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ORIGINAL ARTICLE

Post-Consumer Recycling of Polymers for Sustainable 3D Printing Filament Material

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ABSTRACT – 3D printing technology is rapidly developing in the manufacturing industry in producing complex and easily adjustable three-dimensional objects using the help of controls from computers. Behind its advantages, the 3D printing process requires filaments from virgin polymers which generally have a high price and adversely affect the environment. Post-consumer polymer recycling is a substitute material solution from virgin polymers and is environmentally friendly to support the realization of a circular economy. Studies on 3D printing filaments from post-consumer polymers have been discussed in this article, especially for filaments derived from acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), and polyethylene terephthalate (PET). The sources of recycled raw materials, difficulties during the process, mechanical properties, thermal properties, and efforts to improve the quality of 3D printing products are reviewed. The results show that recycling post-consumer polymers for 3D printing filament applications is a promising approach to reducing the environmental impact of 3D printing while still retaining the mechanical properties and printability of filaments. This article provides insight into several studies that address the development of 3D printing using post-consumer polymer materials.

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INTRODUCTION

Today, the use of plastic is still widely used in everyday life. As the level of plastic use increases, the plastic waste produced increases yearly. The increase in plastic consumption has been supported by the advantages of plastic, including because plastic is a versatile material and can be produced quickly [1]. Furthermore, since the first synthetic process was developed in the 1990s, plastic has been able to replace many types of materials, including wood, metal, and ceramics, in the manufacturing process, as it has lightweight properties, a long life, good corrosion resistance, and low production costs [2]. However, the continuous use of plastic without good governance will harm the environment, so it can produce plastic waste that is difficult to decompose (non-biodegradable). Consumers use plastic bags that are used daily with an average usage of at most 20 minutes, but it takes a long time, up to 200 years, to degrade [3]. Plastic waste seen globally can come from several sectors, such as packaging, construction, electronics, consumer products, industrial machinery, textile materials, transportation, etc. The sector that produces the highest plastic waste is the packaging sector, with a figure of around 140 million tons [4]. Therefore, this plastic waste issue is a primary environmental concern. Millions of plastic waste end up in landfills, oceans, and other natural environments every year, causing severe pollution complications [5].

Plastic waste not only creates visual pollution but also poses a threat to wildlife, aquatic life, and human health. Some of them are chemical, physical, biological, and microplastic pollution. Chemical pollution occurs when plastic waste dissolves harmful chemicals such as bisphenol A (BPA) and polychlorinated biphenyls (PCBs) into water and soil. It can affect soil fertility rates and harm the health of soil organisms and plants growing in that soil. Similarly, if it occurs in water, BPA and PCBs can affect the health of aquatic organisms and humans who consume contaminated water [6]. Physical pollution, namely plastic waste, can physically change soil structure and affect soil aeration and water retention, causing a decrease in soil fertility. Similarly, if it occurs in water, it can alter the flow, temperature, and light level of water, thus affecting the survival and behavior of aquatic organisms [7]. Biological pollution occurs when plastic waste damages soil microbes, causing soil ecosystems to become unbalanced [8].

To reduce uncontrolled plastic waste in the environment, 3D printing filaments can be used as one solution. 3D printing filaments are made of various materials; some of the most commonly used materials are acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), and polyethylene terephthalate (PET) because they are easy to print and produce good print quality [9].

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ABS, PLA, and PET waste have different sources. ABS waste is the most dominant type of plastic waste and is a fossil-based type of polymer with good strength, heat resistance, and durability [10]. ABS waste comes from toys [11], electronic equipment, and automobile [12]. In addition to ABS waste, PET waste is abundant in the environment and easy to find. It can be found easily in everyday life, such as mineral water bottles, juices, carbonated soft drinks, and other food packaging [13]. The same goes for PLA waste, which can be found in food waste containing many carbohydrates, such as corn and sugarcane [14]. PLA bio-based waste makes it a renewable and environmentally friendly resource [15]. Plastic waste used as raw material for 3D printing filaments, particularly from ABS, PLA, and PET materials, has the potential to be a substitute material for filaments derived from virgin polymer raw materials, which generally come from petroleum. Our objective in this paper is to examine the possibility of using plastic waste for 3D printing filament materials, particularly polymer materials such as ABS, PLA, and PET, which are frequently used as 3D printing filaments.

