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Review

Advancing Sustainable Practices in Additive Manufacturing: A Comprehensive Review on Material Waste Recyclability

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Abstract: This review investigates the pivotal challenge of recycling material waste in the context of additive manufacturing. We place an emphasis on decentralized 3D printing, shedding light on its environmental and economic implications. As additive manufacturing experiences exponential growth, the environment impact of waste generation during 3D printing processes has become increasingly significant. This paper explores various recycled materials commonly used in 3D printing, including polymers like polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), and polyethylene terephthalate glycol (PETG), evaluating their characteristics and usability. General recycling methodologies, encompassing mechanical and chemical processes, are examined, with attention paid to challenges such as polymer sorting, additives, coatings, contamination, and thermoset reprocessing. The economic, societal, and environmental impacts of integrating recycled materials into 3D printing are examined. By identifying research gaps and proposing future trends, this review contributes to the development of a deeper understanding of how recycling can play a pivotal role in achieving environmental sustainability and economic viability within the decentralized 3D printing landscape.

Keywords: additive manufacturing; sustainable manufacturing; waste recycling; 3D printing; decentralized manufacturing; circular economy

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1. Introduction

The growing global demand for additive manufacturing indicates that a transformative trend is emerging across various industries. Additive manufacturing, characterized by the layer-by-layer deposition of material, is a recently developed and widely studied production method [1,2]. It includes terminologies such as 3D printing (3DP), rapid prototyping (RP), direct digital manufacturing (DDM), rapid manufacturing (RM), and solid freeform fabrication (SFF). As an advancing technology, 3D printing, or additive manufacturing (AM), has applications in diverse sectors such as the aerospace, automotive, medical and healthcare, construction and architecture, and food and fashion industries [1]. The aerospace sector has started utilizing AM technology due to its ability to create lighter structures, resulting in lighter airplanes and spacecrafts. Similarly, the automotive industry has recognized the potential of additive manufacturing to produce complex and high-quality parts that were previously unachievable and to replicate difficult-to-find parts. In the healthcare sector, AM makes it possible to perform complex transplants and produce precise anatomical models for surgical planning. Moreover, studies evaluating the strength of products manufactured through additive processes, including non-metallic and metallic materials, have been conducted, highlighting the viability and limitations of the technique.

The decentralization of 3D printing represents a significant change in the manufacturing sector, making it accessible for large-scale industrial applications, general domestic use, and small-scale manufacturing enterprises. The number of people using 3D printers for small-scale businesses and personal use has increased as they become more widely available, cheap, user-friendly, and portable. One of the advantages of decentralized 3D printing is that it allows users to express their ideas by creating complex, personalized objects on demand without requiring massive production facilities.

A notable use case for 3D printing is seen in rapid prototyping, with the technology emerging as an indispensable tool across various industries. The ability to quickly transform digital designs into physical prototypes enables an iterative design process, allowing engineers, designers, and researchers to test and refine their concepts rapidly. This accelerates the product development cycle and significantly reduces lead times, providing a competitive edge to industries such as the aerospace, automotive, and consumer electronics sectors. The efficiency and precision of 3D printing in rapid prototyping contribute to cost savings and enhance innovation, highlighting its role in shaping the future of product design and development [1].

There is no doubt that 3D printing has transformed several industries by providing unprecedented flexibility in terms of design and production. However, there are challenges, particularly in terms of sustainability and environmental impact, due to the rapid pace of decentralization. However, by integrating recycled elements into the 3D printing process, we may overcome many difficulties. For instance, converting plastic waste into printed filaments not only reduces the environmental impact of the process but also provides a range of material choices with varying degrees of rigidity, flexibility, and transparency. This increased flexibility fosters design innovation, enabling the creation of unique products tailored to specific needs and preferences.

This comprehensive review analyzes the evolving landscape of material waste recyclability in additive manufacturing, starting with its role in decentralized manufacturing. It then evaluates the usability and characteristics of various recycled materials in the AM sector. This is followed by an in-depth analysis of current recycling methodologies, such as mechanical, chemical, and thermal processes. The economic and societal impacts of additive manufacturing are also discussed in this review. It highlights the necessity of adopting sustainable practices in AM and stresses the significance of improving waste management by highlighting research gaps and future trends.

1.1. Evolution of Additive Manufacturing

The invention of additive manufacturing relates to the 1980s, when Charles "Chuck" Hull invented stereolithography (SLA). SLA uses ultraviolet (UV) light, focused on a UV photo-curable liquid polymer solution, to build patterns layer by layer to create a three-dimensional object. This invention paved the way for the establishment of 3D systems in 1986, which led to the creation and production of 3D printers. After that, the United States Patent and Trademark Office (USPTO) patent grant was issued in 1986, marking the development of rapid prototyping systems and pushing AM to the forefront of manufacturing technology [3].

Despite its initial challenges, additive manufacturing is a significant technological advancement that combines materials using a variety of processes like fusion, binding, and solidification. The parts are assembled layer by layer with the help of 3D CAD modeling, which stores complicated object geometries using 3D computer data or Standard Tessellation Language (STL) files. AM consists of three key stages: design, processing, and testing. Today's industries use a wide range of methods, such as direct metal laser sintering (DMLS), laminated object manufacturing (LOM), fused deposition modeling (FDM), stereolithography (SLA), and selective laser sintering (SLS) [4,5]. While additive manufacturing has many advantages, there are disadvantages, having slower build times and lower precision than CNC machines. The orientation of various parts plays a significant role in improving accuracy, build times, the number of supports required, and, eventually, manufacturing costs.

1.2. Decentralized Manufacturing—3D Printing

Decentralized manufacturing (distributed manufacturing) is defined by its capacity to customize production at different scales and locations, whether at the point of consumption, point of sale, or within production facilities utilizing local resources. This approach increases user involvement in product design, fabrication, and supply. Digitalization and emerging production technologies, like additive manufacturing, often drive this decentralization. This approach has great potential, particularly in terms of enabling manufacturing close to areas with the highest demand while accommodating customized needs. Large-scale customization using inventory-light production methods and improved accessibility to new markets and customers are possible with decentralized manufacturing, particularly in the healthcare industries [6].

Despite widespread attention, many people are unaware of additive manufacturing's ability to decentralize production processes. The resulting localization movement is anticipated to replace globalization and dramatically reduce air, land, and sea travel. It is expected to significantly change global commerce, inducing a decline in the goods trade and related macroeconomic changes in nations [7]. Due to simplified logistics, supply chains will undergo significant changes as fewer businesses participate. Distribution will be made more accessible, and the problems with international supply chains will be lessened by production being both closer to the consumer and driven by consumer demand. It is also anticipated that the skill required by and the occupational needs of the new economy will change, with more logical, integrative, creative, and self-sufficient roles like designers, consultants, engineers, and product developers replacing jobs in installation, retail, packaging, transport, delivery, and construction. To manage socio-cultural difficulties, this shift needs careful attention and should be managed via education and training [8]. AM can enhance technical progress, providing underdeveloped nations with an alternate path to economic prosperity. The revolutionary potential of AM, which enables small companies to launch new goods without depending on international supply chains, is recognized by both big and small businesses [8].

