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REVIEW

Biopolymers Applied to Packaging: A Brief Literature Review on Their Impact on Sustainability

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ABSTRACT

The replacement of fossil raw materials by renewable alternatives is imperative. Renewable, biodegradable, and compostable polymers are options to be developed and adopted. Embedded in this concept, the present study evaluates whether biopolymers are sustainable alternatives to replace traditional polymers used in packaging, such as polyethylene. To that end, a systematic literature review (SLR) was carried out on biopolymers applied to packaging, with an analysis of its impacts. Three sustainability criteria were adopted: a) Criteria for Developing Sustainable Packaging; b) Goals of Sustainable Development; and c) Circular Economy Criteria. The Methodology Section presents the state of the art of potential polymers for packaging and their characteristics related to the evaluation criteria adopted based on the SLR. Through data collection, it was observed that advanced obtaining techniques enable polymers economically and that, environmentally speaking, there is a positive consensus about some types of those materials. However, technological maturity and productive scale capacity are necessary to reduce costs in a competitive scenario with conventional polymers.

1. Introduction

According to the Brazilian Bioinnovation Association, bioeconomy must consider the advanced scientific knowledge in order to promote innovations in industrial processes that use renewed resources. It also calls for the impacts of those advances to be directed towards the circular economy for the benefit of society in general and the environment [1]. Other definitions of bioeconomy are found in researches, policies, strategies among other sources [2,3]. But all of them share a common sense: the recognition that natural resources are limited and must be used effi-

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ciently. This statement correlates to economic growth, development, and environmental protection [4]. Regarding society's concern about bioeconomy, plastic materials are in the spotlight, whether in what concerns the use of non-renewable materials or in the generation/disposal of waste. Between 1950 and 2019, 9210Mt of plastic was produced. Up to 2015, 6300Mt of waste was generated and only 21% was recycled or incinerated. The other 79% was accumulated in landfills or improperly disposed of in the environment. About 38% of this material composed basically of materials from non-renewable sources was used by the packaging industry [5]. Embedded in the circular economy context, biopolymers can be designed to be degradable or compostable within months or years. They can also contribute to carbon capture due to its mostly plant-based origin and mitigate both the negative impacts arising from the consumption of fossil-sourced material [2]. Figure 1 illustrates the carbon cycle of fossil-sourced polymers and that of biopolymers.

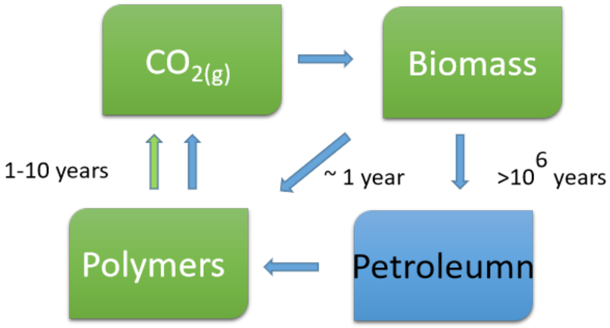


Figure 1. Carbon cycles of conventional polymers and biopolymers [6]

Biopolymers stand out in biomedical [7], 3D printing filaments [8], agricultural [9], electronic [10], and coating [11] applications. Advances in obtaining technologies and increased productive capacity make it economically feasible to use this material in packaging [12,13]. In order to be competitive, they must meet the expected requirements in packaging such as mechanical strength, thermal resistance, ease of processing, water-vapor barrier properties, and durability [10]. Although the environmental impact of packaging is widely reported and criticized as environmental pollutants, packaging plays an important role in reducing waste. It is estimated that the environmental damage for not using packaging would be much greater, considering that 70% is used for food packaging [14].

1.1 Motivations and Goals

The diversity of renewable materials for packaging, obtaining and processing techniques introduced in recent years has contributed to the emergence of new paradigms. Such scenario has uncovered a lack of literature that cross-references to explain common issues within the packaging supply chain, with the adoption of criteria to guide the development of those new materials [15]. The purpose of the present review is not to introduce a new paradigm, but to investigate issues regarding the use of polymers as packaging materials and their impacts on sustainability. Therefore, the present review aims to answer the following research question:

RQ1: Are polymers sustainable alternatives to replace conventional polymers in packaging applications?

