

## Advances in biopolymer production and applications: a comprehensive review of key biomaterials

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### ABSTRACT

This article provides a comprehensive review of recent advancements in biopolymer technology, focusing on their environmental and economic impact across various industries. Key biopolymers discussed include cellulose, lignin, starch, algal polysaccharides, and protein-based polymers such as whey and casein, alongside essential biopolymers like chitin, chitosan, pectin, guar gum, xanthan gum, natural polyesters, and polyamides. These biopolymers have experienced rising demand due to their renewable nature and biodegradability, supporting the shift toward sustainable materials in sectors such as food technology, biomedical applications, and eco-friendly packaging.

By synthesizing insights from industry reports, market trends, and scientific studies, the review highlights the growth trajectory, environmental benefits, and economic viability of biopolymers. The analysis emphasizes how these materials contribute to reducing fossil fuel dependency and waste, positioning them as critical components of the green economy. Furthermore, it addresses challenges such as production costs and scalability, advocating for ongoing research and technological development to maximize their potential. This work underscores the increasingly vital role of biopolymers in sustainable development and sets the stage for further innovation in the field.

**Keywords:** natural polymers, sustainability, industry trends, biodegradable materials.

### 1. Introduction

Biopolymers, defined as polymers produced by living organisms, are not a new concept but have garnered significant attention over the past decade due to their potential in various sustainable applications. These natural polymers differ fundamentally from synthetic polymers in their derivation from renewable resources, such as plants, animals, and microorganisms, and their inherent biodegradability. The distinction is critical in today's environmental context, where the depletion of fossil resources and environmental pollution are major concerns. The primary categories of biopolymers – polysaccharides, proteins, polyesters, and polyamides—each offer unique properties and functionalities that make them suitable for specific applications ranging from packaging and textiles to medical devices and food additives (Das et al., 2023).

Historically, biopolymers were first utilized in their most primitive forms such as wood, natural rubber, and animal leather. Over the centuries, their applications expanded with the advent of industrial processing techniques in the 19<sup>th</sup> and 20<sup>th</sup> centuries (Demain et al.,

2017). In recent years, the push towards sustainability has further amplified the importance of biopolymers, positioning them as pivotal elements in the transition to a greener economy (Machado et al., 2022).

The shift toward biopolymers is fueled not only by the tightening of global regulations around waste and emissions but also by increasing consumer awareness and demand for sustainable products recent (Patti et al., 2022; Kumari et al., 2022; Kakadellis et al., 2020). Economically, biopolymers are becoming increasingly viable due to advances in biotechnology and material science that have improved their cost-competitiveness and performance characteristics (Getahun et al., 2024; Asthana et al., 2024). Environmentally, they offer significant benefits, including reduced carbon footprints and decreased dependency on fossil-based resources. Their biodegradability also presents an answer to the global waste crisis, particularly in the context of single-use products such as packaging (Dey et al., 2021; Walker et al., 2021).

Technological innovations in the last decade have dramatically altered the production and processing landscapes for biopolymers. Genetic engineering, for instance, has enabled the modification of bacteria to produce biopolymers like poly (lactic acid) (PLA) and poly (hydroxyalkanoates) (PHAs) more efficiently (Sehgal et al., 2020; de Castro et al., 2022; Fernandez-Bunster et al., 2022). Similarly,

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advancements in fermentation techniques have facilitated increased yields and lowered costs of biopolymers derived from microbial sources (Sehgal et al., 2020; Fernandez-Bunster et al., 2022). These technological strides have not only enhanced the material properties of biopolymers – such as strength, flexibility, and heat resistance – but also expanded their application potential (Das et al., 2023).

Biopolymers' versatility allows for their application across a diverse range of industries. In food industry biopolymers such as alginate, carrageenan, and pectin are used extensively as thickeners, stabilizers, and gelling agents (Bagal-Kestwal et al., 2019). They are preferred for their natural origin and perceived safety compared to synthetic additives.

The biocompatibility and biodegradability of biopolymers make them ideal for applications such as drug delivery systems, wound dressings, and scaffolds for tissue engineering (Biswal, 2019). For example, chitosan, collagens, poly (glycolic acid) and PLA, are used in tissue engineering and wound healing due to its natural antibacterial properties and ability to promote cell growth (Biswal, 2019; Belaid et al., 2020).

Biopolymers are gaining traction as an environmentally friendly alternative to traditional petroleum-based plastics, especially in the packaging industry. PLA and starch-based bioplastics stand out as prominent examples, prized for their biodegradability and compostability (Teixeira et al., 2023). These materials are derived from renewable resources such as corn starch or sugarcane, processes that not only contribute to reducing carbon emissions but also help in mitigating the accumulation of waste in landfills (Bhatia et al., 2023; Srivastava et al., 2021). The adoption of PLA and similar biopolymers in various packaging applications – from disposable cutlery to agricultural films and food packaging – demonstrates their practical utility and growing acceptance in sectors that are actively seeking sustainable alternatives (Srivastava et al., 2021; Teixeira et al., 2023).

Further extending their utility beyond packaging, research is intensively exploring the potential of biopolymers in high-value applications that were traditionally dominated by conventional plastics and metals. One exciting area of development is in the electronics industry, where biopolymers are being experimented with for creating biodegradable circuits (Li et al., 2020; Piro et al., 2020). This advancement could significantly impact electronic waste management by providing safer degradation of devices post-use, thereby addressing one of the most daunting environmental challenges posed by the tech industry today. For instance, prototypes of biodegradable circuit boards made from biopolymers like PLA, silk fibroin, keratin are being tested to assess their feasibility and performance against standard materials (Ko et al., 2017; Zhu et al., 2016; Madhavan Nampoothiri et al., 2010a).

Additionally, the automotive industry is exploring biopolymers for manufacturing bio-based composites (Volvo Car Corporation, 2024;

BMW group, 2024; Ford Motor Company, 2024). These composites are being developed to replace metal and traditional plastics in various car components such as dashboards, bumpers, and door panels (Carvalho et al., 2024; Pradeep et al., 2024). Made from natural fibers reinforced with biopolymer matrices, these materials not only help in reducing the vehicle's overall weight – thereby improving fuel efficiency – but also enhance the recyclability of vehicle parts at the end of their life cycle (Pradeep et al., 2024). Major car manufacturers are beginning to incorporate such sustainable materials into their new models, aligning with global environmental goals and consumer demand for greener products.

These developments underscore the versatility and vast potential of biopolymers across multiple sectors. As industries continue to pivot towards sustainability, the role of biopolymers is set to grow, driven by advancements in material science and consumer awareness (Ko et al., 2017; de Castro et al., 2022; Getahun et al., 2024). The integration of biopolymers into mainstream applications signifies a critical shift in manufacturing practices, highlighting a collective move towards more sustainable industrial operations (Dragone et al., 2020). This ongoing transition not only supports environmental conservation efforts but also opens up new avenues for innovation in fields that were once heavily reliant on non-renewable materials. Thus, biopolymers are not just a passing trend but a fundamental component of the future materials landscape, promising to redefine how industries think about and use materials in the context of ecological responsibility and sustainability (de Jesus et al., 2016; Patti et al., 2022).

Despite the promising outlook, several challenges hinder the broader adoption of biopolymers. Scalability remains a concern, with current production volumes insufficient to meet global demand for some applications (Machado et al., 2022). Additionally, the performance of biopolymers under various conditions can be inconsistent, and their cost competitiveness is often dependent on volatile agricultural prices (Bagal-Kestwal et al., 2019; Gamage et al., 2022). Regulatory challenges also exist, particularly with regard to food contact applications and international standards for biodegradability (Fletcher et al., 2021).

