Sustainability in 3D Printing Process: Filament Recycling and Manufacturing Process

Vinícius Duarte Virtuoso [a,*], Marcio Tadayuki Nakaura [a].

[a] Fabrication Laboratory of Innovation Center of the Federal University of Technology - Parana (FabLab UTFPR-PB), Faculty of Mechanical Engineering, Federal University of Technology - Parana, Campus Pato Branco, 85503-390, PR, Brazil.
*vdvirtuoso@gmail.com

Abstract. 3D printing, or additive manufacturing, has transformed object and component production with customization and waste reduction. Yet, material diversity necessitates filament recycling and material reuse. This review addresses filament recycling challenges and underscores their importance for technology and sustainability. We explore 3D printing's history, disruptive nature, and industrial applications. Focusing on filament recycling, we discuss efficiency, material contamination, new material development, "homemade" extruders, and community education. Effective recycling methods are pivotal for sustainability. Identifying and mitigating impurities is crucial for recycled material quality. Research on new materials expands 3D printing possibilities, reducing non-renewable resource dependence. The inclusion of recycling in low-cost extruders increases accessibility. Awareness and education promote sustainable 3D printing. This article emphasizes tackling these challenges to foster sustainable additive manufacturing practices and spur further research.

Keywords. 3D printing, Filament recycling, Material reuse, Additive Manufacturing, Sustainability.

1. Introduction

3D printing, also known as additive manufacturing, has represented one of the most remarkable technological innovations of recent decades, fundamentally transforming the way we produce objects and components (1). This revolutionary advancement has been accompanied by an equally notable evolution in materials and processes, expanding the boundaries of manufacturing across many sectors (2). However, this technology has also brought forth significant challenges (3), and one of the most pressing is the issue of filament recycling (4) and material reuse (5). In this review, we will delve deeply into the challenges and prospects related to filament recycling in 3D printing, analyzing crucial issues such as recycling efficiency, material contamination, the development of new materials, recycling in "homemade" extruders, and the importance of awareness and education within the 3D printing community. 3D printing is not just a technology but a revolutionary approach to manufacturing that allows the creation of three-dimensional objects layer by layer from a digital model. The history of this technology dates to the 1980s when Charles Hull developed stereolithography (6), ushering in an era of custom manufacturing and rapid prototyping. Since then, 3D printing has evolved exponentially, moving from prototype production to applications in a wide range of industries, including aerospace (7), medical (8), automotive (9), and even food production (10).

One of the primary reasons 3D printing is often treated as a disruptive technology is its capacity for customization (11). It enables objects to be tailored to individual needs, a feat previously difficult to envision in mass manufacturing. This customization extends beyond aesthetics, encompassing the properties of the materials used. Additionally, 3D printing significantly reduces material waste compared to traditional manufacturing methods, a crucial advantage in an increasingly environmentally conscious world (12). However, this diversity of materials and small-scale production has also brought forth a significant challenge: the management and recycling of used filaments (13). While the benefits of 3D printing are undeniable, the issue of sustainability in additive manufacturing has not been fully resolved (14). It is in this context that some of the most pressing and intriguing scientific challenges related to 3D printing are found. One of the initial challenges to address is the efficiency of filament recycling. Recycling is essential to reduce waste and environmental impact in filament production. However, recycling processes need refinement to ensure that recycled materials meet the necessary quality standards for 3D printing (15). Furthermore, the variety of materials used in 3D printing, including plastics (15–17), metals (18), and even food (19), makes recycling a complex and challenging task (20). Another critical challenge is material contamination (21). During the recycling process, materials are often exposed to impurities and contaminants that can compromise the quality of the recycled material. This can lead to printing failures, loss of mechanical properties, and even safety issues. Identifying and mitigating these impurities are fundamental to the successful recycling of filaments (22). The pursuit of new materials is also an important research area. While the variety of materials used in 3D printing is impressive, there is still room for the development of more sustainable, robust, and versatile materials. This research has the potential to expand the applications of 3D printing and reduce reliance on non-renewable resources (23). Another aspect to consider is recycling in "homemade" extruders. Many enthusiasts and small businesses use low-cost 3D printers, and incorporating recycling in this context can be both a challenge and an opportunity to make the practice more accessible and sustainable (24). Finally, awareness and education play a crucial role in promoting filament recycling within the 3D printing community. Understanding the importance of recycling and adopting sustainable practices are essential for the long-term success of this technology (25).