POLYMER CIRCULAR ECONOMY

As it is well known that plastic waste has a great impact on the environment, the amount of plastic waste produced from various countries worldwide tends to increase every year, as shown in Figure 1. Circular economy (CE) has emerged as a concept to provide solutions to economic growth and sustainability [16]. Currently, many authors discuss that a circular economy is related to a regenerative and restorative industrial economy [17], [18]. The circular economy system aims to reduce waste in an effort to conserve resources, namely by keeping materials in use for a long time [19].

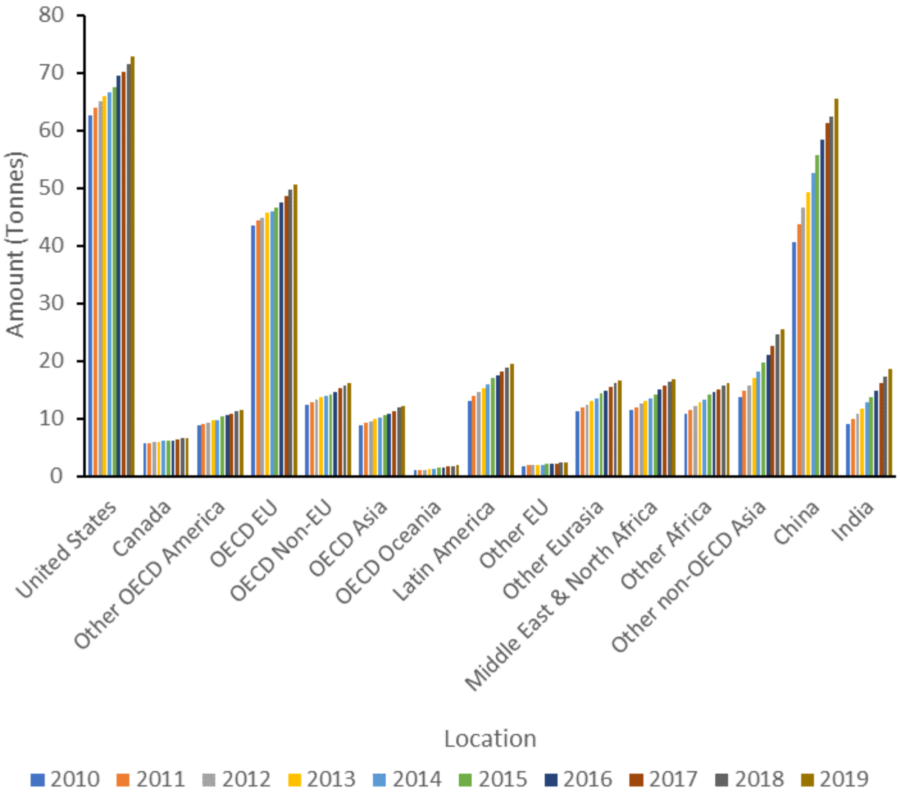

Figure 1. Amount of plastic waste worldwide in 2010–2019 [20]

In relation to polymers, the concept of a circular economy is useful for directing plastics and other synthetic materials to be designed, manufactured, and managed by minimizing negative impacts on the environment while ensuring sustainable use. Various studies related to the circular polymer economy have also developed a lot from year to year, as shown in Figure 2.

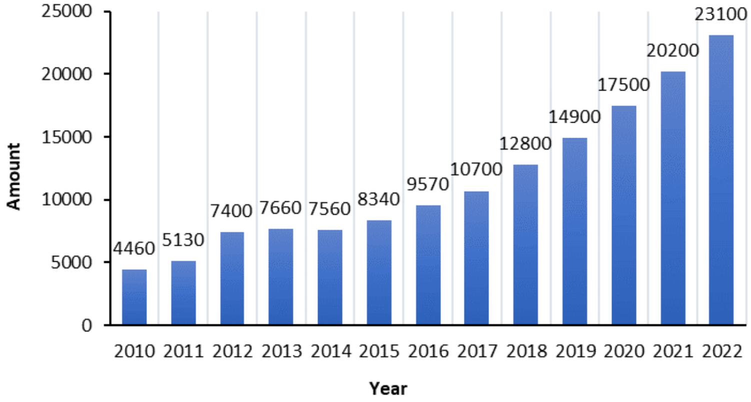

Figure 2. Number of research papers on polymer circular economy from 2010–2022 based on Google Scholar, keywords: polymer circular economy (accessed on Feb 14, 2023)

One of the widely known ways is through the development of plastic materials that are biodegradable or bio-based. These properties are necessary for plastics because they can be broken down into harmless substances, and a closed-loop recycling process allows plastic products to be reused and recyclable rather than directly thrown into the environment. Another way is to improve the design of products that are durable and can be improved so that they have a longer lifetime [21].

