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Review Article

From a Sustainability Perspective, Why Should Bioplastics Be Used for Additive Manufacturing?

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ISSN: 2770-6613

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Submission: 📅 January 25, 2023
Published: 📅 February 02, 2023

Volume 4 - Issue 4

How to cite this article: Keren Vivas, Ronalds Gonzalez, Daniel Saloni. From a Sustainability Perspective, Why Should Bioplastics Be Used for Additive Manufacturing?. Polymer Sci peer Rev J. 4(4). PSPRJ. 000594. 2023.
DOI: 10.31031/PSPRJ.2023.04.000594

Abstract

As climate change awareness increases, the worldwide interest in efficiently using resources, materials, and energy increases. From producers to consumers, the demand for sustainability-oriented processes has become stronger across all stock market sectors. Additive Manufacturing (AM) is a promising and relatively new manufacturing process that helps to overcome supply chain, logistics, and environmental issues that traditional processes face. Fortunately, AM can process different raw materials, such as glass, metal, ceramics, and plastics. Even though AM helps to reduce the use of the material in general, in the case of plastic, the environmental impact of their production and biodegradability remains an issue. As a response, plastics made from natural and renewable resources have become an alternative to the harmful conventional petroleum-based and no biodegradable plastics. Fortunately, there is evidence of products done through AM from these environmental-friendly plastics. The following review is intended to highlight (1) the opportunities and challenges for AM, (2) the comparison between bio and petroleum-plastic in 3D printing from a sustainability point of view, and (3) the economic and environmental benefits of this innovative combination of manufacturing processes and materials. This review provides a fundamental understanding and applied knowledge to create a new additive manufacturing platform based on renewable plant-based feedstocks.

Keywords: Additive manufacturing; 3D printing; Bioplastics; Biodegradable plastics; Sustainability

Abbreviations: AM: Additive Manufacturing; CAGR: Compound Annual Growth Rate; PLA: Polylactic Acid, PHAs: Polyhydroxyalkanoates; FDM: Fused Deposition Modeling; ABS: Acrylonitrile Butadiene Styrene; PVA: Polyvinyl Alcohol; PET: Polyethylene Terephthalate; HIPS: High Impact Polystyrene; PA: Nylon Plastic; PS: Polystyrene; PE: Polyethylene; PP: Polypropylene; GHG: Greenhouse Gases; PCL: Polycaprolactone; PBS: Polybutylene Succinate; PBAT: Polybutylene Adipate Terephthalate; CAB: Cellulose Acetate Butyrate; CAP: Cellulose Acetate Propionate; HPC: Hydroxypropyl Cellulose

Introduction

The interest in and use of additive manufacturing tools to manufacture a wide range of products has increased globally. This technology enables the production of goods that can be individually customized because it uses Computer Aided Design (CAD) to replicate the design into a 3D object [1]. 3D printing and AM are interchangeable terms, which denote the deposition of material in consequent layers to each other, producing a three-dimensional product even with complex shapes [1]. In AM, several materials can be used, such as metals, ceramics, resins, rubbers, glass, concrete, and plastics, to name a few [2]. AM technologies provide technical, economic, environmental, and social benefits [1-6]. From a technical side, these technologies are flexible and adjustable, which allows for the adjustment and reduction of steps and time inside the production process. Economically, AM helps reduce investment costs and material spending because it simultaneously uses what is required, reducing waste management costs [7]. From an environmental point of view, this technology lessens the intensive use of material, chemicals, and energy in conventional manufacturing processes, as well as decreases the disposition of waste in landfills [8]. Additionally, AM technologies transform employees' working environments and reduce their exposure to hazardous components during manufacturing because they are faster and more energy and material-effective technologies [9]. In general, this technology is expected to grow even more in the following years due to the benefit of supply chain capabilities, which have been critically affected nowadays [1]. There are multiple efforts around AM, which are well documented in the literature and by the formation of new companies and sales of AM systems [7,10,11]. One important AM technique that uses plastics as raw materials is Fused Deposition Modeling (FDM). This AM technique makes 3D objects by extruding filament (raw materials), principally polymers [12]. FDM is considered one of the most cost-effective AM technology and uses various thermoplastic materials [13]. Although petroleum-based plastics have been the most used polymers, bioplastics have gained importance in FDM from an economical and sustainable standpoint [9,14,15]. Fortunately, there is a series of promising reports on the manufacturing of end-goods through AM technologies, like FDM, using emerging bio-based and biodegradable plastics principally produced by renewable resources, such as PLA, PHA, nylon 11 among others [5,12,16].

