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From Corn to Cassava: Unveiling PLA Origins for Sustainable 3D Printing

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Abstract

The focus of this paper is to review the polylactic acid (PLA) sourcing for 3D printing and investigating with a specific emphasis on corn starch, sugarcane, and cassava starch. PLA is recognized for its biodegradable nature and versatility as a thermoplastic, has witnessed a notable evolution in the global context of material selection for 3D printing. While regions such as the United States and Canada have traditionally derived PLA from corn starch, there is a growing trend in Asia where cassava starch have emerged as prominent alternatives. This study seeks to discover the complexities of the of PLA origins, looking into the sustainability considerations that contribute to the selection of source materials. By shedding light on the diverse trajectories of PLA sourcing, this study provides valuable insights into the ever-changing dynamics of material preferences for 3D printing on a worldwide scale. Moreover, the understandings generated through this study are composed to play a pivotal role in shaping the trajectory of future practices in additive manufacturing. As the industry continues to evolve and grapple with the imperative of environmental responsibility, a nuanced understanding of the sustainability dimensions of PLA sourcing becomes a compass guiding researchers, practitioners, and manufacturers toward ecologically sound choices. Ultimately, the study serves as a valuable resource, empowering participants to navigate the complex landscape of PLA-based 3D printing with a thorough judgement on sustainability, thereby fostering a more environmentally responsible future for additive manufacturing.

Keywords: Additive Manufacturing, 3D Printing, Polylactic Acid, Corn Starch, Sugarcane, Cassava Starch, Sustainability

1. Introduction

Additive Manufacturing (AM) innovation is an exceptionally expansive term incorporating various strategies, for example, Fused Deposition Modeling (FDM) from plastic filament, Laminated Object Manufacturing (LOM) by plastic overlays, and Selective Laser Sintering (SLS) by plastic or metal powders [1], [2], [3]. FDM strategy is exceptionally compelling because it be performed using desktop 3D printing machines [4]. 3D printing constitutes a transformative technology that fabricates three-dimensional objects by layering successive strata of molten thermoplastic materials. This process enables the creation of intricate and customized geometries through the deposition of successive layers. One of the key materials commonly employed in this technique is polylactic acid (PLA), a biodegradable thermoplastic known for its versatility and environmentally friendly properties [5], [6].

The process begins with the extrusion of a thermoplastic filament, such as PLA, from a heated nozzle. PLA is chosen for its relatively low melting temperature, makes it well-suited for use in melt extrusion within open-air, non-dedicated facilities. As the nozzle moves across the designated surface, it precisely deposits the molten PLA in a layer-by-layer fashion, gradually building up the desired three-dimensional object [7], [8], [9]. The ability of PLA to undergo controlled melting and solidification processes at accessible temperatures is a critical factor in the success of this 3D printing technique. The low melting temperature of PLA ensures that it can be efficiently extruded and solidified without the need for highly specialized or enclosed environments, making the technology more accessible and versatile [10], [11], [12].

The layer-by-layer approach not only allows for the precise reproduction of complex geometries but also facilitates the customization of designs according to specific requirements. This versatility makes 3D printing a valuable tool across a multitude of industries, ranging from manufacturing and prototyping to healthcare and architecture [13], [14].

There were various stages taken to complete the additive manufacturing process. Firstly, a graphical data of a product that designed using computer-aided manufacturing (CAM) were taken. The data were cuts by using slicer tools to separate object layers or components. The graphical data that have been split is sent to the 3D printer and next the printer then adding up the product progress layer after layer until the product is completely done according to the design criteria [15], [16].