In order to address this issue, a systematic literature review (SLR) was carried out to identify the state of the art of biopolymers applied to packaging and their impacts on sustainability criteria.

1.2 Packaging

Packaging may be defined as a product made of material of any nature used to contain, protect, transport, distribute, and present commodities, from natural to processed material goods, from producers to consumers [16]. Complex concepts can be used to evaluate whether the packaging is sustainable. But mainly it must address the use of innovative and functional materials that promote economic and environmental health [17]. In this regard, packaging must meet some principles for sustainable materials such as: *functionality,* effectively protecting the packaged product; *efficiency*, consuming a minimum of materials, water, and energy; *cyclic*, generating minimal waste; *safety*, clean and safe and causing no risks to the environment [18,19]. For the development of packaging, a set of mechanical and chemical properties is evaluated. Throughout the present review, it was observed that permeability and mechanical strength of biopolymers are among the greatest concerns and have been the sources of several studies [20,9,12,21].

1.3 Biopolymers and Packaging

Biopolymers are polymers derived from renewable sources that can be biodegradable or non-biodegradable. Non-biodegradable products play a role in capturing CO_2 emissions and may be used in infrastructure applications such as pipes, building materials, and roofing. In turn, biodegradable products play a role in short to middle life cycle products, neutral CO_2 balance, and projected degradation time designed according to application [2]. Currently, packaging is in the spotlight of scientific research that seeks the development of sustainable materials [22,23]. And biopolymers are at the forefront as substitutes for fossil-sourced materials. However, the mechanical and water vapor barrier properties are relatively poor when compared to conventional polymers [17]. When technical-commercial requirements are put together, it is possible to explain why there are few commercially successful biopolymers [24]. On the other hand, since 2009, the productive capacity has been increasing and confirming production forecasts. Although there are small divergences between the production forecast and what was actually produced, the projections shown in Figure 2 for the coming years are for an increase in production capacity [25].

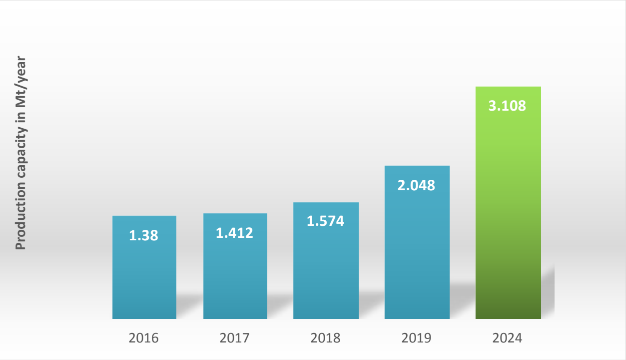


Figure 2. Global biopolymer production capacity [26]

In addition to their rising production capacity, polymers have a technical potential to replace 90% of conventional materials [27]. In order to overcome some technical deficiencies, the use of reinforcements can promote properties such as antimicrobial characteristics for food product protection [12].

1.4 Types of Biopolymers

The diversity of raw materials for obtaining sustainable polymers is subdivided into carbon dioxide, terpenes, vegetable oils, and polysaccharides. The present research focuses on groups of materials with characteristics applicable to packaging, among which polysaccharides showed the greatest potential [24]. Polysaccharides are polymers found naturally in the environment. With minor modifications, they are polymerized to obtain the desired material, such as starch, cellulose, lignin and hemicellulose [10]. The production of biopolymers from polysaccharides is one of the most studied alternatives. Those carbohydrates are abundant in nature and can be easily extracted and processed [24]. This processing involves breaking them down into monosaccharides from starch- or sugar-rich sources to obtain glucose. With this basic structure, carboxylic acids can be obtained [17]. Subsequently, these acids are polymerized through chemical reactions or enzymatic routes to produce the desired monomers. Vegetables such as sugarcane and corn are examples of sources of polysaccharide that can be transformed into biopolymers, such as polylactic acid (PLA) and polyhydroxyalcanoate (PHA) [28,29]. Another possible route is through biomass fermentation to produce methane and subsequent conversion to ethanol, to obtain Bio Polyethylene Terephthalate and polymerization of Bio PET (Polyethylene Terephthalate) and Bio PE (Polyethylene) [2].

