https://doi.org/10.48047/AFJBS.6.Si4.2024.4588-4608

African Journal of Biological Sciences

Journal homepage: http://www.afjbs.com

Research Paper Open Access

The use of biopolymers in the agroindustry, from corn-based plant material

Carlos Jácome Pilco [1], Universidad Estatal de Bolívar 0009-0008-2092-9577
Ana Pacheco Segura [2], Universidad Estatal de Bolívar 0009-0002-2179-6506
Danna Díaz Aranda [3] Universidad Estatal de Bolívar 0009-0007-2141-7672

SUMMARY

Corn, a vital crop native to the Americas, plays an essential role in global nutrition, animal feed, and various industrial applications, including the production of biopolymers. This cereal, noted for its high content of starch, proteins, oils and nutrients, has positioned itself as a key raw material for the development of biodegradable and renewable materials. The transformation of corn into biopolymers responds to the growing demand for sustainable alternatives to petroleum-based plastics, focusing on minimizing environmental impact and encouraging eco-friendly practices in the industry.

Research and development in this area seeks to overcome challenges related to the production, material properties and economic viability of corn biopolymers, with the aim of offering products with mechanical and barrier properties similar to those of conventional plastics, but with the advantage of being biodegradable. The processes involved in obtaining these biopolymers include starch extraction, microbial fermentation and chemical polymerization, underlining the importance of technological innovation for the sustainable use of corn.

The implementation of corn-derived biopolymers in agribusiness promises significant environmental benefits, such as reducing the carbon footprint and improving waste management, marking a step towards sustainability and the circular economy. However, to achieve wider adoption, it is crucial to address the current technical and economic challenges, thereby promoting a future where renewable and sustainable materials play a central role in the industry and contribute to a more environmentally friendly environment.

Keywords: biopolymers, agribusiness, maize plant matter, sustainability, biodegradable packaging, processing technologies.

Article History

Volume 6, Issue Si4, 2024

Received: 1 July 2024

Accepted: 20 July 2024

Doi:

10.48047/AFJBS.6.Si4.2024.4588-4608

ABSTRACT

Corn, a vital crop native to the Americas, plays an essential role in global nutrition, animal feed and various industrial applications, including the production of biopolymers. This cereal, noted for its

high content of starch, proteins, oils and nutrients, has positioned itself as a key raw material for the development of biodegradable and renewable materials. The transformation of corn into biopolymers responds to the growing demand for sustainable alternatives to petroleum-derived plastics, focusing on minimizing environmental impact and promoting ecological practices in the industry. Research and development in this area seeks to overcome challenges related to the production, material properties and economic viability of corn biopolymers, with the aim of offering products with mechanical and barrier properties similar to those of conventional plastics, but with the advantage of being biodegradable. The processes involved in obtaining these biopolymers include starch extraction, microbial fermentation and chemical polymerization, underlining the importance of technological innovation for the sustainable use of corn. The implementation of biopolymers derived from corn in agribusiness promises significant environmental benefits, such as reducing the carbon footprint and improving waste management, marking a step towards sustainability and the circular economy. However, to achieve broader adoption, it is crucial to address the current technical and economic challenges, thus promoting a future where renewable and sustainable materials play a central role in the industry and contribute to a more environmentally friendly environment.
Key words: biopolymers, agroindustry, corn plant material, sustainability, biodegradable packaging, processing technologies.

1. INTRODUCTION

Corn is a cereal native to America that has become one of the most important crops worldwide, both for its versatility and its nutritional value (Naranjo, 2020). It is essential in the diet of millions of people and in animal feed, as well as having industrial applications, such as in the production of ethanol, starch and oil. Its importance lies not only in its contribution to food security but also in its economic role for farmers and as a raw material in various industries (Huamán et al., 2021).

In terms of its composition, corn is rich in carbohydrates, mainly starch, which makes it an essential energy source. It also contains protein, oils, and fiber, along with vitamins and minerals, which contributes to its nutritional value (Gutiérrez & Ávila, 2024). This composition makes it ideal for the construction of biopolymers, taking advantage of starch and other components to create biodegradable and sustainable materials. Research and development in this field seeks alternatives to conventional plastics, reducing dependence on fossil sources and minimizing environmental impact, marking a step forward towards greener practices in various industries (Mendoza &Riera, 2022).

Growing concerns about environmental sustainability and the need to reduce reliance on petroleum-based plastics have driven the search for biodegradable and renewable alternatives (Gutiérrez & Ávila, 2024). In this context, the use of biopolymers produced from plant matter, such as corn, emerges as a promising solution, not only to mitigate adverse environmental impacts but also to foster the bioeconomy in the agro-industrial sector (Molina & Flórez, 2020). However, the development and implementation of corn-based biopolymers face significant challenges, including optimizing their production methods, economic viability,

and material yield compared to conventional plastics (Huamán et al., 2021).
Biopolymer process methods from corn focus on the use of its natural components, such as starch, to generate biodegradable polymers through processes that include microbial fermentation and chemical polymerization (Angamarca & Delgado, 2022). These methods seek not only to efficiently exploit the intrinsic properties of corn but also to improve the functionality and applicability of the resulting biopolymers in various agro-industrial applications (Mendoza &Riera, 2022).
The results obtained to date suggest that corn-derived biopolymers can offer similar mechanical and barrier properties to traditional plastics in certain applications, in addition to their advantage in terms of biodegradability and renewable origin. However, research continues to overcome limitations such as moisture sensitivity and variability in the quality of the final product (Ugsiña et al., 2021a).
From a future perspective, the development of biopolymers from corn represents an opportunity to move towards more sustainable production systems, reducing the carbon footprint of agribusiness and promoting the use of renewable resources (Alucho et al., 2021). Innovation in production processes and improving the properties of biopolymers are key to their adoption on a larger scale (Guerberoff&Londero, 2022).
The aim of this article is to provide a comprehensive overview of the current status and future prospects of the use of corn-derived biopolymers in agribusiness, highlighting advances in production methods, results obtained and remaining challenges (Rendón, 2021). In doing so, we seek to contribute to the dialogue on the transition to more sustainable practices in agribusiness and the importance of innovation in the development of new biodegradable materials.
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2. Corn as an input for the production of Biopolymers

