. 264, p. 121602, 2020. DOI:10.1016/j.jclepro.2020.121602

[3] S. Kaewunruen, D. Li, Y. Chen, and Z. Xiang, "Enhancement of dynamic damping in eco-friendly railway concrete sleepers using waste-tyre crumb rubber," Materials, vol. 11, no. 7, p. 1169, 2018. DOI:10.3390/ma11071169

[4] K. Mikula, M. Skrzypczak, M. Khajavi, and A. Torabi, "3D printing filament as a second life of waste plastics-a review," Environ. Sci. Pollut. Res., vol. 28, pp. 12321-12333, 2021. DOI:10.1007/s11356-020-10657-8

[5] D. Mohan, Z. K. Teong, A. N. Bakir, M. S. Sajab, and H. Kaco, "Extending cellulose-based polymers application in additive manufacturing technology: A review of recent approaches," Polymers, vol. 12, no. 9, p. 1876, 2020. DOI:10.3390/polym12091876

[6] N. Mervine, K. Brätt, and D. Saloni, "A review of sustainable materials used in thermoplastic extrusion and powder bed melting additive manufacturing," in Advances in Manufacturing, Production Management and Process Control, Springer, 2020, pp. 95-102. DOI:10.1007/978-3-030-51981-0_12

[7] I. S. Jawahir and R. Bradley, "Technological elements of circular economy and the principles of 6R-based closed-loop material flow in sustainable manufacturing," Procedia CIRP, vol. 40, pp. 103-108, 2016. DOI:10.1016/j.procir.2016.01.067

[8] A. Lanzotti, M. Grasso, G. Staiano, and M. Martorelli, "The impact of process parameters on mechanical properties of parts fabricated in PLA with an open-source 3-D printer," Rapid Prototyp. J., vol. 21, no. 5, pp. 604-617, 2015. DOI:10.1108/RPJ-09-2014-0135

[9] N. Li, Y. Li, and S. Liu, "Rapid prototyping of continuous carbon fiber reinforced polylactic acid composites by 3D printing," J. Mater. Process. Technol., vol. 238, pp. 218-225, 2016. DOI:10.1016/j.jmatprotec.2016.07.025

[10] Z. Abdullah, M. A. Maleque, M. M. Rahman, and M. A. Ali, "The effect of layer thickness and raster angles on tensile strength and flexural strength for fused deposition modeling (FDM) parts," J. Adv. Manuf. Technol., vol. 12, no. 1(4), pp. 147-158, 2018.

[11] A. N. Dickson, H. M. Abourayana, and D. P. Dowling, "3D printing of fibre-reinforced thermoplastic composites using fused filament fabrication-A review," Polymers, vol. 12, no. 10, p. 2188, 2020. DOI:10.3390/polym12102188

[12] N. Shahrubudin, T. C. Lee, and R. Ramlan, "An overview on 3D printing technology: Technological, materials, and applications," Procedia Manuf., vol. 35, pp. 1286-1296, 2019. DOI:10.1016/j.promfg.2019.06.089

[13] I. Antoniac, D. Popescu, A. Zapciu, A. Antoniac, F. Miculescu, and H. Moldovan, "Magnesium filled polylactic acid (PLA) material for filament based 3D printing," Materials, vol. 12, no. 5, p. 719, 2019. DOI:10.3390/ma12050719

[14] Ł. Miazio, "Impact of print speed on strength of samples printed in FDM technology," Agric. Eng., vol. 23, no. 2, pp. 33-38, 2019. DOI:10.1515/agriceng-2019-0014

[15] X. Wang, M. Jiang, Z. Zhou, J. Gou, and D. Hui, "3D printing of polymer matrix composites: A review and prospective," Compos. Part B Eng., vol. 110, pp. 442-458, 2017. DOI:10.1016/j.compositesb.2016.11.034

[16] A. Dey and N. Yodo, "A systematic survey of FDM process parameter optimization and their influence on part characteristics," J. Manuf. Mater. Process., vol. 3, no. 3, p. 64, 2019. DOI:10.3390/jmmp3030064

[17] J. Saroia, A. Wang, Y. Wei, Y. Zhang, and Y. Liu, "A review on 3D printed matrix polymer

composites: Its potential and future challenges," Int. J. Adv. Manuf. Technol., vol. 106, pp. 1695-1721, 2020. DOI:10.1007/s00170-019-04534-z

[18] S. Wickramasinghe, T. Do, and P. Tran, "FDM-based 3D printing of polymer and associated composite: A review on mechanical properties, defects and treatments," Polymers, vol. 12, no. 7, p. 1529, 2020. DOI:10.3390/polym12071529