Highly complex or even hybrid parts can be designed with the help of additive manufacturing, which allows for customized mass production that uses less material to minimize weight. Thus, the development of specialized materials has dramatically benefited from AM technologies. Because printable materials can now be precisely deposited in three dimensions with high accuracy, fewer production processes and resources are needed to build a desired framework. The primary materials for fused deposition modeling (FDM) 3D printing are thermoplastics, increasing overall plastic use. The most prominent problem with plastic use is its adverse impact on the environment and people. As a result, increasing sustainable production is becoming increasingly crucial, particularly given the modern world's dense population and the rising living standards caused by global industrialization [9].

2. Materials and Methods

Recycling has become increasingly significant with the growing amount of waste accumulated. This has led to the exploration of more innovative methods of recycling plastics. One such approach involves using recovered and recycled materials as inputs for the AM process. The process of converting plastic waste into printable filaments offers a variety of material options, improving design creativity and enabling customized goods.

In the upcoming sections, we identify the various materials utilized in AM. This is followed by a comprehensive review of the usability and properties of recycled materials and current recycling methodologies related to AM.

2.1. Material Landscape in Additive Manufacturing

Identifying various materials used in AM is vital for producing high-quality products through this technology, as the proper material selection is paramount for achieving quality outcomes [10]. The raw materials used for different types of AM must be prepared to ensure compatibility with the specific manufacturing process (e.g., powder, sheet, wire, liquid). For instance, a liquid thermoset plastic monomer that crosslinks when exposed to suitable electromagnetic radiation is required as a feedstock for vat polymerization and photopolymer-based material jetting. Material extrusion and powder bed fusion processes utilize thermoplastic polymers, leveraging thermal layer adhesion mechanisms, though each employs different techniques to achieve this. Amorphous thermoplastics work best for material extrusion, whereas powder bed fusion usually uses semicrystalline polymers. The typical photopolymer materials used in AM are composed of monomers, oligomers, photoinitiators, and a variety of other additives, including inhibitors, dyes, antifoaming agents, antioxidants, toughening agents, etc., that help to fine-tune the photopolymer's behaviors and properties [11]. Table 1 outlines the general categories of polymers utilized in AM, displaying with their respective properties and symbols [11].

Table 1. The material landscape in additive manufacturing.

Polymer	Properties	Symbols	Ref.
Polylactic acid (PLA)	Tensile strength: 64.93 MPa Impact strength: 17.04 MPa	7 OTHER	[12]
Acrylonitrile butadiene styrene (ABS)	Tensile strength, type 1, 2″/min, (51 mm/min): 22 MPa Tensile strength, type 1, 2″/min, (51 mm/min): 1627 MPa Tensile strength, type 1, 2″/min, (51 mm/min): 6% Flexural strength: 41 MPa Flexural modulus: 1834 MPa Izod impact strength, notched (730 F, 230 C): 22 MPa	7 OTHER	[13]
High density polyethylene (HDPE)	Ultimate tensile strength of 19.08 MPa Onset degradation temperature of 430 °C Full degradation temperature of 520 °C	2 HDPE	[14]
Polyethylene terephthalate (PET)	RPET Tensile modulus of 1932.78 MPa Yield strength of 47.51 MPa Ultimate tensile strength of 52.44 MPa Tensile strain at break of 98.86%. RPET soda bottle Tensile modulus of 2009.66 MPa Yield strength of 43.08 MPa Ultimate tensile strength of 46.08 MPa Tensile strain at break of 7.46%.	1 PET	[15]
Polyvinyl chloride (PVC)	Tensile strength (psi): 7500 Flexural strength (psi): 12,800 Hardness (Rockwell R): 115	3 PVC	-
Polystyrene (PS)	Tensile strength: 46 MPa Impact strength: 5 J/cm Yield strength: 0 MPa Young's modulus: 3250 MPa	6 PS	-
Polypropylene (PP) (homopolymer)	Tensile strength: 33 MPa Hardness on Rockwell "R" scale: 90 Tensile modulus: 1.4 GPa	5 PP	-

2.2. Usability and Properties of Recycled Materials

Some emerging polymeric materials, such as polyesters, polyamides, and acrylic compounds, are characterized by their chemical composition, which influences their recyclability. PP and PET accounted for 46% of the world's polymer output in 2015; the packaging sector used 63.4% of these polymers. The most recycled polymer is PET, which is frequently used to make water bottles, followed by HDPE, which is used to make shampoo bottles [16]. Common commercial polymers, including LDPE, HPDE, PP, PS, and PVC, exhibit high mechanical strength up to 100 °C. Conversely, nylon, PET, and ABS polymers can withstand temperatures beyond 100 °C without losing their mechanical qualities.

Most commodity polymers are olefin-based, making up more than 50% of plastic waste, whereas PET makes up just 10% of all plastic garbage. The strong C-C covalent link between the polymer chains in olefin-based polymers makes them difficult to recycle, resulting in the need for high temperatures and effective catalysts. However, the recycling cost does not add value to recycled material, resulting in a recycling rate of <10% for these polymers [16].

Because of the low molecular diffusion rate, polymers frequently contain additives like colors, plasticizing agents, antioxidants, and reinforcing material, which makes it challenging to recover the basic polymer. When combined with organic coatings and additives, the polymers create intense van der Waals pressures that increase the energy used by and expense of recycling. For recycling, the thermoset polymer coating must first be removed and separated from the thermoplastic polymer. Additionally, the commercial value of recovered polymers is reduced when dyes are used to produce colored polymers. To overcome these major challenges in polymer recycling, innovative and cost-effective methods for removing coatings and additives are essential [17].

Martijn Roosen et al. (2020) investigated the compositional hurdles experienced during the mechanical and thermochemical recycling of a few plastic packaging waste products [17]. Table 2 summarizes their findings.

Table 2. Compositional hurdles experienced during mechanical and thermochemical recycling.