PLA is a bioplastic produced from maize, tapioca, and sugar cane through a bacterial fermentation process. PLA is widely used in packaging applications and can be recyclable and biodegradable under specified conditions [8,17,18]. On the contrary, PHA is a bioplastic fully biodegradable even in unfavorable conditions, such as plastics released on the soil or in the aquatic environment. PHAs are made from bacteria by a fermentation process [7]. In addition, another emerging and alternative bio-based plastic is nylon 11, a biopolymer produced from castor beans, a natural and renewable resource. Nylon 11 is a commercial product manufactured in the US, Europe, and Asia [19,20]. The review presented below explains the commercial potential of AM or 3D printing to produce end-goods products. In addition, it highlights the opportunities and challenges of AM and the use of more environmentally-friendly plastics that allow the production of goods with similar performance to those made from conventional hazardous plastics.

Additive Manufacturing

AM or 3D printing is a new manufacturing process where components are fabricated directly from computer models by selectively depositing successive layers of raw materials (0.001-0.1 inches in thickness) and then consolidating, curing, or fusing (Figure 1), [21]. This technology emerged in the late 1980s to accelerate the time-consuming and costly process of iterative product design, thereby reducing time to market, improving product quality, and ultimately reducing the costs for low-volume or specialty items [22]. Recently there has been a growing interest in utilizing these technologies for the manufacturing and production of consumer goods [4,5]. We are now beginning to see AM used for fabricating a range of materials, including plastics, metals, and ceramics. From the standpoint of sustainability, AM has the potential to reduce the consumption of raw materials and energy profoundly and to mitigate our impact on the environment directly [23]. The worldwide market opportunity for AM has been estimated to be more than $21 billion by 2020 [24]. This technology also has the potential to create new opportunities for entrepreneurs and small businesses [25]. Most plastic products we consume are manufactured using mass production processes like injection molding, casting, extrusion, thermal forming, stamping, and machining [26]. Each of these processes requires some form of tooling (mold, die, flask, stamp, fixture, etc.) and extensive, energy-intensive support infrastructure (i.e., supply chains, transportation and distribution networks, etc.) [27]. While the actual cost of producing a single 'part' is usually modest, the high set-up costs require large production runs or very high prices for a commercially viable business [11]. By manufacturing parts directly from a 3D image using a layer-by-layer deposition process, AM processes eliminate the requirement for extensive toolings, such as the molds required for injection molding [27]. This fact facilitates the economical production of small lot sizes of parts (as low as one), reduces the lead time (because the tools do not need to be produced), allows individual customization, and ultimately increases flexibility in the supply chain and product diversity [11]. Production is no longer dependent on traditional factory infrastructures; parts can be made where and when needed, resulting in reduced fuel and transportation costs [1]. AM has promise to move the manufacturing frontier. This approach also allows entrepreneurs to make small investments and lower the financial barriers to creating jobs and economic opportunities in rural and historically underserved areas [25]. The complete environmental impact of these new opportunities has yet to be fully quantified. However, it is predicted that the ability to manufacture goods on demand will dramatically improve efficiency, reduce materials use, energy consumption, and process waste while creating new business opportunities for small manufacturers who cannot afford expensive molds [12,15,16]. The efficient use of the material is often a vital concern for many applications and is of growing interest to many consumers [28]. Traditional or subtractive manufacturing often involves machining parts from large billets of material, resulting in significant waste associated with raw materials and the energy associated with machining processes [6].

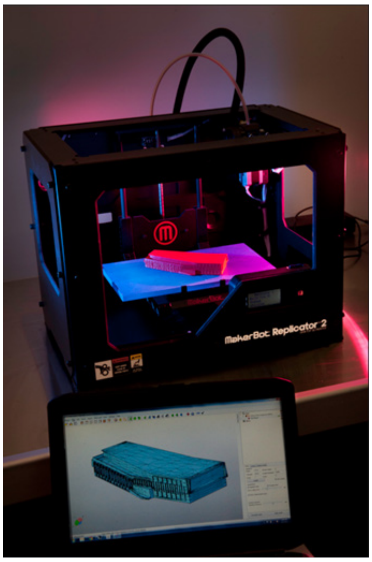

Figure 1: 3D printer using computer models [66].