In this context, this review aims to provide a comprehensive understanding of the challenges and prospects in filament recycling in 3D printing, with a focus on material reuse and the manufacturing process. Key issues related to recycling efficiency, material quality, the development of new materials, recycling in "homemade" extruders, and education within the 3D printing community will be discussed.

2. Literature Review

2.1 General Aspects of 3D Printing

The history of 3D printing is a fascinating narrative that dates to the early 1980s when Charles Hull, an American engineer, coined the term "stereolithography" and gave birth to the first 3D printing technique known as stereolithography. Charles Hull founded 3D Systems Corporation in 1986, introducing the first commercial 3D printing machine, the SLA-1, which utilized stereolithography (26). However, the seeds of 3D printing were sown even before SLA. In the 1970s, researchers like David E. H. Jones at the University of Exeter were exploring layer-by-layer material synthesis methods. Layer-by-layer printing would evolve to become the fundamental principle behind 3D printing (27).

Figure 1 provides a graphical view of the historical progression of 3D printing, from early innovations to the most recent technologies and applications. It serves as a visual guide that complements the textual narrative, highlighting technological achievements over time.

The 1990s witnessed the development of various 3D printing techniques, expanding the possibilities of materials and applications. One notable technique was Selective Laser Sintering (SLS), patented by Carl Deckard and Joseph Beaman at the University of Texas in 1989 (28). SLS allowed for the use of a variety of powdered materials, including polymers and metals, to create three-dimensional objects. This technique played a pivotal role in prototyping and complex component production. Affordable 3D printers for consumers and small businesses were introduced at the turn of the century (26,27). One of the most influential techniques during this period was Fused Deposition Modeling (FDM), patented by Scott Crump in 1989 (29). FDM used melted thermoplastic filament to build objects layer by layer and became the foundation for many consumer 3D printers. In the 1980s and 1990s, 3D printing technologies were primarily used for rapid prototyping in industries such as aerospace (30) and automotive (31). During this period, techniques like stereolithography and SLS emerged, enabling the faster and more precise manufacturing of prototypes. However, these systems were expensive and generally restricted to industrial settings, presenting limitations in terms of accessibility and widespread application. Moreover, the quality of printed parts and the variety of available materials were challenges to be addressed. The popularization of FDM-based technology, which relies on fused filament deposition, made it possible for enthusiasts and educators to explore 3D printing in their own environments. This opened the doors to a wide range of applications, from creating custom toys to manufacturing tailor-made medical prosthetics (32). However, the expansion of 3D printing did not come without challenges. The accuracy and quality of printed parts were often questionable, and the variety of available materials was limited. The development of new materials was a response to this need, resulting in significant diversification that includes engineering plastics, metals, ceramics, and even biocompatible materials (13,23,27,33–35). The versatility of 3D printing found applications in various industries, highlighting its disruptive nature. In aerospace, 3D printing produces lightweight, complex parts, reducing aircraft weight and enhancing efficiency (30). Previously impossible components are now precisely and efficiently manufactured. In medicine, the technology is applied in the production of custom prosthetics, anatomical models for surgical planning, and even in the bio-printing of tissues (32,36). The ability to create custom medical implants has the potential to significantly improve patients' quality of life and optimize surgical outcomes (37).