Components	Paper and Polymeric Hurdles	Elemental Hurdles
Polyethylene terephthalate bottles	Polymeric contamination by bottle caps	High O content in the bottle
	Polymeric contamination by labeling stickers	-
	Paper contamination by bottle lids	High Cl content in the bottle
	Inseparable polymeric contamination that comes from parts of multilayer packaging	High metal content in inherent contaminations
Polyethylene terephthalate trays	Polymeric contamination by bottle lids	High O content in the tray
	Paper contamination by labels	Elevated chlorine content in innate pollutants
	Layers of inseparable polymeric contamination on the surface	Elevated metal content in inherent contaminations
Polyethylene bottles	Polymeric contamination by bottle caps	Elevated metal content in innate pollutants
	Polymeric contamination by labeling stickers	
	Paper contamination by bottle labeling	
Polypropylene bottles	Polymeric contamination by bottle caps	Elevated metal content in inherent contaminations
	Polymeric contamination by labeling stickers	
	Paper contamination by bottle labeling	Elevated O content in inherent contaminations
Polypropylene trays	Polymeric contamination by bottle lids	High Cl content in tray
	Polymeric contamination by bottle labeling	-
	Paper contamination by labeling stickers	Elevated metal content in tray

Table 2. *Cont.*

Components	Paper and Polymeric Hurdles	Elemental Hurdles
EPS trays	Polymeric contamination by bottle lids	High Cl content in the tray
	Polymeric contamination by labeling	Increased metal concentration in innate pollutants
	Paper contamination by labels	Increased O content in inherent contaminations
Monolayer film	Possibility of multilayer film contamination as a result of inaccurate sorting	Rise in Cl content in film Increased metal content in the film
Multilayer films	Paper contamination	High O content in film
	Unbreakable polymeric contamination that comes from elements within multilayer packaging	Elevated O content in inherent contaminations
	Inseparable aluminum contamination	Increased N content in film Increased Cl content in film Elevated metal content in film High metal content in inherent contaminations

Additive manufacturing involves the use of various materials that include combinations of polymers, additives, reinforcing agents, plasticizers, pigments, and antioxidants. These components are incorporated to enhance the mechanical and chemical properties of the final product. Table 3 summarizes a few specialized material compositions which can be utilized in sustainable additive manufacturing processes that have been identified through various studies.

HDPE mixed with RF demonstrates varying weight loss percentages, with HDPE 70% notably exhibiting a weight loss of 82.59%. Reinforcing 3D-printed mortar with steel cables leads to enhanced flexural strength and bond strength, while also ensuring specific flow ranges for both the fresh mortar and the fluidity of the reinforced steel cables. Recycled ABS (RABS)/virgin ABS (VABS) blends exhibit enhancements in various mechanical attributes, with superior properties observed in samples printed with a 50% RABS/50% VABS composition. Incorporating recycled plastic waste, such as Resin8, into 3D-printed concrete (3DPC) impacts compressive and flexural strengths in a way that is inversely proportional to the amount of Resin8 utilized. Materials derived from PET in filament form and from water and soft drink bottles display distinct mechanical properties, including elasticity, strength, and hardness. Young's modulus increases when PET and HDPE are combined as feedstock materials for large-scale 3D printing.

Table 3. Different specialized material compositions.

SI No	Material	Processing/Description	Properties	Ref.
1	HDPE mixed with RF	Temperatures of 190 °C and 230 °C. According to field emission scanning electron microscopy (FESEM), the ideal amount of RF for both polymer blends is 30%, as this makes the structure look ductile.	Weight loss of V-HDPE: 101.51%. The lowest weight loss: 82.17%. Weight loss was recorded: 88.36% for PP 30%. 82.59%. for HDPE 70%. 90.90% for PP 70%. 101.51% for V-PP.	[18]
2	Reinforcement 3D-printed mortar with steel cables	In the 3D-printed cement mixture, 30% of the cement was swapped out for recycled smelted brick powder. The range for the open time is from 10 to 40 min.	Bond strength 2–2.5 MPa. Flexural strength increased by 172–357%. The flow range of fresh mortar: 154–187 mm. Reinforced steel cable fluidity: 160–180 mm.	[19]
3	For the production of 3D-printed concrete, FS and AS were used as fine aggregates (3DPFAC).	The most suitable print parameters are 50 mm/s print travel speed, an 8 mm print layer height, and a 20 mm print nozzle diameter.	Mechanical properties are best when the AS content is 30%. Frost resistance is best when the content is 80–100%.	[20]

Table 3. *Cont.*

SI No	Material	Processing/Description	Properties	Ref.
4	Recycled acrylonitrile butadiene styrene (RABS)/virgin acrylonitrile butadiene styrene (VABS).	It has different weight proportions such as: 100, 90/10, 80/20, 70/30, 60/40, 50/50.	A small increase of 11.49% in flexural strength. 5.45% of flex modulus. 17.31% work of fracture. 7.71% average increase in Young's modulus. 5.19% of average tensile strength at yield. 3.51% of ultimate tensile strength. Samples printed with 50% RABS/50% VABS blends show superior mechanical properties.	[21]
5	For the first time, recycled plastic waste was put into 3D-printed concrete (3DPC) as Resin8.	Replacement values of 5%, 10%, and 15% of natural sand by volume, with varying Resin8 particles. The particle sizes of the Resin8 included are sub 5 mm, sub 1 mm, and a combination of the two in equal proportions. Recycled flakes are eventually mixed at temperatures ranging from 190 to 200 °C.	The compression strength decreased as the percentage of Resin8 in the blocks increased; in the 5% and 50% Resin8 replacement blocks, there were 20% and 70% reductions, respectively. For mold casting at orientations D1 and D3, there was a reduction in the average flexural strength of 37%, 40%, and 19% for the 15% replacement Resin8 mixes. For mold casting at orientations D1 and D3, there was a drop in the average compressive strength for the 15% replacement Resin8 mixes of 30%, 31%, and 37%.	[22]
6	PET from water and soft drink bottles	Without breaking or dissolving, the bottle is transformed into a filament with a diameter of 1.75 mm.	The elasticity is about 230 MPa. 29 MPa is the maximum mechanical strength. A 10 MPa hardness is found.	[14]
7	Asphalt mixtures produced by incorporating waste plastic aggregate (WPA)	The incorporation of WPA into base (BB-2) and middle (MC-1) asphalt layers at various percentages (0%, 3%, 5%, 7%, and 10%). To improve the mixtures' qualities, additive materials like magnesium, fly ash, and steel slag powder were added.	Overall: - Mixtures with 5% WPA tend to meet or exceed ITS standards. - WPFM 5% consistently outperforms 7% and 10% mixtures. - Non-linear relationship between WPA content and ITS observed, indicating the influence of WPA type and its proportion on tensile strength properties. - None of the 7% WPA mixtures met standard requirements. - BB-2 mixture with 5% WPFM showed the highest TSR value (97.7%), indicating excellent moisture resistance. - MC-1 mixture with 5% WPFM had the highest TSR value (85.9%), considered to have the best moisture resistance among 5% WPA mixtures.	[23]
8	Regranulate of biodegradable and biobased polymeric materials in 3D filaments based on polylactic acid (PLA) and polyhydroxy butyrate (PHB).	1st stream: simulated the potential for adding regranulate and blending a polymer blend that would be appropriate for creating filaments for 3D printing using FDM technology. 2nd stream: filaments for 3D printing with varying ratios of NONOILEN® 3D 3056-2 and NONOILEN® prepared, non-recycled material. • Extruder temperature: initial layer at 195 °C, followed by layers at 190 °C.	- Tensile strength of PLA/PHB filament reaches around 40 MPa, unaffected by the blend's regranulate content. - 20% regranulate addition reduces filament elongation by 12% to roughly 4%. - Flexibility of filament varies from 6.7% to 19.2% without regranulate; no significant change with over 20% regranulate. - Addition of regranulate decreases material elasticity but retains strength characteristics above 40 MPa. - No significant influence of the filament preparation process on mechanical properties was observed. - 3D-printed objects show almost identical strengths at break values regardless of regranulate content. - Strength at break decreases from 17 MPa to around 15 MPa with 100% regranulate in 3D-printed objects. - In comparison to filament, the 3D printing process' anisotropy leads to reduced strength at break values. - Relative elongation at break decreases from 20% to around 8% with 20% regranulate in 3D-printed objects. - Further decrease in elongation with higher regranulate.	[24]

