

Utilization of Cellulose Derived from Agro-Industrial Waste for Biopolymer Formulation: A Systematic Review

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Abstract — The objective of this systematic review is to analyze the main scientific advances related to the use of cellulose extracted from agro-industrial residues for the formulation of biopolymers. To this end, a systematic review of the scientific literature published between 2015 and 2024 was conducted using the Dimensions database, considering studies associated with agro-industrial residues, biomaterials, and biopolymer production methods. The selected studies were evaluated through bibliometric analysis and keyword co-occurrence tools, which enabled the identification of research trends, scientific output, and predominant technological approaches.

The results indicate that agro-industrial residues constitute an abundant and sustainable source of cellulose, whose valorization promotes the circular economy and reduces environmental impact. Various cellulose extraction methods were identified, including alkaline treatment, acid treatment, bleaching, enzymatic processes, and methods based on green solvents. The latter represents one of the most recent trends and, compared to other methods, yields cellulose with a high degree of purity; however, its main drawback is the high production cost. In this context, acid hydrolysis remains one of the most widely used methods despite involving corrosive reagents.

Cellulose extracted from agro-industrial residues is used as a raw material in the production of biopolymers. For the fabrication of biopolymer films, molding is the most commonly employed technique. The main applications of biopolymers derived from agro-industrial residues were identified in the food industry, particularly in food packaging and containers. Overall, the literature demonstrates the growing scientific interest and technological potential of these materials as sustainable alternatives to conventional polymers.

Keywords: polysaccharides; biomass; coffee husk; sugarcane bagasse.

Resumen — El objetivo de esta revisión sistemática es analizar los principales avances científicos relacionados con el uso de celulosa extraída de residuos agroindustriales para la formulación de biopolímeros. Para ello, se realizó una revisión sistemática de la literatura científica publicada entre 2015 y 2024 utilizando la base de datos Dimensions, considerando estudios asociados con residuos agroindustriales, biomateriales y métodos de producción de biopolímeros. Los estudios seleccionados fueron evaluados mediante análisis bibliométrico y herramientas de co-ocurrencia de palabras clave, lo que permitió identificar tendencias de investigación, producción científica y enfoques tecnológicos predominantes.

Los resultados indican que los residuos agroindustriales constituyen una fuente abundante y sostenible de celulosa, cuya valorización promueve la economía circular y reduce el impacto ambiental. Se identificaron varios métodos de extracción de celulosa, incluyendo el tratamiento alcalino, el tratamiento ácido, el blanqueo, los procesos enzimáticos y los métodos basados en solventes verdes. Estos últimos representan una de las tendencias más recientes y, en comparación con otros métodos, producen celulosa con un alto grado de pureza; sin embargo, su principal inconveniente es el elevado costo de producción. En este contexto, la hidrólisis ácida sigue siendo uno de los métodos más utilizados a pesar de involucrar reactivos corrosivos.

La celulosa extraída de residuos agroindustriales se utiliza como materia prima en la producción de biopolímeros. Para la fabricación de películas de biopolímeros, el moldeo es la técnica más comúnmente empleada. Las principales aplicaciones de los biopolímeros derivados de residuos agroindustriales se identificaron en la industria alimentaria, particularmente en envases y recipientes para alimentos. En general, la literatura demuestra el creciente interés científico y el potencial tecnológico de estos materiales como alternativas sostenibles a los polímeros convencionales.

Palabras Clave: polisacáridos; biomasa; cascarilla de café; bagazo de caña.

I. INTRODUCTION

THE world population is increasing daily; consequently, food production and distribution are rising to meet population demand. The agro-industrial sector is responsible for processing products from agriculture, livestock, fishing, and forestry activities. It is classified into the food sector, which refers to food

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production, and the non-food sector, responsible for processing products such as wood, flowers, tobacco, fibers and dyes, among others. Due to these processing activities, approximately 3.045 billion tons per year (t year⁻¹) of agro-industrial waste are generated worldwide [1], making them potential sources of contamination and risks to the environment and human health. Therefore, alternatives for the utilization of agro-industrial waste are being sought. It is observed that population growth is directly proportional to the demand for plastics used in human activities. In 2019, the United Nations reported that approximately 300 million tons of plastic waste are produced globally each year, of which only 14% is recycled. Petroleum-based plastic materials are inexpensive polymers with good mechanical properties. However, their main disadvantage is that they are non-biodegradable and cause pollution in water bodies, soil, and air [2]. Globally, greenhouse gas emissions generated by food waste account for 8% of global emissions [3].

An alternative to reduce the pollution caused by this waste is the generation of biopolymers from these agro-industrial residues. Biopolymers have become an alternative to single-use plastics. These materials are characterized by being biodegradable under appropriate conditions, with a decomposition period of around 180 days. Because they are manufactured from renewable resources, their production does not depend on fossil fuels [4].

This approach contributes to the circular bioeconomy model, which aims to create a closed-loop system where waste is minimized. The valorization of food waste not only reduces waste but also contributes a matrix of cellulose, hemicellulose, and lignin, in addition to enhancing environmental, economic, and social sustainability [5]. In this context, this review seeks to evaluate the major results, methods, and technologies involved in transforming cellulose derived from agro-industrial waste into biopolymers.

A. Agro-industrial Waste as a Source of Cellulose

The United Nations Food and Agriculture Organization (FAO) estimates that approximately one-third of the food produced for human consumption is lost, equivalent to 1.3 billion tons per year. The agro-industry is responsible for the processing of fruits, vegetables, tubers, pods, seeds, roots, and leaves; some of which are commercialized as flours, oils, nectars, juices, wines, jams, among others, thereby generating significant waste [6]. FAO [7] reports the global crop production of sugarcane, agave and fibers, avocado, rice, bananas, coconut, soybeans, cocoa, maize, mango, guavas, papaya, roots, tubers, grapes, and coffee (Table I). Sugarcane and maize are the primary crops produced worldwide.

The agro-industry generates various types of waste, which include crop residues, processing by-products, and waste from the food and beverage industries (Table II) [8]. Agro-industrial wastes are predominantly solid and organic in nature. Most of these wastes are rich in lignocellulosic biomass, composed primarily of pectin and ashes. The composition of cellulose, hemicellulose, and lignin in agro-industrial wastes varies according to the type of residue [9].

Globally, the crop with the highest production is sugarcane, which generates waste such as bagasse, filter cake (cachaza), and ash. In this context, it is reported that 37 to 42% of sugarcane bagasse is generated per ton processed [10], [11].

TABLE I
GLOBAL PRODUCTION BY CROP

Crop	Production (tons per year)
Sugarcane	2,025,797,465.39
Agave and fibers	40,221.86
Avocado	10,466,560
Rice	799,999,504.87
Bananas	139,277,894.61
Coconut	64,675,221.98
Soybeans	371,173,609.31
Cocoa	5,600,100.42
Maize (Corn)	1,241,557,811.36
Mango and guavas	61,107,091.76
Papayas	14,232,583.07
Roots and tubers	9,630,951.90
Grapes	72,486,522
Coffee	11,064,205.47

Fuente: [7]

TABLE II
TYPES OF WASTE GENERATED BY THE AGRO-INDUSTRY

Agro-industry Sector	Type of Waste
Crop Harvesting	Plant remnants, leaves, stalks, and roots.
Processing By-products	Pulps, peels/rinds, and seeds.
Food Industry Waste	Fruit and vegetable waste, and non-conforming products.
Beverage Production Waste	Sugarcane bagasse, grape pomace (orujo).

According to the literature, for every ton of stalks entering the agro-industrial processing line, 250 kg of bagasse are generated [11]. Bagasse has been used as animal feed, as a raw material for the production of ethanol, fuel, cellulose, paper, and compost [12]. The composition of bagasse is approximately 40% cellulose, 30% hemicellulose, and 20% lignin.