This review aims to synthesize the trends in production and utilization of biopolymers over the past decade, assess their impact on sustainable development, and explore potential future directions based on current technological advancements and market dynamics. By doing so, it seeks to provide a comprehensive overview of the field, highlighting the economic, environmental, and technological factors that will shape the future of biopolymers.

## 2. Classification and Properties of Biopolymers

This section provides an in-depth look at the classification of biopolymers, detailing various types such as polysaccharides, proteins,

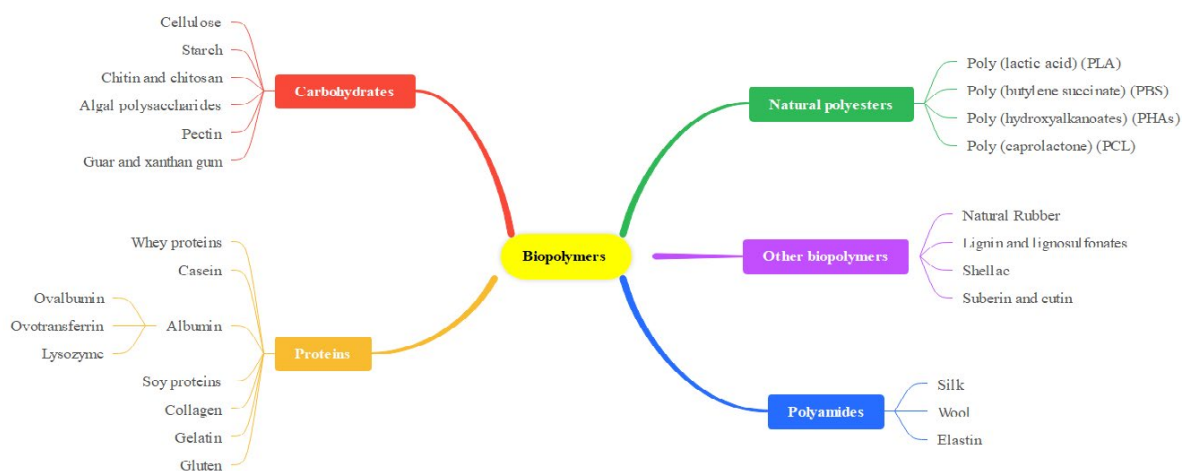


Fig. 1. Classification of Biopolymers

polyesters, and polyamides. It examines their sources, structural properties, and industrial applications, while also discussing the environmental impacts associated with each biopolymer type. This overview will emphasize the importance of biopolymers in promoting sustainable practices across various industries, providing insights into their ecological benefits and the challenges they pose in sustainable development. In the [Figure 1](#) is given the classification of biopolymers based on their chemical structure.

## 2.1. Carbohydrates

### 2.1.1. Cellulose

Cellulose is the most abundant organic polymer on Earth, primarily sourced from the cell walls of plants. It is extracted from cotton, wood, and agricultural residues, which make it not only abundant but also renewable and sustainable. Cotton fibers are nearly pure cellulose, contributing to their comfort and breathability as a textile material (Mahbubul Bashar et al., 2013). Wood cellulose is typically extracted through a pulping process that removes lignin and other components, leaving behind the fibrous cellulose used in paper and other products. Agricultural residues such as corn stalks and wheat straw have also been recognized as valuable sources of cellulose, especially for bioenergy and material applications, promoting a waste-to-wealth model in industrial practices (Sadh et al., 2023).

Cellulose is renowned for its strength and insolubility in water, attributes that stem from the robust hydrogen bonds between its molecular chains. These bonds impart high tensile strength and make cellulose a supportive structural component in plant cell walls. The crystalline structure of cellulose also contributes to its stiffness and resistance to degradation, which are valuable traits in both natural and industrial contexts (Jakob et al., 2022). In addition to its physical properties, cellulose's chemical properties allow it to be processed into various derivatives, each with unique characteristics suitable for specialized applications.

Cellulose is extensively used in the paper and textile industries, where its applications capitalize on its durability and textural properties (Lawson et al., 2022). In paper manufacturing, cellulose provides the primary structure of paper products, contributing to their strength, longevity, and printability (Boufi et al., 2016). This use is critical in everything from everyday printing paper to specialty papers for archival and artistic purposes. In the textile industry, cellulose is the foundation of cotton, linen, and other natural fibers, which are valued for their comfort, absorbency, and dye retention. The versatility of cellulose extends into the production of cellulose derivatives such as cellulose acetate, which are used in making photographic films, eyeglass frames, cigarette filters and coatings (Nisha Yadav et al., 2021). Another very important derivative is cellulose nitrate, known for its use in producing high-energy mixtures, lacquers, and early photographic films due to its flammability and strong adhesive properties (Josmi John et al., 2024). The film industry, for instance, relies on the clarity and dimensional stability of cellulose acetate film bases for both photography and cinematography. In the food industry, microcrystalline cellulose serves as an anti-caking agent and fat substitute, enhancing the texture and stability of processed foods without contributing to caloric intake (Nsor-Atindana et al., 2017). This application is particularly important in low-fat and reduced-calorie food products, where maintaining desirable mouthfeel and consistency can be challenging (Nsor-Atindana et al., 2017).

The sustainable profile of cellulose is also noteworthy. As a biodegradable and compostable material, cellulose contributes to environmental sustainability, reducing waste and facilitating a circular economy. Its natural origin and decomposition capability mean that cellulose-based products can return to the earth without leaving harmful residues, unlike many synthetic polymers. The push towards green chemistry has further elevated the role of cellulose in developing eco-friendly technologies, including biofuels, biocomposites, and bioplastics

(Christina et al., 2024). These developments reflect a broader trend towards leveraging natural materials to reduce environmental impact across industries, making cellulose not only a staple of the current material landscape but also a critical component of future innovations.

### 2.1.2. Starch

Starch, a fundamental polysaccharide, is synthesized by a vast array of plants as an energy reserve and is extracted primarily from crops that are staples in human diets, such as corn, potatoes, wheat, and rice. Each source offers a starch with slightly different properties, influencing its use in various applications. Corn, one of the most widely cultivated sources, yields a high amount of starch per kernel and is heavily used in both food products and industrial applications. Potatoes provide a starch that is notably effective as a thickener due to its high viscosity and gel strength, while rice and wheat starches are prized in the food industry for their texture and neutral taste (Makroo et al., 2021).

Starch is composed of two types of molecules: amylose and amylopectin. Amylose is mostly linear and is responsible for the gelation properties of starch, which are critical in food processing. Amylopectin, on the other hand, is highly branched, contributing to the viscosity and stability of starch pastes. These molecular structures allow starch to exhibit unique properties such as retrogradation and syneresis (water release) upon cooling, which are important in food preparations. Starch's ability to absorb water and swell makes it an excellent thickening, binding, and stabilizing agent. This hydrophilic nature also makes it useful in pharmaceuticals as a disintegrant in tablets (Garcia et al., 2020).

In the food industry, starch is extensively utilized as a thickener, stabilizer, and texture enhancer in products such as soups, sauces, gravies, puddings, and pie fillings (Garcia et al., 2020). Its film-forming ability makes it suitable for edible films and coatings that improve the shelf-life and quality of fresh and processed foods. Beyond food, starch finds significant applications in the papermaking industry, where it is used to improve paper strength and printability. It is also employed in the textile industry for sizing and finishing fabrics, providing a smooth surface for weaving and protecting the fibers during the manufacturing process (Adewale et al., 2022).

Starch-based bioplastics are another growing area of interest, driven by the need for sustainable materials in packaging and disposable products. Polymers derived from starch exhibit biodegradability and are seen as an eco-friendly alternative to conventional petroleum-based plastics. These are used in items such as biodegradable bags, packaging materials, and disposable cutlery, aligning with global efforts towards reducing plastic waste and carbon footprints (Ashok et al., 2018).