Table 3. *Cont.*

SI No	Material	Processing/Description	Properties	Ref.
9	Cementitious–glass composite bricks (CGCBs) with 3D-printed reinforcement structures made of PET-G Recycling glass waste (78%) and PET-G (8%).	• The temperature of the nozzle is 240 °C. • Temperature of the build plate: 85 °C • Diameter of the nozzle is 0.4 mm. • Layer thickness is 0.2 mm. • Part cooling intensity: 40%. • Printing speed is 50 mm/s. • Infill density: 100%.	The CGCBs exhibited a 12% lower thermal conductivity and a 17% lower specific heat. There was a remarkable 72% increase in flexural strength in the vertical direction and a 32% increase in the horizontal direction.	[25]
10	Blending PET and HDPE to create a feedstock material for 3D printing on a large scale.	90% PET (body of the bottle) and 10% HDPE (cap)	They confirmed the increase in Young's modulus from 1.7 GPa of the pure PET to 2.1 GPa for all the HDPE concentrations. Thermal properties of rPET, rHDPE, and rPET90//rHDPE10. The melting points of rHDPE and rPET are 131.7 and 249.9 °C	[26]
11	Polyethylene terephthalate (PET)	Without breaking or dissolving, the bottle is transformed into a filament with a diameter of 1.75 mm.	About 230 MPa is the elasticity. Maximum mechanical strength is found to be 29 MPa. Hardness is around 10 MPa.	[27]

One experiment employed physical, chemical, and thermal characterization to assess the reinforcement effects of polymer blends by using various percentage compositions of recycled flexible plastic alongside virgin PP and HDPE [18]. Another investigation showed that adding virgin pellets restored the mechanical performance of 3D-printed samples. Reinforcement from virgin pellets can help recycled polymers regain their lost mechanical characteristics. Incorporating the appropriate quantities of fibers and particles into polymers is another effective method with which to enhance their mechanical properties [16].

It is easy to create complex, personalized items with 3D printing. By using recycled materials in 3D printing, we may explore a diverse array of material qualities and features. Waste plastic can be transformed into printable filaments, which can then be used to produce a diverse range of rigid, flexible, and even transparent objects. This adaptability creates new opportunities for design innovation and makes it possible to create unique items that meet requirements and preferences [28].

2.3. Current Recycling Methodologies

The market for 3D printing is a rapidly expanding industry. A wide range of thermoplastic compounds, including recyclable ones, may be used to create printable filaments [29]. Such polymeric material recycling usually involves several steps, including material separation, purification and decontamination, grinding, remelting, and extrusion. Figure 1 depicts the predominant methodology used for recycling in AM. Several recycling processes for 3D printing filaments are described in this section.

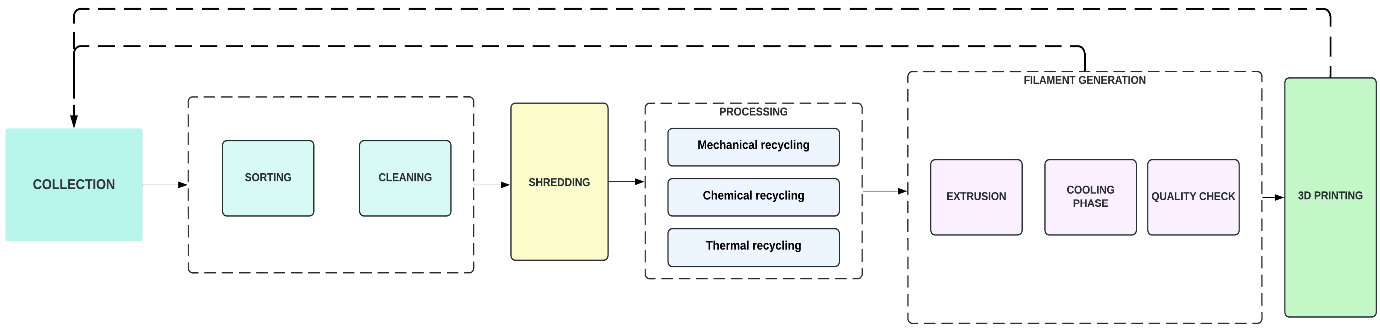

Figure 1. General recycling methodology for additive manufacturing.

The first step is 'collection', where suitable plastic materials for recycling are collected by different means depending upon the classification. Solid waste can be classified into different types according to sources, such as municipal solid waste (MSW), industrial waste, agricultural waste, municipal sludge, and other wastes [30]. The effectiveness of waste management becomes crucial in educational institutions where there is constant waste generation. Collecting waste directly from the point of generation and then recycling it locally is more effective and significantly easier to manage than other methods. On the other hand, a different kind of waste collection strategy is required in centralized areas like industries and municipalities. This strategy utilizes existing waste management techniques, such as those used by municipalities globally, including curbside collection, vehicle collection, drop-off waste disposal, buy-back centers, and deposit/refund programs [31].

The second step, which accounts for approximately 25% of the recycling process, is known as 'sorting'. During this process, all the plastic waste collected is separated into different types based on its characteristics. Most plastics are classified as HDPE, PP, or PET; however, if other polymers cannot be recycled, they are separated from the other plastics and used for other purposes. Sorted plastic is then further divided into categories based on hues and kinds [31]. The recycling process is not uniform and varies significantly depending on the type of polymer. Interestingly, even polymers with similar chemical structures, such as the CeC bond found in LDPE and PP, cannot melt together. Once mixed, these polymers pose a considerable challenge in terms of separation [16]. This issue is often compounded in commercial products as they typically contain multiple types of polymers within a single product. This makes the task of polymer sorting a significant challenge. Automating the sorting procedure guarantees that the recovered polymer is of a consistent quality and can be handled efficiently, which is essential to the success of mechanical recycling [24]. This is typically achieved using near-infrared spectroscopy (NIR). However, X-ray fluorescence (XRF) is the preferred method for larger volumes. The subsequent sizes of the shredded polymer pieces depend upon their intended use. There is a growing demand for high-efficiency sorting techniques in the recycling industry and this highlights the need for innovative solutions to improve the efficiency and effectiveness of polymer-recycling processes.

The third step in the recycling process is 'cleaning', which involves removing contaminants like labels and adhesives from waste. This step incurs additional costs for drying and wastewater treatment. Effectively removing food-related pollutants is a significant challenge, as caustic cleaning methods are ineffective at eliminating odor-causing components. For instance, PET is washed in hot water to remove label residues or dirt, and it undergoes various procedures to eliminate materials such as paper or metal. However, detergent bottles often require mechanical cleaning to thoroughly remove all contaminants.

'Shredding' is a process that involves breaking down used or defective prints, along with other plastic waste, into smaller pieces to enable easier handling and further processing. Shredding significantly increases surface area. This helps with melting, facilitating effective heat transfer and ensuring a complete and consistent melting process. It contributes to improved processing efficiency and homogeneity in material melting. For instance, a FriendTM plastic mill was used to shred the 3D-printed specimens. Since the goal of the study was to simulate the closed-loop recycling of 3D-printed products, washing and sorting were not included in the experiment; instead, the PLA's source and end use were analyzed [32].

Figure 2 gives the process stages for the preparation of the collected material, showing (A) a schematic representation outlining the process of material preparation, (B) the materials utilized in the process, and (C) the resultant material [26].

The next step involves processing the shredded plastics into a desired form, such as pellets. The processing of these plastics can be broadly divided into the following subsections.

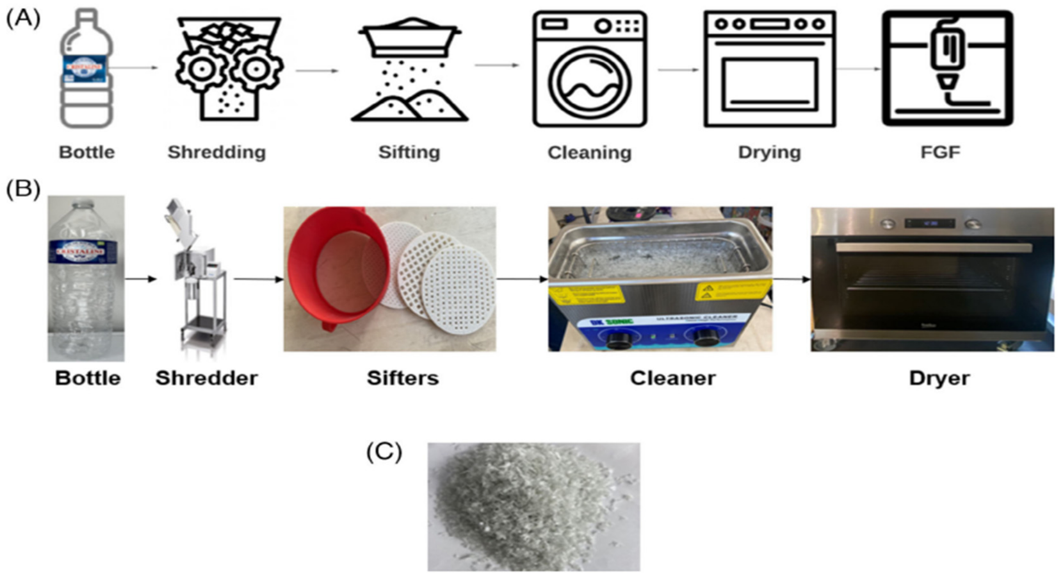

Figure 2. (**A**) Various steps in plastic recycling. (**B**) Various tools utilized in each step. (**C**) Shredded plastic. Reproduced with permission from ref. [26] and with permission from Elsevier, 2024, Arunav H.

2.3.1. Mechanical Recycling

Polymers are recovered and recycled into new products through mechanical recycling by utilizing specialized mechanisms capable of deforming the waste without altering its chemical structure. Technologies used for size reduction, remelting, decontamination, sorting/separation, and production are all incorporated into mechanical recycling. Many studies highlight the energy and environmental benefits of mechanical recycling, particularly for waste streams consisting solely of plastic or bioplastic. It is essential to complete the use circle for polymer wastes and enable the development of a circular economy [31,33].

Not all types of plastic are suitable for mechanical recycling, and the quality of the recycled plastic can degrade after multiple times being recycled [34]. However, in addition to technical concerns about plastic degradation, mechanical recycling faces difficulties with intricate management and collection procedures [33]. In one of the studies, the reference-grade printing wastes were ground up and placed through a severe 85 °C washing process. The detergent used was Triton X-100 (0.3% wt.) and used a water-based solution of NaOH (1.5% wt.) similar to the ones used by the mechanical recycling companies [35]. The purified components were dried in a vacuum oven for two hours at 85 °C before being processed in a vacuum oven [35,36].

2.3.2. Chemical Recycling

Chemical recycling (feedstock recycling) uses procedures like hydrolysis, pyrolysis, gasification, condensation, glycolysis, hydrocracking, dissolution, etc., to break down synthetic fibers for repolymerization and produce monomers of the polymers (or partially depolymerized to oligomers) [37]. Polymerization, purification, and depolymerization are some of the phases involved in this process. Chemical recycling technologies provide supplementary solutions to the mechanical recycling of polymeric waste.

In research, depolymerization is a chemical recovery technique used to produce initial carboxylic acids, diols, or diamines from polymers that undergo condensation (polyamides, polyesters, polyethers, and PET). Acidolysis, glycolysis, alcoholysis, and hydrolysis are examples of depolymerization processes. These reactions hold significance in deconstructing polymer structures, playing a pivotal role in regenerating constituent monomers [34].

Fourier transform infrared spectroscopy (FTIR) was used to determine the chemical composition of the filaments by measuring reflectance using the non-destructive attenuated total reflectance (ATR) sampling technique [38]. A Perkin Elmer Frontier Spectrometer

(FTNIR/MIR, Waltham, MA, USA) fitted with an FR-DTGS detector and a KBr beam splitter were used in another study to record the infrared spectrum (4000–550 cm^{-1}) [38].

2.3.3. Thermal Recycling

Thermal degradation, also known as thermal recycling, uses heat to break down polymers into their component monomers or other compounds. Used to break the polymer down into smaller molecules, this technique usually entails heating the polymer to high temperatures without the presence of oxygen. New polymer goods and other compounds, such as fuels and waxes, can be made from the resultant products [24].

The process of pyrolysis—which takes place in the absence of oxygen and usually at temperatures ranging from 400 to 980 °C—was used to thermally break down polyethylene terephthalate, polystyrene, polymethylmethacrylate, and certain polyamides into their monomers. The resultant products include fuel gas consisting of CO, CO_2, H_2, and C_nH_m, liquid components in the form of oils, and a solid residue known as char [34].

The mechanical recycling approach requires a minimal amount of energy, the thermal recycling approach utilizes a moderate amount of energy, while the chemical recycling approach demands the highest level of energy consumption. All these modern recycling methods consume less energy than conventional methods like incineration and landfilling. In addition, the number of cycles in which the polymer composite materials can be recycled depends on the individual components of these materials [39].

Extrusion is the last step, during which the processed-shredded plastic is fed into an extruder. In this process, the polymer is subjected to heat and pressure, which causes it to melt. This is usually performed in an extruder head, a unique device that pushes the polymer through a heated barrel using a screw mechanism. The polymer is forced through a die once it has melted. This procedure produces pellets to create a finished solid or flexible film product carefully designed for other applications [40]. These pellets can serve as raw materials for producing a wide array of new products, including plastic containers, toys, and automotive parts. This demonstrates the versatility and potential of recycled polymers across various sectors [16].

To achieve the correct dimensions and structural qualities of the extruded material, effective cooling is necessary. This plays a critical role in determining the final product's quality. As the extruded material moves through solidification and cooling, controlling the rate and uniformity of cooling takes on greater importance. This accuracy is essential to preventing errors and ensuring the final product's structural integrity [40]. Quality control procedures are essential throughout the process to ensure that the produced plastic feedstock fulfills the required specifications. The extrusion system's complexity arises from the collaborative operation of the cooling assembly, die assembly, plasticizing extruder, and winding apparatus.

In a study evaluating former waste plastic extruder designs, referred to as "Recycle-Bots", a weighted evaluation matrix was employed. An updated design was developed and analyzed, which included a comprehensive component summary, testing procedures, life cycle analysis, and extrusion results. The study focused on measuring power consumption and evaluating filament characteristics, enabling a thorough examination of the performance and sustainability aspects of the newly developed extruder system [41].

PET shreds can be dried under a vacuum at 120 °C overnight to prevent melt hydrolysis. This study utilizes equal weights of each polymer and 5% of either SEBS or SEBS-MA to fix compatible blend ratios [42].

3. Economic and Societal Impacts

As an emerging manufacturing process, additive manufacturing impacts a product's life cycle and offers sustainability benefits at various stages. While serving as a direct substitute for traditional manufacturing processes, its economic advantages lie in producing customized single items or small batches of goods. The technology's potential sustainability improvements are evident in its ability to provide design freedoms, enabling the redesign of components, products, and processes. However, realizing these benefits requires the development of additive manufacturing skills, emphasizing the need for national policies that promote educational programs in such a way as to equip designers and engineers with the necessary skills [16].

By enabling localized production, AM can reduce transportation costs by up to 25 times, significantly lowering the CO_2 emissions typically associated with long-distance logistics. Table 4 summarizes the impact of each production process during a product's lifetime Decentralization supports workforce reallocation, creating jobs in rural areas by establishing AM hubs, which reduces urban overpopulation. This approach encourages a more equitable distribution of skilled jobs in areas such as design and production, while supporting sustainable growth. Such efforts not only reduce transportation costs but also contribute to a 20% energy saving through optimized designs. Strategic control in AM plays a critical role in its economic viability and societal influence. With optimized planning, additive manufacturing can eliminate the need for extensive supply chains, resulting in a significant reduction in overall transportation costs. Research has shown that employing gradient processing within AM reduces the coefficient of friction by 50%, further contributing to a 20% energy saving in production. Moreover, by controlling key sustainability indicators like EPI and GDP per capita, AM can contribute significantly to national development goals while maintaining a smaller environmental footprint [43].

Table 4. Impact of each production process during product lifetime [44].

Impact Categories	Scenarios	PLA Production	Supply Transport	Filament Production	Delivery
Climate change ($kgCO_2$-Eq)	Virgin	337.36	5.69–18.19	1.94–32.60	54.43–785.24
	Recycled	-	5.4523	2.289	4.957
Fossil depletion (kgOil-Eq)	Virgin	96.79	2.30–6.96	0.50–13.13	19.58–285.14
	Recycled	-	1.961	0.615	1.783
Freshwater eutrophication (kgP-Eq)	Virgin	0.14	0.001–0.002	0.001–0.003	0.011–0.024
	Recycled	-	0.0011	0.0016	0.0010
Ionizing radiation (kgU235-Eq)	Virgin	26.51	0.45–1.49	0.12–0.15	4.46–52.78
	Recycled	-	0.476	122.98	0.406
Marine eutrophication (kgN-Eq)	Virgin	0.89	0.004–0.041	0.003–0.009	0.09–1.30
	Recycled	-	0.009	0.011	0.008
Water depletion(m^3)	Virgin	37.3669	0.005–0.028	0.008–0.112	0.064–0.439
	Recycled	-	0.006	0.546	0.006

These advanced additive manufacturing technologies present an unprecedented opportunity to reshape the organization of manufacturing activities. Beyond innovations in processes, these technologies can influence manufacturing distribution and the flow of materials and goods, offering numerous sustainability benefits [45]. A key avenue for realizing these benefits is the potential transition towards a circular economy, an economic method model to enhance society's resource efficiency by eliminating the concept of waste and breaking away from the linear take–make–waste model. The core of a circular economy revolves around transforming end-of-life goods into resources for others, fostering closed loops in industrial ecosystems, and minimizing waste. This shift challenges traditional economic models by emphasizing sufficiency over excessive production, encouraging reuse, recycling, repair, and remanufacturing. The idea of replacing energy with labor was initially proposed forty years ago in a paper submitted to the European Commission. During the period of rising energy prices and high unemployment in the early 1970s, the idea gained traction, particularly in the architectural realm, where refurbishing existing structures proved more labor-efficient than constructing new ones [46].

Circular economy business models generally fall into two categories, namely, (i) those promoting reuse and the extension of service life through repair, remanufacture, upgrading, and retrofitting and (ii) those converting old goods into new resources through recycling materials. Central to this model is a shift from ownership to stewardship, where consumers transform into users and creators. The emphasis on remanufacturing and repair contributes to sustainability and generates skilled job opportunities in local workshops involving people of various ages and skill sets [47].

Current industrial applications of additive manufacturing are already contributing to more circular production systems by incorporating recycled and reclaimed materials as inputs for additive manufacturing processes. In metal additive manufacturing, more than 95% of the unused powder can be locally filtered and reused directly, while the remaining 5% is sent to a centralized recycling facility to produce virgin powder [48]. The additive nature of 3D printing, which involves adding material only where necessary, reduces material consumption compared to subtractive processes, thereby minimizing waste material. Moreover, the entire system surrounding the 3D printing process can be designed to facilitate a closed-loop circulation of materials, enhancing sustainability. Implementing material reuse methods in a circular economy can yield cost reductions per process, such as a 10% reduction for selective laser sintering (SLS) and a substantial 70–80% reduction for fused deposition modeling (FDM). With breakaway support, FDM is indicated to be a more economical and less wasteful solution than SLS. FDM parts are about 20% more expensive than SLS parts when the materials are used until they degrade, but they generate only 15% more waste per part than SLS [49]. Despeisse et al. (2017) elucidated the diversity and span of the entire product and material life cycles, as illustrated clearly in Figure 3 [48].