Another agro-industry that generates significant waste is the coffee industry, which uses on average 9.5% of the fruit for beverage preparation, while the remaining 90.5% are by-products such as pulp, mucilage, spent coffee grounds, and husks or parchment [12]. A similar case is cocoa, where only the bean, which corresponds to about 10% of the fresh fruit's weight, is commercially utilized [6]. Melon processing agro-industries, within their linear production of food items like juices, salads, and snacks, generate between 8 and 20 million tons of waste annually. This waste has a composition rich in cellulose, hemicellulose, and lignin [13]. Table III shows the composition of various lignocellulosic wastes, which represent a sustainable and abundant source of cellulose. Currently, this cellulose has been used as a basis for the formulation of biopolymers [13], [14], [15], [16], [17], [18], [19], [20]. It has been demonstrated that the utilization of

this waste contributes to the circular economy and reduces the environmental impact of agricultural waste [21].

TABLE III
COMPOSITION OF AGRO-INDUSTRIAL WASTE

Waste	Composition (%)			Reference
	Cellulose	Hemicellulose	Lignin	
Sugarcane Bagasse	40	20	30	[10], [11]
Coffee Husk	44.5	28.5	34	[22]
Melon Peel	55.03	36.21	1.76	[13]
Corn (Maize)	18	45	-	[23]
Rice	44	22	-	[23]
Wheat	35	22	-	[23]
Banana Rachis	42.4	13.7	17.3	[24]
Garlic Stem	41	18	6.3	[25]
Grape Pomace	19.3	7.20	15.60	[18]

B. Environmental Impact of Agro-industrial Waste

Waste rich in lignocellulosic biomass exhibits a very low degradation rate. When not utilized, it is often disposed of without any regulation, primarily in vacant lots or green spaces [26], [27], [28].

The inadequate treatment and disposal of this biomass waste have a negative environmental impact, primarily generating atmospheric pollution and greenhouse gases, soil degradation, water pollution, and ecological problems [29]. Atmospheric pollution and greenhouse gas emissions generated by the open-air burning of agricultural waste release large quantities of carbon dioxide, methane, and particulate matter, contributing to climate change and public health issues [30]. According to reports by the IPCC, 24% of global GHG emissions correspond to direct agricultural activities and those derived from the burning of residual biomass [31]. Another effect generated by this waste is the reduction of nutrient availability in the soil and an increase in the leaching of phenolic compounds, which adversely affects water quality [32].

C. Valorization of Agro-Industrial Waste: Biopolymers

Due to their composition, agro-industrial wastes have high potential to be utilized for generating value-added products [6], [33]. Currently, one of the main applications is the production of compost and bioenergy sources such as bioethanol, biodiesel, and biogas, as well as in the production of biopolymers [34], [35], [36]. Biopolymers represent an alternative for reducing the production of non-biodegradable, petroleum-based polymers, as they are derived from renewable resources [37], [38], [39]. Biopolymers are classified into three categories based on their origin: a) Polymers derived from renewable resources, such as starch and cellulose; b) Biodegradable polymers, produced from bio-derived monomers, such as vegetable oils and lactic acid; c) Biopolymers synthesized by microorga-

nisms, such as polyhydroxyalkanoates (PHA) [40]. Biopolymers can be obtained using different techniques, depending on the synthesis method, processing, and desired application. The most common forms include films, fibers, hydrogels, nanocomposites, filaments, granules, and powders [41].

The polymers derived from renewable resources, such as cellulose is formed by the linkage of β -glucose molecules via β -1,4-O-glycosidic bonds; it has a linear structure where multiple hydrogen bonds are established between the OH groups of the glucose chains, forming the compact fibers that constitute the cell wall [42]. Cellulose possesses several notable properties that make it suitable for use in various polymeric compounds. These characteristics include its density, non-abrasiveness, combustibility, non-toxicity, biodegradability, and low cost [25], [43]. Although, it presents some disadvantages, such as poor interfacial adhesion and high water absorption. In this context, some authors state that these properties can be improved through the chemical modification of cellulose fibers. However, it is a biopolymer with high mechanical strength, biocompatibility, and biodegradability, making it a biomaterial with high potential for industrial applications, including paper, textiles, and food additives [13], [44], [45]. This work will focus on the utilization of cellulose extracted from agro-industrial waste for the production of biopolymers.

D. Methods for Cellulose Extraction and Purification

Lignocellulosic biomass is primarily composed of cellulose, a linear, crystalline, and water-insoluble polymer that forms the primary structure; hemicellulose, an amorphous, branched, and heterogeneous polymer that acts as a connector between cellulose and lignin; and lignin, a complex, cross-linked phenolic polymer that provides structural support. Consequently, efficient cellulose extraction requires a biomass pretreatment to remove hemicellulose and lignin [14].

Pretreatment can be performed through alkaline treatment using a concentrated solution of sodium hydroxide or potassium hydroxide at concentrations of 4–20% by weight and temperatures ranging from 70°C to 160°C [19]. Another method is bleaching, which aims for the complete removal of lignin using various chemical combinations such as sodium chlorite, hydrogen peroxide with sodium hydroxide, or hydrogen peroxide in acetic acid and water [46]. For instance, a pretreatment for grape waste has been reported using a 5% hydrogen peroxide solution (0.05 g/mL) at pH 11.5 (adjusted with NaOH) and 50°C for 8 hours, followed by cooling at room temperature for 15 hours. The bleaching effect is enhanced by an additional 8-hour bleaching step [18]. Furthermore, some cellulose extraction techniques combine alkaline and bleaching treatments with ultrasound applied to fibers, resulting in increased crystallinity and improved cellulose stability. For example, in the case of mango endocarp waste, an alkaline treatment with 2% (w/v) sodium hydroxide at 80°C for two hours is applied, followed by bleaching with a solution of hydrogen peroxide and 4% sodium hydroxide under agitation at 50°C for two hours. Finally, the material undergoes acid hydrolysis in combination with ultrasound [47]. Once the hemicellulose and lignin have

been removed, a method for cellulose extraction is applied, which can be achieved through three distinct approaches: acid hydrolysis, enzymatic hydrolysis, and mechanical treatment, with hydrolysis being one of the most common.

According to the literature [14], there are three important factors to consider in the hydrolysis process: reaction time, temperature, and acid concentration, as these influence the properties of the obtained cellulose. Furthermore, another factor influencing cellulose yield is particle size. In this regard, some authors indicate that cellulose at the nanometric particle scale results in an increase in mechanical strength greater than that of conventional materials, such as steel [48]. However, this method presents several limitations, including high water consumption and the generation of acidic wastewater.

Enzymatic hydrolysis is a process that uses specific enzymes to degrade lignocellulosic components to obtain pure cellulose. One of its advantages is that enzymes preferentially attack the amorphous regions of cellulose, preserving the crystalline regions; moreover, it is a process that is less aggressive to the environment. In contrast, a disadvantage of this technique is that it requires longer processing times and is more costly [20]. Another environmentally friendly and efficient alternative for cellulose extraction is the use of green solvents, which have low toxicity and are biodegradable, with glycerol, levulinic acid, and urea being the most common [49]. When the use of green solvents is combined with intensification techniques such as microwaves or ultrasound, the yield and quality of the extracted cellulose increase [50].

Table IV summarizes the main cellulose extraction methods from agro-industrial residues, highlighting their advantages and limitations. Chemical treatments show high efficiency but involve environmental risks and possible material degradation. Mechanical and biological methods offer more sustainable alternatives, although they require higher energy input, longer processing times, or greater costs.

TABLE IV
CELLULOSE EXTRACTION METHODS: ADVANTAGES
AND DISADVANTAGES

Extraction methods	Advantages	Disadvantages
Alkaline treatment	Low cost High efficiency in hemicellulose removal	Generation of alkaline effluents Possible partial degradation of cellulose.
Acid treatment	High purification efficiency. Enables nanocellulose production.	Use of corrosive reagents. Environmental risk.
Bleaching	Improves cellulose purity and whiteness Increases crystallinity.	Degrade the polymer chain.
Mechanical methods	Does not require large amounts of chemical reagents Lower environmental impact	Low selectivity without chemical pretreatment High energy consumption
Biological (enzymatic) methods	Lower generation of toxic residues	Longer processing time Higher production cost
Green solvents	Production of high-purity cellulose	Greater operational complexity Higher costs

E. Transformation of Cellulose into Biopolymers

The transformation of cellulose into biopolymers involves physical, chemical, and biotechnological processes that enable the production of advanced, eco-friendly materials with applications in multiple sectors [51]. Different transformation pathways exist for cellulose, where it can be used as a fiber, nanocellulose, or chemically derivatized (esters, ethers) to create biopolymers and biocomposites. Another form of transformation is biotechnological, which utilizes bacteria and fungi to produce bacterial cellulose [52]. Bacterial cellulose is a biopolymer with characteristics similar to those of plant-based polymers but differs in its degree of polymerization and hardness, exhibiting more stable and resistant nanofibers with an ultra-fine network structure, high crystallinity, tensile strength, elasticity, and durability [53]. A disadvantage of bacterial cellulose production is its high cost and low yield [54].