[19] B. G. Mwanza and C. Mbohwa, "Drivers to sustainable plastic solid waste recycling: A review," Procedia Manuf., vol. 8, pp. 649-656, 2017. DOI:10.1016/j.promfg.2017.02.083

[20] W. Leal Filho, L. Salvia, A. L. Pretorius, and A. O. Brandli, "An assessment of attitudes towards plastics and bioplastics in Europe," Sci. Total Environ., vol. 755, p. 142732, 2021. DOI:10.1016/j.scitotenv.2020.142732

[21] R. Kumar, A. Singh, A. K. Pandey, and A. K. Singh, "Impacts of plastic pollution on ecosystem services, sustainable development goals, and need to focus on circular economy and policy interventions," Sustainability, vol. 13, no. 17, p. 9963, 2021. DOI:10.3390/su13179963

[22] S. M. Al-Salem, P. Lettieri, and J. Baeyens, "Recycling and recovery routes of plastic solid waste (PSW): A review," Waste Manag., vol. 29, no. 10, pp. 2625-2643, 2009. DOI:10.1016/j.wasman.2009.06.004

[23] N. Singh, D. Hui, R. Singh, I. P. S. Ahuja, L. Feo, and F. Fraternali, "Recycling of plastic solid waste: A state of art review and future applications," Compos. Part B Eng., vol. 115, pp. 409-422, 2017. DOI:10.1016/j.compositesb.2016.09.013

[24] S. Kumar, A. K. Panda, and R. K. Singh, "A review on tertiary recycling of high-density polyethylene to fuel," Resour. Conserv. Recycl., vol. 55, no. 11, pp. 893-910, 2011. DOI:10.1016/j.resconrec.2011.06.010

[25] K. Ragaert, L. Delva, and K. Van Geem, "Mechanical and chemical recycling of solid plastic waste," Waste Manag., vol. 69, pp. 24-58, 2017. DOI:10.1016/j.wasman.2017.07.044

[26] A. A. Shah, F. Hasan, A. Hameed, and S. Ahmed, "Biological degradation of plastics: A comprehensive review," Biotechnol. Adv., vol. 26, no. 3, pp. 246-265, 2008. DOI:10.1016/j.biotechadv.2007.12.005

[27] I. Gibson, D. W. Rosen, and B. Stucker, Additive Manufacturing Technologies, 3rd ed., Springer, 2021. DOI:10.1007/978-3-030-56127-7

[28] B. Silver, "BCC Research," Charleston Advis., vol. 23, no. 3, pp. 10-16, 2022. DOI:10.5260/chara.23.3.10

[29] K. Kellens, M. Baumers, T. G. Gutowski, W. Flanagan, R. Lifset, and J. R. Duflou, "Environmental dimensions of additive manufacturing: Mapping application domains and their environmental implications," J. Ind. Ecol., vol. 21, no. S1, pp. S49-S68, 2017. DOI:10.1111/jiec.12629

[30] F. Decuir, K. Phelan, and B. C. Hollins, "Mechanical strength of 3-D printed filaments," in Proc. 32nd Southern Biomed. Eng. Conf. (SBEC), IEEE, 2016, pp. 47-48. DOI:10.1109/SBEC.2016.11

[31] J. Griffey, "Types of filaments for FDM printing," Libr. Technol. Rep., vol. 53, no. 15, pp. 12-16, 2017.

[32] X. Zhang and F. Liou, "Introduction to additive manufacturing," in Additive Manufacturing, Elsevier, 2021, pp. 1-31. DOI:10.1016/B978-0-12-818411-0.00009-4

[33] T. Grimm, "Fused deposition modeling: A technology evaluation," Time-Compression Technol., vol. 11, no. 2, pp. 1-6, 2003.

[34] V. Mazzanti, L. Malagutti, and F. Mollica, "FDM 3D printing of polymers containing natural fillers: A review of their mechanical properties," Polymers, vol. 11, no. 7, p. 1094, 2019. DOI:10.3390/polym11071094

[35] M. Biron, Thermoplastics and Thermoplastic Composites, 2nd ed., William Andrew, 2018. DOI:10.1016/B978-0-08-102501-7.00009-6

[36] M. M. Mbow, P. R. Marin, and F. Pourroy, "Extruded diameter dependence on temperature and velocity in the fused deposition modeling process," Prog. Addit. Manuf., vol. 5, no. 2, pp. 139-152, 2020. DOI:10.1007/s40964-019-00107-4