AM only uses material where needed and dramatically reduces the so-called "buy to fly" ratio. This term refers to the mass of material required to build a component divided by the mass of the final of this component [9]. For near-net shape parts fabricated with toolless AM (such as high-performance turbine blades), the buy-to-fly ratio approaches one [21]. The design of structural components often involves making tradeoffs between conflicting objectives. With AM, complexity in design is essentially free, which means that components can be optimized for reduced weight while maintaining key performance objectives [4].

Additive Manufacturing Challenges and Opportunities

Additive manufacturing presents many challenges related to the materials used, the design and manufacturing process, skilled personnel, and the post-processing required based on the final shape and quality of the parts needed [17,29]. Moreover, printing for three-dimensional fabrication is a highly complex process with challenging technical issues throughout [30]. Fiber reinforcement is another challenge for AM; it is complicated with traditional layered manufacturing because the size of the fibers cannot be larger than the layers themselves, or it could affect resolution [31]. The alignment of these fibers also affects how they add to the strength of the part. The alignment of these fibers also affects how they add to the strength of the part. Orienting fibers and mixing them into the materials are challenging based on the fiber size [32]. On the other hand, when using 3D printing to produce finished goods, using a thermoplastic is more critical, and it may be the only choice for many applications, which represents an excellent opportunity for nylon 11 that is not only a thermoplastic but also a natural and renewable source [21,22]. Consequently, a significant challenge and enormous opportunity is the utilization of bioplastics that might be more sustainable for additive manufacturing, yet more research needs to be conducted to move from petroleum-based plastics to bioplastics in large-scale production.

Sustainability Perspective of Bio-based vs. Petroleum-Based Plastics Used in Additive Manufacturing

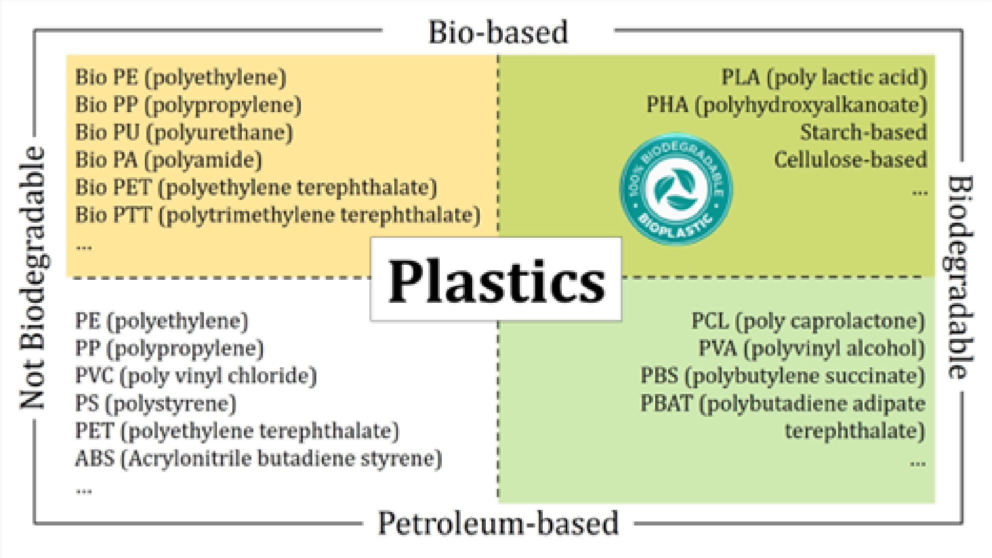

Figure 2: Categories of plastics based on raw material origin and biodegradability. Source: Redrawn from [42,47].