F. Characterization of Biopolymers

Characterization techniques for biopolymers are essential for understanding their structural, physical, chemical, and functional properties. The most commonly used spectroscopic techniques include Fourier Transform Infrared (FTIR) spectroscopy, which identifies functional groups and analyzes the chemical composition of biopolymers; UV-Vis spectroscopy, useful for studying optical absorption and the presence of chromophores; and Nuclear Magnetic Resonance (NMR) spectroscopy, which provides information on molecular structure and purity [55]. Furthermore, microscopic techniques are employed, such as Scanning Electron Microscopy (SEM) to examine surface morphology and microstructure, and Transmission Electron Microscopy (TEM) to observe the internal structure at the nanometric level [56]. Additionally, diffraction and thermal analysis techniques are used to evaluate the crystallinity, structure, and thermal stability of biopolymers [57].

Biopolymers exhibit a variety of physical, chemical, and mechanical properties that make them attractive for sustainable and biomedical applications. Physical properties allow the determination of the material's macroscopic behavior through characteristics such as density, flexibility, transparency, thermal stability, and permeability [58]. Chemical properties enable the study of molecular composition and the possibility of modifying the material for specific applications. Other highly relevant properties are mechanical ones, which define the biopolymer's ability to withstand forces, deform, and resist wear [59].

G. Applications of Cellulose-Derived Biopolymers

Cellulose-derived biopolymers are sustainable materials with reported applications across various industrial and technological sectors. In the biomedical field, they are used as materials in tissue engineering, controlled drug release systems, implants, and customized medical devices (3D printing) [60], [61], [62]. In the environmental sector, they are applied in the removal of heavy metals and contaminants from wastewater, serving as bio sorbents and membranes for water purification, among other applications [63], [43]. Within the food industry, they are utilized in the form of biodegradable food films,

coatings, protective layers, and packaging [15], [16], [64]. In agriculture, they are employed as hydrogels for the controlled release of water and nutrients, and as films for crop protection [65], [66]. These represent some of the reported applications for cellulose-derived biopolymers, which are enabled by their biodegradability, high mechanical strength, thermal stability, and ease of chemical modification [67].

H. Environmental and Economic Impact

The use of biopolymers represents a sustainable alternative to conventional polymers, with the potential to reduce environmental impact and dependence on fossil fuels. However, their environmental and economic impact varies depending on the type of biopolymer, the raw materials used, and the production processes. Life cycle analysis indicates that biopolymers generally have a lower carbon footprint and reduced consumption of fossil resources, but they can present economic and environmental challenges at specific stages of their life cycle [68].

It has been demonstrated that biopolymers such as polylactic acid (PLA) can generate up to 50% fewer carbon emissions compared to polyethylene terephthalate (PET). Furthermore, their ability to decompose under specific conditions, such as composting, reduces waste accumulation [69]. In contrast, the production of biopolymers can lead to agricultural impacts stemming from biomass cultivation, potentially causing eutrophication in water bodies and soil acidification [68], [69]. Another challenge facing biopolymer production is its higher cost compared to conventional plastics, but economic viability can be improved by utilizing waste materials as feedstock [70].

II. METHODOLOGY

A systematic search for scientific references published between 2015 and 2024 was conducted using the Dimensions database. The search criteria were: agro-industrial waste, biomaterials, cellulose, and biopolymer production methods. This search yielded 549 published articles.

Once the database was obtained, duplicate entries were removed, leaving 505 articles. Subsequently, these articles were screened based on their title, keywords, and abstract, in addition to assessing full-text availability. This process resulted in a final selection of 156 articles directly related to the utilization of cellulose extracted from agro-industrial waste (Fig. 1).

Using the reference manager Zotero, a bibliometric analysis was performed, revealing the annual scientific production and the leading countries with the highest number of published articles. Based on this database and using the keywords from each article as the unit of analysis, a co-occurrence map was generated using the software VOSviewer, version 1.6.20.

A. Limitations of the Study

This systematic review has certain limitations that should be acknowledged in order to reinforce scientific transparency. The literature search was restricted to the Dimensions database and to the period between 2015 and 2024; therefore, relevant studies indexed in other databases or published outside this timeframe may not have been included.

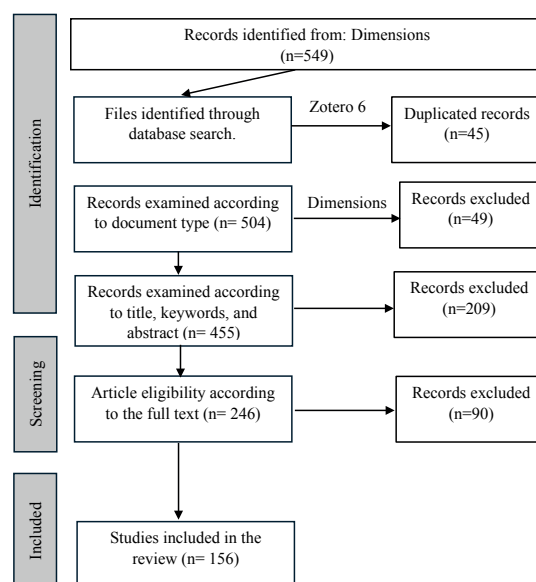


Fig. 1. PRISMA flowchart for screening and selection of studies.

Likewise, the bibliometric indicators employed—such as the number of publications, keyword co-occurrence, and country productivity—allow the identification of trends in scientific output but do not necessarily reflect research quality, technological maturity, or the feasibility of industrial scaling. Moreover, citation patterns may be influenced by database coverage and language bias. Furthermore, the co-occurrence analysis depends on the consistency of author-defined keywords, which may affect the interpretation of thematic networks. In addition, methodological heterogeneity among the analyzed studies—particularly regarding extraction techniques, characterization methods, and performance evaluation of biopolymers—limits direct comparisons and hinders the possibility of conducting integrative quantitative analyses.

III. RESULTS AND DISCUSSION

Scientific production related to the utilization of cellulose extracted from agro-industrial waste for obtaining biopolymers showed a considerable increase starting in 2021 within the period from 2015 to 2024. This trend may be associated with efforts to meet the Sustainable Development Goals (SDGs), driving the search for alternatives to petroleum-derived materials. This has stimulated increased research into biodegradable polymers, particularly those produced from agro-industrial waste (Fig. 2).

A total of 156 articles addressing the utilization of cellulose extracted from agro-industrial waste for the formulation of biopolymers were identified. The analysis revealed that Brazil, Italy, and Spain stand out with the highest number of scientific publications, accounting for 18.6%, 9.0%, and 7.7% of the total, respectively, between 2015 and 2024. Despite the significant scientific contributions from these countries, Brazil is notable as a representative of emerging economies. In Latin America, Mexico ranks fourth, contributing 6.4% of the scientific production on this topic. This trend is likely related to the

significant agricultural potential of both Latin American countries as major producers of coffee and sugarcane (Table V), and the ongoing search for alternatives focused on the valorization of waste generated by the agroindustry.

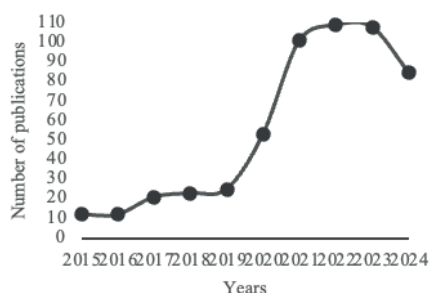


Fig. 2. Scientific production per year from 2015 to 2024 on the utilization of cellulose extracted from agro-industrial waste for biopolymer production.