Figure 3. Polymers circular economy

A circular economy can help address the global plastic waste crisis by reducing dependence on pure plastic and increasing the use of recycled plastic [22]. An integral part of a circular economy is the redesign of products and materials, the use of renewable energy sources, and the restoration of natural systems, all of which minimize waste generation and maximize resource efficiency through sustainable design, remanufacturing, efficient distribution, responsible consumption, practical collection, and recycling, as illustrated in Figure 3. Implementing circular economy principles can ultimately lead to developing attractive business models and creating new economic opportunities in the plastic waste management sector [23].

Related to the phenomenon of plastic waste that tends to continue to increase, several steps that can be applied, starting from oneself, are by applying 3R (reduce, reuse, recycle) [24]. 3R is known as the "waste hierarchy", which is the three principles of sustainable waste management and is a series of systematic approaches to reduce the amount of plastic waste generated and reduce adverse effects on the environment [25]. 3R is fully supportive of sustainability to help conserve natural resources. The concept of reduce refers to reducing the amount of waste produced using fewer natural resources so as to minimize the production of waste produced. This can be achieved by using fewer materials, choosing products with minimal packaging, and choosing durable products so they can be reused [26]. The concept of reuse is to use the product again either for the same purpose or for a different purpose than disposing of the product after use. This can be done by repairing the product so that it can be reused, using a refillable container, or reusing the product for a different purpose of use [27]. Then, the recycling concept involves several stages ranging from collecting, managing, and remaking waste products to being used as new products. It is intended to conserve natural resources and reduce the amount of waste sent to landfills. Recycling can be applied to different types of materials, such as paper, plastic, glass, and metal [28].

The four types in the recycling process start with primary recycling, which is better known as the "close loop", which is a situation where the product is reused but has the same purpose as the original plastic. Then for secondary recycling, namely recycling which is carried out with the help of machinery or often called mechanical recycling, where the product is enumerated using a machine (sorting, grinding, washing, and drying) to produce various materials that are in accordance with the performance requirements of the original material. The concept of tertiary recycling is known as chemical recycling, which is carried out by restoring monomer mixtures using high temperatures with the help of catalysts but without the use of oxygen (pyrolysis), and the last one, namely quaternary recycling, is carried out by burning with or without energy recovery [29]. In essence, the 3R concept can be carried out by individuals to large groups to achieve the same goals in conserving natural resources and waste management in order to realize a circular economy.

The circular economy of 3D-printed plastics is an exciting area of research for researchers. One of them is like a study conducted by Zhu et al., which focuses on the recycling and degradation of various materials for 3D printing, including acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), and polyethylene terephthalate (PET). They explain that the performance of recycled ABS waste and PET 3D printing waste is similar to that of products printed by the fused filament fabrication process. This can open up that recycled ABS and PET waste can be used to make new products to reduce the amount of plastic waste that ends up in garbage dumps or oceans. The paper also discusses various recycling approaches that can benefit 3D printing waste to achieve more efficient circular applications [30]. Similar to the paper discussed by Babaremu et al., his circular economy theory and practice focus on never turning plastic into waste. It is in this case that the emphasis is on reducing the use of plastics. This is in line with the fact that in low- and middle-income countries, the circular economy model has a significant influence [31]. In addition, discussions on the circular economy of plastic waste as well as the manufacture of sustainable products from plastic waste, such as oil and charcoal, have been conducted by Payne et al. His review introduces PLA, bioplastics, and the latest research in the field focusing on plastic waste management. The article concludes that a circular economy approach to plastic waste is a promising solution to solve the plastic waste problem [32]. Uekert et al. compared closed-loop recycling technology to plastics. The paper found that mechanical recycling and PET glycolysis displayed the best economic and environmental performance, providing economic benefits ranging from 9% to 73% lower than competing technologies and environmental benefits ranging from 7% to 88% lower. The article highlights the importance of cost as a key driver of recycling for companies investing in it. Closed-loop recycling methods such as PET glycolysis are performed to break down plastic into its constituent monomers and then repolymerize it to become new plastics [33].