For generations, plastics have been used across almost all industry sectors. It is thanks to their strength, corrosion resistance, flexibility, plasticity, durability, lightness, and inexpensiveness [33]. However, its excessive use and improper waste management have resulted in alarming pollution and greenhouse gas emissions worldwide, affecting society and the environment [22,23]. In 2021, the U.S. reported around 40 million tons of plastic waste. On average, an American produces 231 pounds of plastic waste yearly, of which only 9% is successfully recycled [34]. It means that 91% of plastic waste is disposed of in a landfill, incinerated to produce energy, or leaked into the environment [35]. Petroleum-based plastics, the first plastic generation, are associated with several environmental issues. When they are incinerated, a vast amount of CO_2, greenhouse gas emissions [36], and hazardous synthetic substances are released, contributing to global warming and the deterioration of living beings' health [18]. Moreover, due to their no biodegradability, they cause air, land, and water pollution, resulting in the death of wildlife, marine life, and avifauna [22,26,27]. In response to this environmental concern, bioplastics (made from biological entities) have emerged as a promising alternative to alleviate the petroleum-based plastic environmental impact [37,38]. It is essential to clarify that not all bio-based plastics are biodegradable (Figure 2). Global bioplastic production is about 2.4 million tonnes (Figure 3), but 64% is biodegradable and truly compostable [28,39]. Commercially, there are specifications that they should contain 50% organic molecules, not exceed the limits for heavy metals, and degrade (>90%) within six months under controlled environmental conditions [33]. Biodegradable bioplastics can quickly break down through microbial mechanisms (year or less) and come back to nature, blending harmlessly into the soil [15]. Biodegradable plastics are considered savior products because they decrease the accumulating solid waste, greenhouse gas emission levels, CO_2 emissions, and energy used in manufacturing [40]. Even though they have also been related to some environmental issues, the harm produced is less severe than petroleum-based plastic [36]. 3D printing or AM technologies like Fused Deposition Modeling (FDM) use plastics to build objects from 3D model data [8,41,42]. It joins thermoplastic filament layer upon layer until it forms the final object [37]. The most common plastic filaments used for FDM are petroleum-based plastics and bio-based plastics. Petroleum-based such as Acrylonitrile Butadiene Styrene (ABS), Poly Vinyl Alcohol (PVA), Poly Ethylene Terephthalate (PET), High Impact polystyrene (HIPS), and Nylon Plastic (PA). And bio-based plastics such as Poly Lactic Acid (PLA) and Poly Hydroxy Alkanoates (PHAs) [33].

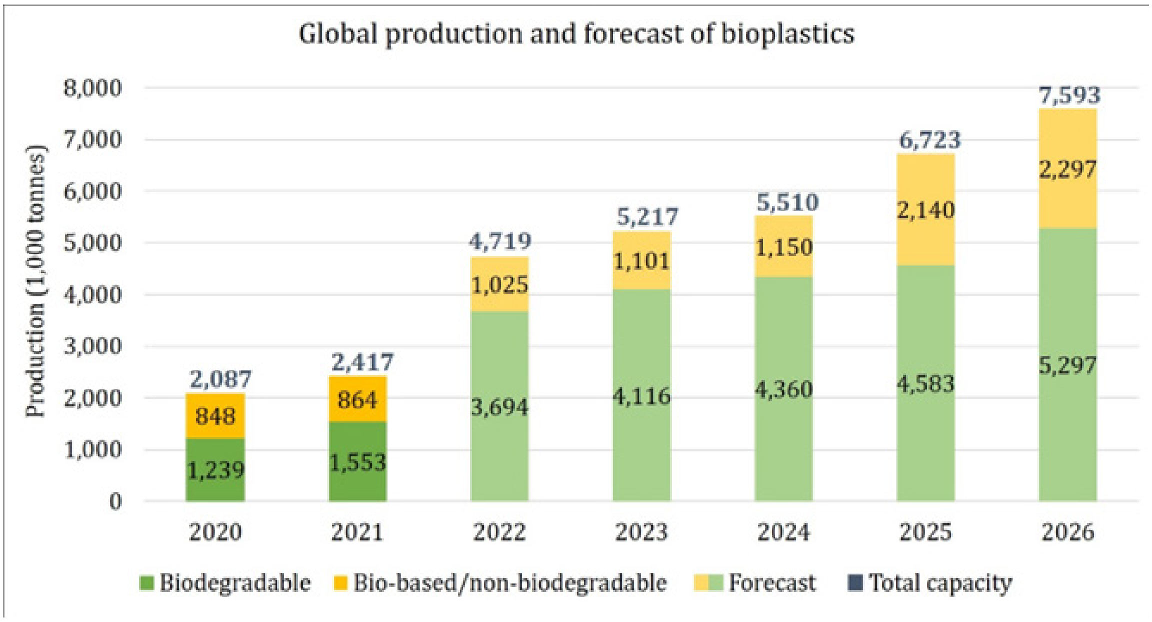

Figure 3: Global production capacities and forecast of bioplastics redrawn from [48].