TABLE V
SCIENTIFIC OUTPUT BY COUNTRY

Country	Continent	Published articles (%)
Brazil	America	18.6
Italy	Europe	9.0
Spain		7.7
Mexico	America	6.4

In the keyword co-occurrence network, the term “bacterial cellulose” is prominent, around which other secondary terms such as cellulose, biopolymers, agro-industrial waste, and biomaterials are linked (Fig. 3).

A. Properties vs. Applications

Agro-industrial waste represents an alternative for generating polymers that can degrade in a shorter period compared to conventional ones. It was identified that the utilization of this waste is highly diverse, with notable applications including compost, biodiesel, biogas, and biopolymers. Various authors have proposed formulations for biopolymers using cellulose extracted from residues such as sugarcane bagasse, mango and papaya peels, cocoa shells, grape pomace, and avocado seeds and peels, among others. However, it is crucial to consider factors like particle size and the use of plasticizers, as they enhance the mechanical strength of the biopolymer. For instance, cellulose at the nanometric particle scale results in increased mechanical strength [48]. Plasticizers improve material flexibility by reducing intermolecular forces [71]. Mechanical, rheological, and thermal properties can be enhanced by adding plasticizers such as polyvinyl alcohol, glycerol, carboxylic acids, sorbitol, xylitol, mannitol, corn syrup, propylene glycol, ethylene glycol, polyethylene glycol, triethyl citrate, triacetin, formamides, urea, acetamide, glucose, polyaminoacids, lipids, sorbates, and phosphates [72], [73]. Glycerol is the most widely used plasticizer in the production of biodegradable films due to its high availability, low cost, compatibility with a wide range

of materials, and its ability to impart good elasticity to films without significantly reducing their tensile strength [74].

In contrast, an increase in plasticizer concentration reduces intermolecular forces, resulting in greater flexibility but reduced strength of the materials. At low glycerol concentrations, the tensile strength of the films is higher [75].

Some authors report the use of other plasticizers, such as glucose, which can improve the mechanical properties of the biopolymer. For instance, elongation can be increased by up to 51.4% [15].

Formulating a biopolymer using both starch and cellulose enhances tensile strength and Young’s modulus. According to the literature, a starch-based biopolymer with a cellulose concentration between 5% and 15% exhibits improved tensile strength, Young’s modulus, and reduced water vapor permeability [76]. In most applications, polysaccharides such as cellulose, hemicellulose, starch, pectin, alginate, chitosan, and fibers are used as raw materials to develop biodegradable films and coatings in the food industry. This is because their ordered network of hydrogen bonds makes them more effective at blocking oxygen. However, they are less effective as a barrier against water [44].

The use of agro-industrial waste as a source of cellulose for obtaining biopolymers reduces the generation and use of synthetic plastics, helping to mitigate environmental pollution.

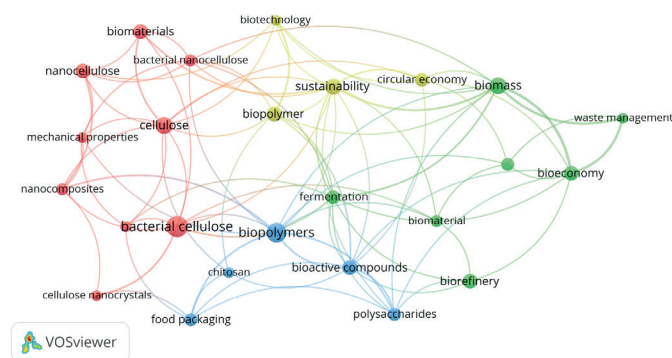


Fig. 3. Keyword co-occurrence network related to the utilization of cellulose extracted from agro-industrial wastes.

However, challenges remain in the study of mechanical properties, such as strength, and water vapor barrier properties, which limits certain applications. Therefore, the study of biopolymers still presents an area of opportunity for improving their mechanical and water vapor barrier properties.

B. Biopolymer Formulation

The formulation of biopolymers from cellulose, starch, and polylactic acid involves variations in their production processes, which modify their mechanical and thermal properties (Table VI).

In the development of edible wraps based on sugarcane bagasse cellulose [15], the sugarcane bagasse was chemically modified by acid hydrolysis to obtain microcrystalline cellulose for the formulation of biofilms using glucose, glycerol, and a

fatty acid. The wraps were produced using the casting method, a process where the solution is poured into plastic molds and the solvent is evaporated.

Biopolymers have been developed from cocoa cellulose and sugarcane bagasse fiber by varying the composition of cellulose and fiber, glycerol, distilled water, and sorbitol. It was observed that decreasing the cellulose concentration reduces the moisture percentage of the film. Regarding water vapor permeability, the formulation with 75% cellulose and 25% fiber showed the lowest permeability [16]. It has been demonstrated that films based on grape pomace cellulose nanocrystals can be reinforced by adding starch, distilled water, and glycerol. This allowed films with a composition between 5% and 15% cellulose nanocrystals to achieve better tensile strength and Young's modulus [76].

The combination of starch and cellulose present in avocado peel and seed [18] has been used in the formulation of biopolymers with starch, 30% NaOH, cellulose, glycerin, and polyvinyl acetate (PVA). The film with the best mechanical prop-

erties had a concentration of 2 g of glycerol and 6 g of PVA, demonstrating a tensile strength of 1.53 MPa, an elongation of 21.25%, and an elastic modulus of 10.04 MPa. In the development of a biopolymer based on papaya and mango peel, starch, glycerol, acetic acid, and distilled water, the polymer based on papaya peel showed greater hardness, a melting point of 400 °C, and higher mechanical strength [77]. Other authors explore the formulation of bionanocomposites by adding reinforcing materials using starch and cellulose nanofibers as a base. The biopolymer formulation used cassava starch, carob gum, distilled water, glycerol, and cassava cellulose nanofibers at different concentrations. The developed biopolymer showed good tensile strength; however, the addition of 2.5% cellulose nanofibers significantly reduced this tensile strength [17].

The identified parameters involved in the matrix of reinforced polymers are related to fiber pretreatment, the percentage of the filler to be used, the dispersion of the fibers within the matrix, and the fiber length [78].

TABLE VI
FORMULATION OF CELLULOSE-BASED BIOPOLYMERS
OBTAINED FROM AGRO-INDUSTRIAL WASTE

Raw Material (Source)	Polymer Base	Additives/Plasticizers	Processing Method	Key Properties	Application	References
Sugarcane bagasse	Microcrystalline cellulose	Glucose, glycerol, fatty acid	Casting	Edible film formation	Food packaging	[14]
Cocoa shell, sugarcane fiber	Cellulose, fiber composite	Glycerol, sorbitol, distilled water	Solution casting	Low water vapor permeability (75% cellulose)	Biodegradable films	[15]
Grape pomace	Cellulose nanocrystals + starch	Glycerol, distilled water	Casting	Improved tensile strength (5-15% CNC)	Food packaging	[17]
Avocado peel/seed	Starch-cellulose blend	Glycerol, PVA, 30% NaOH	Casting	Tensile: 1.53 MPa, Elongation: 21.25% Elastic modulus: 10.04 MPa	Biopolymer films	[31]
Papaya/Mango peel	Starch-cellulose	Glycerol, acetic acid, distilled water	Thermal processing	Melting point: 400°C, high hardness	Food packaging	[75]
Cassava residues and carob tree	Starch, cellulose nanofibers	Carob gum, glycerol	Solution casting	Variable tensile strength (fiber-dependent)	Bionano-composites	[16]
Lignocellulosic biomass	PLA composite	Lignin (20-40%)	3D printing (215°C)	Reduced elasticity but improved layer adhesion	3D printing filaments	[79]

Note: CNC = Cellulose Nanocrystals; PVA = Polyvinyl Acetate; PLA = Polylactic Acid

Another important parameter considered in the formulation of biopolymers based on lignocellulosic biomass is the processing temperature, as their main components degrade at specific ranges. Amorphous cellulose and hemicellulose degrade between 200°C and 250°C, microcrystalline cellulose between 240°C and 360°C, and lignin between 360°C and 540°C [79], [80]. This parameter can affect the tensile strength and stiffness of the resulting biopolymer. Furthermore, temperature can modify organoleptic characteristics, such as odor and color; although a property that favors the use of cellulose is its high thermal resistance.