1.4.1 Polylactic Acid (PLA)

Lactic acid is produced through the microbial fermentation of starch or sugar from corn, potatoes and sugarcane, with lower manufacturing costs and higher yields, but can be obtained by chemical synthesis. Subsequently, it is transformed into polylactic acid by polycondensation [8]. This biopolymer has properties that can replace petrochemical polymers in packaging applications, including those in which there is contact with food, approved by the US Food and Drug Administration (FDA). Therefore, it can be used in films, trays, and packaging for that purpose [24,30,8]. In terms of its life cycle, PLA can be recycled, degraded, and metabolized naturally in soil in an aqueous environment. However, its degradation capacity is reduced [2]. Chemical recycling through catalysis is preferred and, in addition to the original monomer, can provide other products depending on the technique used. Composting under anaerobic conditions can show 90% degradation in a 60-day period [10]. With regard to greenhouse gas (GHG) emissions, there can be a 40% reduction and a 25% reduction in non-renewable energy use when compared to petrochemical derivatives [31,32].

1.4.2 Polyhydroxyalkanoates (PHAs)

Polyhydroxyalkanoate is a type of biopolymeric polyester similar to PLA, but with distinct physical properties due to its low glass transition temperature (-35 °C to 10 °C) [33] when compared to PLA [34]. They are obtained by sugar fermentation, collected directly from microorganisms without the need for isolating monomers that are synthesized by controlling the growth conditions of bacteria. This second-generation biopolymer has been intensively studied, with more than 150 types of monomers from this class of biopolymer being reported [35]. Its biosynthesis takes place in an environment with low concentrations of nitrogen, phosphorus, oxygen, and excess carbon [36]. Figure 3 shows the chemical structure of PHAs.

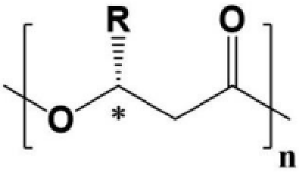
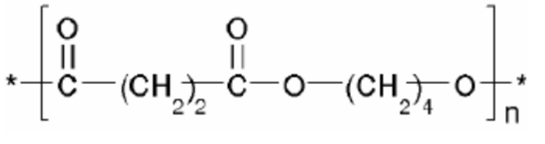


Figure 3. Chemical structure of PHAs [36]

PHAs are semicrystalline biopolymers with thermal properties that vary with the nature of the radical group present in the monomeric structure. Families of PHAs have distinct mechanical, thermal, biocompatibility, and biodegradability properties [37]. Polyhydroxybutanoate (PHB) is one of the most studied PHAs. It is used for food packaging and in medical applications such as tissue engineering [38] and in studies related to the development of PHB-based vaccines [39]. In degradation studies, it degraded by 90% through composting in 14 days in aqueous media, soil, and in industrial composting systems [2,10]. Despite being biopolymers still with low industrial scale production (up to 10,000 t/a), currently two companies stand out in the global market: Kaneca and Danimer [40].

1.4.3 Polybutylene Succinate (PBS)

This biopolymer, already available on an industrial scale, comes from glucose fermentation producing succinic acid with subsequent polycondensation of the bioderived 1.4-butanediol to obtain PBS, which can be degraded by microorganisms [41]. In general, this polymer is expensive and has few applications, as it has low mechanical properties. PBS films can have an elasticity modulus of up to 380 MPa and 15% elongation at break [42]. In order to circumvent those issues, some studies related to the application of those polymers to packaging consider mixing them with other stronger and cheaper polymers, such as PET and humic acid [42,43]. For packaging, it is used to promote a water vapor barrier and has recyclability [24]. Regarding degradation, in just 96 days, 3% of the material degraded in anaerobic medium and in aerobic media with enzymes. Significant degradation was observed in just 4 days [44,45]. Figure 4 shows the chemical structure of PBS. It is an aliphatic polyester.



$$*\!\left[\overset{\overset{\textstyle O}{\|}}{C}-(CH_2)_2-\overset{\overset{\textstyle O}{\|}}{C}-O-(CH_2)_4-O\right]_n\!*$$

Figure 4. Chemical structure of PBS [33]