Using native corn as the basis for the generation of biopolymers in agribusiness, we chose this variety for its excellent adaptation to the local environment and its ability to resist diseases, which supports genetic diversity and the maintenance of ancestral seeds (Fernández et al., 2022). Amylolytic enzymes from natural sources, from endemic microorganisms, were used in production, which made it possible to reduce the use of foreign chemical substances and highlight the importance of local biodiversity for a greener manufacture of biopolymers (Ojeda, 2023). We innovate with the creation of economical and efficient glass reactors, specifically designed for controlled starch fermentation, thus facilitating the expansion of the method and its implementation in low-resource areas (Pinilla et al., 2019).
We adopt circular economy principles, reincorporating agricultural by-products and organic waste into the biopolymer production cycle, minimizing waste and optimizing the use of resources towards a greener business model (Martínez, 2021). Innovations in the process included fermentation at lower than usual temperatures, which resulted in lower energy demand and prevented thermal degradation of biopolymers, preserving their qualities (Aráuz, 2020). We used advanced characterization techniques, such as scanning electron microscopy and near-infrared spectroscopy, to analyze the morphology and composition of biopolymers, which gave us a detailed view of their structure and application potential (Pina et al., 2021). This holistic approach to the manufacture of biopolymers from corn underscores the relevance of regional agriculture and technological advancement in promoting sustainable practices in agribusiness, opening promising paths for future research and applications (Angamarca& Delgado, 2022).
The characteristics of maize: physical and chemical composition
Corn, also known as Zea mays, is one of the most important cereals worldwide due to its versatility and nutritional value. Its physical and chemical composition makes it suitable for a wide range of applications, from human and animal feed to the production of bioplastics and bioethanol. The physical and chemical composition of corn is detailed below:

Physical Composition:

- **Grains:** Corn comes in the form of grains that are the fruits of the plant. These grains have a structure that includes the pericarp (the outer covering), the endosperm (the main source of starches and proteins), and the germ (rich in oils and nutrients).
- **Color and Size:** The beans can range in color from yellow and white to red and purple, depending on the variety. The size and shape also vary, although they are typically oblong and flattened.

Chemical Composition:

- **Carbohydrates:** Corn is mainly known for its high starch content, which accounts for about 70-80% of the dry weight of the grain. It also contains a small amount of fiber.
- **Protein:** Corn kernel has a protein content of about 10%, although it is not a complete protein, as it has low levels of some essential amino acids such as lysine and tryptophan.
- **Fats:** Corn contains about 4-5% fat, concentrated mainly in the germ of the grain. Most of these fats are unsaturated, with linoleic acid as the main fatty acid.
- **Vitamins and Minerals:** It is a good source of several B vitamins, especially niacin and folic acid. It also contains vitamin E and minerals such as phosphorus, magnesium, zinc, copper, and iron.
- **Phenolic Compounds and Antioxidants:** Corn kernels, especially dark-colored varieties, are rich in phenolic compounds, which have antioxidant properties.
- **Water:** The water content in fresh corn can be significant, but it decreases considerably once the grain dries out (Pérez et al., 2023).

The components of corn for plastics

1. **Starch:** Corn starch is the main component used in the production of biodegradable plastics. It is extracted from the endosperm of the corn kernel and processed to produce polymers such as polylactic acid (PLA).
2. **Polylactic Acid (PLA):** Through a process of fermentation and polymerization of corn starch, PLA is obtained. This biopolymer is one of the most widely used to manufacture biodegradable plastics due to its characteristics similar to traditional plastics such as polystyrene or polyethylene terephthalate (PET).
3. **Corn Oils:** Oils derived from corn germ can be chemically transformed to produce plasticizers or can be used as monomers for the synthesis of other polymers.
4. **Corn Fibers:** Although not as common, corn fibers can be used as reinforcement in plastic compounds to improve their mechanical properties.
5. **Fermentation Products:** In addition to lactic acid, the fermentation of corn starch can produce other products such as ethanol, which in turn can be converted into ethylene and polymerized to form biodegradable polyethylene.
6. **Glycerol Products:** Glycerol, which can be derived from corn oils, is used as a plasticizer or as a monomer for the production of polymers.

These components allow corn products to be a renewable source for the creation of a variety of plastics with various applications, from packaging to consumer products and beyond. In addition, the use of corn for the production of plastics has the added benefit of being biodegradable under appropriate conditions, which contributes to the reduction of plastic pollution and more sustainable waste management (Ugsiña et al., 2021).

Board 1.

Hypothetical table showing different varieties of maize categorized according to their starch content.

Variety of Corn	Description	Starch Content (%)	Typical Use
Dented Corn	Grain with a depression at the top, typically yellow.	70-72%	Animal feed, ethanol production, and dry milling for human food.
Waxy Corn	It contains almost exclusively amylopectin, which gives it a waxy texture.	75-78%	Food industry, especially in the production of sauces and as a thickener.
Sweet corn	Known for its sweet taste and high sugar content, low in starch.	28-32%	Direct human consumption, preserves, and frozen.
Floury Corn	Soft and white grain, rich in starch with a high proportion of amylose.	80-85%	Bakery, production of modified starch, and industrial products.
Blue Corn	Variety with dark blue grains, high in antioxidants and starch.	68-70%	Human food, bakery products, and as a natural colorant in food.
Purple Corn	Similar to blue corn, with purple-hued kernels and high anthocyanin content.	65-70%	Snacks, bakery products and nutritional supplements.

Note: The percentages indicated are approximate and may vary depending on the specific conditions of each crop. In addition, the starch content in corn can be influenced by the maturity of the grain at harvest time and by the drying process. The applications mentioned are just some of the typical uses of these varieties and do not represent an exhaustive list.

Fountain: (Angamarca& Delgado, 2022).

Board 2

Production of Biopolymers from Corn.

Biopolymer	Quantity produced (kg per ton of corn)
Polylactic acid (PLA)	200 - 250
Bioplastics	150 - 200
Bioethanol	400 - 500
Polyhydroxyalkanoates (PHAs)	50 - 100

Note: The amounts listed in the table are approximate and may vary depending on multiple factors, including the processing technology used, the genetics of the corn, the environmental conditions during crop growth, and agricultural practices. In addition, the process of converting corn into biopolymers also involves considerations about the sustainability and environmental impact of the entire production chain, from the field to the final product. It is crucial to continue researching and developing methods that maximize efficiency and minimize environmental impact to make this a truly sustainable option in the long term.

Fountain: (Angamarca& Delgado, 2022).

3. BIOPOLYMERS

According to Angamarca& Delgado, (2022), the evolution of polymers, from the first moldable materials such as Parkesin to modern highly durable resins such as Bakelite, reflects continuous human innovation in the creation of versatile materials (Patiño, 2020). This landmark development shows us how humanity has advanced in the creation of increasingly adaptive materials, culminating in the revolutionary understanding of polymers in the 20th century as extensive chains of macromolecules. Today, polymers are classified into several categories, such as thermoplastics, fibers, thermosets, and elastomers, each with specific properties and applications that make them essential in various industries.