Furthermore, the formulation of biocomposites reinforced with lignocellulosic biomass in a PLA matrix has been reported to improve material properties. In this context, filaments based on biocomposites containing 20% and 40% lignin with PLA

as the polymeric matrix have been developed. The result was a more brittle biocomposite with lower resistance to deformation before fracture, showing a 25% to 32% decrease in its elastic modulus compared to pure PLA [81]. However, when the printing temperature was increased to 215°C, the biocomposite exhibited enhanced mechanical properties, which is associated with improved adhesion between the 3D-printed layers.

One of the most relevant factors in obtaining biopolymers is the type and quantity of plasticizer used. It is observed that plasticizers like glycerol and sorbitol significantly influence the material's flexibility and strength. Nevertheless, an excess of plasticizer can affect the structural stability, reducing tensile strength.

On the other hand, the casting method was identified as the most commonly used technique for producing biopolymers, enabling the formation of films. Key factors here are the drying

temperature and time, which directly influence the strength and uniformity of the formed films. Reinforcing materials through the formulation of biocomposites using materials such as nanocellulose, lignin, and PLA demonstrates significant improvements in mechanical strength. However, most applications for these biopolymers remain in the food packaging industry. An area of opportunity still exists in the study of cellulose-based filaments for application in 3D printing.

Although acid hydrolysis is widely reported as the predominant method for cellulose extraction due to its efficiency and the high degree of purity it yields [18], [44], [48], the reviewed studies exhibit marked heterogeneity in experimental conditions (including acid concentration, temperature, reaction time, and type of biomass residue) which makes direct comparisons of yield and structural quality difficult [24], [34], [45]. In many cases, high crystallinity levels are reported without discussing the environmental impact associated with the use of corrosive reagents or the costs related to effluent neutralization, thereby limiting a comprehensive assessment of sustainability.

Furthermore, although enzymatic methods are frequently described as more environmentally friendly alternatives [27], [30], several studies fail to include comparative productivity analyses or economic feasibility evaluations at the industrial scale [26], [31], making it unclear whether their lower environmental impact offsets their longer processing times. Similarly, the use of green solvents, particularly deep eutectic solvents [47], is presented as a promising alternative; however, the literature still lacks systematic analyses comparing their technical performance, energy consumption, and costs with those of conventional methods, revealing a gap between experimental innovation and industrial applicability.

In biopolymer formulation, significant methodological inconsistencies are also observed. While some studies focus primarily on mechanical and thermal properties [55], [74], others prioritize environmental indicators such as carbon footprint and life cycle assessment [66], [67], without establishing common comparative frameworks. Moreover, variability in plasticizer selection, reinforcement ratios, and processing techniques [36], [41], [52] leads to results that are difficult to extrapolate. This lack of standardization limits the possibility of conducting integrative analyses and highlights the need for comparative protocols capable of simultaneously evaluating mechanical performance, environmental impact, and economic feasibility.

V. CONCLUSION

The development of biopolymers from renewable sources has proven to be a viable and sustainable alternative for creating materials with diverse applications. However, current cellulose extraction methods still present certain disadvantages, including high water consumption, generation of acidic wastewater, lengthy processing times, and high production costs. Furthermore, the production of cellulose-based biopolymers highlights the critical importance of raw material selection, particle size, type and quantity of plasticizer, and material reinforcement, as these factors significantly influence the mechanical and thermal properties of the formulated biopolymers.

The primary techniques identified for biopolymer production are casting, extrusion, and compression molding, with cas-

ting being the most commonly used method for creating films from polymer solutions. The main applications of biopolymers derived from agro-industrial waste were identified in the food industry, particularly for food packaging. According to life cycle analysis, biopolymers are notable for generating a lower carbon footprint and reduced consumption of fossil resources; however, economic and environmental challenges persist in certain stages of their life cycle.

There is a need to generate knowledge focused primarily on the extraction and manufacturing stages of biopolymers, aiming to utilize agro-industrial waste through sustainable, large-scale processes that reduce production costs. Future research should therefore prioritize the transition from laboratory-scale studies to pilot and industrial-scale validation of cellulose extraction and biopolymer production processes. In particular, scale-up strategies must address process optimization, energy efficiency, solvent recovery, and waste management to ensure technical feasibility under real production conditions. Additionally, comprehensive and standardized life cycle assessment (LCA) studies are required to evaluate environmental performance across the entire value chain, from raw material sourcing to end-of-life scenarios. The integration of techno-economic analyses will also be essential to assess cost competitiveness, investment requirements, and market viability compared to those of conventional petroleum-based polymers. Addressing these aspects will be crucial to bridging the gap between academic research and industrial implementation, thereby strengthening the sustainable potential of agro-industrial waste-derived biopolymers.

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The authors declare that they have no conflict of interest.

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The authors declare that no generative artificial intelligence tools were used in the preparation of this manuscript.

REFERENCES

- [1] I. M. Ríos-Baldrán, I. Luzardo-Ocampo, J. Santos-Cruz, J. F. García-Trejo, C. Gutiérrez-Antonio "Biocombustibles sólidos: una alternativa económica y sostenible para la generación de energía eléctrica en México", *Digital ciencia@UAQRO*, vol. 12, No.2, pp. 41-50, 2019 [online]. Available: <https://revistas.uaq.mx/index.php/ciencia/article/view/32>.
- [2] M. Y. Abdullaye and A. Y. Guliyev, "Environmental Impact Assessment of Petroleum-Based Bioplastics", *World Science*, vol. 5, 2022. https://doi.org/10.31435/rsglobal_ws/30092022/7867.
- [3] J. Zhu, Z. Luo, T. Sun, W. Li, W. Zhou, X. Wang, X. Fei, H. Tong and K. Yin, "Cradle-to-grave emissions from food loss and waste repre-