The concept of a circular economy has benefits in various sectors. There is an economic sector by applying the concept of a circular economy, can create attractive business opportunities and develop innovative technologies to support sustainable production and consumption activities [34]. This can affect cost savings as materials and energy are reused, as well as reducing waste and pollution in the environment [35]. The ongoing effect of this sector is an increase in resource security and also helps not to rely on limited resources. Social benefits are often felt when applying circular economy concepts such as creating job opportunities, improving community welfare, and promoting sustainable development [36]. One example is recycling and managing good waste. The benefits that can be generated are from the side that the local community will get jobs. In contrast, the consumer side will get welfare from the development of sustainable products and services. In addition to the benefits in the economic and social sectors, there are environmental benefits. Recycling means reusing the material to help reduce the need for virgin raw materials, thereby reducing greenhouse gas emissions and creating an energy recovery [37].

Overall, the circular economy offers a systematic approach to economic and environmental sustainability that can provide many benefits to society and the planet. The concept can also address global challenges such as climate change, waste loss, pollution, and biodiversity while addressing important social needs. By switching to renewable energy and materials, at least waste is not produced in the first place. It also has the potential to protect the environment, boost the economy, and improve social justice. In addition, towards a more circular economy can stimulate innovation, increase competitiveness, create jobs, and promote economic growth. Consumers will receive more innovative and durable products that will improve quality of life and save them money in the long run [38].

POST-CONSUMER RECYCLING OF POLYMERS FOR 3D PRINTING FILAMENT

Post-consumer recycling relates to the reuse of materials that would otherwise be disposed of as waste after consumption. In the case of polymers, post-consumer recycling refers to plastic products that have reached the end of their service life and will usually be disposed of [39]. The purpose of post-consumer recycling is to reduce waste and save resources by reusing materials that have reached the end of their life so that they can automatically reduce waste sent to landfills and reduce demand for virgin materials [40]. The main ultimate goal of post-consumer recycling is to create a circular economy where materials remain in use for a long period and minimize the amount of waste to help protect the environment and reduce greenhouse gas emissions [41].

This is also discussed in the paper studied by Ohno et al. In his paper, post-consumer recycling potential has significant potential to reduce carbon emissions and provides insight into economic factors that can affect the effectiveness of recycling programs. In particular, the article estimates that a 10% increase in recycling rates will lead to 0.14% in total carbon emissions. This may seem like a small amount, but at the economic level, this reduction is very significant [42]. With regard to the rapidly growing applications in the industrial world, post-consumer recycled polymers can be used as raw materials for new products, including 3D printing filaments. 3D printing, also known as additive manufacturing, creates physical objects by building material layers based on digital design [43]. 3D printing works based on the design of digital 3D models created using computer-aided design (CAD) software, or it can also be from a 3D scanner. Then the 3D printer will read the entire instruction and build the object layer by layer by melting and compacting the material using heat or light. For the final stage, 3D products can be sanded, polished, and painted [44].

In the article reported by Jandyal et al., the current state of 3D printing technology and its potential to transform manufacturing in the context of Industry 4.0, including prototyping, tooling, and the production of end-use parts, 3D printing is used by many people in the industry because of its many advantages [45]. This allows for fast and efficient prototyping and production of complex objects, which can save time and money compared to traditional manufacturing methods [46]. 3D printing also enables the customization and creation of unique and complex designs, making it a valuable tool for businesses, especially in the areas of product development [47]. Even 3D printing has a lower cost to produce with a high level of product satisfaction because it can be adjusted to customer demand, so the inventory needs are automatically much smaller [48].

Some of the most commonly used materials for 3D printing filaments include polylactic acid (PLA), acrylonitrile-butadiene-styrene (ABS), glycol-modified PET (PETG), nylon, thermoplastic polyurethane (TPU), carbon fiber, and metal powders. There are also other materials that can be used as 3D filaments, such as wood, ceramics, and graphene [49]. Recycled materials can also be used as 3D filaments, and many studies have used recycled materials for 3D filament applications, as illustrated by Figure 4.