Starch's role in sustainable practices extends beyond its applications. As a renewable resource, starch supports the circular economy model by providing a biodegradable material that minimizes waste generation. Its plant-based origin ensures a lower environmental impact compared to synthetic polymers, particularly in terms of greenhouse gas emissions during production. The development of advanced technologies in enzyme biotechnology and microbial fermentation has further enhanced the efficiency of starch modification processes, making it possible to tailor its properties for specific industrial needs without the extensive use of chemicals.

### 2.1.3. Chitin and chitosan

The second most abundant natural polysaccharide in the world is chitin, primarily found in the exoskeletons of crustaceans such as crabs, shrimps, and lobsters, as well as in the cell walls of fungi and the scales of fish and insects (Iber et al., 2022). It is typically harvested from waste products of the seafood industry, making it a prime example of value extraction from byproducts. Chitosan, a derivative of chitin, is produced through a deacetylation process that removes acetyl groups from chitin, enhancing its solubility in water and expanding its application

possibilities (Christina et al., 2024).

Chitin is known for its toughness and versatility, attributed to its long, linear polymer chains packed closely together, forming strong hydrogen bonds. These properties impart significant structural support to the organisms that contain it, helping to protect them against physical damages and infections. Chitosan, due to its increased solubility and positive charge, exhibits unique biological properties including biocompatibility, biodegradability, and non-toxicity, alongside notable antimicrobial and antifungal activities (Biswal, 2019). These attributes make chitosan highly effective for various medical and biotechnological applications.

Chitin and chitosan have wide-ranging applications across several industries. In the medical field, chitosan is used for wound healing dressings due to its natural antibacterial properties and ability to promote faster coagulation and tissue regeneration (Belaid et al., 2020). It is also used in drug delivery systems, where it facilitates controlled release of drugs and enhances the bioavailability of medications. In the field of water treatment, chitosan is employed as a biofilter to capture heavy metals and other pollutants, offering an eco-friendly solution to water purification (Elgarahy et al., 2021). Beyond these, chitosan's film-forming ability makes it useful in the food industry as a coating material that extends the shelf life of perishable goods by inhibiting microbial growth and preventing moisture loss. In agriculture, chitosan serves as a natural biopesticide and biostimulant, enhancing disease resistance and promoting growth in plants (Saberri Riseh et al., 2022).

The extraction and processing of chitin and chitosan have minimal environmental impact, especially compared to synthetic polymers, due to their natural origins and the biodegradable nature of the end products. Utilizing chitin and chitosan contributes to waste reduction, particularly in the seafood industry, by turning crustacean shells, which are typically discarded, into valuable biopolymers. This not only helps in waste management but also reduces the reliance on non-renewable resources.

Furthermore, the application of chitosan in environmental remediation, such as in water purification and as an eco-friendly alternative to chemical pesticides and fertilizers in agriculture, underscores its role in supporting sustainable practices (Saberri Riseh et al., 2022; Elgarahy et al., 2021). The ongoing development in chitin and chitosan chemistry continues to uncover new modifications and applications, enhancing their effectiveness and applicability in various fields. This development is crucial in addressing global challenges related to health, pollution, and sustainability.

#### 2.1.4. Algal polysaccharides

Algal polysaccharides, derived from the cell walls of various algae species, are critical biopolymers with extensive applications across multiple industries. These polysaccharides are predominantly extracted from three major groups of algae: red, brown, and green, each contributing unique characteristics and functionalities. For example, agar and carrageenan are obtained from red algae species such as *Gelidium* and *Eucheuma*, which are cultivated extensively in coastal regions around the world (Porse et al., 2017). Brown algae, such as *Ascophyllum nodosum* and *Laminaria hyperborea*, are the primary sources of alginate (Cajnko et al., 2019). These algae are typically harvested from their natural habitats or grown in aquaculture systems that mimic their natural growing conditions to ensure the sustainability of the supply.

Agar, carrageenan, and alginate, sourced from red and brown algae, exhibit distinct properties that make them invaluable across multiple industries. Agar is known for its robust gelling ability, which does not require additives and forms stable gels at room temperature. This characteristic is essential in both culinary and scientific settings, where it is used as a culture medium in microbiology due to its stability and inertness to microbial enzymes (Basu et al., 2015). In food, agar serves as a vegetarian alternative to gelatin, often found in desserts such as

gels, custards, and marshmallows (Pegg, 2012).

Carrageenan is a versatile polysaccharide containing varying levels of sulfate groups, which influence its gel strength and solubility. This versatility makes carrageenan ideal for complex formulations, particularly in food processing and pharmaceuticals (W R Thomas, 1997). Its role in the food industry is notable for enhancing the texture, mouthfeel, and stability of a wide array of products, including plant-based meat and dairy alternatives (McClements, 2024). The ability of carrageenan to interact with proteins enhances its application in structured products like vegan cheeses, where it provides cohesion and desirable texture.

Alginate, primarily obtained from brown algae, is appreciated for its ability to form gels under mild conditions, typically through interaction with calcium ions. This property is highly useful in both food and non-food applications (Milivojević et al., 2023). In the food sector, alginate provides structural integrity in products without requiring heat, making it ideal for applications such as forming edible films and encapsulation (Parreidt et al., 2018). In the medical field, alginate is valuable in wound care due to its high water absorption capacity, which helps maintain a moist healing environment. Its precise molding properties also make it popular in dentistry, where it is used for creating detailed and comfortable impressions.

The cultivation and harvesting of algae for polysaccharide extraction presents a sustainable alternative to terrestrial crop cultivation, requiring fewer resources such as freshwater and fertilizer, and offering higher yields per acre. Since atmospheric CO<sub>2</sub> levels are believed to impact climate change, algae play a role in carbon capture and sequestration by reducing CO<sub>2</sub> atmospheric content (Moreira et al., 2016). The biodegradability of extracted algal polysaccharides ensures that they break down into non-toxic components in natural environments, contrasting with many synthetic polymers that contribute to microplastic pollution.

#### 2.1.5. Pectin

Pectin is a complex polysaccharide found mainly in the cell walls of terrestrial plants, particularly in the skins and cores of fruits such as apples and citrus fruits. High-pectin fruits, which include apples, pears, quinces, and citrus peels, are typically used as primary sources for commercial pectin extraction (Güzel et al., 2019). The commercial production of pectin primarily involves extracting it from citrus peels and apple pomace, the byproducts of juice production, which not only provides a valuable use for what would otherwise be waste material but also aligns with sustainable manufacturing practices (Güzel et al., 2019).

Pectin is a heteropolysaccharide composed of galacturonic acid units, which can be methylated to varying degrees. This methylation affects pectin's gelling abilities, which are also influenced by the pH and the presence of divalent cations, typically calcium. There are two primary forms of pectin: high-methoxyl pectin, which gels in the presence of high sugar concentrations and acid, and low-methoxyl pectin, which gels in the presence of calcium ions, regardless of sugar concentration (Wan et al., 2021). This ability to form a gel under different conditions makes pectin highly versatile and valuable in food processing, pharmaceuticals, and cosmetics.

In the food industry, pectin is widely used as a gelling agent, thickener, and stabilizer. It is essential in the production of jams and jellies, where it helps to create the desired spreadable but firm texture. Pectin is also used in fruit preparations for yogurts, desserts, and as a fat substitute in baked goods, contributing to reduced-calorie products while maintaining texture and moisture (Cherian et al., 2024). Beyond its role in food, pectin is utilized in the pharmaceutical industry as a drug delivery agent, particularly in gel formulations that require controlled release (Lara-Espinoza et al., 2018). In cosmetics, pectin acts as a stabilizer and thickener in creams and lotions, improving their texture and application properties.