PLA and PHAs are the two most important thermoplastic aliphatic polyesters used in AM. They are bio-based, biocompatible, no toxic, and biodegradable polymers produced principally from starches and sugars by biosynthesis [30,31]. Both have similar performance attributes to polystyrene (PS), polyethylene (PE), and polypropylene (PP) and are sustainable alternatives to substitute petroleum-based plastics in 3D printing for several reasons [37]. PLA is a natural, biodegradable, and recyclable polymer obtained by converting starch extracted from corn and potatoes into glucose, which ferments into lactic acid and polymerizes [42]. The degradation of PLA is complex in a typical environment, for instance, in-home compost, where the temperature does not exceed 40 °C. However, it may biodegrade within two weeks at a temperature of 60 °C under certain conditions [15]. It has an anticipated market of $5.2 billion by 2020, and some characteristics that make it an excellent polymer source for AM such as glossiness, melt flow index, low printing temperature (180 °C) and energy consumption, inexpensive, easy printing, good quality, multicolor look and comparative fewer CO_2 emissions [28,43]. Regarding sustainability, PLA is made from cornstarch, sugar cane, potato starch, wheat, beet, or tapioca roots, renewable resources that can sequester a massive amount of CO_2 during its cultivation, emitting less GHG emissions than traditional plastics [26,33,37]. The production of PLA can save two-thirds of the energy required to produce petroleum-based plastics [26,33], and they can be easily produced in existing production plants, making them cost-effective [43]. Lower printer energy consumption has been reported when PLA is used as a thermoplastic filament in 3D printing [44].

Moreover, using PLA and thermoplastic from starch in 3D printing can reduce CO_2 by 50-70% compared to petroleum-based plastics [45]. The waste management of PLA can be addressed by two paths, recycling and degradation [8]. PLA degradation can emit 70% less GHG emissions when the degradation is carried out in a landfill [23,33]. PLA can be recyclable several times, releasing no toxic fumes when it oxygenates and providing a sweet aroma at printing [37,38]. During the 3D printing process, most petroleum-based plastics release toxic substances and evaporated particles [46]. On the other hand, PLA is not related to any toxic or carcinogenic effect, which positively influences human health and the environment [27,37,47]. A drawback of PLA is that they are made from nutritious food for human beings. Thus, the uncontrolled use of these food crops might aggravate anger issues worldwide [47]. PHA is another exciting biopolymer developed and used in 3D printing [37,48]. Bacterial fermentation is the process of obtaining PHA, where several bacteria in the soil can produce it [7]. PHAs are 100% bio-based, biodegradable, and compostable as PLA is [49,50]. However, PHA can be composted under industrial conditions and in other environments like marine waters and is fully biodegradable compared to PLA [49,50]. Also, regarding biodegradability, PHA has a brief period to degrade, around 85% in 7 weeks [51]. It considerably reduces the space required to bury their waste, helping to reduce the environmental impact compared with other plastics, such as petroleum-based ones that take several years [27,47]. A drawback is the cost of PHA, which is 3-4 times higher than petroleum-based plastics. It is due to the food required for bacteria and the complexity of the production, separation, extraction, and treatment of waste fluid [47]. PHA's melting point and thermal decomposition are close, making the printing process more challenging than PLA; however, thanks to research advances, its handleability has improved [39,52]. Due to the significant environmental benefit of using bioplastics and their performance in 3D printing, bioplastics can be a potential alternative to replace conventional petroleum-based plastics in additive manufacturing applications.

Market Growth of Biodegradable Plastics Used in Additive Manufacturing

Bio-based plastics (PLA, PHA, starch blends, etc.) and petroleum-based plastics (PCL, PVA, PBS, PBAT, etc.) are found inside the biodegradable plastics category. These plastics are used in different sectors, such as packaging, consumer goods, textile, agriculture, and horticulture [33]. Due to the global problem of single-use plastic pollution, there is a claim coming from producers to consumers for biodegradable materials that meet environmental and government regulations. By 2021, the market size value was $7.7 billion; however, the increasing demand for biodegradable plastics will drive an increase in the market, projected to reach $23.3 billion by 2026 at a CAGR of 24.9% [53]. In terms of shares, the consumer goods sector constituted 14.2% of the biodegradable plastic market share by 2020 and is expected to grow more in the forecast period [53]. As there is a growing interest in using AM technologies for manufacturing and producing consumer goods, this fact constitutes an attractive opportunity for AM market players in the next five years [4,5]. Today, the leading countries in the biodegradable plastics market are Germany, United States, Japan, Netherlands, Italy, United Kingdom, and Australia. However, some emerging countries of Asia-Pacific have developed strategies. For example, in 2019, the Thailand company Total Corbion established a plant to produce 75,000 tons of PLA annually [53]. Even though biodegradable plastic has a premium price that is higher than conventional petroleum-based (no degradable) ones, the fluctuation in oil prices and sustainability-oriented advantages make biodegradable plastics a potential alternative to conventional plastics, even more in countries like the US where political and economic conditions allow the market penetration of these plastics [54]. At the same time, there is a rapidly increasing interest in biobased polymers and composites. Traditional biobased thermoplastic polymers include cellulose esters such as Cellulose Acetate Butyrate (CAB), Polylactic Acid (PLA), and Polyhydroxyalkanoates (PHA) [17]. They have all attracted commercial interest. Biobased ethylene glycol has been incorporated into Polyethylene Terephthalate (PET), and even more recently, a 100% 'biobased' PET competitor, polyethylene furandicarboxylate, has been introduced into the market [55]. All these thermoplastics are attractive due to their ease of processing. However, these polymers all contain hydrolytically unstable ester linkages. PLA and PHA are also relatively brittle materials with poor elongation properties and some processing challenges related to their processing temperature being close to their decomposition temperature [47].