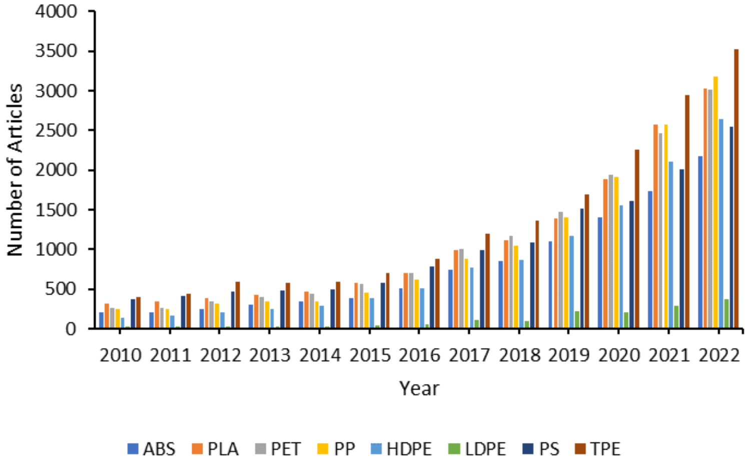

Figure 4. Development of various polymer recycled materials for 3D printing filament applications from 2020–2022 based on Google Scholar, keywords: ABS, PLA, PET, PP, HDPE, LDPE, PS, TPE – recycle for 3D printing filament (accessed on Feb 09, 2023)

Of the many recycled materials used, polymer materials such as ABS, PLA, and polyethylene terephthalate (PET) have a high development. Thermoplastic elastomer (TPE) is also a material that has a high development in 3D filament applications, but TPE is not commonly used because of its flexible and elastic properties due to its low melting temperature and high flexibility that causes deformation or bending during printing [50].

PLA, ABS, and PET are often used because of their widely available, affordable, and easy to process [51]. That materials also have good mechanical properties, such as strength and durability, suitable for various 3D printing applications [52]. The mechanical properties, especially the tensile strength of some recycled polymers and composites shown in Figure 5. These values are approximate and can vary depending on the specific composition and processing conditions of the materials. Also, different testing standards and procedures can result in slightly different results.

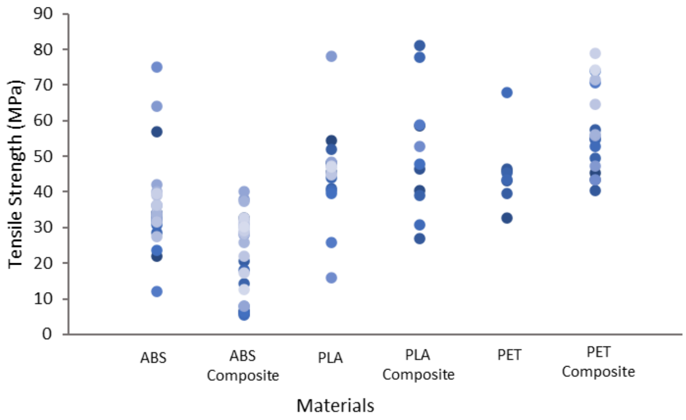

Figure 5. Mechanical properties of tensile strength from various polymer recycled materials for 3D printing filament [53]–[65]

In addition to mechanical properties, thermal properties such as glass transition temperature (T_g), crystallization temperature (T_c), and melting temperature (T_m) of some recycled materials for 3D printing filament applications have been reported and shown in Figure 6. These values may vary depending on the specific composition and processing conditions of the recycled material, as well as the method used for measuring the temperatures.