[37] A. Kijo-Kleczkowska and A. Gnatowski, "Recycling of plastic waste, with particular emphasis on thermal methods-review," Energies, vol. 15, no. 6, p. 2114, 2022. DOI:10.3390/en15062114

[38] A. K. Panda, R. K. Singh, and D. K. Mishra, "Thermolysis of waste plastics to liquid fuel: A suitable method for plastic waste management and manufacture of value added products-A world prospective," Renew. Sustain. Energy Rev., vol. 14, no. 1, pp. 233-248, 2010. DOI:10.1016/j.rser.2009.07.005

[39] J. Maris, S. Bourdon, J.-M. Brossard, L. Cauret, L. Fontaine, and V. Montembault, "Mechanical recycling: Compatibilization of mixed thermoplastic wastes," Polym. Degrad. Stab., vol. 147, pp. 245-266, 2018. DOI:10.1016/j.polymdegradstab.2017.12.011

[40] Z. O. G. Schyns and M. P. Shaver, "Mechanical recycling of packaging plastics: A review," Macromol. Rapid Commun., vol. 42, no. 3, p. 2000415, 2021. DOI:10.1002/marc.202000415

[41] S. Escudero Cuadrado, "Diseño de un triturador de basura para conectar a una máquina compactadora de residuos," B.Sc. thesis, Univ. Politécnica de Valencia, 2015.

[42] C. Abeykoon, K. Li, M. McAfee, P. J. Martin, and G. W. Irwin, "Extruder melt temperature control with fuzzy logic," IFAC Proc. Vol., vol. 44, no. 1, pp. 8577-8582, 2011. DOI:10.3182/20110828-6-IT-1002.02642

[43] N. Kumar, P. K. Jain, P. Tandon, and P. M. Pandey, "Experimental investigations on suitability of polypropylene (PP) and ethylene vinyl acetate (EVA) in additive manufacturing," Mater. Today Proc., vol. 5, no. 2, pp. 4118-4127, 2018. DOI:10.1016/j.matpr.2017.11.642

[44] B. Zhang, K. Kowsari, A. Serjouei, M. L. Dunn, and Q. Ge, "Reprocessable thermosets for

sustainable three-dimensional printing," Nat. Commun., vol. 9, no. 1, p. 1831, 2018. DOI:10.1038/s41467-018-04292-8

[45] K. Mikula, M. Skrzypczak, M. Khajavi, and A. Torabi, "3D printing filament as a second life of waste plastics-a review," Environ. Sci. Pollut. Res., vol. 28, pp. 12321-12333, 2021. DOI:10.1007/s11356-020-10657-8

[46] M. Kamran and A. Saxena, "A comprehensive study on 3D printing technology," MIT Int. J. Mech. Eng., vol. 6, no. 2, pp. 63-69, 2016.

[47] R. Scaffaro, L. Botta, E. Passaglia, W. Oberhauser, M. Frediani, and L. Di Landro, "Comparison of different processing methods to prepare poly(lactic acid)-hydrotalcite composites," Polym. Eng. Sci., vol. 54, no. 8, pp. 1804-1810, 2014. DOI:10.1002/pen.23718

[48] P. E. Le Marec, A. Ferry, J. P. Pascault, and A. Saiter, "Influence of melt processing conditions on poly(lactic acid) degradation: Molar mass distribution and crystallization," Polym. Degrad. Stab., vol. 110, pp. 353-363, 2014. DOI:10.1016/j.polymdegradstab.2014.09.014

[49] B. Tuna and G. Ozkoc, "Effects of diisocyanate and polymeric epoxidized chain extenders on the properties of recycled poly(lactic acid)," J. Polym. Environ., vol. 25, pp. 983-993, 2017. DOI:10.1007/s10924-016-0856-6

[50] J. D. Badia, E. Strömberg, S. Karlsson, and A. Ribes-Greus, "Material valorisation of amorphous polylactide. Influence of thermo-mechanical degradation on the morphology, segmental dynamics, thermal and mechanical performance," Polym. Degrad. Stab., vol. 97, no. 4, pp. 670-678, 2012. DOI:10.1016/j.polymdegradstab.2012.03.021

[51] T. Rogers, "Everything you need to know about polylactic acid (PLA)," Creat. Mech., vol. 7, 2015.

