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Bioplastics: Environment-friendly materials and their production technologies

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ABSTRACT

Objective: To analyze the recent contributions of bioplastics in addressing environmental problems caused by plastic pollution.

Design/Methodology/Approach: A literature review was carried out on the definitions of plastics and bioplastics, the sources of raw materials, processing technologies and methods to assess biodegradation. Current practices for final disposal and/or reuse were also examined. Special emphasis was placed on polylactic acid (PLA), one of the most widely used biodegradable materials today.

Results: Over the years, there have been significant developments in the definitions of plastics and bioplastics, as well as in the sources of raw materials and processing technologies used to create final plastic products. By using bioplastics instead of conventional plastics, it is possible to reduce the dependence on petroleum and mitigate the pollution associated with plastic production and disposal. Furthermore, the enhanced biodegradability of bioplastics ensures that they break down more readily in natural environments, reducing the accumulation of plastic waste and its detrimental impact on ecosystems. The production of bioplastics using plant fibers, biological materials, and polymeric waste materials presents an opportunity for integration into the productive activities of the agro-industrial sector. This integration brings several benefits and synergies between agriculture and industry.

Study limitations/Implications: We provide a report based on the literature.

Findings/Conclusions: there is a notable current trend in the utilization of bioplastics as a viable substitute for conventional plastics. In order to assess the biodegradability and compostability of these materials, specific testing and certification standards have been established by reputable organizations. These standards serve as a reliable framework for evaluating the environmental impact and degradation characteristics of bioplastics. By adhering to these guidelines, manufacturers can ensure that their bioplastic products meet the necessary criteria for sustainable use.

Keywords: Bioplastics, Plant residues, Waste.

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INTRODUCTION

The increasing levels of plastic pollution both in land and water degrade the environment (García and Robertson, 2017). Conventional plastics exhibit inherent resistance to degradation due to their high molecular weight, complex three-dimensional

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structure, minimal water content, and hydrophobic nature. These characteristics impede degradation processes caused by factors such as exposure to light, water, and the activities of living organisms or their enzymes (Kale *et al.*, 2015; Chamas *et al.*, 2020). When burned, plastics generate CO_2 and other toxic gases (Wu *et al.*, 2021), such as dioxins (Kale *et al.*, 2015). A significant amount of plastic waste ends up in landfills. While recycling technologies do exist for certain types of plastics, such as polyethylene terephthalate (PET) and polyethylene (PE), but effective recycling requires proper separation and collection of these materials (Song *et al.*, 2009). However, it is important to note that the costs of recycling can be high, and the quality of recycled plastic products may be lower compared to their virgin counterparts (García and Robertson, 2017).

One effective approach to minimize the reliance on traditional plastics is by substituting them with biodegradable (Ferreira *et al.*, 2019) and compostable (Sabapathy *et al.*, 2020) alternatives. These innovative materials can be broken down by microbial extracellular enzymes (Bano *et al.*, 2017; Sabapathy *et al.*, 2020) or through exposure to light, water, and oxygen (Siracusa, 2019). As a result, they generate carbon dioxide (CO_2), water (H_2O), methane (CH_4), and other light compounds (Siracusa, 2019), which have a reduced environmental impact compared to traditional plastics.

Definition of plastics

Plastics are polymers, which are large molecules composed of repeating subunits called monomers whose composition does not change when molded through heat and pressure (WWF, 2018). They are characterized by low density, low electrical conductivity, transparency, which allows their transformation into a variety of products. Polyethylene, polypropylene, and polyvinyl chloride are affordable, versatile, and extensively utilized plastics. They are commonly employed for short-term applications. Polycarbonates, polyether ether ketones, and polyimides are durable plastics that have a longer-term applications with a higher cost compared to other plastics (Feldman, 2008; Ramos, 2018). All these products come from the petrochemical industry and constitute over 80% of globally-used plastics (Urbanek *et al.*, 2018).

Classification of plastics by a degradability criteria. Plastics can be classified into recalcitrant and biodegradable. Recalcitrant plastics are derived from petroleum, transformed by synthesis into polymers with a high molecular weight, and do not degrade easily. Biodegradable plastics undergo degradation within a few months.

Bioplastics: definition and production

The International Union of Pure and Applied Chemistry (IUPAC) defines biodegradable polymers as materials that are susceptible to degradation by biological activity, with the degradation accompanied by a decrease in their molar mass (Haider *et al.*, 2019). According to the American Society for Testing and Materials (ASTM), biodegradable polymers can be distinguished from other plastics by their ability to decompose into carbon dioxide, water, inorganic compounds, and biomass at a similar rate to other recognized compostable materials. Additionally, it is crucial for these polymers not to leave any noticeable or harmful residues behind, ensuring their environmental compatibility (Food Packaging Forum, 2021). The determination of biodegradability and compostability of materials relies on specific testing and certification standards, such as those established by ASTM. These standards provide a systematic framework for evaluating and verifying the environmental characteristics of materials in order to ensure accurate assessment of their biodegradability and compostability. The European Bioplastics Organization defines bioplastics as those included in one of the following categories: a) of biological origin; b) biodegradable; or c) both. This categorization includes products containing raw materials derived from petroleum. Thus, some bioplastics, such as Bio-PET, are naturally occurring polymers combined with petroleum-derived polymers and are not biodegradable (Van Crevel, 2016). Some bioplastics are made of polymers of plant or animal origin, such as polysaccharides (cellulose, starch, chitin, and lignin); others contain proteins (gelatin, casein, gluten); and still others, lipids (Arikan and Ozsoy, 2015). Other biodegradable polymers are synthesized from precursors of microbial fermentation and subsequently polymerized through chemical and physical transformations (Arikan and Ozsoy, 2015). Most biodegradable polymers are aliphatic polyesters, like polylactic acids (PLA) and polyhydroxyalkanoate (PHA), manufactured from precursors of microbial origin that are biodegradable and compostable (Van Crevel, 2016; Sabapath *et al.*, 2020). Others are plant-based polymers such as thermoplastic starches (TPS) and polybutylene succinate (PBS) (Zhao *et al.*, 2020). Production of bioplastics is currently growing (Figure 1) (Verbeek and Uitto, 2017). In Mexico, the agricultural products —sugar cane, citrus fruits, and bananas (INEGI, 2019) (Figure 2)— generate waste that can be used in the production of bioplastics (Riera *et al.*, 2018; Rivera-Mackintosh and Nevárez-Moorillón, 2019).

Polylactic (PLA) production

PLA is a biodegradable aliphatic polyester known for its thermoplastic properties (Figure 3). It is derived through the polymerization process of lactic acid. Lactic acid, the precursor for PLA, can be obtained through either chemical synthesis or fermentation methods (Li *et al.*, 2020). Chemical synthesis primarily results in the production of DL-

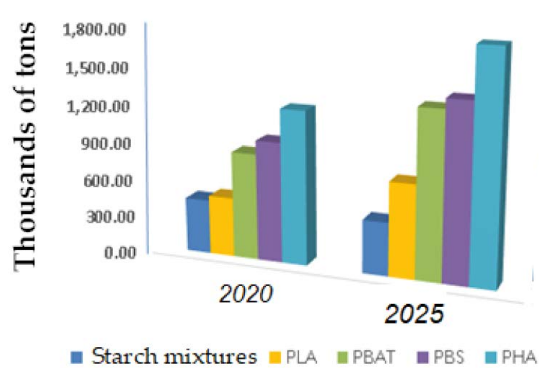

Figure 1. Comparative forecast for the production of biodegradable bioplastics from 2020 to 2025. Abbreviations: PLA, polylactic Acid; PBAT, polybutylene adipate; PBS, polybutylene succinate; PHA, polyhydroxyalkanoates (elaborated with data from the European Bioplastics Organization, https://www.european-bioplastics.org/bioplastics/materials/).

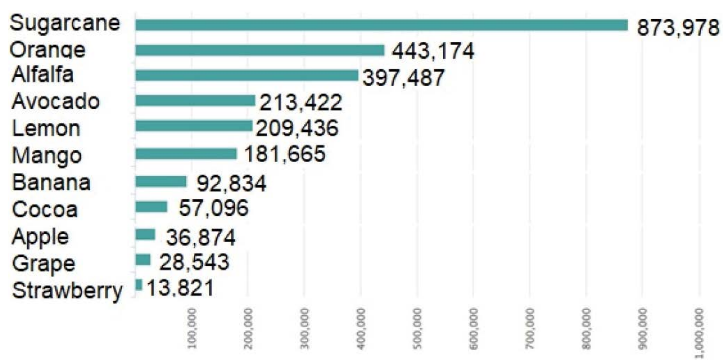

Figure 2. National agricultural survey. Source: INEGI, 2019.

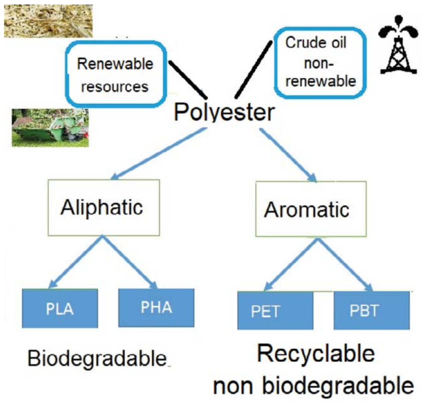

Figure 3. Bioplastics: biodegradable and from biological origin (renewable sources). PLA, polylactic acid; PHA, polyhidroxyalkanoates.

lactic acid, whereas microbial fermentation can yield D- or L-lactic acid or a combination of isomers, depending on the bacterial species and the substrate employed. When PLA is derived from either the L-isomer or the D-isomer, the polymer exhibits a crystalline structure and greater stability compared to the amorphous polymer obtained from a racemic mixture. The choice of isomer in PLA production can influence its physical and chemical properties, making it important to consider the desired characteristics for specific applications (Calabia and Tokiwa, 2007). To produce lactic acid, whether it is the D or L isomer, maintaining pure bacterial cultures is essential to prevent contamination. Achieving aseptic conditions is crucial during this process. However, the sterilization of culture media can be an expensive step. In the production of polylactic acid, lactic acid is purified and subjected to condensation to form lactides. Lactides are cyclic dimers that undergo polymerization to form the desired polylactic acid. However, direct condensation is hindered by the presence of water and impurities. This can result in the production of polymers with low molecular weight and inferior mechanical properties.

To address this issue, chain extenders are utilized to facilitate longer chain polymerization, resulting in improved mechanical properties.

PLA properties. PLA has good transparency, gloss, crease retention, twist retention, heat sealability, flavor and aroma barrier properties, low heat sealing temperature, and a suitable surface for printing (Levytskyi *et al.*, 2021). It is insoluble in water and resistant to moisture and grease. Its mechanical properties depend on molecular weight and crystallinity. Current applications include transparent packaging films and food-grade disposable thermoformed articles. It can also be spun into fibers for fabrics and textiles. The recent production of biocomposites with a matrix of cellulose microfibers from sugar cane straw and polylactic acid (Figure 4) has led to renewed properties, such as a higher melting point and an increase in the elasticity modulus, which reduces the biocomposite's elongation index (López Velazquez *et al.*, 2020). PLA has properties similar to polyethylene terephthalate (PET) and is also used for packaging, but unlike PET, it is compostable. PLA is non-enzymatically degraded, the resulting monomers being degraded by microorganisms, and it is also compostable (Siracusa, 2019). Polylactide degradation occurs at >60 °C, in the presence of oxygen and moisture, by hydrolysis and photooxidation or thermal oxidation mechanisms (Chamas *et al.*, 2020) —although it also depends on pH, the polymer's molecular weight, and crystallinity (Levytskyi *et al.*, 2021).

Processing of bioplastics

The melting temperature of PLA falls within the range of 169-180 °C, which allows the processing of this polymer by the following methods: a) extrusion; b) blowing; c) thermoforming; and d) injection molding (Contreras *et al.* 2018; Levytskyi *et al.*, 2021). A) Extrusion: a die is used to melt the materials through friction forces (Figure 5), with a subsequent final cooling phase that allows the materials to harden. B) Blowing: this process follows the plastic's extrusion using a circular die with a hole in the center to blow the extruded material, which inflates like a balloon (Figure 5). The bubble of molten plastic cools with the external air and solidifies along the tube. This method is used to produce bottles. C) Thermoforming: this hot molding method includes variants based on thermoplastic heating (Figure 5). Molding can take place using vacuum, blowing, or mechanical means (vacuum, temperature, and pressure), and said methods can be combined. The machinery employed, besides being simple, is economical and compact, so that this method is widely used to manufacture large-sized and thin-walled molds of complex configurations (Figure 5). D) Injection: in this process, a thermoplastic is melted using heat. A machine injects

Figure 4. Biocomposite made of cellulose microfibers from sugarcane straw and polylactic acid.

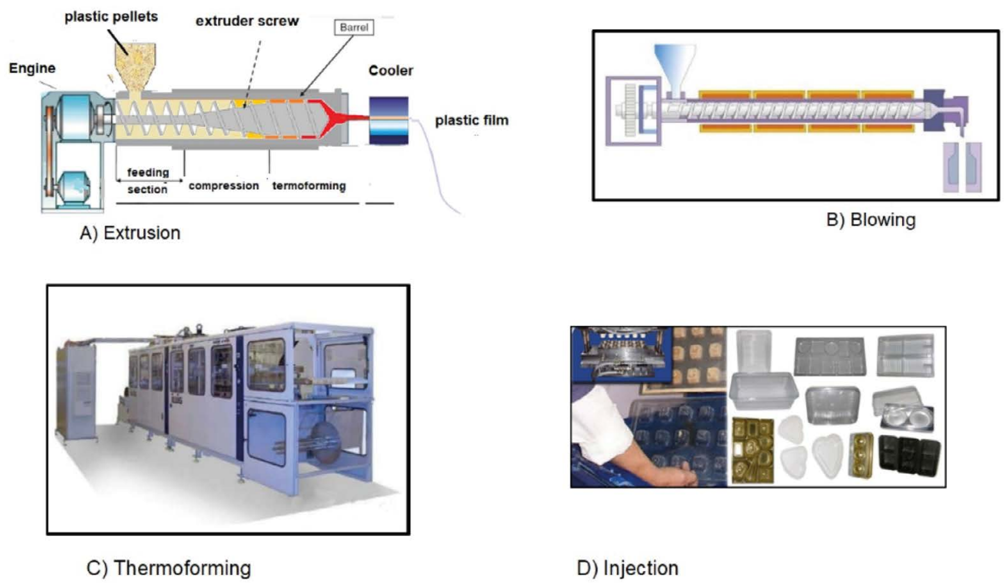

Figure 5. Technologies for the processing of bioplastics/biomaterials.

heat into the mold's cavities with an adequate pressure and temperature. Subsequently, the materials cool into a solid plastic shape with dimensions similar to those of the mold. To evaluate and define the optimal use of bioplastics, one must examine their physical, mechanical, and chemical properties.

Biodegradability

According to the ASTM, a compostable material should disappear within 12 weeks without leaving fragments, residues, heavy metals, or toxins that may affect plant growth. Tables 1 and 2 present the main differences between biodegradable and conventional plastics.

Table 1. Differences between biodegradable and conventional plastics.

Characteristics	Biodegradable plastics	Conventional plastics
Source of raw materials	Natural polymers such as starch, cellulose and chitin extracted from living organisms such as plants, animals or produced by microorganisms. Polymers synthesized from natural compounds	Petroleum derivatives
Examples	PLA, PHA, PBS, PBAT	PE, PP, PET
Uses	Food packaging, textiles,	Wide use
Decay time	6 months	Up to 500 years
Type of pollution generated	Minimum	Wastes and microplastics in land, water and air
Type of treatment for degradation	Composting	burning

With data from: Intención del uso del plástico biodegradable en hogares y su incidencia en la contaminación ambiental, Arana and Miranda (2019), Emadian *et al.*, 2017, and Goel *et al.*, (2021).

Table 2. Biodegradability of bioplastics in different environments.

Bioplastic	Environment	Temperature/Relative humidity	Biodegradability (%)	Methods of assessment	Test period (days)
PLA	Compost	58 °C, 60 % RH	13-84	CO_2	28-60
	Soil	25 °C, 30% −60% RH	10%	Weigth loss	28-98
PHA	Soil/compost (90/10%)	25 °C, 65% RH	40–50	CO2	15
	Soil	35 °C, 60 % RH	35-48	Weigth loss, CO_2	60, 280
PHB	Compost	58 °C, 70 % HR	80	CO_2	110
	Soil	30 °C, 80 % HR	64-98	Weigth loss	180-300
	Sea water	25 °C	80-99	Weigth loss, CO_2	14-49
Starch based	Compost (termoplástic)	58 °C	73.1	CO_2	56
	soil (plastic made from starch)	20 °C, 60 % HR	14.2	CO_2	110
	Marine environment	26 °C	100	Weigth loss	50
Celullose	Compost (celulose acetate)	53 °C	100	CO_2	18
	soil (celulose)	25 °C	100	Weigth loss	180

PLA, polylactic acid; PHB, polyhydroxybutyrate. With data from: Intención del uso del plástico biodegradable en hogares y su incidencia en la contaminación ambiental, Arana and Miranda (2019), Emadian *et al.*, 2017, and Goel *et al.*, (2021).

It is crucial to assess the limitations and characteristics of bioplastics to understand their potential applications and performance. Testing the mechanical properties, resistance, and permeability of bioplastics to water and gases helps evaluate their suitability for specific uses. Bioplastics, derived from diverse sources, exhibit variations in their properties compared to traditional plastics. It is important to consider their origin, lifetime, and beneficial properties for the environment, and for the producers involved. In many cases, production costs need to be optimized.

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