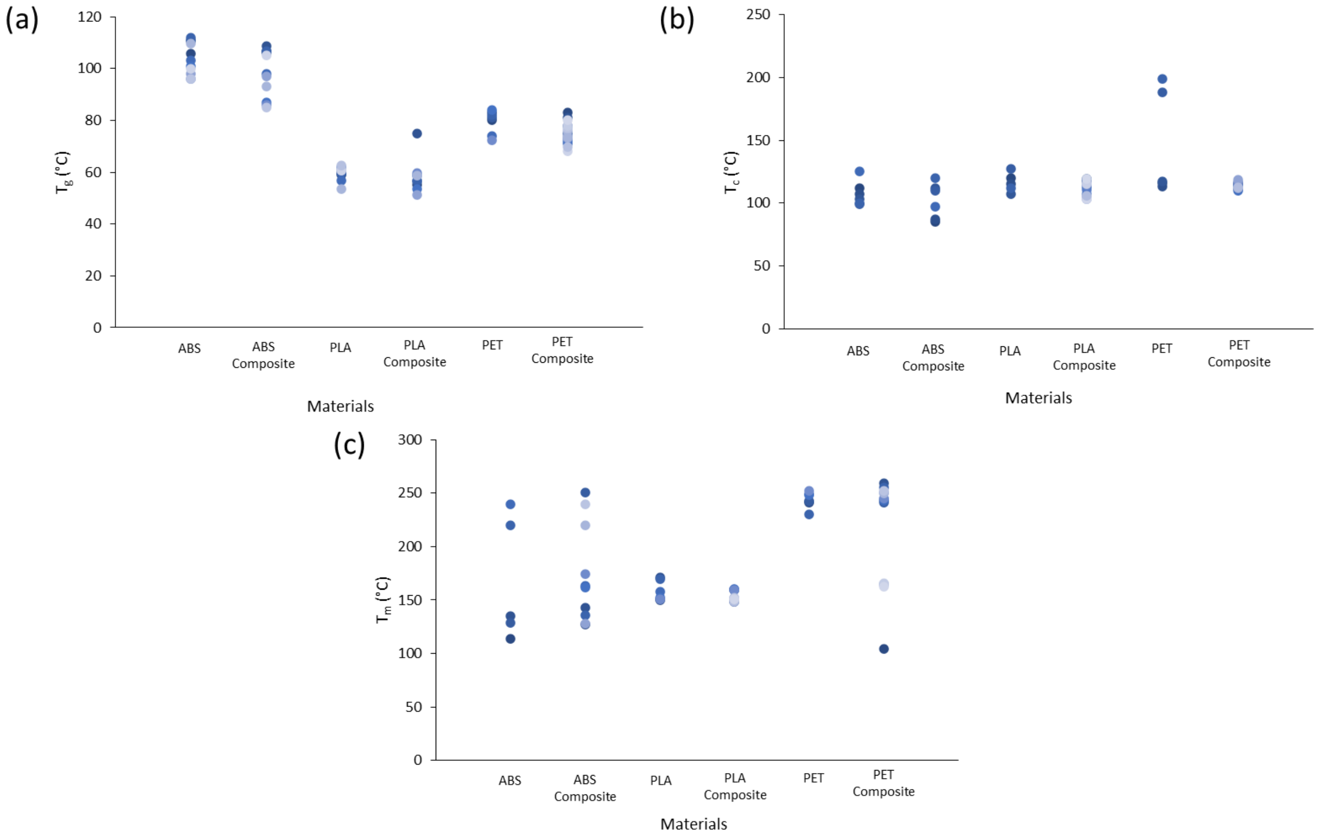

Figure 6. Thermal properties of various polymer recycled materials for 3D printing filament: (a) glass transition temperature, (b) crystallization temperature, and (c) melting temperature [66]–[70]

Overall, the use of recycled PLA, ABS, and PET materials in 3D printing filament applications provides several benefits, including reducing waste and production costs [71] while maintaining good mechanical properties. By using post-consumer recycled polymers as raw materials, it is possible to reduce the demand for pure plastics and minimize waste [72].

Post-Consumer Recycling of ABS in 3D Printing Filament

ABS recycled materials used for 3D printing filament applications are typically obtained from post-consumer waste such as e-waste [73], computer waste [74], or household appliance waste [75]. The common method used in making 3D printing filaments from ABS starts with waste collection, sorting, cleaning, size reduction, and extrusion. The resulting filaments are then rolled up and used in a 3D printer to create new objects.

A similar method has also been discussed by Huang et al., who recycle ABS waste from computer cases into 3D filaments using twin screw extruders. Some of the obstacles that have been faced, such as the need to tear apart, mixing waste materials correctly, and the importance of controlling the temperature and speed of the screws, can affect the physical and mechanical properties of the filament. His research shows that recycled ABS filaments have similar mechanical properties to virgin ABS, including tensile strength and impact resistance [76].

The article discussed by Hoggatt et al. explains that the effects of different pressing parameters, such as temperature and cooling rate, affect the quality of recycled filaments. Hoggatt et al. found that the optimal processing conditions for producing high-quality filaments from recycled ABS were a temperature of 235ºC and a cooling rate of 8ºC/min. In his article, it was also found that recycled filaments perform relatively the same as virgin filaments. However, this study was conducted on a small scale, so more research is needed to investigate the scalability of recycling as well as the long-term durability of parts printed with recycled ABS filaments [77].

In addition, a study by Singh et al. focused on developing the process of recycling ABS plastic waste into 3D printing filaments. The study explores various parameters involved during the process, such as temperature, feed rate, and screw speed, to determine optimal conditions in the recycling process. The machine used is a single-screw extruder. Singh et al. found that by adjusting the processing parameters, it can produce filaments with mechanical and physical properties comparable to virgin ABS filaments. In his research, additives such as acrylonitrile butadiene rubber (NBR), ethylene propylene diene monomer (EPDM), and polyethylene terephthalate (PET) were also added which affect the mechanical properties of filaments such as tensile strength and modulus which increase after the addition of NBR and EPDM, while the elongation at break decreases. On the other hand, the addition of PET resulted in an increment in elongation at break, but there was a decrease in tensile strength and modulus [78].