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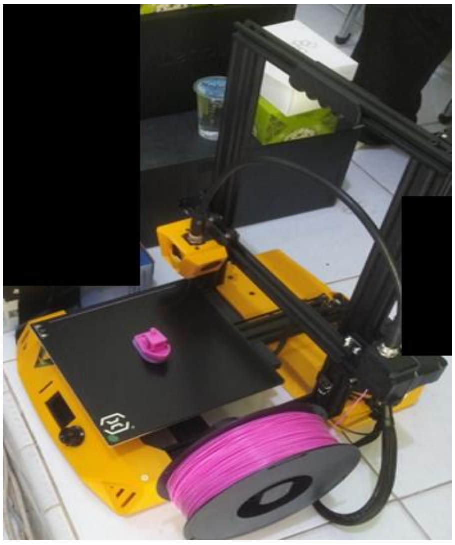
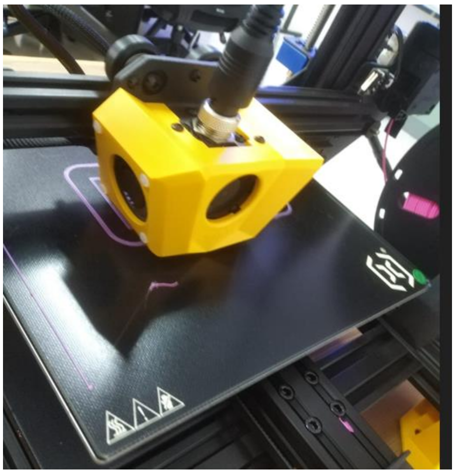
The primary phase of 3D printing includes making an advanced model to the object that will be printed. This is commonly finished with Computer-Assisted Design (CAD) software or by any devoted online services gave by some of the 3D printing stages. 3D scanners can be utilized to consequently make a model of a current object simply like 2D scanners are utilized to digitize photographs, illustrations or reports as well. At the point when a project is printed, the 3D object is flustered into progressive layers that are printed one at time [17], [18]. The 3D printing machine with PLA as filament material and nozzle of 3D printing extruding heated PLA are presented in Figure 1.



(a)



(b)

Figure 1. (a) 3D printing machine with PLA as filament material (b) Nozzle of 3D printing extruding heated PLA

The mechanical properties of 3D printed PLA are greatly influenced by various technological parameters such as size of nozzle, layer thickness, degree of filling, filling pattern, filling speed and production temperature. It is interesting to note that other parameters also play a significant role during the fabrication process. For example, due to the basic chemical composition of the material used, pigments affect not only its mechanical properties but also its degree of crystallinity. In this context, the filling orientation is certainly one of the most important variables that influence the mechanical total, strength and fracture behavior of synthetically manufactured plastics [19], [20].

2. Methodology

This study is based on literature survey that explores the landscape of PLA production, with a specific focus on its synthesis utilizing various starch-rich substrates such as corn starch, sugarcane, and cassava starch. The objective of this investigation is to synthesize a nuanced understanding of PLA manufacturing when derived from these distinct agricultural sources. The utilization of corn starch as a precursor for PLA has been a subject of considerable research interest. Existing literature provides insights into the intricate processes involved in extracting fermentable sugars from corn starch, subsequently undergoing fermentation to yield lactic acid, and ultimately polymerization to form PLA.

3. Results and Discussion

3.1. Polylactic Acid (PLA)

PLA is somewhat less demanding to print than ABS because of its low print temperature and its capability to print on and stick onto an cold print platform. In spite of not requiring a heated build plate, many PLA users still print at a build plate temperature of around 50°C to 60°C. PLA displays substantially less print twisting. Since it experience more of a phase-change than ABS, it can print substantially better finer details. Active cooling empowers PLA to print significantly more honed corners without the danger of twisting, distorting and breaking. PLA can likewise be printer at a high flow rate, which prompts more stronger over layer bonds [21], [22].

Polylactic acid (PLA) for 3D printing is typically made from renewable resources, most commonly derived from plant-based materials. The primary feedstock for PLA used in 3D printing is lactic acid, which is produced through the fermentation of starches [23], [24]. The process of producing PLA from these bio sources is depicted in Figure 2.

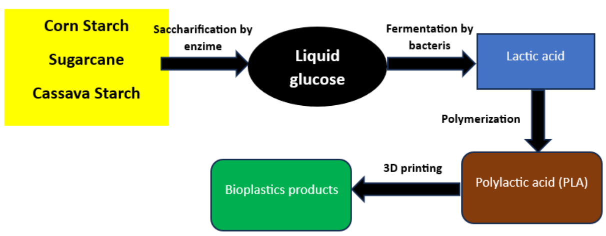


Figure 2. The process of producing PLA from bio sources; corn starch, sugarcane, and cassava starch

3.2. Corn Starch

Polylactic acid (PLA), derived from corn starch, constitutes a prominent category among biodegradable polymers. Corn starch, a renewable resource, undergoes a sophisticated conversion process wherein sugars are extracted and subsequently fermented to yield lactic acid. This method exemplifies a sustainable approach to polymer production, aligning with the growing imperative to transition away from conventional petroleum-based plastics [25], [26].

The initial phase involves the breakdown of corn starch, a polysaccharide, into its constituent sugars. This extraction process serves as a pivotal precursor, providing the requisite substrates for the subsequent stages of PLA synthesis. The utilization of corn starch as a starting material is a strategic choice, rooted in its abundance and renewable nature, thereby contributing to the overarching goal of fostering environmentally responsible manufacturing practices [27], [28].