1.4.4 Polyethylene Furonoate (PEF)

PEF, whose structure is shown in Figure 5, is a promising substitute for conventional polyethylene terephthalate (PET). Although it is not commercially available, its pilot-scale production is expected to grow in the coming years. This material is copolymerized by polycondensation of furanedicarboxylic acid (FDCA) and ethylene glycol, compounds that can be obtained from renewable sources of glucose and fructose. The resulting polymer is analogous to PET, with superior water vapor barrier characteristics and oxygen permeability. Due to its similarity to PET, the possible applications are the same [46,35]. It is important to emphasize that the structures for polymerization, oxidation, and recycling are also equivalent to those of PET, which may accelerate its development. But, due to the current low production scale, its cost is still high. A disadvantage of PET is its lack of degradation capacity due to the presence of aromatic esters. However, other points favor its sustainable development, such as the 55% reduction in GHG emissions when compared to the conventional analogue [47,48].

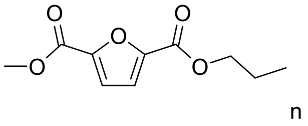


Figure 5. Chemical structure of PEF

1.4.5 Cellulosic Materials

Cellulose is known as one of the first polymers to be commercially used in packaging. Cellophane and cellulose acetate, whose structure is shown in Figure 6, have been available since the early 20th century. However, these materials have limited use in packaging [24]. Cellophane is a thin, transparent film, obtained from cellulose and produced through the viscose process. Unfortunately, that process relies on hazardous material. As it is highly hydrophilic, it loses mechanical strength and water vapor barrier in the presence of moisture. They are easily degraded in aqueous media, in soil, and in industrial composting systems [35,2].

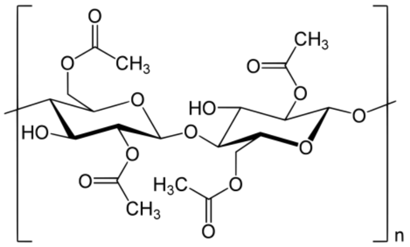


Figure 6. Chemical structure of cellulose acetate.

1.4.6 Bio PET

The production of this material involves starch degradation, glucose fermentation, ethanol dehydration, ethylene oxidation, and hydrolysis of the final product. Despite its complexity, this material can provide a 20%-25% reduction in GHG emissions when compared to the fossil-sourced PET equivalent [49,10]. They do not degrade in any type of medium, but are recyclable [2,35].

1.4.7 Bio PE

Bio PE is obtained from the dehydration of ethanol sourced exclusively from sugarcane. The polymerization of ethylene provides a polymer identical to the fossil-sourced equivalent [50]. This method is controversial, as it participates in a linear life cycle and potentially ends up in the regular trash or in the environment [10]. On the other hand, sugar bagasse waste can be used for energy generation at the processing plant. Due to its chemical equivalence and petrochemical type, the same applications have been identified for packaging, cables, fabrics, and automotive components [27]. Bio PE does not degrade in any type of medium, but is recyclable [2].

1.5 Sustainable Development

Sustainable development is defined as "development that meets the needs and aspirations of the present generation without compromising the ability of future generations to meet their own needs" [51]. Metrics for product and process development, such as the Life Cycle Assessment (LCA) approach, can be used to quantify sustainability performances. This technique is based on the quantification of energy and flow of the materials used in each stage of the production cycle [52,53]. Another technique that can be used is the *Green Design Metrics (GDM)*, which provides a more comprehensive assessment based on the principles of sustainable chemistry, summarized by the following topics: the use of renewable and local sources; atom economy; the use of less hazardous reagents and syntheses; lower waste generation; maximum energy efficiency; products designed for recycling and degradation; and cost efficiency [10]. Quantitative metrics for assessing environmental sustainability are not universally accepted as metrics for assessing economic sustainability, and more comprehensive models have been evolving. However, those approaches have been criticized for not sufficiently valuing social issues, demanding the need to include this topic in a social agenda to identify possible conflicts of interest [54]. For a qualitative assessment of the biopolymers presented in the current research, three sustainability criteria were evaluated during the literature review: 1) Sustainable packaging development [15], 2) Sustainable Development Goals [55], and 3) Circular Economy Criteria, consisting of the directives of the European Waste Commission 2008/98/CE [15] and the US Environmental Protection Agency [56].