- sent half of total greenhouse gas emissions from food systems”, *Nature Food*, vol. 4 (2023). <https://doi.org/10.1038/s43016-023-00710-3>.
- [4] M. Z. Mahmud, M. H. Mobarak, N. Hossain, “Emerging trends in biomaterials for sustainable food packaging: A comprehensive review”, *Helvion*, vol. 10, N° 1, 2024. <https://doi.org/10.1016/j.helivon.2024.e24122>
 - [5] P. Pal, A.K. Singh, R.K. Srivastava, S.S. Rathore, U. K. Sahoo, S. Subudhi, P.K. Sarangi and P. Prus, “Circular bioeconomy in action: transforming food wastes into renewable food resources”, *Foods*, vol. 13, 2024. <https://doi.org/10.3390/foods13183007>.
 - [6] N. Mejías-Brizuela, E. Orozco-Guillen, N. Galán-Hernández, “Aprovechamiento de los residuos agroindustriales y su contribución al desarrollo sostenible de México”, *Revista de Ciencias Ambientales y Recursos Naturales*, vol. 6, N0.2, pp. 27-41. 2016. [online]. Available: https://www.ecorfan.org/spain/researchjournals/Ciencias_Ambientales_y_Recursos_Naturales/vol2num6/Revista_de_Ciencias_Ambientales_y_Recursos_Naturales_V2_N6.pdf.
 - [7] P. Özkaya, S. Dağbaşı and M. Uyarcan, “Utilization of food waste in production of bacterial cellulose”, *Journal of Agriculture Faculty of Ege Univ.* vol. 60, N° 18, January 2024. <https://doi.org/10.20289/zfdergi.1350359>.
 - [8] H. Rostamabadi et al., “Recent trends in the application of films and coatings based on starch, cellulose, chitin, chitosan, xanthan, gellan, pullulan, Arabic gum, alginate, pectin, and carrageenan in food packaging”, *Foodfrontiers*, vol. 5, N° 2, 2024. <https://doi.org/10.1002/fft2.342>.
 - [9] M. A. Riera, S. Maldonado and R. R. Palma, “Residuos agroindustriales generados en Ecuador para la elaboración de bioplásticos”, *Revista Ingeniería Industrial*, vol. 17 N° 3 pp.227-246, 2018. <https://doi.org/10.22320/S07179103/2018.13>.
 - [10] K. Cury, Y. Aguas, A. Martínez, R. Olivero, L. Chams, “Residuos agroindustriales su impacto, manejo y aprovechamiento”, *Revista Colombiana de Ciencia Animal*, vol. 9 N° S1, May. 2017. <https://doi.org/10.24188/recia.v9.nS.2017.530>.
 - [11] J. Velasco-Velasco, “Residuos agroindustriales con potencial de compostaje”, *AP*, vol. 9, N° 8, ago. 2018. [Online]. Available: <https://revista-agroproductividad.org/index.php/agroproductividad/article/view/795>.
 - [12] J. Verma, M. Petru and S. Goel, “Cellulose bases materials to accelerate the transition towards sustainability”, *Industrial Crops and Products*, vol. 210, April 2024. <https://doi.org/10.1016/j.indcrop.2024.118078>.
 - [13] A. Sharma, M. Thakur, M. Bhattacharya, T. Mandal and S. Goswami, “Commercial application of cellulose nano-composites-A review”, *Biotechnology Reports*, vol. 21, pp. e00316, 2019. <https://doi.org/10.1016/j.btre.2019.e00316>.
 - [14] V. D. C. Bastidas-Flores. “Envoltura comestible a base de celulosa microcristalina de bagazo de caña de azúcar”, *B.S.*, 2016. [Online]. Available: <https://repositorio.utm.edu.ec/handle/123456789/5313>.
 - [15] S. N. H. M. Azmin, N. A. B. M Hayat and M. S. M. Nor, “Development and characterization of food packaging bioplastic film from cocoa pod husk cellulose incorporated with sugarcane bagasse fibre”, *Journal of Bioresources and Bioproducts*, vol. 5 N°4, pp. 248-255, 2020. <https://doi.org/10.1016/j.jobab.2020.10.003>.
 - [16] P. Fronza, M. J. P. A. Batista, A. S. Franca and L. S. Oliveira, “Bio-nanocomposite Bases on Cassava Waste Starch, Locust Bean Galactomannan, and Cassava Waste Cellulose Nanofibers”, *Foods*, vol. 13, N° 2, January 2024. <https://doi.org/10.3390/foods13020202>.
 - [17] C. C. S Coelho, M. Michelin, M. A. Cerqueira, C. Goncalves, R. V. Tonon, L. M. Pastrana, O. Freitas-Silva, A. A. Vicente, L. M. C. Cabral, J. A. Teixeira, “Cellulose nanocrystals from grape pomace: Production, properties, and cytotoxicity assessment”, *Carbohydrate Polymers*, vol. 192, July 2018. <https://doi.org/10.1016/j.carbpol.2018.03.023>.
 - [18] F. Luzzi, D. Puglia, F. Sarasini, J. Tirillo, G. Maffei, A. Zuurro, R. Lavecchia, J. M. Kenny, L. Torre, “Valorization and extraction of cellulose nanocrystals from North African Grass: *Ampelodesmos mauritanicus* (Diss)”, *Carbohydrate Polymers*, vol. 209, January 2019. <https://doi.org/10.1016/j.carbpol.2019.01.048>.
 - [19] F. A. dos Santos, G. C. V. Iulianelli, M. I. Bruno Tavares, “The Use of Cellulose Nanofillers in Obtaining Polymer Nanocomposites: Properties, Processing, and Applications”, *Materials Sciences and Applications*, vol. 7, N° 5, pp. 257-294, 2016. <https://doi.org/10.4236/msa.2016.75026>.
 - [20] I. M. Toplicean and A. Datcu, “An Overview on Bioeconomy in Agricultural Sector, Biomass Production, Recycling, Methods, and Circular Economy Considerations”, *Agriculture*, vol. 14 (2024). <https://doi.org/10.3390/agriculture14071143>.
 - [21] J. Apuzzo III, “Cellulosic composition containing coffee parchment cellulose and uses thereof”, U.S. Patent N° 10,633,521 B2, Apr.28,2020.
 - [22] M. A. Souza, I.T. Vilas-Boas, J. M. Leite-da-Silva, P. d. N. Abrahão, B. E. Teixeira-Costa, V. F. Veiga-Junior, “Polysaccharides in Agro-Industrial Biomass Residues”, *Polysaccharides*, vol. 3, N° 1, January 2022. <https://doi.org/10.3390/polysaccharides3010005>.
 - [23] A. F. Alzate-Arbeláez, E. Dorta, C. López-Alarcón, F. B. Cortés, B. A. Rojano, “Immobilization of Andean Berry (*Vaccinium meridionale*) polyphenols on nanocellulose isolated from banana residues: A natural food additive with antioxidant properties”, *Food Chemistry*, vol. 294, October 2019. <https://doi.org/10.1016/j.foodchem.2019.05.085>.
 - [24] F. Kallel, F. Bettaieb, R. Khiri, A. García, J. Bras, S. E. Chaabouni “Isolation and structural characterization of cellulose nanocrystals extracted from garlic Straw residues”, *Industrial Crops and Products*, vol.87, 2016. <https://doi.org/10.1016/j.indcrop.2016.04.060>.
 - [25] Y. A. Vargas-Corredor y L. I. Pérez-Pérez, “Aprovechamiento de residuos agroindustriales en el mejoramiento de la calidad del ambiente”, *Rev. Fac. Cienc. Básicas*, vol. 14, N° 1, pp. 59–72, abr., 2018. <https://doi.org/10.18359/rfcb.3108>.
 - [26] M. Mujtaba, L. Fraceto, M. Fazeli, S. Mukherjee, S. M. Savassa, G. A. de Medeiros, A. do Espírito Santo Pereira, S. Manini, J. Lipponen and F. Vilaplana, “Lignocellulosic biomass from agricultural waste to the circular economy: A review with focus on biofuels, biocomposites and bioplastics”, *Journal of Cleaner Production*, vol. 402, 2023. <https://doi.org/10.1016/j.jclepro.2023.136815>.
 - [27] Z. Gao, K. Alshehri, Y. Li, H. Qian, D. Sapsford, P. Cleall and M. Harbottle, “Advances in biological techniques for sustainable lignocellulosic waste utilization in biogas production”, *Renewable and Sustainable Energy Reviews* (2022). <https://doi.org/10.1016/j.rser.2022.112995>.
 - [28] C. Redondo-Gómez, M. Rodríguez Quesada, S. Vallejo Astúa, J. P. Murillo Zamora, M. Lopretti and J. R. Vega-Baudrit, “Biorefinery of Biomass of Agro-Industrial Banana Waste to Obtain High-Value Biopolymers”, *Molecules*, 25(17),3829,2020. <https://doi.org/10.3390/molecules25173829>.
 - [29] M. R. Cherubin, J. L. Nunes-Carvalho, C. E. Pellegrino-Cerri, L.A. Horta-Nogueira, G.m. Souza and H. Cantarella, “Land use and management effects on sustainable sugarcane-derived bioenergy”, *Land*, vol. 10, 2021. <https://doi.org/10.3390/land10010072>.
 - [30] O. B. Chukwuma, M. Rafatullah, H. A. Tajarudin and N. Ismail, “Lignocellulolytic Enzymes in Biotechnological and Industrial Processes: Areview”, *Sustainability*, vol.12, 2020. <https://doi.org/10.3390/su12187282>.
 - [31] I. Almaraz-Sánchez, A. Amaro-Reyes, J. A. Acosta-Gallegos and M. Mendoza-Sánchez, “Processing Agroindustry By-Products for Obtaining Value-Added Products and Reducing Environmental Impact”, *Journal of Chemistry* (2022). <https://doi.org/10.1155/2022/3656932>.
 - [32] D. Nava-Pacheco, I. A. Juárez-García, O. Landeta-Escamilla, S. Del Moral y E. S. Rosas-Mendoza, “Bioenergy potential from agroindustrial wastes of the State of Veracruz”, *Renewable Energy, Biomass & Sustainability (REB&S)*, Vol.2, No. 2, pp. 1-6, 2020. [Online]. Available: <http://repositorios.orizaba.tecnm.mx:8080/xmlui/bitstream/handle/123456789/601/4.%20ALDESER.pdf?sequence=1&isAllowed=y>.
 - [33] J. D. Cabos Sanchez, M. K. Lezama-Escobedo, C. B. Bardales-Vásquez, K. M. E. Medina-Vásquez, C. A. León Torres, “Production of biogas and biofertilizers from lignocellulosic waste in a anaerobic biorreactor”, *ALFA, Revista de Investigación en Ciencias Agronómicas y Veterinarias*, vol.7, 2023. <https://doi.org/10.33996/revistaalfa.v7i21.239>.
 - [34] R. Gómez-García, S. C. Sousa, Ó. L. Ramos, D. A. Campos, C. N. Aguilar, A. R. Madureira, M. Pintado, “Obtention and Characterization of Microcrystalline Cellulose from Industrial Melon Residues Following a Biorefinery Approach”, *Molecules*, vol.29, 2024. <https://doi.org/10.3390/molecules29143285>.
 - [35] D. Dutta and N. Sit, “A comprehensive review on types and properties of biopolymers as sustainable bio-based alternatives for packaging”, *Food Biomacromolecules*, vol.1, (2024). <https://doi.org/10.1002/fob2.12019>.
 - [36] M. Flórez, P. Cazón and M. Vázquez, “Selected Biopolymers’ Processing and Their Applications: A Review”, *Polymers*, vol. 15 (2023). <https://doi.org/10.3390/polym15030641>.