The extraction and use of pectin emphasize the importance of

using byproducts sustainably in industry. Utilizing fruit waste not only helps reduce overall waste in food production but also lessens the environmental impact associated with the disposal of organic materials, which can produce methane, a potent greenhouse gas, when decomposed anaerobically. Additionally, pectin itself is fully biodegradable and non-toxic, making it an environmentally friendly alternative to synthetic polymers in various applications. The demand for natural and sustainable products continues to grow, and pectin perfectly aligns with consumer preferences for clean-label ingredients, further promoting its use across industries.

#### 2.1.6. Guar and xanthan gum

- Guar gum

Guar gum is derived from the seeds of the guar plant (*Cyamopsis tetragonoloba*), which is predominantly grown in India, Pakistan, and the United States (Morris, 2010). The plant thrives in semi-arid regions, making it ideally suited to the climates of these countries. The gum is extracted from the guar seeds and then ground into a fine powder. This process involves removing the husk from the seeds, hydrating them to activate the endosperm, and then milling and screening to produce the guar gum powder.

Guar gum is a high-molecular-weight carbohydrate composed of mannose and galactose sugars. This polysaccharide is highly water-soluble and forms a viscous gel when mixed with water, which is non-ionic and can hydrate rapidly in cold water to form highly viscous solutions at low concentrations (Mudgil et al., 2014). The thickening property is due to the high galactomannan content, which makes it an effective stabilizer and emulsifier in various formulations. Additionally, guar gum has excellent thickening, emulsifying, and stabilizing properties and is resistant to oil, greases, and solvents (Mudgil et al., 2014).

In the food industry guar gum is used as a thickener in sauces and dressings, as a stabilizer in ice cream to prevent ice crystals, and as a binding agent in baked goods to improve texture and extend shelf life. Its ability to control viscosity and build texture makes it suitable for dairy products, soups, and gravies. In the pharmaceutical industry, guar gum is used as a binder in tablets, and as a disintegrant, it helps in the controlled release of drugs (Krishnaiah et al., 2002). Guar gum is also employed in the cosmetics industry as a thickener in lotions and creams, enhancing product consistency and feel.

Guar gum is an environmentally friendly product due to its natural, biodegradable nature. Cultivation of the guar plant also has a positive impact on the ecosystems where it is grown, as it helps to stabilize soil and prevent erosion. Additionally, guar farming requires minimal chemical fertilizers and pesticides, reducing the environmental load and enhancing the sustainability of the production process. The plant's ability to fix nitrogen also improves soil quality, making it beneficial for crop rotation practices.

- Xanthan gum

Xanthan gum is a polysaccharide secreted by the bacterium *Xanthomonas campestris*. This microbial polysaccharide is synthesized in large-scale fermentation processes using glucose, sucrose, or lactose as the carbohydrate substrate (Pollock et al., 1997). The bacterium ferments these sugars to produce xanthan gum as an extracellular product. The commercial production of xanthan gum is highly efficient and scalable, catering to various industrial demands.

This polysaccharide is known for its exceptional viscosity and stability in a wide range of temperatures and pH levels. It is unique in that it can produce a large increase in the viscosity of a liquid by adding a very small quantity of gum, typically on the order of one percent. Furthermore, xanthan gum solutions exhibit pseudoplastic properties, meaning they become less viscous under shear force (when stirred, shaken, or processed) and return to a highly viscous state once the force is removed (Wüstenberg, 2015). This shear-thinning property makes

it very useful in applications where easy flow under normal conditions and high viscosity upon application are required.

In the food industry, xanthan gum is used to improve the texture, consistency, and shelf life of products. It acts as a thickener in sauces and dressings, provides stability in frozen foods, and improves mouthfeel in beverages (Alam et al., 2024). Xanthan gum is also prevalent in gluten-free baking, where it provides the elasticity and stickiness that gluten usually contributes. Beyond food, xanthan gum is used in oil drilling to thicken drilling mud, which carries the drill cuttings to the surface. In the cosmetics industry, it is used to stabilize and thicken formulations, enhancing the application properties of lotions and creams.

The production of xanthan gum is relatively eco-friendly as it utilizes microbial fermentation, which can be carried out using waste products as substrates. This method reduces waste and the need for chemical processes, aligning with sustainable manufacturing practices. Moreover, xanthan gum's biodegradability ensures minimal environmental impact, contributing further to its credentials as a sustainable additive.

#### 2.2. Proteins

##### 2.2.1. Whey proteins

Whey protein is derived from whey, the liquid byproduct of cheese production. When milk is coagulated during the cheese-making process, it separates into curds and whey. The curds are used to make cheese, leaving whey as a byproduct. Historically considered a waste product, whey has gained recognition for its nutritional value and is now processed to extract whey protein, which is a vital dietary supplement and food ingredient. The extraction process involves several steps including filtration and drying, which help concentrate the proteins while removing fats and carbohydrates. The result is whey protein concentrate and whey protein isolate, which are higher in protein content compared to raw whey.

Whey protein is highly regarded for its robust nutritional profile, especially its high levels of essential amino acids and easy digestibility. It contains a higher proportion of branched-chain amino acids (BCAAs) - leucine, isoleucine, and valine - which are crucial for muscle protein synthesis and overall health (Gorissen et al., 2018). Whey protein is not only rapidly absorbed by the body but also contains bioactive components that provide health benefits beyond basic nutritional content, such as immunoglobulins and lactoferrin that support immune function and improve gut health (Solak et al., 2012). Additionally, whey protein exhibits several functional properties that make it invaluable in the food industry. It is highly soluble over a wide pH range, making it ideal for beverages and smoothies (Mehra et al., 2021). Its ability to form gels upon heating contributes to the texture and mouthfeel of yogurts and desserts. Furthermore, whey protein can stabilize emulsions, which is useful in products like salad dressings and mayonnaise, and it can also improve the foaming properties of whipped products (Ma et al., 2013). These characteristics, combined with its nutritional benefits, make whey protein a multifunctional ingredient favored in both health supplements and a variety of food products.

Whey protein is a staple in the sports nutrition industry due to its ability to support muscle repair and growth. It is widely consumed in the form of protein shakes and bars by athletes and fitness enthusiasts. Beyond supplements, whey protein is incorporated into enhanced or functional foods, including infant formula, to improve the nutritional profile. It is also used in medical nutrition products, aiding in the dietary management of individuals recovering from illness or surgery (Solak et al., 2012). Whey protein contributes to the texture and stability of many processed foods. It is used as a binder in meat products, as a stabilizer in whipped creams and foams, and as an emulsifier in salad dressings. Its heat-induced gelation properties are exploited in yogurts and desserts to improve mouthfeel and viscosity. In beverages, whey protein provides cloudiness, viscosity, and nutritional enhancement. It is used in protein-fortified fruit juices, smoothies, and dairy beverages. The less refined forms of whey, such as whey powder and whey permeate, are



used in animal feed to enhance the protein content, benefiting livestock growth and health.

The production of whey protein has environmental implications, primarily related to dairy farming and processing. The dairy industry is a significant contributor to greenhouse gas emissions, water consumption, and land use. However, the utilization of whey protein helps reduce waste by valorizing the byproducts of cheese production. Health-wise, whey protein is considered beneficial for muscle building, weight management, and improving metabolic health. However, it should be consumed in moderation as part of a balanced diet to manage potential impacts on kidney function due to its high protein content.

### 2.2.2. Casein

Casein, the predominant protein found in milk, accounts for approximately 80% of the protein content in cow's milk (Cerbulis et al., 1975). It is extracted through a process of precipitation, which can be initiated by adding specific enzymes or acids that cause the casein to coagulate and separate from the liquid whey and other soluble components. The curds that form are primarily composed of casein, which is then washed and dried to produce casein powder. This process not only maximizes the extraction of protein from milk but also ensures that valuable nutrients are retained in a concentrated form (Kalab, 1979). The primary source of commercial casein is the dairy industry, which processes vast quantities of milk and generates casein as a key byproduct of cheese manufacturing.

Casein is unique among milk proteins due to its complex molecular structure, which allows it to form micelles – spherical aggregates that are soluble in water. These micelles are stable under a wide range of conditions and are able to carry calcium, potassium, magnesium and phosphate groups, making casein an important source of these macroelements (Swaigood, 1993). This structure also imparts casein with excellent emulsifying and stabilizing properties, which are highly valued in various food products. The slow digestibility of casein is another defining characteristic, as it coagulates in the stomach to form a gel that slowly releases amino acids (Sadiq et al., 2021). This slow-release mechanism helps maintain a prolonged sense of satiety and provides a steady supply of nutrients, which is particularly beneficial during periods of fasting.

Casein's unique properties make it a versatile ingredient across several industries. In the food industry, it is used extensively to improve the texture and nutritional quality of products such as cheese, yogurt, and protein-enriched beverages. Its ability to stabilize emulsions makes it ideal for use in ice creams and creams, where it helps prevent the separation of fats and other liquids. Casein is also used in non-food applications such as the production of biodegradable plastics, fibers, and adhesives, where its binding properties are essential. In pharmaceuticals, casein is employed as a carrier for drug delivery systems, exploiting its ability to encapsulate drugs and release them gradually into the body (Sripriyalakshmi et al., 2014).

From a health perspective, casein is beneficial due to its high-quality protein content and the presence of essential amino acids and macronutrients. Nevertheless, it can pose allergenic risks to individuals sensitive to milk proteins and is unsuitable for those with lactose intolerance when not properly isolated from lactose. Its role in various health conditions, such as cardiovascular health due to its modulation of blood pressure and lipid absorption, is also under continuous study, highlighting its complex impact on human health.

### 2.2.3. Egg proteins (albumin)

Egg proteins are predominantly extracted from chicken eggs, which are a staple in global agriculture. The extraction process focuses on separating egg whites and yolks, with the majority of protein being derived from the egg whites. Egg white contains about 10% proteins by weight, primarily ovalbumin, along with other proteins like

ovotransferrin and lysozyme (Abeyrathne et al., 2014). These proteins are isolated using techniques that include simple mechanical separation followed by processes like ultrafiltration or precipitation to ensure purity and functionality (Abeyrathne et al., 2014). The widespread availability of eggs, due to intensive poultry farming, supports a reliable and scalable supply chain for egg protein production.

Egg proteins are renowned for their exceptional nutritional and functional properties. They provide a complete amino acid profile, making them one of the highest-quality protein sources available (Garcés-Rimón et al., 2016). This high biological value signifies that egg proteins are efficiently used by the body for growth and repair. Functionally, egg proteins have diverse applications (Abeyrathne et al., 2013):

- **Ovalbumin** is responsible for the majority of an egg's ability to gel when cooked, a property utilized in food preparation and industrial applications.
- **Ovotransferrin**, known for its iron-binding capabilities, contributes to egg white's antimicrobial properties, making it useful in food preservation.
- **Lysozyme** has enzymatic properties that allow it to break down bacterial cell walls, thus acting as a natural preservative.

These functional traits make egg proteins versatile in various processing environments, enhancing their appeal in multiple sectors.

In the food industry, the multifunctionality of egg proteins is leveraged to improve the texture, stability, and nutritional content of many products. They act as foaming agents in meringues and soufflés, emulsifiers in dressings and mayonnaise, and are essential in gluten-free baking to provide structure and volume (Aguilera, 2018). Beyond culinary uses, the pharmaceutical industry utilizes lysozyme as an antimicrobial agent in formulations designed to combat or prevent infections. In the cosmetics industry, the nurturing effects of egg proteins are harnessed in formulations designed to strengthen hair and moisturize skin.

On the health front, while egg proteins are generally regarded as safe and beneficial for most people, providing essential nutrients for muscle maintenance and overall health, they can also be allergenic. Eggs are one of the most common food allergens, especially among children, necessitating careful management in food products to prevent allergic reactions.

### 2.2.4. Soy proteins

Soy protein is derived from soybeans, a legume native to East Asia but now cultivated globally. The process to extract soy protein typically involves cleaning and dehulling the soybeans, followed by oil extraction, which can be achieved either mechanically or using solvents like hexane. The remaining soybean meal is then processed to produce different types of soy protein products, such as soy protein isolates, concentrates, and textured soy protein. These products differ primarily in their protein content and the presence of other soybean components, such as carbohydrates and fats (Dilawari et al., 2022).

Soy protein is a complete protein, meaning it contains all nine essential amino acids necessary for human health, making it an excellent alternative to animal proteins (Singh et al., 2008). It exhibits strong functional properties including water absorption, gelation, emulsification, and adhesive strengths. These properties make soy protein highly versatile in food formulations and beyond. The protein's structure allows it to be processed into various forms, including powders, textured flakes, and chunks, which mimic the texture of meat, making it popular in vegetarian and vegan diets.

In the food industry, soy protein is valued for its ability to enhance texture, retain moisture, and improve the nutritional profile of products (Singh et al., 2008). It is widely used in processed meat products for its water and fat-binding capabilities, helping to improve yield and texture. Soy protein is also a staple in vegetarian and vegan products, serving as a primary protein source in items like veggie burgers, sausages, and

other meat substitutes. Additionally, it is used in dairy alternatives such as soy milk, yogurts, and cheese, where it provides a dairy-free source of high-quality protein. Beyond food, soy protein finds applications in the paper industry as an adhesive and in the plastics industry as a biodegradable polymer component (Schmitz et al., 2008).

Soy protein production is associated with significant environmental considerations. While soybeans fix nitrogen and can improve soil health, large-scale soy cultivation, especially in countries like Brazil, has led to deforestation and loss of biodiversity (Fearnside, 2001). Efforts to mitigate these impacts include promoting sustainable farming practices and using certified organic and non-GMO soybeans. Health-wise, soy protein is recognized for its benefits, including lowering cholesterol levels, providing phytoestrogens that may reduce the risk of certain cancers, and offering a plant-based protein alternative that is lower in saturated fats and free from cholesterol. However, soy also contains allergens and anti-nutritional factors, though these are generally reduced or eliminated during processing.

### 2.2.5. Collagen

Collagen is extracted from various animal tissues where it serves as a primary structural protein. The most common sources include bovine hides, porcine skins, and marine fish scales and skins, which are typically byproducts of the meat and fish processing industries (Coppola et al., 2020). These sources are processed through steps that include cleaning, enzymatic hydrolysis, or acid and alkaline treatments to extract collagen in its most usable forms. This process not only maximizes the yield of collagen but also ensures that less of the animal goes to waste, aligning with principles of sustainable production. Innovations in sourcing now include exploring more sustainable and less controversial sources like poultry and lab-grown collagen, which aim to address ethical and environmental concerns associated with traditional sources (Kumar et al., 2021).

Collagen's structure is distinguished by its triple-helical form, which resembles a tightly wound cable, contributing to its strength and durability. This structure is crucial in the role collagen plays in the body, providing scaffolding for cells and contributing to the elasticity and regeneration of skin, tendons, and bones (Sorushanova et al., 2019). When processed into gelatin, collagen loses its helical structure and takes on new properties that include the ability to form thermo-reversible gels at certain concentrations and temperatures. Collagen peptides are significantly smaller and more broken down than gelatin, which allows them to dissolve more easily in liquids and be absorbed more effectively by the body, making them particularly powerful as dietary supplements.

Collagen is utilized not only in confections but also to enhance the protein content and texture of meat products, and to act as a binding agent in sausages. Its ability to retain water and fat improves the succulence and mouthfeel of processed foods. Collagen peptides are popular in the wellness industry for their purported health benefits, including supporting joint health, bone density, and skin elasticity. They are marketed in various forms, from powders to capsules, as part of beauty and health regimens. In the medical field, collagen's biocompatibility makes it ideal for products like wound dressings, which support natural healing, and for use in surgical sutures (Deng et al., 2022). Its application in tissue engineering is particularly groundbreaking, with researchers developing collagen-based matrices that support the growth of human cells for tissue regeneration and repair. In cosmetics, collagen is valued for its anti-aging properties, used in creams and serums that claim to enhance skin firmness and reduce wrinkles (Gomez-Guillen et al., 2011).

While collagen production utilizes byproducts of the meat and fish industries, thereby promoting waste reduction, the environmental impact of these industries cannot be overlooked. They are significant contributors to greenhouse gas emissions, water pollution, and biodiversity loss. Efforts to mitigate these impacts include better

management practices in farming and processing, as well as the development of alternative sources like marine collagen, which has a lower environmental footprint. Health-wise, while collagen supplements are considered safe for most people, they can sometimes cause digestive side effects, and the benefits can vary widely among individuals. Moreover, consumers are advised to use collagen products from reputable companies to avoid contaminants and ensure they are getting a product that accurately reflects labeling claims.

### 2.2.6. Gelatin

Gelatin is primarily derived from the collagen in animal tissues, particularly from bovine hides, pork skins, and bones. These sources are byproducts of the meat processing industry, making gelatin production a method of valorizing parts of the animal that would otherwise be discarded (Gomez-Guillen et al., 2011). The production of gelatin involves several steps: pre-treatment to prepare the raw materials, partial hydrolysis to break down collagen into gelatin, and extensive purification to ensure the final product is fit for consumption or use in various applications. This process not only maximizes the use of animal parts but also aligns with sustainable practices by reducing waste.

Gelatin is a biopolymer that is distinguished by its ability to form gels when dissolved in hot water and then cooled. It is essentially a mixture of peptides and proteins produced by partial hydrolysis of collagen. The unique properties of gelatin include its thermo-reversible gelation, melt-in-the-mouth characteristics, and its ability to form clear, strong gels. These properties make gelatin highly valuable in food processing, pharmaceuticals, and photographic applications. Gelatin's viscosity and film-forming capabilities also make it useful as a binding and coating agent (Mhd Sarbon et al., 2013).

Gelatin is extensively used as a gelling agent in the production of jellies, marshmallows, and gummy candies. It is also employed in dairy products like yogurt and ice cream to improve texture and consistency. Additionally, gelatin is used in the clarification of juices and vinegar. In the pharmaceutical industry, gelatin is crucial for the production of capsules and tablets. It serves as a safe, digestible coating that can also control the release of active ingredients. Gelatin is also used in the manufacturing of suppositories and hemostatic sponges (Jiang et al., 2019). Gelatin plays a vital role in the production of photographic films and papers, where it acts as a binder for light-sensitive silver halides (Mikhailov, 2023). In cosmetic products, gelatin is used for its skin-conditioning properties and as a base in various creams and lotions.

The production of gelatin is intrinsically linked to the meat processing industry, which involves significant environmental concerns, including resource-intensive farming practices. However, using byproducts from this industry to produce gelatin helps mitigate some environmental impacts by reducing waste and promoting a more circular economy. Health-wise, gelatin is generally recognized as safe and beneficial due to its protein content and unique amino acid profile. It can aid in skin, hair, and nail growth, improve joint mobility, and even support gut health. However, as a derivative of animal collagen, gelatin is not suitable for vegetarians or vegans, and its consumption can raise ethical concerns for some groups.

### 2.2.7. Gluten

Gluten is a complex mixture of proteins primarily found in wheat, and similar proteins are present in other grains such as barley, rye, and oats (Biesiekierski, 2017). It is extracted from wheat flour by kneading the dough in water, which washes out the starch granules, leaving behind a sticky network of gluten proteins. This process capitalizes on the natural occurrence of gluten in wheat, allowing for its extraction and use in various applications.

The properties of gluten include its elasticity and viscosity, which are critical in baking and food processing. Gluten's unique viscoelastic properties allow it to trap air bubbles, helping bread and other baked

goods rise and maintain their shape. Additionally, gluten's ability to absorb water contributes to the moistness and freshness of baked products. Its capacity to form a cohesive network makes it essential for the texture and structural integrity of many baked goods.

Industrially, gluten is utilized extensively in the food industry, particularly in baking. It is vital for producing a variety of bread, pasta, and cereal products, where gluten's elastic properties are crucial for the texture and volume of these products (Day et al., 2006). Beyond traditional baking, gluten is used in meat substitutes, where it serves as a base for products aimed at mimicking the texture of meat, commonly referred to as seitan or wheat meat (Maningat et al., 2022). Gluten is also employed as a stabilizing agent and protein supplement in a variety of processed and packaged foods.

The environmental impact of gluten production is primarily associated with wheat farming, which involves significant land use, water consumption, and the use of fertilizers and pesticides. These agricultural practices can lead to soil degradation, water scarcity, and pollution due to runoff. However, as gluten is derived from a staple crop that is widely grown and consumed, its production is integrated into existing agricultural systems, which can be optimized for greater sustainability. Health-wise, gluten is safe and nutritious for the majority of the population, providing essential proteins that contribute to a balanced diet. However, for individuals with celiac disease, non-celiac gluten sensitivity, or wheat allergy, gluten can cause serious health issues, leading to a growing demand for gluten-free products. This has spurred innovation in food processing to develop alternative grains and binding agents that can replace gluten in baking and other culinary applications.

### 2.3. Natural polyesters

#### 2.3.1. Poly (lactic acid) (PLA)

This natural originated polyester is derived from renewable resources like corn starch, sugarcane, or cassava. These plants are processed to extract glucose, which is further fermented with microorganisms, resulting in the production of lactic acid. This lactic acid is polymerized to form PLA, making it one of the most prominent bioplastics due to its renewable origins (de Castro et al., 2022). The use of agricultural resources to produce PLA aligns with sustainable practices, as it relies on crops that can be regrown each season, reducing reliance on fossil fuel-derived plastics.

PLA is known for its rigidity and glossy finish, which make it comparable to petroleum-based plastics like poly (ethylene terephthalate) (PET). It has a relatively low melting point (around 130 to 160 °C), which makes it easier to process using standard plastic manufacturing technologies such as injection molding, extrusion, and thermoforming (Lim et al., 2008). Generally, under proper and controlled composting conditions, PLA is designed to fully break down into carbon dioxide and water within 90 days (Madhavan Nampoothiri et al., 2010b).

PLA's biodegradability and origin from renewable resources make it highly valued in packaging applications, especially for food packaging and disposable tableware (Dey et al., 2021). It is also used in the textile industry for producing biodegradable fabrics, in medical applications such as sutures and drug delivery systems, and in 3D printing, where its ease of use and low melting temperature are advantageous (Khouri et al., 2024). Additionally, PLA is used in agricultural applications, including mulch films that biodegrade and thus reduce the need for physical removal and disposal.