[52] E. Karahaliou and P. A. Tarantili, "Stability of ABS compounds subjected to repeated cycles of extrusion processing," Polym. Eng. Sci., vol. 49, no. 11, pp. 2269-2275, 2009. DOI:10.1002/pen.21474

[53] M. I. Mohammed, A. Das, E. Gomez-Kervin, D. Wilson, and I. Gibson, "EcoPrinting: Investigating the use of 100% recycled acrylonitrile butadiene styrene (ABS) for additive manufacturing," in Proc. 28th Solid Freeform Fabrication Symp., 2017.

[54] H. Schneevogt, K. Stelzner, B. Yilmaz, B. E. Abali, A. Klunker, and C. Völlmecke, "Sustainability in additive manufacturing: Exploring the mechanical potential of recycled PET filaments," Compos. Adv. Mater., vol. 30, p. 26349833211000064, 2021. DOI:10.1177/26349833211000063

[55] O. Basurto-Vázquez, E. P. Sánchez-Rodríguez, G. J. McShane, and D. I. Medina, "Load distribution on PET-G 3D prints of honeycomb cellular structures under compression load," Polymers, vol. 13, no. 12, p. 1983, 2021. DOI:10.3390/polym13121983

[56] I. G. Kim, S. Y. Hong, B. O. Park, H. J. Choi, and J. H. Lee, "Polyphenylene ether/glycol modified polyethylene terephthalate blends and their physical characteristics," J. Macromol. Sci. Part B, vol. 51, no. 4, pp. 798-806, 2012. DOI:10.1080/00222348.2011.610207

[57] N. E. Zander, M. Gillan, and R. H. Lambeth, "Recycled polyethylene terephthalate as a new FFF feedstock material," Addit. Manuf., vol. 21, pp. 174-182, 2018. DOI:10.1016/j.addma.2018.03.007

[58] S. Chong, G.-T. Pan, M. Khalid, T. C.-K. Yang, S.-T. Hung, and C.-M. Huang, "Physical characterization and pre-assessment of recycled high-density polyethylene as 3D printing material," J. Polym. Environ., vol. 25, pp. 136-145, 2017. DOI:10.1007/s10924-016-0793-4

[59] K. Q. Nguyen, C. Mwiseneza, K. Mohamed, P. Cousin, M. Robert, and B. Benmokrane, "Long-term testing methods for HDPE pipe-advantages and disadvantages: A review," Eng. Fract. Mech., vol. 246, p. 107629, 2021. DOI:10.1016/j.engfracmech.2021.107629

[60] G. P. Thomas, "Recycling of high-density polyethylene (HDPE or PEHD)," AZoCleanTech, 2012. [Online]. Available: https://www.azocleantech.com/article.aspx?ArticleID=171

[61] E. Iunolainen, "Suitability of recycled PP for 3D printing filament," B.Sc. thesis, Tampere Univ. Technol., 2017.

[62] N. Vidakis, M. Petousis, E. Velidakis, E. Mountakis, and D. Tzounis, "Sustainable additive manufacturing: Mechanical response of polypropylene over multiple recycling processes," Sustainability, vol. 13, no. 1, p. 159, 2020. DOI:10.3390/su13010159

[63] S. I. Atsani and H. Mastrisiswadi, "Recycled polypropylene filament for 3D printer: Extrusion process parameter optimization," in IOP Conf. Ser.: Mater. Sci. Eng., vol. 771, p. 012022, 2020. DOI:10.1088/1757-899X/771/1/012022

[64] G. A. Miranda Salgado and T.-L. Sun, "Performance analysis on fitness equipment: Application of an inertial sensor toward quality of life," in Sustainable Design and Manufacturing 2017, Springer, 2017, pp. 68-76. DOI:10.1007/978-3-319-57078-5_7

[65] T. Y. Ng, S. C. Koay, M. Y. Chan, H. L. Choo, and T. K. Ong, "Preparation and characterisation of 3D printer filament from post-used styrofoam," in AIP Conf. Proc., vol. 2203, p. 020060, 2020. DOI:10.1063/5.0000212

[66] E. P. Mynio, "Recycled material selection for affordable and sustainable homes using large scale additive manufacturing," M.Sc. thesis, Massachusetts Inst. Technol., 2020.

[67] S. Thakur, A. Verma, B. Sharma, J. Chaudhary, S. Tamulevicius, and V. K. Thakur, "Recent developments in recycling of polystyrene based plastics," Curr. Opin. Green Sustain. Chem., vol. 13, pp. 32-38, 2018. DOI:10.1016/j.cogsc.2018.04.007

[68] I. Turku, S. Kasala, and T. Kärki, "Characterization of polystyrene wastes as potential extruded feedstock filament for 3D printing," Recycling, vol. 3, no. 4, p. 57, 2018. DOI:10.3390/recycling3040057