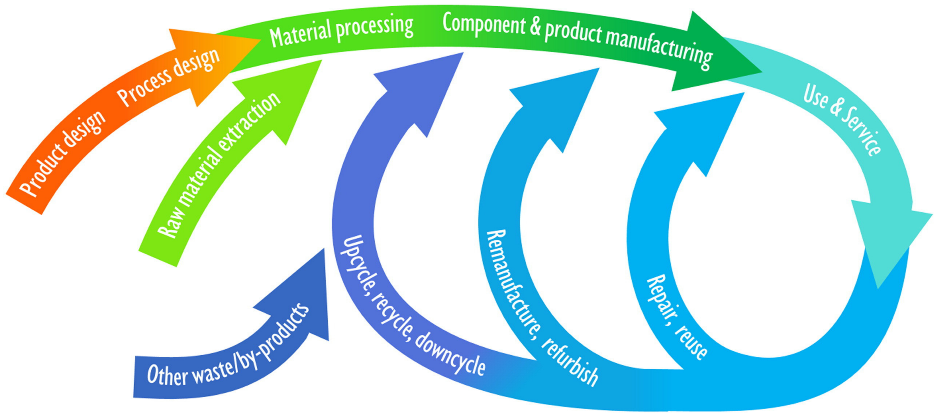

Figure 3. Circular economy. Reproduced with permission from Ref. [48] and with permission from Elsevier, 2024, Arunav H.

4. Environmental Impact

The management of plastic waste has emerged as one of the most important environmental issues confronting humanity today. The continuous environmental threat posed by non-biodegradable plastics is a grave concern due to their widespread presence in the waste stream. The accumulation of these waste plastics has led to significant challenges, including environmental litter, drain blockages, and critical health-related issues. Numerous countries practice careless dumping without efficient waste management and without following scientific waste disposal methods. This causes waste plastic pyramids to build up in landfills, taking up lots of space and worsening general environmental problems. Further challenges to the recycling process are low profitability and the high technological difficulty of breaking down plastics into their constituent chemicals. Due to the growing demand for plastic-related products, their non-biodegradable nature, and the social risks they bring, handling plastics recovered from MSW is becoming increasingly difficult.

These environmental problems have pushed the study of environmentally friendly plastic recycling methods. Despite its effectiveness, mechanical recycling presents drawbacks, such as the limited amounts of recyclable polymers and the potential for molecular weight reduction. Chemical recycling is a method that can convert plastic waste into valuable feedstock materials to produce fuel and monomers. Although chemical recycling shows promise, it is more costly and more labor- and energy-intensive than mechanical recycling and may produce additional pollutants. However, employing modern recycling methods, such as chemical recycling, can significantly decrease energy consumption, save costs, and contribute to the creation of a more sustainable future. In the context of plastic waste, AM or 3D printing stands out as a distributed and inexpensive method with which to reuse polymer waste. Its adoption, primarily through innovative techniques, can lead to the widespread reuse of polymer waste, providing an accessible solution for companies and individuals and promoting circular economy principles [49]. A study on 3D-printed PPE production during the COVID-19 pandemic found that 34% of the materials used in 3D printing ended up as waste, largely coming from support structures and failed prints. However, by recycling this waste into new filaments and creating useful products like personal protective equipment, the process supported the circular economy and considerably lowered the overall environmental footprint [50].

The application of additive manufacturing technology is increasing, but there has not been a thorough analysis of how it affects the environment. Conventional manufacturing techniques frequently combine steps like casting, molding, bending, and welding, each of which impacts the environment differently. In contrast, AM typically eliminates the need for such a combination in the production of parts. Additive manufacturing stands out for its ability to produce highly precise, intricately shaped products and significantly reduce material wastage on a layer-by-layer basis. Compared to traditional manufacturing methods, AM technologies offer several positive environmental advantages. Significantly reducing raw material waste and incorporating new, intelligent materials further enhances sustainability. Additive manufacturing emphasizes component output efficiency, minimizing material waste, energy consumption, and machine emissions [51].

When evaluating AM procedures, three environmental aspects can be considered: energy consumption, waste disposal, and air pollution. The particular set of parameters for each process directly influences the energy consumption in AM operations. For instance, increased the printing resolution leads to higher energy consumption and extended production periods. Energy-intensive processes, such as heating elements in 3D printers, lead to significant electricity consumption. Some AM processes require temperatures as high as 200 °C for specific plastics, which increases the total energy load. However, the ability to localize production and reduce transportation distances offsets these energy demands, making AM a more sustainable option in the long term [52]. Effective waste material management in additive manufacturing can involve reuse and recycling methods. Reusing waste polymer materials to create filaments is an effective technique to lessen the environmental impact. Minimizing waste materials can enhance the energy efficiency of AM operations.

Additive manufacturing is pivotal in metal recycling due to its use in metallic additive processes. Producing aluminum from recycled materials consumes 95% less energy than using raw materials, while recycling copper saves between 75 and 90% in terms of energy. This substantial energy savings underscore AM's potential to foster a more sustainable industrial environment by reducing reliance on virgin resources and promoting closed-loop material use [53].

AM technologies have both direct and indirect impacts on air pollution. Air pollution can be reduced directly by using non-toxic materials and biopolymer filaments. The decentralization seen due to additive manufacturing reduces shipping costs and causes goods to be produced closer to customers, indirectly improving air quality. Practical factors, such as the use of 3D printing to make replacement parts, help to extend the lifespan of products that do not have support from their original manufacturers.

Additive manufacturing has demonstrated considerable potential in cutting carbon emissions and energy consumption compared to traditional manufacturing. AM processes using recycled plastics emit approximately 0.75 tons of CO_2 per ton of plastic, whereas conventional manufacturing (CM) can produce up to 2.4 tons of CO_2. Transportation-related emissions are substantially lower in AM, with 55 tons of CO_2 emissions per ton of plastic versus 1375 tons for CM, due to shorter supply chains and localized production. This localized approach leads to a 25-fold decrease in transportation-related CO_2 emissions [43].