The second phase of this intricate process entails the fermentation of the extracted sugars to produce lactic acid. This step embodies a biotechnological application, wherein microorganisms act upon the sugars to effectuate the conversion into lactic acid. The orchestrated interplay of biological agents and industrial processes underscores the intricate nexus between biotechnology and materials science in the realm of sustainable polymer development [29], [30].

Lactic acid, as the resultant product of fermentation, assumes a central role in the subsequent polymerization process leading to PLA formation. Polymerization transforms the lactic acid molecules into long-chained structures characteristic of PLA, rendering it a resilient and moldable bioplastic. The controlled synthesis of PLA from renewable resources underscores its potential as a sustainable alternative to conventional plastics [31], [32].

Corn-based PLA encapsulates the principles of the circular economy, wherein agricultural resources are repurposed to generate environmentally benign materials. This approach ensures a diminished carbon footprint compared to petroleum-derived counterparts. Moreover, the inherent biodegradability of PLA augments its environmental credentials, facilitating decomposition into benign byproducts under suitable conditions [33], [34].

The sustainability of corn starch for PLA (polylactic acid) production is a complex topic that involves various environmental, economic, and social considerations. Corn starch is a renewable resource because it comes from corn, which is a plant-based crop. This contrasts with fossil fuels used in the production of traditional plastics. The renewable nature of corn starch contributes to a lower environmental impact compared to non-renewable resources. The sustainability of corn starch for PLA production is influenced by the agricultural practices involved in cultivating corn. Sustainable farming practices, such as crop rotation, minimal pesticide use, and efficient water management, can enhance the overall sustainability of corn cultivation. Concerns may arise regarding the impact of corn cultivation on land use and biodiversity. Sustainable farming practices aim to minimize negative effects on ecosystems, ensuring that the production of corn starch for PLA does not lead to deforestation or the loss of biodiversity [35], [36].

3.3. Sugarcane

Polylactic acid (PLA) can also be sourced from sugarcane, broadening the scope of sustainable raw materials for bioplastic production. Sugarcane, a robust and starch-rich crop, stands as an alternative feedstock for the generation of PLA, complementing the existing reliance on cornstarch. This diversification is particularly significant in the context of enhancing resource efficiency and mitigating concerns related to resource competition in the agricultural sector [37], [38].

Sugarcane, recognized for its high sugar content, becomes a reservoir for the sugars crucial in the synthesis of PLA. Through a series of refining processes, the starch in sugarcane is effectively converted into fermentable sugars. These sugars then undergo a fermentation process, akin to the corn-based PLA production, wherein microorganisms catalyze the conversion of sugars into lactic acid. This enzymatic transformation underscores the versatility of PLA production methodologies, showcasing adaptability to different agricultural feedstocks [39], [40].

The ensuing polymerization of lactic acid derived from sugarcane serves as the foundation for the formation of PLA. The resulting polymer possesses similar properties to corn-based PLA, rendering it suitable for a wide array of applications, from packaging materials to disposable items. This utilization of sugarcane not only broadens the resource base for PLA but also reinforces the sustainable ethos of bioplastic production by tapping into the renewable potential of diverse crops [41], [42].

The use of sugarcane as a PLA precursor aligns with the principles of crop rotation and diversified agriculture. By incorporating sugarcane into the PLA production cycle, the environmental impact is further reduced, as it mitigates the strain on specific crops, promoting a balanced and sustainable approach to resource utilization. Additionally, the inherent renewability of sugarcane contributes to the overall sustainability narrative, addressing concerns about the long-term viability of bioplastic production. The derivation of PLA from sugarcane underscores the adaptability and versatility of bioplastic manufacturing. This expansion beyond corn-based sources not only broadens the resource base for PLA but also reflects a commitment to sustainable practices by embracing diverse agricultural inputs. Sugarcane, with its starch-rich composition, adds another dimension to the ongoing quest for ecologically sound alternatives to traditional plastics [43], [44].

The sustainability of sugarcane is achieveable since it is a renewable resource as it is a fast-growing grass crop. It has a relatively short harvest cycle compared to many other crops, making it a potentially sustainable source for industrial processes like PLA production. Sugarcane is known for its high yield per hectare, making it an efficient land-use option. Efficient land use is crucial for sustainability, as it allows for the production of a significant amount of raw material without the need for extensive agricultural expansion, which could contribute to deforestation or habitat destruction. Sugarcane cultivation has the potential to contribute to lower greenhouse gas emissions compared to other crops. The crop itself can act as a carbon sink, and the processing of sugarcane into PLA may have a lower carbon footprint compared to traditional petroleum-based plastics. Sugarcane is a relatively water-efficient crop, but the sustainability of its cultivation also depends on responsible water management practices. Assessing the water footprint of sugarcane cultivation is essential to ensure that water resources are used efficiently and do not contribute to water scarcity or environmental degradation [45], [46], [47].

3.4. Cassava Starch

Cassava is a starchy tuberous root that provides a source of fermentable sugars for lactic acid production. PLA (Polylactic acid) incorporated with cassava roots exhibits enhanced mechanical properties. The addition of cassava starch improves tensile strength and water vapor performance of PLA bioplastics. Cassava, a versatile starchy tuberous root, emerges as an intriguing alternative source for the production of polylactic acid (PLA), further contributing to the diversification of raw materials in the realm of bioplastics. Recognized for its high starch content, cassava serves as a valuable reservoir of fermentable sugars, thus proving instrumental in the synthesis of lactic acid, the precursor to PLA [48], [49].

The integration of cassava-derived components into PLA formulations imparts notable enhancements to the mechanical properties of the resulting bioplastic. In particular, the incorporation of cassava roots into PLA matrices has been observed to significantly improve tensile strength. This augmentation in mechanical strength is attributed to the unique structural and compositional characteristics of cassava-derived starch, reinforcing the integrity of the PLA polymer matrix and enhancing its overall durability. The utilization of cassava in PLA formulations contributes to improved water vapor performance. The inherent properties of cassava starch act as reinforcing agents, creating a more robust barrier against water vapor permeation in the resulting bioplastics [50], [51].

The sustainabilty of cassava starch is very good since it is a renewable resource as it is a tropical root crop that can be harvested annually. Its relatively fast growth cycle makes it a potential sustainable source for industrial processes, including PLA production. Cassava is known for its adaptability to diverse soil conditions and efficient land use. It can be grown in marginal lands, which may reduce competition with food crops and minimize the need for deforestation. Efficient land use is crucial for sustainable agriculture. Cassava cultivation may have a lower environmental impact compared to some other crops. It is a hardy plant that requires fewer pesticides and fertilizers, contributing to reduced chemical inputs in the agricultural process. Cassava is generally considered a relatively water-efficient crop. However, as with any agricultural product, responsible water management practices are essential to ensure efficient water use and minimize the risk of water scarcity. Sustainable cassava cultivation involves practices that protect biodiversity. This includes avoiding the conversion of natural habitats for cassava cultivation and implementing agroecological approaches that support the ecosystem [52], [53].

Table 1. The characteristics of Corn Starch, Sugarcane, Cassava Starch [2], [8], [32], [33], [34], [45], [47], [50], [51], [52], [53]

Characteristics	Corn Starch	Sugarcane	Cassava Starch
Availability	Widely available, especially in the Americas and Europe.	Abundant in tropical regions, with major production in Asia, South America, and Africa.	Commonly grown in tropical and subtropical regions, with high production in Asia, Africa, and South America.
Source	Extracted from corn kernels.	Extracted from sugarcane plants.	Derived from cassava tuberous roots.
Sustainability	Considered sustainable if sourced from responsibly managed crops.	Generally sustainable, as sugarcane is a high-yield crop with efficient land use.	Considered sustainable, as cassava is a hardy crop with low input requirements.
Performance	Exhibits good mechanical properties and ease of printing.	Fairly good mechanical properties and good printability.	Good mechanical properties and suitable for general 3d printing applications.

The biodegradable and renewable nature of PLA, combined with its ability to be processed through 3D printing technologies, has made it a popular choice in the field of additive manufacturing. PLA is known for its ease of use, low environmental impact, and suitability for a wide range of 3D printing applications [54], [55].

4. Conclusion

This paper reviews the dynamics of acquiring polylactic acid (PLA) for 3D printing, highlighting the transition from traditional corn starch sources to the investigation of alternative materials such as sugarcane and cassava starch. PLA, known for its biodegradability and versatility as a thermoplastic, has undergone a significant transformation in its global selection for additive manufacturing. While the United States and Canada have historically derived PLA from corn starch, there is a noticeable shift in Asia, particularly with the prominence of cassava starch as a viable alternative. This study illuminates the varied paths of PLA sourcing, offering valuable insights into the evolving preferences for materials in 3D printing on a worldwide scale. By thoroughly examining sourcing practices, the research contributes to a deeper comprehension of the sustainability of PLA-based 3D printing processes, with the goal of guiding future practices in the additive manufacturing field.

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