The production of PLA offers environmental benefits by reducing CO<sub>2</sub> emissions compared to conventional plastics and by offering a product that is derived from renewable resources. The biodegradability of PLA also contributes positively by potentially reducing plastic waste in the environment, assuming it is correctly processed in appropriate composting facilities. However, the cultivation of crops for PLA production can have environmental drawbacks, such as the use of

agricultural chemicals and water, and the potential for land use changes that may impact biodiversity. Health-wise, PLA is considered safe for contact with food and is used in medical implants and devices due to its biocompatibility and ability to degrade within the body without harmful side effects. Its use in consumer products does not pose significant health risks, making it a preferred material in applications where product safety is critical.

#### 2.3.2. Poly (butylene succinate) (PBS)

PBS is a biodegradable plastic derived primarily from renewable resources such as corn starch, sugarcane, or another biomass. The production of PBS involves the polymerization of succinic acid and 1,4-butanediol, which can be synthesized from bio-based materials. Both succinic acid and 1,4-butanediol can be produced through the fermentation of glucose and dextrose, respectively (Saxena et al., 2016; Burgard et al., 2016). This bio-based origin positions PBS as an environmentally friendly alternative to petroleum-based plastics, aligning with global efforts towards sustainability and reduced carbon footprints.

Also, PBS is recognized for its excellent biodegradability and thermal properties. It possesses a melting point similar to poly (ethylene), making it suitable for common plastic processing techniques such as injection molding, extrusion, and blow molding. PBS's mechanical properties are comparable to those of many non-biodegradable polymers, such as poly (ethylene) and poly (propylene), which include good resistance to oils and greases, high flexibility, and strength. These properties make PBS highly versatile and suitable for a wide range of applications, particularly in contexts where disposability and biodegradability are desired (Rafiqah et al., 2021).

This biopolymer is extensively used in packaging materials, agricultural films, disposable cutlery, and containers where biodegradability is a critical factor (Barletta et al., 2024). Its ability to decompose into water and carbon dioxide under composting conditions makes it an attractive choice for single-use applications that reduce environmental waste. Furthermore, PBS is employed in the automotive and electronics industries for manufacturing biodegradable components, offering an eco-friendly alternative to traditional plastics used in these sectors. Its application in the textile industry is also growing, particularly in developing disposable non-woven fabrics and as a binding agent in natural fiber composites.

The environmental benefits of PBS are significant, primarily due to its biodegradability and renewable biomass sources. By converting agricultural byproducts and other organic materials into valuable plastics, PBS helps in reducing waste and the environmental impact associated with plastic pollution. It also contributes to the reduction of greenhouse gas emissions since its raw materials can sequester carbon during their growth phase, and the end products can biodegrade naturally. However, the agricultural practices involved in growing the feedstock for PBS can have environmental downsides, such as the use of fertilizers, pesticides, and water resources, which need to be managed sustainably.

Health-wise, PBS is considered safe for use in contact with food and other sensitive applications. It does not contain bisphenol A or other harmful monomers, making it suitable for consumer products where human health safety is a concern. The biocompatibility of PBS also makes it a candidate for medical applications, including biodegradable medical implants and drug delivery systems, where temporary support or treatment is required.

#### 2.3.3. Poly (hydroxyalkanoates) (PHAs)

PHAs are a family of biodegradable polymers naturally produced by various microorganisms as a means of carbon storage. These polymers are synthesized by bacterial fermentation processes that use renewable resources as substrates, such as plant oils, sugars, or even waste products like wastewater sludge (de Castro et al., 2022).



The production of PHAs is particularly attractive because it can potentially utilize a wide range of agricultural by-products, reducing waste and making efficient use of resources (Fernandez-Bunster et al., 2022). The ability of certain bacteria to produce PHAs when exposed to nutrient-limiting conditions with excess carbon sources is harnessed industrially to produce these bioplastics at scale.

PHAs are known for their biodegradability and biocompatibility, which vary depending on the specific type of PHA and the microbial production route. They can range from brittle and hard to rubbery and flexible, making them suitable for a wide variety of applications. The physical properties of PHAs, such as melting temperature, tensile strength, and elasticity, can be fine-tuned by altering the feedstock or the bacterial strain used in their production (Anjum et al., 2016). This versatility allows PHAs to be processed by most conventional plastic processing techniques, such as extrusion, injection molding, and film blowing.

In the packaging industry, PHAs are used to produce items like biodegradable bags, containers, and wrappings, particularly where compostability is a desired trait. In agriculture, PHA films serve as mulch films that naturally degrade in the soil after their useful life, reducing waste and labor costs associated with removal (Teixeira et al., 2023). Additionally, PHAs find applications in the medical field for making sutures, bone plates, and drug delivery systems, where their biocompatibility and ability to degrade in the body are crucial (Ali et al., 2016). The automotive and electronics industries are also exploring the use of PHAs for internal components to enhance sustainability in consumer products.

The environmental advantages of PHAs are significant since they are fully biodegradable in natural environments, including marine and terrestrial systems, where they break down into CO<sub>2</sub>, water, and biomass through microbial activity. This reduces pollution and the accumulation of persistent plastics in ecosystems. The production of PHAs also contributes to carbon sequestration, particularly when plant-based feedstocks are used, which absorb CO<sub>2</sub> during their growth (Teixeira et al., 2023). However, the sustainability of PHA production can vary based on the type of feedstock used and the efficiency of the fermentation process. Optimizing these factors is key to minimizing the overall environmental footprint.

From a health perspective, PHAs are considered safe for use in medical and food contact applications, as they do not leach toxic substances and are derived from natural materials. Their use in medical implants and devices is particularly beneficial, as these polymers can be designed to degrade in the body at rates that match the healing process, eliminating the need for surgical removal and reducing the risk of chronic inflammation.

#### 2.3.4. Poly (caprolactone) (PCL)

This synthetic, biodegradable polyester is manufactured through the ring-opening polymerization of  $\epsilon$ -caprolactone, a cyclic ester. While PCL is synthetically produced, the monomer can be derived from renewable resources such as corn or other biomass, aligning its production with more sustainable practices (Okolie et al., 2023). The synthesis of PCL typically involves catalysts that help in polymerizing the caprolactone under controlled conditions, ensuring the production of PCL with desired molecular weights and properties suitable for various applications.

PCL is known for its semi-crystalline nature, which gives it excellent solubility in various organic solvents and a relatively low melting point from 59 to 64 °C (Mohamed et al., 2015). This low melting point makes PCL particularly useful in applications requiring thermal processing at lower temperatures. Additionally, PCL exhibits remarkable blend compatibility with other biopolymers and excellent biodegradability in natural environments. Its mechanical properties include high flexibility, good tensile strength, and elongation at break, which can be adjusted through copolymerization or blending with other polymers.

In the biomedical field, PCL is used for developing sutures, drug delivery systems, and scaffolds for tissue engineering, where its biodegradability and biocompatibility are critical (Wang et al., 2013). These medical applications benefit from PCL's ability to degrade slowly, providing support to the body as it heals or regenerates tissue. In the packaging industry, PCL is used in compostable packaging solutions that contribute to reducing plastic waste. Additionally, its compatibility with various fabrication techniques makes it popular in 3D printing applications, particularly for prototyping and the production of complex biomedical devices and structures.

One of the primary advantages of PCL is its biodegradability. Unlike many petroleum-derived plastics that persist in the environment for centuries, PCL can degrade into water and carbon dioxide within a year when exposed to the enzymes produced by microorganisms in composting conditions (De Kesel et al., 1997). This characteristic significantly reduces its long-term environmental impact and contributes to waste reduction strategies. From a health perspective, PCL is considered safe for use in biomedical applications due to its biocompatibility and non-toxicity. It does not provoke a significant immune response and has been approved by regulatory agencies such as the FDA for certain medical uses. However, as with all materials intended for medical applications, products made from PCL must undergo rigorous testing and sterilization to ensure they meet all safety standards.