Within this spectrum, biopolymers emerge as a special category, composed of long chains of monomers that can be extracted from natural sources or synthesized from biological feedstocks. Produced mostly by living beings or through chemical processes that use renewable resources, these materials offer a sustainable and ecological alternative to conventional polymers. With properties such as biodegradability and non-toxicity, biopolymers present themselves as ideal solutions to environmental challenges, especially in sectors such as health, food, electronics, energy and, significantly, in agribusiness (Secundino, 2022).

Agribusiness, in particular, benefits from the use of biopolymers derived from plant materials such as corn, leveraging their ability to develop sustainable packaging, innovative agricultural products, and environmentally friendly conservation solutions (Cornejo et al., 2020). The classification of these biopolymers varies according to their origin, structure and response to heat, ranging from natural polymers extracted from plants and proteins to those chemically synthesized to optimize specific characteristics (Jaramillo et al., 2019).

Starch is a polysaccharide composed of two types of molecules: amylose and amylopectin, which are arranged differently and give starch its unique properties.

1. **Amylose**: It is a linear molecule made up of glucose units linked together mainly by α-1,4 glycosidic bonds. Amylose accounts for approximately 20-30% of the total starch in most plants. Its linear structure tends to form helices, and this ability to form helical structures allows for the inclusion of molecules such as lipids and iodine, which is the basis for some starch identification tests (Rivera et al., 2020).
2. **Amylopectin**: It is a highly branched molecule, which makes up 70-80% of starch. It is composed of glucose chains linked by α-1,4 glycosidic bonds, with branching points occurring approximately every 24 to 30 glucose units via α-1,6 glycosidic bonds. Amylopectin is responsible for the insoluble nature of starch and plays a crucial role in the gelatinization of starch during water heating (Rivera et al., 2020).

The figure you have provided outlines the classification of biopolymers according to different criteria, which reflect the diversity and complexity of these materials. Biopolymers are an important class of polymers that are biodegradable and come from renewable sources. They are derived from natural resources and are instrumental in creating sustainable products. They are classified according to their biodegradability, base of origin, polymer structure, representative unit and heat response function. This classification helps us better understand how these materials can be used in various applications, from packaging to biomedical components.

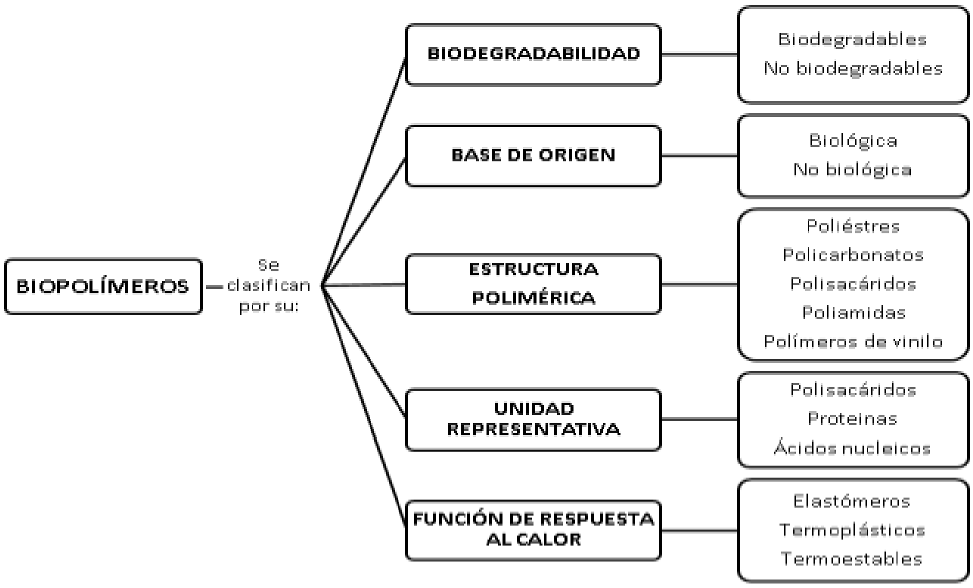

Figure 1. *Role and effects of iron on food quality and safety*. In the original Spanish language Fountain: (Gutiérrez et al., 2023).

Classification begins with biodegradability, distinguishing between biodegradable and non-biodegradable biopolymers. Depending on their origin, they can be biologically or non-biologically based. The polymer structure is divided into several categories, including polyesters, polycarbonates, polysaccharides, polyamides, and vinyl polymers. The representative unit refers to the monomers that make up the polymer, such as polysaccharides, proteins, and nucleic acids. Finally, the heat response function classifies biopolymers into elastomers, thermoplastics, and thermosets, which determines how materials behave at different temperatures.

According to López, (2023), biopolymers emerge as sustainable alternatives to conventional plastics, derived from renewable sources and standing out for their biodegradability (Moreira & Barcia, 2024). These materials are researched for varied applications, including the packaging and biomedical industries, seeking to overcome cost and scalability challenges through collaboration between science and industry (López et al., 2023). Compared to synthetic polymers, biopolymers, produced from plants, offer advantages in sustainability, carbon neutral potential and reduced CO2 emissions (López et al., 2023). Its biodegradability contributes to more efficient waste management, decomposing into CO2 and water, and favors circular economy practices, including the reduction of microplastic pollution.

The biodegradability of biopolymers must adhere to international standards, ensuring their effective decomposition in suitable environments (García, 2022). In the agro-industrial sector, citrus waste, rich in cellulose and pectin, is researched for the production of polyhydroxyalkanoates (PHAs), highlighting the use of orange peels through biotechnological techniques to transform waste into valuable resources and promote the circular economy (Hernández, 2020). The optimization of the production of PHAs from citrus residues is based on adjusting fermentation conditions and developing efficient methods for the extraction of the biopolymer, underlining the role of biotechnology in promoting sustainable practices (Fernández & García, 2021).