The mechanical properties of recycled ABS filaments have been discussed in some papers [79]–[81]. The results of tensile strength, Young's modulus, and break elongation in the study were influenced by the recycling process, filler composition, and parameters used during the printing process. Recycled ABS is feasible for 3D printing because there is a match between the mechanical properties of recycled ABS filaments and virgin ABS.

On the other hand, Singha and Hui have compared the thermal properties of recycled ABS material with virgin ABS. The T_g and T_m of recycled ABS produced are lower than virgin ABS, but the difference is insignificant, so recycled ABS is still suitable for application in 3D printing [82]. Another thing with Sing et al. found higher T_g due to the addition of antioxidants to recycled ABS so that thermal stability increased. They also noted that the addition of flame retardant (aluminum trihydrate) might lower T_g values [83]. Recycled ABS filaments for 3D printing can be used to create a wide variety of products, such as functional prototypes for engineering applications, educational models for STEM learning, household products such as telephone cases, keychains and table organizers as well as artistic and decorative objects.

The resulting recycled ABS value for 3D printing filaments becomes significant, as it provides a way to reuse plastic waste and reduce the environmental impact of plastic disposal. Producing 3D printing filaments from recycled ABS waste can result in cost savings compared to using virgin ABS materials with a potential cost reduction of up to 25% and estimates that the waste value of household appliances converted to 3D printing filaments can reach 1038 USD per ton.

Post-Consumer Recycling of PLA in 3D Printing Filament

PLA recycled materials used for 3D printing filament applications can come from various sources, such as post-consumer waste, and are readily available from everyday products (e.g., food packaging, bottles, etc.) [84]. Industrial waste is also a significant source of PLA recycled materials, especially in printing industries such as office paper [85] and the 3D printing industry, where used and failed prints can be recycled to make new filaments [86]. In addition, agricultural waste is also a more recent source of PLA recycled materials, as researchers have explored the use of plant-based waste as a sustainable source of PLA (e.g., corn stalks, potato starch, sugarcane, etc.) [87]. Several studies have been conducted to find out the methods used, obstacles, and the influence of additive addition.

Lopez et al. have conducted a comparative study between 3D printing and injection molding processes for sustainable biocomposite production using recycled poly lactate (r-PLA) and wood flour (WF). The method used uses a twin-screw extruder followed by 3D printing or injection molding. The results found that biocomposites from the 3D printing process showed higher tensile strength and elongation when breaking than injection-molded biocomposites. On the other hand, injection-molded biocomposites have better thermal stability than 3D-printed biocomposites. One of the main obstacles to using r-PLA in 3D printing is its low melting strength which can lead to poor dimensional stability and curvature. This can be overcome by adding WF to the r-PLA matrix, thereby increasing its melting strength and reducing curvature [88].

Petchwattana et al. modified 3D printing filaments derived from teak wood flour (TWF) and PLA composites using twin screw extruders. In his research, variations in the size of TWF particles were added with silane coupling agents, hoping that the PLA and TWF matrices have a high degree of adhesion. As a result, they found that the particle size of TWF in a composite affects the mechanical and thermal properties of the resulting embroidery. Using smaller particles can improve mechanical and thermal properties and better TWF dispersion in PLA matrices. The addition of a silane coupling agent also improves interfacial adhesion between PLA and TWF matrices so that mechanical properties are improved. One problem is the poor interfacial adhesion between the PLA and TWF matrices. This can lead to poor mechanical properties and dimensional instability in the printed parts, so a silane coupling agent is used to increase its adhesion [89].

In addition, Wang et al. have explored the use of cellulose nanofibrils (CNF) as fillers for PLA to improve its properties for 3D printing of fused deposition modeling (FDM). They extracted CNF from bamboo pulp using the mechanical defibrillation method, then mixed CNF and PLA using twin screw extruders followed by a single screw extruder to prepare composite filaments. The study found that the addition of CNF improved the mechanical and thermal properties of PLA composite filaments and the resulting 3D-printed parts. Tensile strength and bending modulus increase with increasing CNF content in composite filaments. CNF also improves the thermal stability of PLA composite filaments such as T_g and higher thermal degradation temperatures. The obstacle in the study was its poor mechanical properties, especially tensile strength and low bending modulus, so CNF was used as a filler to improve the mechanical properties of PLA composite filaments and the resulting 3D-printed parts [90].