Criterion 1 - Development of sustainable packaging

Sustainable Packaging Coalition (SPC) is an organization that seeks to give its members a voice in developing packaging that is good for the consumer and the environment, bringing together stakeholders to discuss issues related to packaging sustainability. Due to the focus on packaging in the present research, the criteria of this organization will be used for the analysis of biopolymer materials listed in this review. SPC uses the following approaches for the development of sustainable packaging:

A - It is beneficial, safe and healthy for individuals and communities throughout its life cycle;

B - It meets market criteria for performance and cost;

C - It is sourced, manufactured, transported, and recycled using renewable energy;

D - It optimizes the use of materials from renewable or recycled sources;

E - It is manufactured using clean production technologies and the best practices;

F - It is manufactured with healthy materials throughout its life cycle;

G - It is physically designed to optimize materials and energy;

H - It is effectively designed and used in close-loop biological and/or industrial cycles.

Criterion 2 - Sustainable Development Goals (SDG)

According to the 2015 report of the United Nations Organization, growing global awareness of sustainability is changing consumer preferences. In order to meet the 17 main goals detailed in another 168 objectives and 243 indicators, biopolymers enable a new economy vis-à-vis conventional polymers. The 2030 Agenda [55] was declared to meet the wishes of present-day society until 2030. The main objectives and indicators were analyzed together with the literature review, checking whether the biopolymer life cycle is positive, negative or does not interfere with the analyzed SDG.

Criterion 3 - Circular Economy

The *European Commission* [57] establishes a waste hierarchy with five basic levels in Directive 2008/98/EC: 1) prevention, 2) reuse, 3) recycling, 4) other recoveries, and 5) disposal. Similarly, the US Environmental Protection Agency (EPA) has a four-level waste management hierarchy: 1) source reduction or waste prevention (including reuse), 2) recycling (including composting), 3) combustion with energy recovery, and 4) landfill disposal [56]. The concepts of those two directives were unified to analyze the concept of circular economy globally with respect to the biopolymers presented. Therefore, in order of preference, the solid waste management criteria are:

a) reduction, ability to use less mass of material;

b) reuse, reutilization of collected material without changing its form;

c) mechanical recycling, using only mechanical processes;

d) chemical recycling, converting the material into monomer or basic chemical structure;

e) biological recycling (composting), degradation into CO_2 (or CH_4) and H_2O;

f) energy recovery, incineration of material for energy generation;

g) sanitary landfill, disposal in a regular landfill.

2. Discussion

The availability and costs of materials from renewable sources impact the feasibility in using those materials in packaging [17,58]. Other factors that hinder the analysis of sustainability in biopolymers are related to the diversity of resources used to obtain them when compared to fossil-sourced materials [59]. The competition with areas destined for food production is discussed in some forums, but it is controversial. According to IfBB's forecast for a production scenario of 3.108 Mt, in 2024 the allocation of land available for cultivation to meet this demand will be less than 0.2% [26]. Based on [60,61] reported that, for a production scenario of 300 Mt/year of PLA, only 0.9% of the 5 billion hectares of agricultural land available for the production of corn will be needed. Even so, the transition to obtain biopolymers from non-food sources is desired, such as the lignocellulosic biomass. Besides avoiding competition with the food chain, a reduction in biopolymers costs is expected, contributing to the achievement of the SDGs established by the UN [62,2]. Although Bio PET and Bio PE are contested for having the same monomer as the fossil source, the advantages are due to the life cycle being well established by the polyolefinic pairs in addition to the renewable provenance. Another consideration about the degradation difficulty of Bio PET and Bio PEF is due to the presence of aromatic esters. A recent study found a bacterium that can accelerate the degradation of those materials, enabling them for a sustainability scenario [63]. In general, chemical recycling of biopolymers is desirable because they provide the original functional group or another one, depending on the catalytic technique used, which makes reuse in their original form feasible. Although they contribute less to the environment, composting and energy recovery are alternative end-of-life routes for biopolymeric waste [10,35]. For the material reduction criterion, advances in production technologies must be achieved to enable them at a feasible cost. For the reuse and mechanical recycling criteria, waste management must be improved to the point where the type of biopolymer can be identified. Disposal in sanitary landfills, despite being the least desirable destination, does not cause extra risks, in addition to those already existing in this type of environment [8]. Among the advances found, catalysis is a technique that efficiently speeds up the obtaining process, with a cost lower than that of currently used processes. This technique can also be used in degradation by chemical or biological recycling. Many obtaining methods are available, but they are in the process of evolution with advantages and disadvantages to be considered in biopolymer design [10,35]. Figure 7 relates the renewability of raw material to the degradation capacity of the polymer. Materials in the upper-right quadrant in Figure 7 are desirable for packaging applications within the circular and sustainable economy.