- [37] A. Elgarahy, M. G. Eloffy, E. Guibal, H. M. Alghamdi and K. Elwakeel, "Use of biopolymers in wastewater treatment: A brief review of current trends and prospects", *Chinese Journal of Chemical Engineering*, (2023). <https://doi.org/10.1016/j.cjche.2023.05.018>.
- [38] M. F. Valero-Valdieso, Y. Ortegón and Y. Uscategui, "Biopolímeros: avances y perspectivas", *Rev. Fac.nac. minas*, vol.80, N° 181, pp.171-180. Jun, 2013.ISSN 0012-7353. [online] Available:<http://www.scielo.org.co/pdf/dyna/v80n181/v80n181a19.pdf>
- [39] M. Flórez, P. Cazón and M. Vázquez, "Selected Biopolymers' Processing and Their Applications: A Review", *Polymers*, vol. 15, 2023. <https://doi.org/10.3390/polym15030641>.
- [40] A. A. Sundarraj and T. V. Ranganathan, "A review on cellulose and its utilization from agro-industrial waste", *Drug invention Today*, Vol. 10, N° 1, pp.89-94. 2018. [Online]. Available: <https://www.researchgate.net/publication/324442289>
- [41] Y. Liu, S. Ahmed, D. E. Sameen, Y. Wang, R. Lu, J. Dai, S. Li and W. Qin, "A review of cellulose and its derivatives in biopolymer-based for food packaging application", *Trends in Food Science and Technology*, vol. 112, 2021. <https://doi.org/10.1016/J.TIFS.2021.04.016>.
- [42] A. Kumar, M. Hasan, S. Mangaraj, M. Pravitha, D. Kumar-Verma, P. Prakash-Srivastav, "Trends in Edible Packaging Films and its Prospective Future in Food: A Review", *Applied Food Research*, vol. 2, N°1, junio 2022. <https://doi.org/10.1016/j.afres.2022.100118>
- [43] C. Zhong, "Industrial-Scale Production and Applications of Bacterial Cellulose", *Frontiers in Bioengineering and Biotechnology*, vol. 8, 2020. <https://doi.org/10.3389/fbioe.2020.605374>.
- [44] S. J. Owonubi, S. C. Agwuncha, N. M. Malima, G. B. Shombe, E. M. Makhatha and N. Revaprasadu, "Non-woody Biomass as Sources of Nanocellulose Particles: A Review of Extraction Procedures", *Frontiers*, vol.9, April 2021. <https://doi.org/10.3389/fenrg.2021.608825>
- [45] M. A. Lorenzo-Santiago and R. Rendón Villalobos, "Isolation and characterization of micro cellulose obtained from waste mango", *Polímeros*, vol.30, N° 3, 2020. <https://doi.org/10.1590/0104-1428.09119>
- [46] S. R. Alfaro-Flores, M. B. Álvarez-Quiroz, J. E. Asato-Cerna, y J. A. González-Vásquez, "Nanopartículas de celulosa: revisión sistemática", *Gest. Op. Ind.*, vol. 2, n.º 02, pp. 8-20, ene. 2024. <https://doi.org/10.17268/goi4.0.2023.06>
- [47] M. Maja, D. Gašo-Sokač, M. Komar, M. Jakovljevic and V. Bušić, "Potencial of Deep Eutectic Solvents in the Extraction of Organic Compounds Food Industry By-Products and Agro-Industrial Waste", *Separations*, vol.11, N° 1, 2024. <https://doi.org/10.3390/separations11010035>
- [48] D. Pradhan, A. K. Jaiswal, S. Jaiswal, "Emerging technologies for the production of nanocellulose from lignocellulosic biomass", *Carbohydrate Polymers*, vol.285, 16 February 2022. <https://doi.org/10.1016/j.carbpol.2022.119258>
- [49] H. Shaghaleh, X. Xu and S. Wang, "Current progress in production of biopolymeric materials bases on cellulose, cellulose nanofibers and cellulose derivatives", *RSC Advances*, vol 8, pp. 825-842, 2017. <https://doi.org/10.1039/C7RA11157F>
- [50] J. L. W. Morgan, J. T. McNamara, M. Fischer, J. Rich, H. M. Chen, S. G. Withers and J. Zimmer, "Observing cellulose biosynthesis and membrane translocation in crystallo", *Nature*, vol 531, 17 March 2016. <https://doi.org/10.1038/nature16966>
- [51] K. C. de Souza, G. R dos Santos, F. C. S. Trindade, A. F. de S Costa, Y. M. B de Almeida, L. A Sarubbo and G. M Vinhas, "Production of bacterial cellulose biopolymers in media containing rice and corn hydrolysate as carbon sources", *Polymers and Polymer Composites*, vol. 29, N° 9, 2021. <https://doi.org/10.1177/09673911211059706>
- [52] M. Sharma, N. Tellili, I. Kacem and T. Rouissi, "Biopolymers: From Production to Environmental Applications-A Review", *Appl. Sci.*, vol. 14, 2024. <https://doi.org/10.3390/app14125081>
- [53] M. F. Acosta-Humánez, A. A. Arrieta, J. Hernández, Y. Garay, E. M. Combatt, K. H. Castillo, N. Adanasjeva, M. Palencia. "An overview of basic characterization techniques for natural-originated biopolymers: UV-Vis and FTIR spectroscopy - a review", *Journal of Science with technological applications*, vol. 18, 2024. <https://doi.org/10.34294/j.jsta.25.18.106>
- [54] S. Baidurah, "Methods of Analyses for Biodegradable Polymers: Review", *Polymers*, vol. 14, 2022. <https://doi.org/10.3390/polym14224928>.
- [55] B. T. Tomoda, P. H. Yassue-Cordeiro, J. V. Ernesto, P. S. Lopes, L. O. Péres, C. Silva and M. A. Moraes, "Characterization of biopolymer membranes and films: Physicochemical, mechanical, barrier, and biological properties", *Biopolymer Membranes and Films*, 2020. <https://doi.org/10.1016/B978-0-12-818134-8.00003-1>.
- [56] J. L. Fredricks, A. M. Jiménez, P. Grandgeorge, R. Meidl, E. Law, J. Fan, E. Roumeli "Hierarchical biopolymer-based materials and composites" *Journal of Polymer Science*, vol. 61, 2023. <https://doi.org/10.1002/pol.20230126>.
- [57] M. J. Getahun, B. B. Kassie, T. S. Alemu, "Recent advances in biopolymer synthesis, properties & commercial applications: a review", *Process Biochemistry*, vol. 145, 2024. <https://doi.org/10.1016/j.procbio.2024.06.034>.
- [58] H. N. Abdelhamid and A. P. Mathew, "Celulose-Based Nanomaterials Advance Biomedicine: A Review", *International Journal of Molecular*, vol.23, 2022. <https://doi.org/10.3390/ijms23105405>.
- [59] M. Oprea and S. Voicu, "Recent advances in composites based on cellulose derivatives for biomedical applications", *Carbohydrate Polymers*, vol. 247, 2020. <https://doi.org/10.1016/j.carbpol.2020.116683>.
- [60] H. Abdelhamid and A. Mathew, "Cellulose-Based Nanomaterials Advance Biomedicine: A Review", *International Journal of Molecular Sciences*, vol. 23, 2022. <https://doi.org/10.3390/ijms23105405>.
- [61] P. V. Navya, V. Gayathri, D. Samanta and S. Sampath, "Bacterial Cellulose: A promising biopolymer with interesting properties and applications", *International Journal of Biological Macromolecules*, vol. 220, 2022. <https://doi.org/10.1016/j.ijbiomac.2022.08.056>.
- [62] H. Sánchez, W. Ponce, B. Brito, W. Viera, R. Baquerizo and M. Riera, "Biofilms production from avocado waste", *Ing. Univ.*, vol.25, 2021. <https://doi.org/10.11144/Javeriana.ined25.bpaw>.
- [63] R. S. Riseh, M. G. Vazvani, M. Hassanisaad and Y. Skorik, "Micro-/Nano-Carboxymethyl Cellulose as a Promising Biopolymer with Prospects in the Agriculture Sector: A Review", *Polymers*, vol. 15 2023. <https://doi.org/10.3390/polym15020440>.
- [64] N. A. Zainul-Armir, A. Zulkifli, S. Gunaseelan, S. Devi-Palanivelu, K. Mohd-Salleh, M. H. Che Othman and S. Zakaria, "Regenerated Cellulose Products for Agricultural and Their Potential: A Review", *Polymers*, vol.13, 2021. <https://doi.org/10.3390/polym13203586>.
- [65] S. Tanpichai, A. Boonmahithisud, N. Soykeabkaew and L. Ongthip, "Review of the recent developments in all-cellulose nanocomposites: properties and applications", *Carbohydrate Polymers*, vol. 286, 2022. <https://doi.org/10.1016/j.carbpol.2022.119192>.
- [66] D. Šuput, S. Popović, J. Ugarković and N. Hromiš, "Application of life cycle assessment in the packaging sector for the environmental assessment of polymer and biopolymer based materials-a review", *Journal On Processing and Energy in Agriculture*, vol. 2, 2022. <https://doi.org/10.5937/jpea26-39342>.
- [67] A. N. Mafé, G. I. Edo, P. O. Akpogheli, O. A. Joshua, E. F. Isoje, U. A. Igbuku, A. E. A. Essagah, "Comparative Analysis of the Environmental Impact of Biopolymer-Based and Conventional Plastic Packaging in Food Engineering Applications", *Al-Mustaqbal Journal of Sustainability in Engineering Sciences*, vol. 2, 2024. <https://doi.org/10.62723/2959-5932.1017>.
- [68] M. Bugarčić, A. Jovanović, J. Petrović, M. Mišić, M. Sokić and M. Milivojević, "Advances in biopolymer production and applications: a comprehensive review of key biomaterials", *Metallurgical and Materials Data*, vol.3, 2024. <https://doi.org/10.30544/mmd37>.
- [69] G. V. Cornejo Reyes, E. A. Marinero-Orantes, C. R. Funes-Guadrón and P. J. Toruño, "Biopolímeros para uso agroindustrial: Alternativa sostenible para la elaboración de una película de almidón termo plástico biodegradable", *Rev. iberoam. bioecon. cambio clim.*, vol. 6, n.º 11, pp. 1359-1382, jul. 2020. <https://doi.org/10.5377/ribcc.v6i11.9824>.
- [70] A. M. Nafchi, M. Moradpour, M. Saeidi and A. Karim, "Thermoplastic starches: Properties, challenges, and prospects", *Starch*, Vol.65, pp 61-72 2013. <https://doi.org/10.1002/star.201200201>.
- [71] S. M. Avramescu, C. Butean, C. V. Popa, A. Ortan, I. Moraru and G. Temocico, "Edible and Functionalized films/ coatings-performances and perspectives", *Coatings*, vol.10, N° 7, 687, 2020. <https://doi.org/10.3390/coatings10070687>.
- [72] E. Alata-Mayhuire, Y. Cuadros-Huamán, L. Miranda-Zanardi and E. Medina-de Miranda, "Biopelículas producidas con cáscara de naranja y reforzadas con celulosa bacteriana", *Revista de la Sociedad Química del Perú*, vol. 85, N° 2 abr/jun2019. Available: <http://www.scielo.org.pe/pdf/rsqp/v85n2/a10v85n2.pdf>