The mechanical properties between 3D printed sediments made from pure and recycled PLA filaments are relatively small and within an acceptable range for many applications. Research conducted by Lanzotti et al. found that there was a slight decrease in tensile strength and modulus of elasticity in specimens printed with recycled PLA compared to those printed with pure PLA. But overall, the use of recycled PLA can be a viable and context-friendly alternative to many 3D printing applications [91]. Several studies have investigated the economic feasibility of using recycled PLA as a 3D squeeze filament. One of them, Kuo et al., have studied the recycling of PLA for use in the fabrication of fused filaments and found that PLA recycling is economically viable with the potential to reduce production costs by up to 30% [92].

Post-Consumer Recycling of PET in 3D Printing Filament

Various post-consumer PET materials that can be used for 3D printing filament applications are already widely available in the environment, such as those used by Zander et al. in their research, namely plastic water bottles, soda bottles, and salad containers [93].

The method used in making 3D printing filaments from post-consumer PET is the same as other material processes, namely using an extrusion process such as research carried out by Exconde et al. In his research, parts printed using recycled PET filaments showed good print quality and dimensional accuracy. They had mechanical properties comparable to those printed with virgin PET, such as bending strength, modulus, and impact strength. However, there is a reduction in the thermal stability of the breadboard due to the addition of recycled PET. The melting temperature and transition temperature of the glass are slightly lower than the temperature of the breadboard without recycled PET. Nevertheless, the researchers still concluded that recycled PET could be a viable option for 3D printing filaments in certain applications, such as low-load bearing parts or objects that do not require high thermal stability. One of the obstacles faced in this study is the difficulty of obtaining high-quality recycled PET materials. It can affect the print quality and mechanical properties of the printed parts [94].

The influence of processing parameters can affect the mechanical and thermal properties of PET recycling in fused filament fabrication (FFF), so it is necessary to assess the optimal processing to produce high-quality 3D printed parts from rPET, such as research that has been carried out by Voorde et al. In his research, he used twin screw extruders to process rPET to produce a 1.75 mm filament. To improve the mechanical properties of rPET, the researchers added a compatibilizer, a substance that improves compatibility between different materials. The study found that the processing parameters have a significant influence on the crystallinity and mechanical properties of the printed parts. The temperature of the nozzles was found to be the most significant parameter affecting the crystallinity and tensile properties. In contrast, the temperature of the base has a greater effect on the bending properties. The addition of a compatibilizer improves the tensile and flexure properties of the printed parts but decreases the thermal stability of rPET. The obstacles in using recycled PET in FFF are the presence of dirt and difficulty in achieving uniform material flow, so further optimization of the processing parameters and composition of the material is needed [95].

Applications of filament 3D printing products made from recycled PET include rapid prototyping in industries such as automotive [96], aerospace, and consumer products. In addition, household items such as vases, telephone cases, and lamps [97]. In the field of fashion and accessories, namely jewelry, sunglasses, and shoes. Emerging applications, such as those in the medical field, can also be made from materials such as prosthetics and dental implants [98]. It is supported by the fact that PET recycling has good biocompatible properties and flexibility [99].

The importance of lamented 3D printing of recycled PET finds promising results. For example, a study by Huang et al. found that recycled PET filaments produce mechanical properties comparable to virgin filaments, thus potentially becoming a viable alternative [100]. Similarly, a study by Haider et al. found that recycled PET filaments show good adhesion and strength when used for 3D printing [101]. In addition to environmental benefits, using recycled PET in 3D printing filaments can also have economic benefits. A study by Zhu et al. found that recycled PET filaments can reduce material costs by up to 40% compared to virgin PET filaments [102].

CONCLUSION

Post-consumer polymers such as materials made of ABS, PLA, and PET can be a sustainable source of materials for 3D printing filaments. Using recycled materials can reduce environmental impact and contribute to the circular economy. Several studies have shown that 3D printing filaments made of post-consumer polymers exhibit similar or even better properties than those made of virgin materials. This means recycled materials can be a viable alternative to 3D printing filament applications without sacrificing quality. Various applications, including medical, automotive, and consumer goods industries, can be applied using post-consumer polymers. However, there are still some challenges that must be faced, such as the need for a consistent and high-quality source of recycled materials, as well as the development of a more efficient and cost-effective recycling process. Thus, more research is still needed.

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