4. Processes for obtaining biopolymers from corn

Obtaining biopolymers from corn involves several key processes that transform starch, the main component of corn, into polymeric materials with industrial and commercial applications. These processes can be summarized in the following main stages:

1. **Starch extraction**: The first step is to separate the starch from the corn kernels. This is accomplished through a process that includes wet milling, where corn kernels are soaked to soften them and then ground to release starch from the grain's other fractions, such as gluten and fiber (Angamarca& Delgado, 2022).
2. **Liquefaction**: The extracted starch undergoes a liquefaction process, where it is mixed with water and specific enzymes (usually α-amylases) and heated. This step breaks down starch molecules into shorter chains of sugars, facilitating their subsequent fermentation or polymerization (Angamarca& Delgado, 2022).
3. **Saccharification**: After liquefaction, starch undergoes saccharification, a process that converts short chains of sugars into glucose by adding saccharifying enzymes (such as glucoamylase). This step is crucial to producing a fermentable monomer (Angamarca & Delgado, 2022).
4. **Fermentation**: The glucose obtained is then fermented by specific microorganisms (such as bacteria or yeast) that produce biopolymers. Depending on the microorganism and fermentation conditions (pH, temperature, nutrients), different types of biopolymers can be obtained, such as polylactic acid (PLA) or polyhydroxyalkanoates (PHAs) (Angamarca& Delgado, 2022).
5. **Polymerization**: In some cases, glucose or fermentation products can be chemically polymerized to form biopolymers. For example, polylactic acid is produced by the polymerization of lactic acid, which in turn is obtained from the fermentation of glucose (Angamarca& Delgado, 2022).
6. **Purification and modification**: The resulting biopolymers are purified to remove impurities and can be chemically modified or mixed with other additives to improve their physical, mechanical or degradability properties. This step is critical to tailor biopolymers to specific applications (Angamarca& Delgado, 2022).
7. **Forming**: Finally, biopolymers are processed into final products through different forming techniques, such as extrusion, injection molding, or blow molding. These products can range from biodegradable packaging to components for the automotive industry or medical devices (Angamarca& Delgado, 2022).

These processes show how corn, a renewable raw material, can be transformed into sustainable biopolymers, highlighting the importance of technological innovation and sustainable development in the materials industry (Angamarca& Delgado, 2022).

5. Biopolymer characterization

According to Salazar, (2022), in the outstanding research they have explored the conversion of residues from different crops, such as sugarcane, cassava, corn, cocoa, potato peels, and rice straw, into biopolymers (Restan et al., 2023). Although these biodegradable materials currently make up only a small fraction of the global polymer market, their sustained growth suggests a future in which they could effectively replace petroleum-based polymers. The improvement in biodegradability and compliance with technical specifications, including physical-chemical and mechanical properties, positions biopolymers as outstanding innovations with the potential to revolutionize the market.

In addition, lignocellulosic biomass represents a rich source of materials for the production of biopolymers, composed of a complex matrix of polysaccharides (cellulose and hemicellulose), phenolic polymers (lignin), and other components (Burgos &Sablón, 2022). Classified according to its origin into residual waste, virgin biomass and energy crops, this biomass offers a diversity of raw materials for the production of biofuels and other bio-based products (Azurduy&Azurduy, 2023).

In the context of agribusiness and the use of biopolymers derived from corn waste, this approach underscores a comprehensive strategy for waste management, promoting environmental sustainability and resource efficiency. The transformation of agricultural waste into biopolymers not only relieves pressure on landfills, but also offers renewable alternatives to conventional plastics, aligning with the objectives of reducing the carbon footprint and promoting a circular economy. This vision of integrated use of agricultural resources for the production of innovative and sustainable materials reflects a move towards more responsible and environmentally conscious practices in agribusiness (Velásquez et al., 2023).

Types of biopolymers

Biopolymers are macromolecules produced by living organisms. There are several types of biopolymers that are mainly classified according to their origin and chemical structure. Here is a description of the main types of biopolymers:

1. **Polysaccharides:** These are biopolymers composed of long chains of monosaccharides (sugars). Examples include:
    - **Cellulose:** The most abundant biopolymer in nature, the main constituent of the cell wall of plants.
    - **Starch:** An energy storage polysaccharide in plants.
    - **Chitin:** Found in the exoskeletons of crustaceans and insects.
    - **Hemicellulose:** Present together with cellulose in plant cell walls.
    - **Pectin:** Used in the food industry as a gelling agent.
2. **Proteins and Polypeptides:** They are biopolymers formed by the polymerization of amino acids. Examples include:
    - **Enzymes:** Proteins that catalyze biochemical reactions.
    - **Structural:** Such as collagen and elastin, which are part of connective tissues.
    - **Transport:** Hemoglobin, which carries oxygen in the blood.
3. **Nucleic Acids:** They are biopolymers that form the genomes of living organisms. Include:
    - **DNA (Deoxyribonucleic Acid):** Stores genetic information in cells.
    - **RNA (Ribonucleic Acid):** It plays several roles in the encoding, decoding, regulation, and expression of genes.
4. **Polyhydroxyalkanoates (PHAs):** These are polyesters produced in nature by the bacterial fermentation of sugars or lipids.
5. **Polylactic Acid (PLA):** It is a bioplastic derived from renewable resources such as corn starch, sugar cane or tapioca.
6. **Synthetic Biopolymers:** Although they are industrially produced, they are based on biological monomers. Examples include:
    - **Lactic acid polymers:** Used in medical applications and as packaging.
    - **Glycolic acid polymers:** Such as PGA, used in absorbable sutures.
7. **Biopolymers of Microbial Origin:** Such as xanthan and pullulan, used in the food and pharmaceutical industry.
8. **Alginates and Carrageenans:** Extracted from algae, they are used as thickeners and stabilizers in food (Pertuz, 2019).

Structure or constitution

Biopolymers have structures or constitutions that are determined by the type and sequence of their monomers, as well as the way these monomers bind to each other. The structure or constitution of the main types of biopolymers is described below:

1. **Polysaccharides:**

- **Cellulose:** Formed by glucose units linked by beta-1,4-glycosidic bonds, which confers a linear structure and the ability to form strong fibers due to hydrogenation between adjacent chains.
- **Starch:** Composed of amylose, which is linear, and amylopectin, which is branched. Amylose is made up of glucose units linked by alpha-1,4-glycosidic bonds, and amylopectin has branching points with alpha-1,6-glycosidic bonds.

2. **Proteins and Polypeptides:**
    - Proteins are made up of linear chains of amino acids linked by peptide bonds (bonds between the carboxyl group of one amino acid and the amino group of the next). The amino acid sequence (primary) determines the spatial conformation (secondary, tertiary, and quaternary) of the protein, which is crucial to its function.
3. **Nucleic Acids:**
    - **DNA:** Two polynucleotide chains in the form of a double helix with complementary base pairs (adenine with thymine and cytosine with guanine) linked by hydrogen bonds.
    - **RNA:** A single strand of polynucleotides that can take on various structural forms and participate in different functions within the cell.
4. **Polyhydroxyalkanoates (PHAs):**
    - They are linear polyesters with hydroxyl groups in each monomer that can form ester bonds with other monomers. The polymer chain can have various lengths and degrees of branching.
5. **Polylactic Acid (PLA):**
    - PLA is a thermoplastic aliphatic polyester formed by the polymerization of lactic acid. The structure can be mainly amorphous or semicrystalline, depending on the degree of polymerization and molecular orientation.
6. **Synthetic Biopolymers:**
    - Although they are based on biological monomers, their structure can be designed to mimic conventional polymers or to have unique properties. The specific chemical constitution and molecular structure will be determined by the synthesis process used.
7. **Biopolymers of Microbial Origin:**
    - For example, xanthan is a polysaccharide secreted by bacteria that consists of a glucose backbone with trisaccharide branches. Its structure allows it to dissolve in water forming a viscous gel.
8. **Alginates and Carrageenans:**
    - Alginates are linear polymers that contain blocks of manuronic and guluronic acid, which gives them the ability to form gels in the presence of cations. Carrageenans have linear structures with alternating galactose and 3,6-anhydrogalactose units (Montoya et al., 2021).
    - User

Raw materials for biopolymer processing

Raw materials for biopolymer processing generally come from renewable sources, including agricultural resources, industrial by-products, and microbial resources. Here are some examples of commonly used raw materials:

1. **Agricultural Resources:**
    - **Starch:** Derived from crops such as corn, potato, wheat, and tapioca.
    - **Sugars:** Obtained from sugar cane, sugar beet and fruits.
    - **Vegetable Oils:** Such as soybean, sunflower, palm and castor oil.

  - **Vegetable Proteins:** From soy, wheat and corn.
  - **Cellulose:** From wood, cotton, and other sources of plant biomass.
  - **Lignina:** By-product of the paper industry and biorefinery processes.
2. **Industrial by-products:**
  - **Glycerol:** By-product of biodiesel production.
  - **Lactic Acid:** It can be produced by fermentation of by-products of the sugar industry.
  - **By-products of the Food Industry:** Such as sugarcane bagasse, corn residues, cocoa husks and other organic waste.
3. **Microbial Resources:**
  - **Bacteria:** Some bacteria produce polymers such as polyhydroxyalkanoates (PHAs) from the fermentation of sugars or oils.
  - **Yeasts and Fungi:** Capable of converting organic substrates into polysaccharides such as chitosan and pullulan.
4. **Algae and Aquatic Resources:**
  - **Algae:** Source of polysaccharides such as alginate and carrageenan.
  - **Microalgae:** They can produce both PHAs and oils that serve as precursors for biopolymers.
5. **Lignocellulosic Biomasses:**
  - **Wheat and Rice Straw:** Rich in cellulose and hemicellulose.
  - **Bamboo and Other Grasses:** Source of cellulose and other polysaccharides.
  - **Forest Residues:** Such as branches, bark and sawdust.
6. **Energy Crops:**
  - **Miscanthus and Switchgrass:** Plants with high biomass yield, suitable for the extraction of biopolymers.

These raw materials are selected based on their availability, cost, chemical composition and suitability for specific biopolymer production processes. The sustainability of biopolymer production also depends on the responsible management of these raw materials, ensuring that their use does not compete with food resources and that their cultivation and processing minimise environmental impact (Pulido & Fierro, 2022).

Whey is a liquid by-product that is obtained during the manufacture of cheese and casein. Although whey itself is not derived from corn, there is an interesting connection between the two in the agri-food industry, especially in terms of biotechnology and biopolymer production (Párraga& Chávez, 2020).

Whey contains lactose, whey proteins, vitamins and minerals, and has traditionally been used as an additive in animal feed or in the production of foods such as beverages and dietary supplements. However, with the advancement of technology, it is now possible to use whey as a raw material in biotechnological processes to generate value-added products, and this is where corn comes into play (Párraga& Chávez, 2020).

Microorganisms used in fermentation processes can consume the sugars present in whey, such as lactose, to produce various biopolymers. However, lactose is not the only substrate that these microorganisms can use; Some can be fed with glucose derived from corn, which is often cheaper and more energy efficient. Fermentation can be carried out using corn-derived sugars as a substrate to increase yield and process efficiency (Coca &Galvis, 2023).

In some integrated processes, whey can be treated with enzymes that hydrolyze lactose into glucose and galactose, and glucose can then be used to fuel the production of biopolymers. At this intersection, corn provides an additional source of glucose or may enhance the fermentation process by providing nutrients necessary for the growth of microorganisms (Coca &Galvis, 2023).

In addition, corn can be used to create culture media in bioprocesses that convert whey into products such as polylactic acid (PLA), polyhydroxyalkanoates (PHAs), and other biopolymers. The combined use of whey and corn derivatives can optimize the production of biopolymers, making it more cost-effective and sustainable (Cepeda, 2021).
In summary, although whey does not come from corn, there is a functional relationship when it comes to biotechnological applications. Corn, as a source of sugars and nutrients, can play a crucial role in harnessing whey for the production of biopolymers and other biorefinery products (Cepeda, 2021).

6. From corn

Cellulose, made up of millions of units of D-glucose linked by glycosidic β-(1-4) bonds, emerges as the most profuse and accessible organic polymer on Earth, playing an essential role in the structure of a vast range of vegetation, algae and oomycetes. Historically, wood and cotton have been the primary sources of cellulose, mainly benefiting the textile, paper and pharmaceutical industries (Patiño, 2020). However, the growing demand for these sources has motivated the search for sustainable alternatives, such as agricultural crops and non-woody plants, to diversify pulp production without negatively affecting the environment or the availability of food resources. Cellulose extraction processes vary from mechanical methods, such as cryo-shredding, to chemical procedures including carboxymethylation and acetylation (Angamarca& Delgado, 2022b).
On the other hand, hemicellulose, a polysaccharide with an amorphous structure composed of short chains of monomers, is classified into various categories such as xylans and mannans. It is found in abundance in cereals such as wheat, rice, and corn, and has applications in industry for the production of food additives and packaging, thanks to its unique properties.
Lignin, another crucial biopolymer, is characterized by its complex structure and the presence of diverse functional groups. It is a fundamental component of the cell walls of terrestrial plants and some algae, offering significant potential for use in industrial applications given its abundance, low cost, and favorable physical and chemical properties (Salazar, 2022).
In the context of agribusiness and the use of corn residues for the production of biopolymers, cellulose, hemicellulose, lignin and starch present a valuable opportunity to transform waste into resources (Sánchez, 2022). This approach not only fosters sustainability and the circular economy, but also reduces reliance on non-renewable sources, paving the way for innovations in sustainable materials that can be applied in a variety of industrial sectors, from packaging to advanced technological applications (Domínguez, 2023).

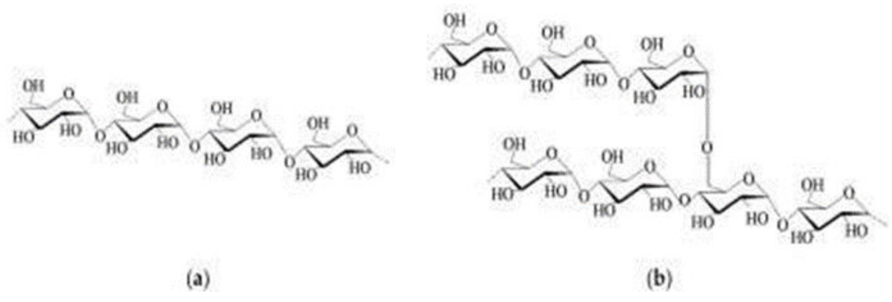

Figure 2. *Characteristics of the biopolymer.*

Fountain: (Gutiérrez et al., 2023).
Bioprocesses for biopolymer production involve the use of biological systems, including microorganisms or enzymes, to produce biodegradable polymers from renewable raw materials. These processes are critical for the sustainable production of bioplastics and other eco-friendly materials (Hernández & Gutiérrez, 2023).

The characteristics of biopolymers and a stoichiometric reaction can be illustrated through the process of producing polylactic acid (PLA), a popular biopolymer derived from renewable resources, such as corn. PLA is known for its biodegradability, biocompatibility, and versatility, making it applicable in many fields, including food packaging, medical applications, and textiles.

PLA production typically involves fermenting corn-derived sugars to produce lactic acid, followed by a polymerization process to form PLA. This process can be represented by stoichiometric reactions in its key stages:

1. **Fermentation of sugar to produce lactic acid:**

Glucose derived from corn is converted into lactic acid by bacteria, such as Lactobacillus. The simplified reaction can be written as:

$C6H12O6 \rightarrow 2\ C3H6O3C6H12O6 \rightarrow 2C3H6O3$

This equation shows that one molecule of glucose (C6H12O6) is fermented to produce two molecules of lactic acid (C3H6O3). The reaction is stoichiometric, which means that the ratio of reactant to products is fixed.

2. **Polymerization of lactic acid to PLA:**

Polymerization can occur through several routes, but a common method involves dehydrating lactic acid to form oligomers, which then undergo a polycondensation reaction to form higher molecular weight polymers. The general polymerization reaction can be represented as:

$n\ C3H6O3 \rightarrow (C3H4O2)n+n\ H2OnC3H6O3 \rightarrow (C3H4O2)n+nH2O$

Here, nn lactic acid molecules polymerize to form a PLA chain, releasing nn water molecules as a byproduct. The stoichiometry of this reaction is crucial to determine the molecular weight of the PLA produced, which in turn will influence its physical and mechanical properties.

In both cases, stoichiometric reactions play a fundamental role in the control of the production process and the quality of the resulting biopolymer. Accuracy in stoichiometry ensures that process throughput is maximized and waste is minimized, aligning with the sustainability inherent in biopolymer production. The understanding and control of these stoichiometric reactions allow the efficient production of biopolymers with specific desirable properties, such as biodegradability and biocompatibility of PLA, highlighting the importance of stoichiometric chemistry in the development of sustainable materials.

(Carrillo et al., 2022).

3.6 Use or Applications

Biopolymers have a wide range of uses and applications in various sectors, including medicine, the food industry, agriculture, and consumer product manufacturing. Specific examples, such as masks and gloves, illustrate the versatility and potential of biopolymers to replace conventional plastics in critical applications. Here are some of these uses and applications:

1. Medicine and Health

- **Masks and Gloves:** Made from biopolymer fibers such as PLA, they offer protection with the added benefit of being biodegradable.
- **Implants and Medical Devices:** Biopolymers such as polyglycolic acid (PGA) and polylactic acid (PLA) are used to make absorbable sutures, stents, and other devices that are biocompatible and break down in the body without causing harm.
- **Drug Delivery Systems:** They allow a controlled release of medications, improving the effectiveness of the treatment and minimizing side effects.

2. Food Industry

- **Packaging:** Biopolymers such as modified starch, PLA, and chitosan are used to produce biodegradable and edible food packaging, helping to reduce plastic waste.
- **Protective Films:** Edible and biodegradable films to extend the shelf life of food, maintaining its freshness.

3. Agriculture

- **Biodegradable Mulch:** Mulching films made from biopolymers break down after use, eliminating the need for collection and reducing plastic pollution.
- **Pest Control and Nutrient Release:** Biopolymer-based delivery systems for pesticides and fertilizers, offering controlled release and reducing environmental impact.

4. Textile Industry

- **Biodegradable Fibers and Fabrics:** Use of biopolymers to produce sustainable textiles, reducing dependence on synthetic fibers and their environmental impact.

5. Electronics & Packaging

- **Bioplastics for Electronics:** Application of biopolymers in electronic device housings and other components, promoting sustainability in consumer electronics.

6. Construction

- **Building Materials:** Use of biopolymers in panels, insulation, and other building materials to improve sustainability and reduce the carbon footprint of buildings.

These examples demonstrate how biopolymers are transforming industries by offering sustainable and biodegradable alternatives to traditional materials, contributing to a circular economy and minimizing environmental impact (Granados, 2022).

From corn

Biopolymers from corn are biodegradable and renewable polymeric materials derived from corn agricultural resources. This plant source serves as a crucial raw material for the production of various biopolymers, taking advantage of components such as starch, oil and even the corn germ itself. These biopolymers offer sustainable alternatives to conventional petroleum-based plastics, with applications across multiple industries. Some of the specific uses and applications of corn-derived biopolymers are explored below:

1. Packaging and Packaging

Corn-based biopolymers are widely used to make biodegradable packaging. For example, polylactic acid (PLA), a bioplastic produced from corn starch, is used in the creation of food packaging, bottles, disposable cutlery, and plates. These products offer an eco-friendly option that reduces the generation of plastic waste and its impact on the environment.

2. Personal Protective Products

In the field of health and safety, corn-derived biopolymers have become key materials for the production of biodegradable masks and gloves. These products not only provide the necessary protection but also promote environmentally responsible practices, by being compostable at the end of their useful life.