For many applications, nylons are an attractive alternative to polyesters. While they are also semicrystalline thermoplastics, they tend to be stronger, tougher, and more thermally and hydrolytically stable than polyesters. By controlling the number of methylene groups between the amide linkages, nylons can be 'designed' to have a wide range of processing temperatures. Biobased nylons can be made from bioderived diacids or modification of fatty acids [39,56]. Nylon 11 is of particular interest to researchers. Initially developed in 1938 [57], nylon 11 is a relatively new commercial material made from aminoundecanoic acid and produced in the US, France, and China. Castor oil is a common starting material for producing the base aminoundecanoic acid monomer, although other C-10 unsaturated fatty acids can also be used. Fermentation routes for the production of intermediate starting materials have also been reported [39,56]. Even though it is derived from a biobased starting material, nylon 11 is not easily biodegraded, although nylon 11 blends and composites can be biodegraded [46,58]. Previous work by Saloni et al. [29] has shown the importance and relevance of additive manufacturing and the sustainable relevance of using bioplastics [10]. Some of the published work by Saloni and the team demonstrate the significance of using bioplastics in additive manufacturing. A summary of some of the work is presented next: Mervine et al. [10] showed that there had been an emergent interest in AM technologies in the last decades because of its non-traditional way of manufacturing products. A critical area in the body of knowledge of AM is focused on using polymers for manufacturing unique and competitive components compared to traditional manufacturing. Recently more sustainable bioplastics like PLA, nylon 11, Cellulose Acetate Propionate (CAP), Cellulose Acetate Butyrate (CAB), and Polycaprolactone (PCL) have surged as a competitor to conventional petroleum-based plastics. Thus, many relevant publications merge material development and characterization components suitable for AM. Additionally, this paper comprehensively reviews the most relevant publications that integrate past and current biopolymers developments applicable to AM technologies, advantages and challenges using developed biopolymers in 3D printed components, and product testing [10].

Further work by Saloni et al. [29] demonstrates the feasibility of using bioplastics in additive manufacturing. Typical thermoplastics common to the injection molding industry are made from petroleum, a nonrenewable resource, and have been widely used in AM. For this study, Cellulose Acetate Butyrate (CAB), Cellulose Acetate Propionate (CAP), Hydroxypropyl Cellulose (HPC), nylon 11, and Polycaprolactone (PCL) were formulated and tested for AM. In addition, ABS and PLA were tested as control materials. Results showed the technical feasibility of some bioplastics for AM [29]. Additionally, McLaughlin et al. [20] showed the potential of utilizing plant-based additives to modify the properties of the materials for additive manufacturing. PLA was mixed with wood flour in different ratios to evaluate the particle size effect, wood species, and concentration of wood flour in the performance of the biopolymer and 3D printed parts. Thermal, mechanical, and structural properties were studied. The results showed the potential of using wood flour as an additive to enhance bioplastics and changing the biopolymer to be suitable and eco-friendly for AM [20].

Conclusion

This review shows the opportunity of using bioplastics in additive manufacturing to respond to many sustainability challenges such as renewable materials, biodegradable, economically feasible, etc. Many challenges are ahead of us to respond to the three pillars of sustainability, environment, social, and economics; however, this paper shows how research and businesses are moving in the right direction. As seen in this review, composites and additives will play an important role by making materials more sustainable and competitive when compared to petroleum-based plastics [59-66]. Finally, additive manufacturing can play a relevant role by taking advantage of bioplastics' sustainability and the meager "buy-to-fly" ratio to reduce the environmental impact of "plastic" products considerably.

Acknowledgment

Thanks to the authors for their contributions to the writing of this manuscript.

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