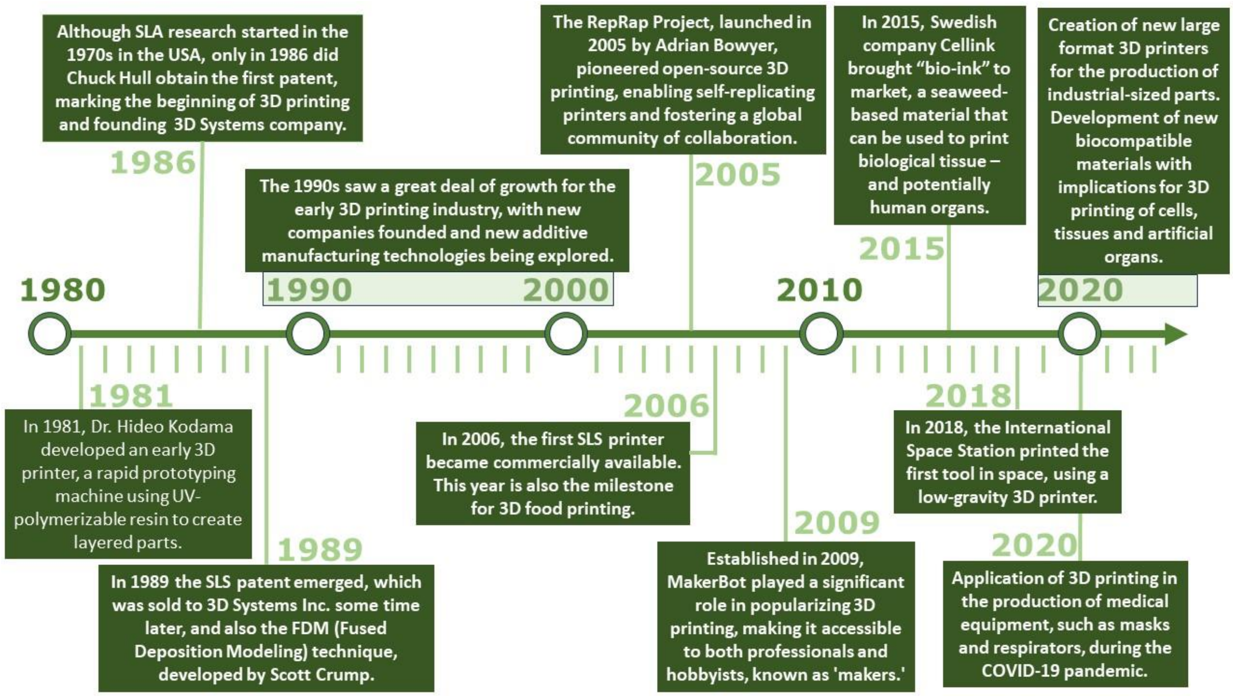

Fig. 1 - Timeline illustrating the historical progression of 3D printing.

The automotive industry uses 3D printing for rapid prototyping and on-demand spare part production. The rapid prototyping of new designs and components allows automakers to test before mass production, saving time and resources. Additionally, the ability to efficiently print spare parts reduces downtime for vehicles and machinery, contributing to effective maintenance in industries (31). The food industry has also benefited from 3D printing, enabling the creation of customized foods tailored to individual preferences (19,38). This application not only meets specific consumer demands but also paves the way for the creation of functional and nutritionally rich foods with complex designs.

2.2 Technological Advancements: New materials, recycling, and sustainability

Efficiently recycling filaments within the realm of 3D printing stands as a multifaceted challenge and a pivotal element for advancing the sustainability of this technology (15). This section explores the intricacies and hurdles associated with recycling 3D printing filaments while also emphasizing their critical importance. Among the key issues that have driven research and development of methods and practices in the search for more sustainable operations, the following stand out:

Efficiency in Recycling. The efficient recycling of 3D printing filaments is pivotal in reducing waste and minimizing the environmental footprint of this technology. Achieving high recycling efficiency involves collecting used or discarded materials, their processing, and transforming them into high-quality feedstock for new prints. The complexity of this process lies in a multitude of factors, including material properties, printing parameters, and waste collection methods (39). Advancements in recycling technologies and processes are essential for streamlining this aspect of 3D printing recycling. Furthermore, exploring more sustainable and eco-friendly methods is imperative to align 3D printing with broader environmental goals (20).

Contamination Concerns. An enduring challenge in filament recycling is the potential for material contamination. Throughout the 3D printing process, filaments may encounter contaminants or impurities that can degrade material quality (40). This issue extends from the initial printing phase to post-processing. Contaminants have the potential to affect print precision and mechanical properties, ultimately rendering the recycled filaments less reliable. Consequently, identifying sources of contamination, implementing effective mitigation strategies, and ensuring the purity of recycled materials remain ongoing challenges in 3D printing recycling (14).

Development of New Materials. Addressing the recycling challenges of 3D printing necessitates the continuous development and exploration of novel, sustainable materials. While traditional thermoplastics like PLA and ABS have dominated the 3D printing landscape, researchers and manufacturers are increasingly venturing into alternative materials. These alternatives include biodegradable polymers, composite materials, and recycled plastics. The objective is to offer materials with enhanced properties, reduced environmental impact, and increased recycling potential. This exploration ushers in a new era of material diversity within the 3D printing ecosystem, paving the way for sustainable innovation (23,27,36).

Recycling in Homemade Extruders. With the proliferation of affordable desktop 3D printers, a growing interest has emerged in developing cost-effective and do-it-yourself (DIY) solutions for filament recycling (22,25,39). Homemade extruders, designed with recycling in mind, empower individuals and small-scale enterprises to repurpose printed objects or failed prints. These efforts contribute significantly to sustainability initiatives. However, optimizing the efficiency and reliability of such extruders remains a significant challenge. Further innovation and development are necessary to harness the full potential of DIY recycling solutions, making them more accessible and effective (17,41).

Awareness and Education. Fostering awareness and education within the 3D printing community regarding material recycling and sustainable practices is paramount. Users, ranging from hobbyists to professionals and educators, must recognize the importance of recycling and adopt sustainable practices. Initiatives aimed at informing users about proper recycling methods, material choices, and the environmental impact of 3D printing play a pivotal role in achieving long-term sustainability. By educating users and encouraging eco-conscious behaviors, the 3D printing community can contribute significantly to reducing the ecological footprint of this technology (20,42).

Therefore, tackling the challenges associated with recycling filaments in 3D printing demands a comprehensive approach. This approach encompasses efficiency improvements in recycling processes, the identification and mitigation of contamination sources, ongoing material development, innovation in homemade extruders, and educational campaigns to promote sustainability. These challenges underscore the significance of continuous research and collaborative efforts to advance the field of 3D printing while minimizing its environmental impact.

2.3 Technological advancements and sustainability

In the ever-evolving landscape of 3D printing, sustainability and material recycling are poised to play a pivotal role. This section explores the potential technological advancements, the broader ramifications of sustainability research, and the critical need for sustained investment in this burgeoning field (39). As we gaze into the future, one can anticipate several significant technological strides in sustainable 3D printing. This includes the refinement of recycling processes, making them more efficient and cost-effective. Moreover, there will be a growing shift towards integrating sustainable materials into the 3D printing ecosystem. The horizon may also witness the integration of automation and artificial intelligence in recycling systems, facilitating smarter material recovery, and recycling operations (43). The impact of sustainability research goes beyond just ecological concerns. It involves reducing the environmental footprint of 3D printing through efficient recycling practices. It also encompasses the concept of a circular economy (15), where materials are continuously recycled and repurposed, reducing waste and resource consumption. The influence of such research will extend far beyond the 3D printing industry, permeating industrial practices across sectors.

What’s particularly intriguing is how material manufacturing for 3D printing will be reshaped by recycling practices. Recycling will no longer be confined to a mere process but will be instrumental in defining the quality, performance, and variety of materials available for 3D printing (22). We can expect a more profound integration of recycled materials into the 3D printing material landscape, thereby reducing waste and promoting sustainability. Significant progress has already been achieved in the realm of 3D printing sustainability. Milestones have been reached through international collaborations and innovative research. Yet, it's imperative to underscore the need for continuous investment in sustainability research. This is pivotal to maintain the current momentum and fully unlock the potential of sustainable 3D printing. As we peer into the future, the trajectory of 3D printing is not only technologically promising but also profoundly sustainable. It mirrors our commitment to preserving precious resources while pushing the boundaries of innovation. It is a future where sustainability and 3D printing coexist harmoniously, shaping a world where creativity meets responsibility.

3. Conclusion

This brief review dealt with the recycling of filaments in 3D printing with the central objective of discussing the challenges and perspectives related to the reuse of materials and sustainable manufacturing processes. Our journey revealed the critical importance of filament recycling as a sustainable practice within 3D printing. It's not merely a choice but a necessity for mitigating environmental impacts, conserving resources, and fostering responsible material management. The challenges encountered, such as recycling efficiency, material contamination, and the need for novel materials, illuminated the ongoing nature of sustainability in 3D printing. It's a dynamic field demanding continuous research and innovation. By embracing recycling and sustainable practices, we shape a future where 3D printing aligns seamlessly with environmental responsibility. Sustainability is not an endpoint but a continuous pursuit requiring research and innovation.

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