3. Medical Applications

PLA and other biopolymers obtained from corn also find applications in the medical field, including the manufacture of biodegradable sutures, implants and drug delivery systems. Their biocompatibility and ability to break down into non-toxic substances within the body make them ideal for medical applications.

4. Agriculture

Corn biopolymers are used in the production of biodegradable agricultural mulching films, which help control weeds and conserve soil moisture without contaminating it with plastic waste.

5. Textiles

The use of biopolymers from corn in the textile industry is emerging as a sustainable alternative to produce biodegradable fibers and fabrics. These materials can be used in a variety of products, from clothing to accessories, reducing reliance on synthetic fibers and their environmental impact.

6. Bioplastics and Biocomposites

Corn is not only used to produce PLA but also other bioplastics and biocomposites used in a wide range of applications, including toys, consumer electronics, automotive components, and more, offering a reduced carbon footprint compared to traditional materials.

The production and use of corn-derived biopolymers highlight the potential of renewable sources to contribute significantly to a greener and more sustainable economy, aligning with global efforts to reduce dependence on fossil fuels and minimize environmental impact (Fuentes et al., 2022).

4. *Challenges and Opportunities in the Production of Corn Biopolymers*

The production and application of corn-derived biopolymers in agribusiness presents a unique set of challenges and opportunities that reflect the current state of research and technological development in this field. As the demand for sustainable solutions increases, corn biopolymers emerge as a promising alternative to conventional petroleum-based plastics, offering environmental benefits such as biodegradability and renewable origin. However, the transition to wider adoption of these materials faces significant technical and economic hurdles that must be overcome (Relinque& Rodríguez, 2022).

One of the main challenges in the production of corn biopolymers is the development of processes that allow obtaining materials with mechanical and thermal properties comparable to or superior to those of their conventional counterparts. Although corn-derived biopolymers, such as polylactic acid (PLA) and polycaprolactone (PCL), show great potential in applications such as packaging manufacturing, agriculture, and regenerative medicine, their intrinsic properties often do not meet the specific requirements for certain applications. The formulation of composites that combine biopolymers with additives or reinforcements, such as ceramic or metal nanoparticles, represents a key strategy to improve these properties, although this introduces additional complexities in the processing and selection of compatible materials (Tejada, 2024).

From a sustainability perspective, the use of corn as a source for biopolymers raises questions about resource efficiency and the impact on food security. Competition between food and non-food uses of maize can influence food prices and the availability of agricultural land, requiring careful balancing and the development of sustainable agricultural practices. In addition, the production of biopolymers must be energy-efficient and minimize the use of harmful chemicals to be truly sustainable, which involves innovations in both cultivation techniques and extraction and polymerization processes (Angamarca& Delgado, 2022).

Meanwhile, the opportunities for innovation in the field of corn biopolymers are vast, especially with the advancement of additive manufacturing technologies, such as 3D printing. The adaptation of 3D printing equipment to accommodate the rheological properties of corn biopolymers, along with the development of new biopolymers and composites specific to 3D printing, could revolutionize manufacturing in various sectors. Studies exploring the use of PLA and PCL in biomedical applications, for example, demonstrate the potential of these materials to create customized products with enhanced mechanical, thermal, and biological properties, opening up new possibilities for regenerative medicine and tissue engineering (Relinque& Rodríguez, 2022).

This figure 3 shows examples of structures created using additive manufacturing techniques, commonly known as 3D printing. This process allows for the production of objects with complex geometries that are often difficult or impossible to manufacture using traditional methods. In part (A) of the image, different fill patterns used in 3D printing are observed. The percentages indicate the density of the infill, which can vary from 20% to 80%, affecting the stiffness, strength and weight of the printed object. A less dense infill will result in a lighter, but potentially less sturdy, piece, while a denser infill will increase strength and weight.

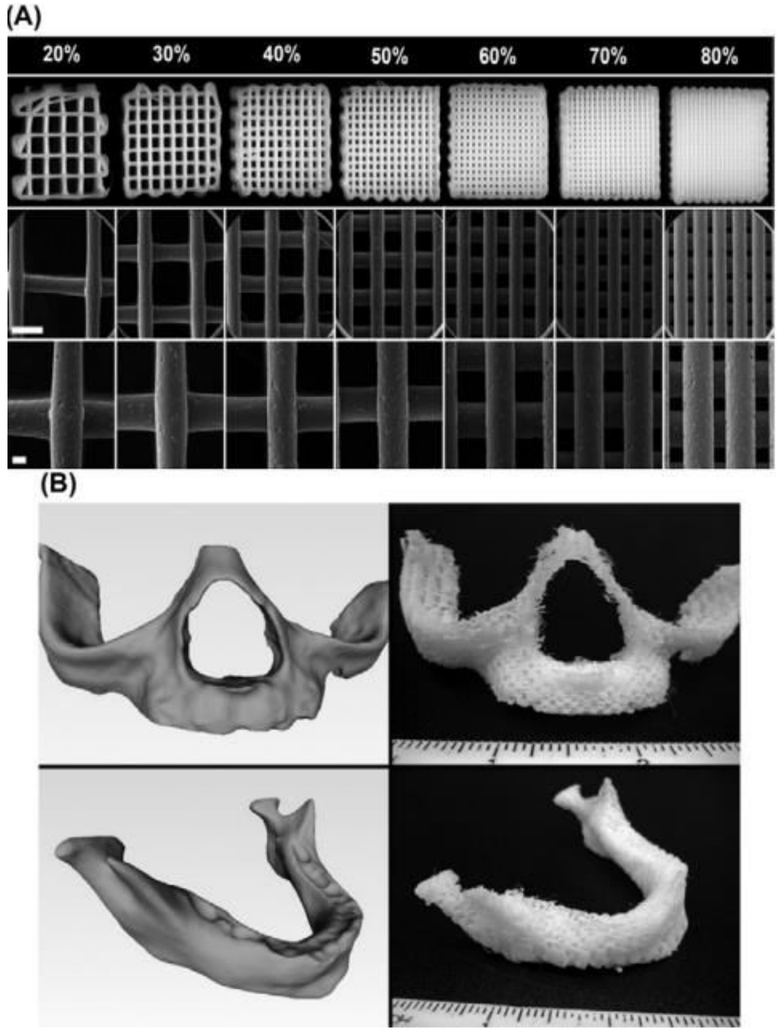

Figure 3. *Challenges and Opportunities in the Production of Corn Biopolymers*
Fountain: (Relinque& Rodríguez, 2022).

Part (B) of the figure shows two views of a 3D printed object. On the left, there are graphic representations of a 3D model, and on the right, the corresponding printed versions. These images illustrate how 3D printing can reproduce complex shapes with high fidelity from digital models. This type of technology has applications in numerous fields, from engineering and manufacturing to medicine, where they are used to create custom anatomical models for surgical planning or bespoke medical devices.

Therefore, the future development of maize biopolymers will depend heavily on collaboration between academic research, industry, and regulators to overcome technical and economic challenges, and to establish regulatory frameworks that encourage the adoption of these sustainable technologies. Creating knowledge about the behavior and processing of these materials, along with investing in advanced processing technologies and developing standards for biodegradability and yield, are essential to maximizing the positive impact of corn biopolymers in agribusiness and beyond (Relinque& Rodríguez, 2022).

4.1 Environmental Impact and Sustainability of Maize Biopolymers

The innovative approach of harnessing corn amero, a frequently discarded agricultural by-product, for lignin extraction and biopolymer production, underscores a significant step towards sustainability in the textile industry. This approach not only recognizes the environmental problem associated with the overuse of plastics and synthetic polymers in industry, but also offers a practical and eco-friendly solution. By turning agricultural waste into a valuable resource for the manufacture of bioplastics, this project illustrates a circular economy model that minimizes waste and takes advantage of renewable sources, aligning with the principles of sustainability and reduced environmental impact (Castañeda et al., 2022).

The extraction of lignin from corn amero for the development of biopolymers stands out for its potential to offer sustainable alternatives to conventional materials used in the textile industry. Lignin, being a natural polymer that confers hardness, can be transformed into bioplastics with physicochemical properties suitable for various textile applications, such as synthetic fibers, packaging, or even as a component in textile composites. This process not only adds value to an agricultural by-product, but also contributes to the reduction of the carbon footprint of the textile industry, one of the most polluting worldwide, by reducing dependence on fossil sources for the production of polymers (Castañeda et al., 2022).

The figure provided illustrates a production process in which a raw material, identified as "Amero", is transformed into different products and by-products through a series of chemical and physical stages. The process begins with drying the material, followed by grinding that divides it into fractions of different sizes. The resulting mixture undergoes hydrolysis in the presence of sodium hydroxide (NaOH), leading to the production of black liquor and a finely ground fiber fraction. Subsequently, an extraction with sulfuric acid (H2SO4) is performed to separate the lignin, and finally, the products are dried to obtain pure lignin and water as by-products.

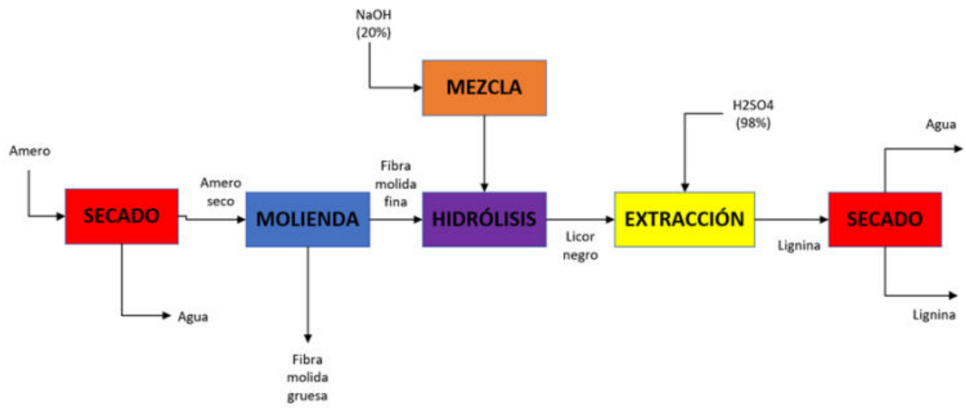

Figure 4. *Detailed biorefinery process.in the original Spanish language*

Fountain: (Castañeda et al., 2022).

This flowchart highlights the importance of consecutive steps in the transformation of biomass into recovered chemicals. The sequence of processes shows how the components of a biomass can be separated and purified for use in various industrial applications. The efficiency of each stage is crucial for the quality of the final product and the sustainability of the process.

According to the author of Jesús & GAYTÁN, (2020), the research and characterization of biopolymers obtained from corn amero lignin represent a technical and scientific challenge, but also an opportunity to move towards greener practices in the textile industry. By studying their physicochemical properties, it is possible to classify and adapt these biopolymers to meet industry-specific requirements, such as strength, durability, and biodegradability. Not only does this have the potential to revolutionize the way materials are produced and used in the textile industry, but it also promotes innovation in the use of eco-friendly materials, marking a significant shift towards environmental responsibility.

Finally, the project to harness corn amero for the production of biopolymers in the textile industry reflects a holistic approach towards solving environmental problems. By integrating sustainable waste management with innovation in materials, a precedent is set for other industries in the search for sustainable solutions. This model not only benefits the environment by reducing waste and promoting biodiversity, but also has the potential to deliver economic benefits through the creation of new markets and employment opportunities in the biopolymer sector, thus demonstrating the viability of sustainable practices in the industrial field (Castañeda et al., 2022).

CONCLUSIONS

The exploration and development of biopolymers derived from maize plant matter in agribusiness represent a significant step towards sustainability and technological innovation. The ability to transform corn stubble and other agricultural waste into valuable materials not only addresses the challenge of waste management, but also contributes to the circular economy, efficiently harnessing the by-products of agriculture. This approach not only reduces dependence on petroleum-based synthetic polymers, with their associated environmental problems, but also promotes the use of renewable and sustainable resources.

The implementation of biopolymers in agribusiness offers multiple environmental benefits, including reducing the carbon footprint and improving waste management. By using corn, a widely grown and economically important source, it opens the door to a vast range of industrial applications, from biodegradable packaging to innovative agricultural products, which can play a crucial role in reducing the industry's environmental impact.

In addition, progress in the research and development of biopolymers from corn points to a future in which agribusiness can lead in the application of green solutions and clean technologies. Adapting production processes to incorporate biopolymers not only improves the sustainability of operations, but can also offer competitive advantages in increasingly environmentally conscious markets.

However, in order to achieve a successful integration of corn-derived biopolymers in agribusiness, it is essential to overcome technical and economic challenges. This includes optimizing extraction and conversion processes, improving the physical and chemical properties of biopolymers to match or exceed their synthetic counterparts, and creating sustainable supply chains that can support large-scale production

Conflict of interest: The authors declare no conflict of interest

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