- [73] D. Sánchez-Aldana, J. C. Contreras-Esquivel, G. V. Nevárez-Moorillón and C. N. Aguilar, "Caracterización de películas comestibles a base de extractos pécticos y aceite esencial de limón Mexicano", *CyTA-Journal of Food*, vol.13, N° 1, pp. 17-25, 2015. <http://dx.doi.org/10.1080/19476337.2014.904929>.
- [74] C. C. de Souza-Coelho, R. B. Soares-Silva, C. W. Piler-Carvalho, A. Linhares-Rossi, J. A. Teixeira, O. Freitas-Silva, L. M. Correa Cabral, "Cellulose nanocrystals from grape pomace and their use for the development of starch-based nanocomposite films", *International Journal of Biological Macromolecules*, vol. 159, pp 1048-1061, 2020. <https://doi.org/10.1016/j.ijbiomac.2020.05.046>.
- [75] L. E. Lozano-Valencia, A. Callejas-Tomás, J. A. Flores-González and L. A. Rojas-Rodríguez, "Síntesis y caracterización de polímeros elaborados a partir de cascarras de frutas", *Revista ConsCiencia*, vol.1, N° 2, pp 32-37, 2019.[Online] Available: https://gaceta.cch.unam.mx/sites/default/files/revistas/2023-05/consencia_2_web.pdf#page=34.
- [76] A. Pacheco, A. Evangelista-Osorio, K. G. Muchaypiña-Flores, L. A. Marzano-Barreda, P. Paredes Concepción, H. Palacín-Baldeón, M. S. Nascimientos-Dos Santos, M. Vinícius-Tres, G. Leone-Zabot and L. Olivera-Montenegro, "Polymeric materials obtained by extrusion and injection molding from lignocellulosic agroindustrial biomass", *Polymers*, vol.20 N° 15, 4046, 2023. <https://doi.org/10.3390/polym15204046>.
- [77] A. Agüero, D. García-Sanoguera, D. Lascano, S. Rojas-Lema, J. Ivorra-Martínez, O. Fenollar and S. Torres-Giner, "Evaluation of different compatibilization strategies to improve the performance of injection-molded green composite pieces made of polylactide reinforced with short flaxseed fibers" *Polymers*, vol.12, N° 4, 821, April 2020. <https://doi.org/10.3390/polym12040821>.
- [78] B. Tsegaye, A. Ström and M.S. Hedenqvist, "Thermoplastic lignocellulose materials: A review on recent advancement and utilities", *Carbohydrate Polymer Technologies and Applications*, vol.5, 2023. <https://doi.org/10.1016/j.carpta.2023.100319>.
- [79] M. Tanase-Opedal, E. Espinosa, A. Rodríguez and G. Chinga-Carrasco, "Lignin: A biopolymer from forestry biomass for biocomposites and 3D printing", *Materials*, vol. 12, N° 18, September 2019. <https://doi.org/10.3390/ma12183006>.
- [80] FAO., "Crops and livestock products", FAOSTAT, 15 de Junio de 2025. <https://www.fao.org/faostat/en/#data/QCL>.
- [81] IPCC, "Climate Change 2021, The Physical Science Basis", Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf.