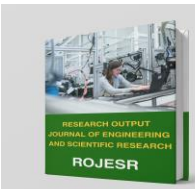

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Developing Sustainable Materials for 3D Printing

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ABSTRACT

The rapid advancement of 3D printing technologies has sparked interest in developing sustainable materials to reduce the environmental impact of additive manufacturing. This paper explores the evolution of sustainable biomaterials, with a focus on bio-based polymers, composites, and recycled materials used in 3D printing. It highlights the potential of bio-renewable resources, such as natural fibers and biomass-derived materials, to replace traditional petroleum-based and mineral materials. Challenges in the development and application of these sustainable materials are discussed, including issues related to mechanical properties, compatibility, and supply chain limitations. Additionally, the role of recycled and upcycled materials in 3D printing is examined, with an emphasis on their potential to create eco-friendly, cost-effective alternatives. The future trends in sustainable 3D printing materials are also considered, including innovations that could lead to broader adoption and enhanced environmental benefits. This study provides a comprehensive overview of current efforts and future directions in developing sustainable materials for 3D printing.

Keywords: Sustainable materials, 3D printing, Bio-based polymers, Bio-composites, Recycled materials.

INTRODUCTION

The quest for sustainable materials is a global challenge in many industrial sectors. The mechanical properties of materials have an important role in their performance. With rapid advances in 3D-printing technologies, efforts have been made to develop new sustainable biomaterials. However, these efforts are largely limited to polymers or plastics, despite the fact that a wide range of metal materials are used in modern additive manufacturing or 3D printing processing. Biocomposite materials aims to alleviate the shortages of petroleum and mineral materials by substituting them with suitable bio-renewable materials. Bio-renewable materials, such as biopolymers, natural fibers, and other materials from the biomass, are the major resources of sustainable materials. However, their inherent weaknesses, such as poor compatibility, low strength, and high hydrophilicity, have limited their applications [1, 2]. Additive manufacturing techniques are especially attractive for a broader range of materials. Metal additive manufacturing has been widely applied to fabricate functional gears, heat exchangers, fuel injectors, and other complex metallic parts in various industries. In the process of powder bed fusion of metals, metal powders are usually in plastic-like bulk and layered structures, which can offer new opportunities for the application of granular materials. Particularly, many granular materials, such as sand and ceramics are often biodegradable or biocompatible materials, which can be easily found in nature. To contribute to the research on sustainable bio-renewable materials, attempts are made to develop a new bio-renewable granular material for 3D bonding deposition. A bio-renewable sand-like powder based on the starch extracted from the loofah and biopolymers is synthesized. Various bonding agents are also engineered for 3D printing. With these materials, a new process of bond jetting manufacturing with a particle size of up to 100 μm is established, which can print 100% eco-friendly parts [3].

CHALLENGES AND OPPORTUNITIES IN DEVELOPING SUSTAINABLE 3D PRINTING MATERIALS

Growing demand for both additive manufacturing and sustainable practices no longer allows processes to be defined purely in technological terms. Indeed, there is a need to understand sustainability issues at a fully systemic level that encompasses not just the process and product, but also the work environment, energy consumption, bio-adaptability, pollutive potential, and social effects across the entire life cycle. A key enabler of the 3DP-sustainability harmony is the raw material employed. While there is unarguably the tech-hype of the 3DP, and the trickle-down tech-convergence with nanotechnology and intelligent (on-board) controls, it is largely in comparison with the industrial processing of plastics and metals, still in its infancy with most materials invented only last century. A good reason could be inferred that any 3DPC on bio-based, renewable, and biodegradable resource may be more sustainable than traditional continuum processes. Unfortunately, this is not necessarily the case, and still better than the status quo is conceivable in the future [4, 5]. This is a timely broad and high-level overview of where alternative materials and resources can be sourced and issues with processing, such as input stock supply and pollution. The major hurdles for developing sustainable 3DPCs largely lie on the supply side domain, particularly in bio-plastics (biopolymers), and clay-based and metal-based composites. Much sustainable effort had to be done on the polymer pre-processing side, as polymer modification criteria are far looser and less standardized than metals. Broadly speaking, polymers can be thermally modified, chemically modified, and mechanically modified. Despite the increasing attention on thermoplastics and elastomers, there is still a lag in bio-plastics and largely an evolutionary leap when it comes to bio-polymers, e.g., tree sap-derived PLA (polylactic acid) [6].

BIO-BASED POLYMERS AND COMPOSITES FOR 3D PRINTING

Bio-based polymers, known as bio-polymers, are substances derived from living or renewable resources. Bio-pollymers, due to their biocompatibility, biodegradability, and low toxicity; have become a popular topic globally. The objective of bio-polymers is to reduce the environmental impact and human health risks caused by current petroleum polymers and other synthetic polymers. For example, polylactic acid (PLA)-based materials are a major class of additive manufacturing feedstocks, widely hailed as an environmentally friendly substitute for petroleum-based polymers [7, 8]. The structural modification of bio-polymers was also investigated. Although portions of bio-polymers are hydrophilic, rendering them unsuitable for filament-based systems, hydrophobic changes to bio-polymers lead to successful filament printing. Recently, focused research on the 3D printing of biomass-derived biocomposites has undergone, focusing on the characteristics and applications of novel bio-composite materials. Various biomass-derived feedstocks such as cellulose, starch, and lignin were employed in 3D printing, highlighting the gray area between bio-plastics and 3D printing biocomposites. In regard to the industries and applications of these materials, 3D printing technologies would allow the low-cost utilization of biomass to create a range of composites for food packaging, consumer products, and bioreactors [9, 10].

RECYCLED AND UPCYCLED MATERIALS IN 3D PRINTING

In light of growing concerns over the sustainability of materials used for 3D printing, a variety of recycled, reclaimed, and upcycled materials have emerged. As the largest market for additive manufacturing technology, fused filament fabrication (FFF) 3D printing was selected as the system of interest for this study of novel materials. FFF uses a spool of filament that is fed through a heated nozzle that melts the filament and prints 3D objects by building up layers. FFF filament materials are solid thermoplastics, which can typically be sourced from high-volume commodity plastics [11, 12]. Commodity plastics like polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) are recyclable but, in practice, are often not recycled and instead become plastic waste. Upcycled filament materials from post-consumer plastics and post-industrial scrap have been developed and are commercially available. The reclaimed filament materials and spools are marketable, as plastics with a "second life" may be desired by eco-conscious consumers. Additionally, the growing supply of wastestreams of reclaimed plastics may create a new source of inexpensive raw materials that are suitable for filament production [13].

FUTURE TRENDS AND INNOVATIONS IN SUSTAINABLE 3D PRINTING MATERIALS

The drive towards environmentally sustainable solutions is expected to surmount discrimination against bio-based additive machines and the materials used in these machines. This will be aided by a continued proliferation of bio-based filament suppliers capable of providing almost any material-based filament combination. Plastics and polymers are currently on the cusp of being completely supplanted by more sustainable desktop and industrial 3D printing methods via the use of bio-based materials, and new bio-based filament designs should keep pace with this burgeoning green technology [14, 15]. As bio-based

materials gain acceptance and dominance across all material categories of particular types and brand names, the next generation of 3D printing technologies will focus more on bio-based consumption and accessibility across demographics. This includes the generation of biodegradable plastics that can be utilized in the production of bioplastics. Bio-material sourcing via biorefineries and local supply chains is expected to surge and expand accessibility via larger community engagement. This outreach should empower women and marginalized groups, allowing them to design prototypes and iterate on bio-machines that subsequently reject entirely plastics [16].

CONCLUSION

The quest for sustainable materials in 3D printing is pivotal for reducing the environmental footprint of additive manufacturing. While bio-based polymers and biocomposites offer promising alternatives to conventional materials, challenges such as mechanical performance, compatibility, and supply chain limitations must be addressed. The integration of recycled and upcycled materials further enhances the sustainability of 3D printing processes, creating opportunities for eco-conscious production. As innovations continue to emerge, the future of 3D printing lies in the widespread adoption of bio-renewable and biodegradable materials, supported by advancements in material science and processing technologies. By embracing sustainable practices and materials, the 3D printing industry can play a significant role in promoting environmental stewardship and reducing reliance on non-renewable resources.

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