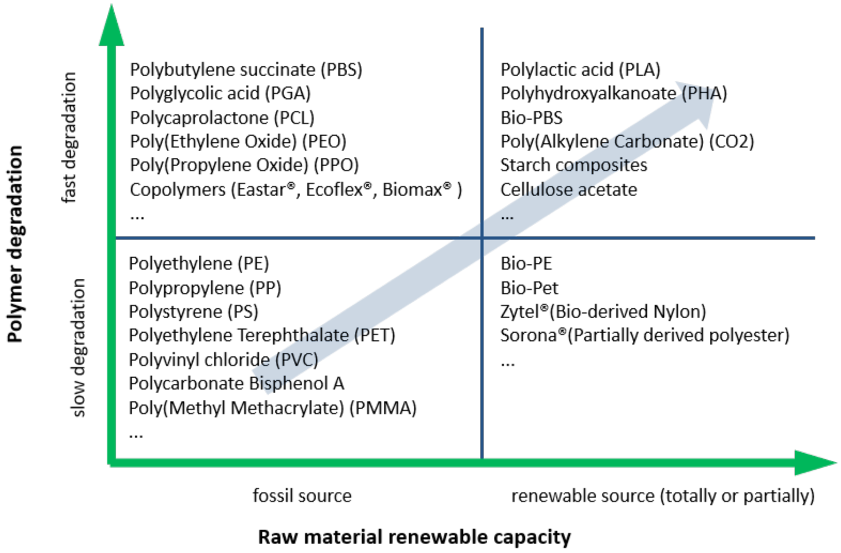


Figure 7. Classification of polymers based on raw material renewable capacity and polymer degradation [10]

In order to mitigate the negative effects of improper disposal, a biodegradable plastic is desired. The type of engineering required for this function is the transformation of the material - by microorganisms - essentially into CO_2 and H_2O, which is then converted into biomass through photosynthesis, completing the life cycle [10]. Some biopolymers such as PBS, PHB, and PLA can act as environmental remediators, that this, with the ability to remove contaminants from the soil through sorption and denitrification mechanisms. Biopolymers in contaminated systems act by absorbing contaminates or providing carbon and energy to microorganisms to facilitate denitrification [8].

2.1 Analysis of Criteria for Developing Sustainable Packaging

Among the economic factors, the low added value of packaging is one of the main barriers to the use of biopolymers for this application. Table 1 evidenced this difficulty, in the light of criterion "B") it meets market criteria for performance and cost, where the authors reported the high cost of those materials associated with technical performance issues.

Favorably, through more efficient processes, new methods of synthesis and reinforcement additions are enablers for use in packaging. Another barrier to make them even more sustainable is obtaining them from non-food sources, avoiding competition with this chain [35]. PEF presented many technical limitations, mainly in obtaining, production, and end of life. But it is a promising substitute for conventional PET. Cellulosic materials demand hazardous components for production in packaging applications that require low permeability, and are then penalized in item "F") it is manufactured with healthy materials throughout its life cycle. Bio PE and Bio PET enable polymers for packaging regarding cost and performance. An important consideration is that life cycles are relatively equivalent to the corresponding polyolefins (PE and PET), suggesting less sustainable materials as they are not biodegradable. Positively, in general, biopolymers meet most SPC criteria. But their disadvantages are: performance, cost, and waste recovery properties. Composites are being studied to improve these characteristics, including potential negative effects when in contact with food, such as migration and toxicity [35]. As can be seen, the criterion related to waste recovery, item H, was not fully met. This issue will be further discussed within the Circular Economy criteria.

2.2 Analysis of the UN Criteria - Sustainable Development Goals

This analysis brought to light the economic and social benefits for meeting the UN sustainability criteria. There was a gain in the promotion of small rural properties encouraged by the increased need for raw materials to obtain biopolymers. This increased demand can provide those rural properties with jobs, stimulate the use of new technologies, promote the development of sustainable agriculture, and create regulations that support small producers. Preferred agricultural products should be those that have better efficiency for obtaining biopolymers, such as corn, sugarcane, and potatoes [8]. Table 2 depicts the analysis of those biopolymers highlighted in the present research regarding the impact on each of the 17 Sustainable Development Goals monitored by the UN. In some goals, no benefit was observed due to the SDG premises, for example, political issues, gender inequality, and conflict between societies, Therefore, SDG's 1, 4, 5, 10, 16, and 17 were market as "not applicable" (na) in all analyzed materials.

Some biopolymers stood out with several published

Table 1. Qualitative evaluation according to SPC criteria

Materials	SPC Criteria								Authors
	A	B	C	D	E	F	G	H	
PLA	x	na*	x	x	x	x	x	x	[26]; [24]; [31]; [32]; [59]; [10]; [2]; [30]; [35]; [8]
PHB	x	na	x	x	x	x	x	x	[26]; [10]; [2]; [35]; [8]
PHA	x	na	x	x	x	x	x	x	[26]; [24]; [10]; [2]; [35]
PBS	x	x	x	x	x	x	x	na**	[26]; [44]; [2]; [8]
PEF	na	na	x	x	x	x	x	na**	[24]; [2]; [35]; [63]
Bio PET	na	x	x	x	x	x	x	na	[26]; [24]; [35]; [2]
Bio PE	na	x	x	x	x	x	x	na	[26]; [27]; [10]; [24]
Cellulosic	x	x	na	x	na	na	x	x	[26]; [24]; [2]; [35]

x - meets criterion

na - not applicable

*possible with reinforcement additions

**under specific conditions

Table 2. Quantitative assessment according to UN criteria, Sustainable Development Goals

Materials	UN criteria - Sustainable Development Goals																	Authors
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	
PLA	na	x	x	na	na	x	x	x	x	na	x	x	x	na	x	na	na	[26]; [24]; [31]; [32]; [59]; [10]; [2]; [30]; [35]; [8]
PHB	na	x	x	na	na	x	x	x	x	na	x	x	x	x	x	na	na	[26]; [10]; [2]; [35]; [8]
PHA	na	x	x	na	na	x	x	x	x	na	x	x	x	x	x	na	na	[26]; [24]; [10]; [2]; [35]
PBS	na	x	x	na	na	x	x	x	x	na	x	x	x	na*	x	na	na	[26]; [44]; [2]; [8]
PEF	na	x	x	na	na	x	x	x	x	na	x	x	x	na*	x	na	na	[24]; [2]; [35]; [63]
Bio PET	na	x	x	na	na	x	na	x	x	na	x	na	x	na*	x	na	na	[26]; [24]; [35]; [2]
Bio PE	na	x	x	na	na	x	na	x	x	na	x	na	x	na	x	na	na	[26]; [27]; [10]; [24]
Cellulosic	na	x	x	na	na	x	x	x	x	na	x	na	x	x	x	na	na	[26]; [24]; [2]; [35]

x - meets criterion

na - not applicable

*possible with reinforcement additions

**under specific conditions

researches and advances in industrial scale. In order of relevance in the SDG analysis, they are: PHB, PHA, PLA, and PBS. In general, biopolymers presented a 14% impact on all 243 indicators, as shown in Figure 8, which summarizes the impact analysis on indicators by the SDG.

The three best rated objectives by their targets and indicators were: 2) End hunger, achieve food security, improve nutrition, and promote sustainable agriculture; 9) Build resilient infrastructures, promote inclusive and sustainable industrialization, and foster innovation; and 12) Ensure sustainable production and consumption patterns. Biopolymers meet the demands of the indicators of those objectives with 57% for SDG-2, 41.7% for SDG-9, and 61.5% for SDG-12.

2.3 Analysis of Circular Economy Criteria

Table 3 summarizes the impacts of biopolymers on the circular economy, with few studies showing the end of cycle of those materials. In the present review, with emphasis on criteria related to recycling - whether mechanical, chemical, or composting -, biopolymers showed limitations or early stages for PLA, PHB, PHA, PBS, and PEF. Due to the nature of those materials, the current recycling technologies do not fully qualify biopolymers for this important circular economy criterion. This little progress reveals the need to develop regulations for waste disposal, which are still in their early stages.

Bio PET and Bio PE already qualify for recycling systems due to their equivalence to current processes. They can be recycled in the same way as their polyolefin counterparts. On the other hand, composting and energy recovery are hampered for the same reason.

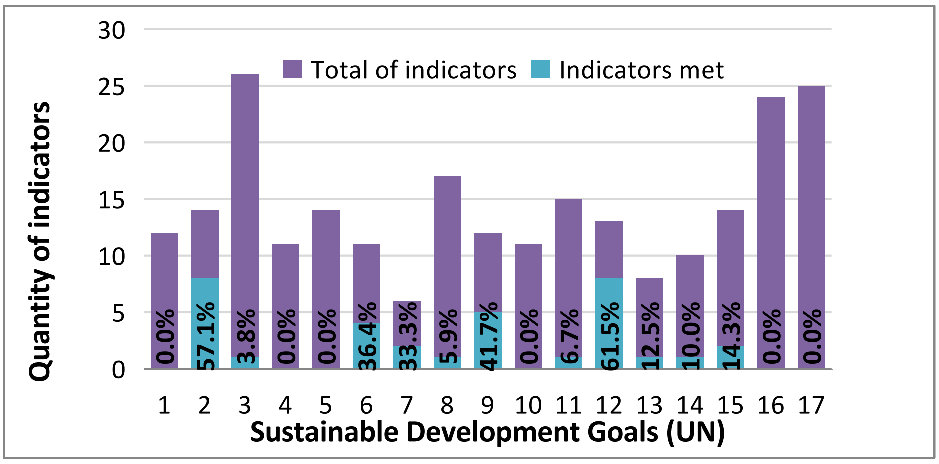


Figure 8. Number of SFG indicators x Indicators met by biopolymers (%)

Table 3. Qualitative evaluation according to Circular Economy criteria

Materials	Circular Economy Criteria							Authors
	a	b	C	d	e	f	g	
PLA	na*	x	na	x	na**	x	x	[26]; [24]; [31]; [32]; [59]; [10]; [2]; [30]; [35]; [8]
PHB	na*	x	na	x	x	x	x	[26]; [10]; [2];[35]; [8]
PHA	na*	x	na	x	x	x	x	[26]; [24]; [10]; [2]; [35]
PBS	na*	x	na	x	na**	x	x	[26]; [44]; [2]; [8]
PEF	x	x	x	x	na**	x	x	[24]; [2]; [35]; [63]
Bio PET	x	x	x	x	na**	na	x	[26]; [24]; [35];[2]
Bio PE	x	x	x	x		na	x	[26]; [27]; [10]; [24]
Cellulosic	na	na	x	x	x	x	x	[26]; [24]; [2]; [35]

x - meets criterion

na - not applicable

*possible with reinforcement additions

**under specific conditions

Source: the author (2019).

3. Conclusions

Although studies comparing biopolymers and conventional polymers are in their early stages, there is sufficient research favoring them. The main opportunities lie in evaluations of human health impacts when used in food-packaging. Specific conditions of degradation, composting, and recycling have been studied mainly using catalysts to promote these characteristics. But there is a vast field to be investigated, considering that technologies still present an initial maturity curve when compared to technologies and processes used to obtain petrochemical-based polymers. However, technical maturity and commercial reach should be attained soon. What became clear in the present study is the need to gain production scale. This way, the costs of processes in this new economy will become feasible for the use of biopolymers in packaging. Apart from the environmental aspects, economic and social gains were observed in the analysis of the SDG criteria, such as the promotion of jobs in small rural properties. In response to the research question, biopolymers depend on development and advances in specific areas to have reach as packaging materials, and scale gains should be the biggest enabler. It is important to emphasize that advances in regulations for polymer waste disposal must be urgently established if there is to be success in using this material to replace conventional polymers.

Conflict of Interest

There is no conflict of interest.

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