Despite the inherent sustainability of additive manufacturing, challenges remain due to the user-friendly nature of 3D printing techniques and the decentralization of production processes, factors which lead to a significant amount of unmanaged plastic waste being generated. The advent of rapid prototyping has, while advancing the field, resulted in the increased generation of small-scale solid plastic waste. This surge necessitates the development of recycling solutions at the point of manufacturing. Given the decentralized nature of additive manufacturing and the progression of 3D printing technologies, managing waste at its source is crucial. Despite the challenges, 3D printing has the potential to play a pivotal role in the sustainable manufacturing industry, contributing to the goal of creating an environmentally friendly manufacturing landscape.

5. Research Gap and Future Trends

Additive manufacturing, or 3D printing, appears promising in several fields, including in the research, construction, architecture, automotive, aerospace, medical, healthcare, and food and fashion industries [1]. It allows various industries to reduce product weight and create complex designs previously thought impractical. Over the recent years, an array of studies has explored the structural integrity of products manufactured through additive processes, spanning both non-metal and metallic materials, in order to shed light on additive manufacturing's feasibility and its limitations. Nevertheless, a more in-depth investigation is essential for completely utilizing this technology, particularly in terms of enhancing material properties.

Over the past few years, the research community has had a particular interest in additive manufacturing, focusing on sustainable practices such as material waste recycling to align with the United Nations Sustainable Development Goals. This trend can be noticed by comparing the number of publications per year, which indicates a significant rise in the number of publications in the last decade. Research communities in the United States, China, India, and Italy have played a significant role in the surge of interest in this area (Figures 4 and 5).

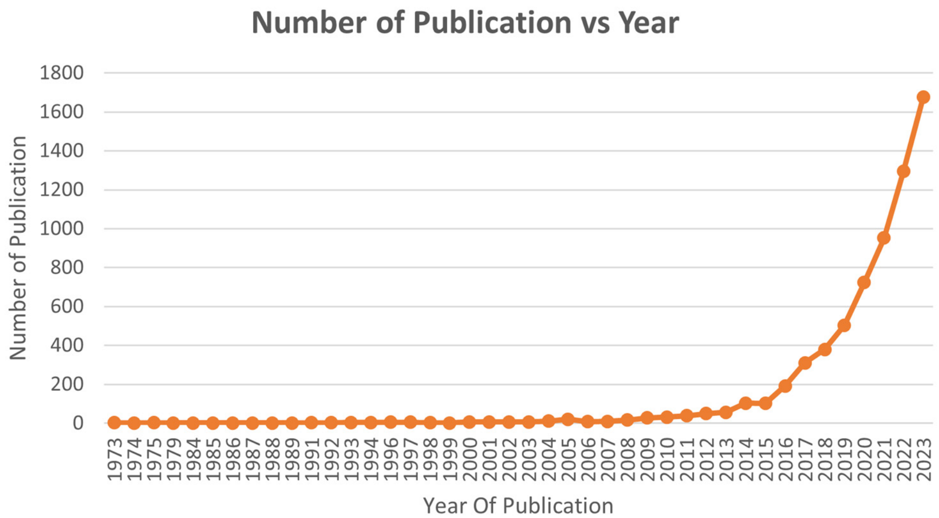

Figure 4. Number of publications vs. the year—generated from the Scopus Database ['TITLE-ABS-KEY (((additive AND manufacturing) OR (3d AND printing)) AND (recycling OR sustainable OR (material AND waste)))'].

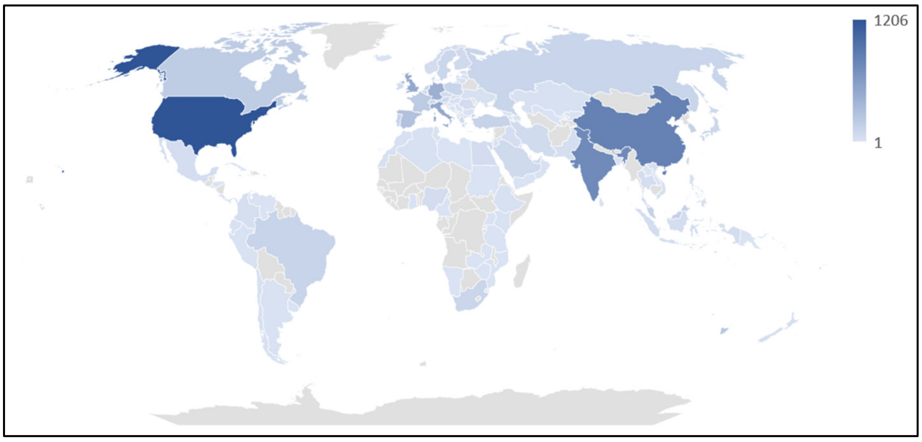

Figure 5. Country vs. number of publications—generated from the Scopus Database ['TITLE-ABS-KEY ((additive AND manufacturing) OR (3d AND printing)) AND ((recycling OR sustainable OR material AND waste))'].

The additive manufacturing industry has several unique problems that demand specialized approaches and solutions, such as the need to increase the efficiency of polymer-recycling procedures. Future research is needed to understand better how the number of reuse cycles affects the material's characteristics to ensure proper quality standards during recycling. In addition, specific optimization conditions, such as the effects of shifting the refresh rate for ABS, are an important issue that needs more investigation because they may have a significant effect on the overall effectiveness of 3D printing methods [51,54]. The lack of research on the degradation of mechanical qualities in PLA and ABS materials after many reuses in 3D-printed structures is significant. It underscores the gap in existing studies on this specific issue and shows the need for further research.

Establishing a circular economy in terms of 3D printing requires the exploration of alternative materials to reduce the virgin feedstock demand for reused materials. The ideal material should be biodegradable to minimize the environmental impact when degraded. Further investigation into 3D printing technologies is crucial to identify methods that reduce fabrication time and thermal degradation [55].

This review emphasizes the importance of conducting thorough research to validate the potential of upcoming trends in 3D printing. It also highlights the necessity of comprehensive investigations to provide a solid foundation for realizing the promise these future trends hold. Through further investigation of these aspects, we can guide the development of additive manufacturing technology towards a sustainable path.

6. Conclusions

This review addresses the critical issue of recycling waste material in additive manufacturing, highlighting the environmental concerns associated with waste generation during 3D printing processes. As the domain of additive manufacturing expands rapidly, the review evaluates various recycling methods, including mechanical and chemical processes, while examining the properties and applications of recycled materials, particularly polymers like PLA, ABS, and PETG. The social and economic impacts of using recycled materials in 3D printing are examined, presenting both the advantages and the challenges of additive manufacturing.

By minimizing transportation emissions and waste materials, decentralized 3D printing enhances sustainability as one of the larger trends in distributed production. Reusing waste materials not only helps to mitigate environmental problems but also promotes innovative thinking, demonstrating how additive printing can be an eco-friendly approach. This comprehensive review contributes to the development of a deeper understanding of the evolving landscape of waste material recyclability in additive manufacturing, emphasizing the importance of sustainable practices and continued innovation to achieving environmental sustainability and economic viability.

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