#### 2.4. Polyamides

##### 2.4.1. Silk

A natural protein fiber (fibroin) produced by certain types of insects, primarily silkworms, specifically the larvae of the mulberry silkworm *Bombyx mori*. These insects produce silk fibers as they spin their cocoons. The most common source of commercial silk, *Bombyx mori*, is cultivated in sericulture operations where the worms are fed mulberry leaves. The silk is harvested by boiling the cocoons to kill the pupae and dissolve the gum (sericin) that holds the cocoon fibers together. The fibers are then carefully unwound in a process called reeling, producing long, continuous silk threads (Chauhan et al., 2017).

Silk is highly prized for its smooth texture, sheen, and inherent strength, which make it one of the most luxurious fabrics. It has good absorbency, which makes it comfortable to wear in warm weather, and its low conductivity keeps warm air close to the skin during cold conditions. Silk's unique protein structure, primarily consisting of fibroin, allows it to be both strong and flexible. This fiber forms a triangular prism-like structure, which allows silk cloth to refract incoming light at different angles, producing a shimmering appearance.

Silk's primary use is in the textile industry for the production of high-end and luxury garments such as dresses, shirts, ties, blouses, formal dresses, high fashion clothes, lingerie, pajamas, robes, dress suits, sun dresses, and Eastern folk costumes. Its aesthetic appeal and comfort make it a staple in fashion. Beyond clothing, silk is used in upholstery, bedding, parachutes, and various types of furnishings (Samanta et al., 2015). Additionally, silk has biomedical applications; due to its biocompatibility and biodegradability, it is used in some sutures and as a material in tissue engineering for constructing ligaments and artificial organs (Holland et al., 2019).

The environmental impact of silk production is significant, primarily due to the need for intensive farming of mulberry trees, which are the sole food source for *Bombyx mori* larvae. This requires large amounts of water and agricultural inputs, potentially leading to habitat destruction and pesticide use. However, compared to many synthetic fibers, silk is biodegradable and less energy-intensive to process. In terms of health impacts, silk is hypoallergenic, making it suitable for sensitive skin (Holland et al., 2019). It does not attract dust mites and resists mold and mildew, which contributes positively to indoor air quality when used in bedding and upholstery. However, the sericulture industry has

faced criticisms related to the ethical treatment of silkworms, as the traditional method of silk production involves killing the larvae.

#### 2.4.2. Wool

Wool is a natural fiber obtained primarily from sheep, with significant contributions from other animals such as goats (cashmere and mohair), rabbits (angora), and alpacas. The process of wool production begins with shearing the animals, typically once a year, to collect the fibrous coat. The raw wool is then cleaned, sorted, and processed through carding and combing, which aligns the fibers and prepares them for spinning into yarn. This sourcing from animals that are raised renewably makes wool a sustainable fiber, assuming ethical farming practices are employed.

This fiber is renowned for its crimp, or natural waviness, which imparts elasticity and bulk, making it an excellent insulator. Unlike synthetic fibers, wool can absorb significant amounts of moisture, up to 30% of its weight – without feeling wet (Coplan, 1953). It also has the ability to manage body temperature, providing warmth in cold conditions while remaining cool in heat due to its breathability. Additionally, wool fibers are naturally fire-resistant, adding an element of safety in textile applications.

In the textile industry, wool's unique texture and insulating properties make it ideal for manufacturing a wide range of products including clothing such as sweaters, suits, and socks, as well as home textiles like carpets, blankets, and upholstery. Its durability and resistance to dirt and wrinkles also make it a favored choice in the production of outerwear and high-performance activewear. Beyond textiles, wool's properties are utilized in non-woven products like insulation, felts, and even in biodegradable mulch mats for agriculture.

The production of wool has a beneficial impact on the environment. No need to mention that wool is a renewable resource, and its biodegradability means it does not contribute to microplastic pollution, unlike synthetic fibers. From a health perspective, wool is generally beneficial as it does not promote the growth of bacteria and can help in regulating skin moisture, reducing the risk of skin irritations. Nevertheless, some individuals may experience allergies or sensitivities to natural lanolin found in wool or the chemicals used during its processing.

#### 2.4.3. Elastin

Elastin is a highly elastic protein found in the connective tissues of animals, predominantly within the extracellular matrix of skin, lungs, arteries, and elastic ligaments. It is typically sourced from the structural components of vertebrates, where it is integral to tissues that require elasticity to function correctly, such as blood vessels and skin. The extraction of elastin for industrial use involves breaking down tissues using either enzymatic or chemical processes to isolate the elastin fibers (Mecham, 2018). This protein is less commonly harvested on a commercial scale compared to collagen, but its unique properties make it valuable in specialized applications.

Elastin is known for its outstanding elasticity, allowing tissues to stretch and then return to their original shape. This ability is attributed to its random coil structure that can extend and recoil like a spring. Elastin's resilience and durability are essential in tissues subjected to frequent stretching, such as blood vessels and lung tissues. Additionally, unlike many other fibrous proteins, elastin is resistant to proteolytic enzymes, which contributes to its longevity in tissues (Heinz, 2021).

While not as broadly used as collagen, elastin has specific applications in both the medical and cosmetic industries. In medicine, elastin's properties are exploited in the development of biomaterials for vascular grafts and tissue engineering, where flexibility and durability are critical (Yeo et al., 2015). Its compatibility with human tissues makes it suitable for implants and other devices that must withstand cyclic mechanical loads. In the cosmetics industry, elastin is valued for its supposed anti-

aging properties. It is incorporated into topical formulations that aim to restore the elastic quality of skin, reduce wrinkles, and promote a youthful appearance.

The environmental impact of elastin production is closely tied to the sources from which it is derived, primarily livestock. Similar to other animal-derived products, concerns include the sustainability of animal farming, the ethical treatment of animals. However, utilizing byproducts from meat processing for elastin extraction can contribute to a more sustainable use of animal resources by reducing waste.

### 2.5. Other biopolymers

#### 2.5.1. Natural Rubber

Natural rubber is primarily sourced from the latex of the rubber tree (*Hevea brasiliensis*), which is native to South America but predominantly cultivated in Southeast Asia, including Thailand, Indonesia, and Malaysia (Nair, 2021). Other sources include the guayule plant and the Russian dandelion, which are gaining interest in rubber production outside the traditional regions (van Beilen et al., 2007). Rubber trees are tapped for their latex, a milky fluid, by making diagonal incisions into the tree's bark, which allows the latex to drip out and be collected in containers. This tapping process is carefully managed to ensure the health and longevity of the tree, typically allowing production from a single tree for up to 30 years (Nair, 2021). The collected latex is then processed through several steps, including acid coagulation to solidify the rubber, followed by pressing into sheets and smoking to preserve it. This method of rubber extraction is labor-intensive but critical for obtaining high-quality natural rubber.

The exceptional properties of natural rubber are largely due to its molecular structure, which consists of long chains of isoprene units. This structure imparts outstanding dynamic and mechanical properties such as high elasticity, excellent tensile strength, and impressive elongation at break. Natural rubber can stretch up to eight times its original length and recover its original shape effortlessly. This high resilience and flexibility make it ideal for applications requiring robust performance under stress and repeated use. Furthermore, natural rubber is highly resistant to abrasion and tearing, making it suitable for heavy-duty uses. Its waterproof qualities and ability to perform well in extreme temperatures enhance its application in outdoor and automotive products, providing reliability and durability where synthetic rubbers might fail (Zhou et al., 2017).

In the automotive industry, natural rubber is critical for the production of tires due to its ability to absorb shock and provide traction. The majority of heavy-duty truck and airplane tires are manufactured using natural rubber because of its superior performance in severe conditions. Beyond tires, natural rubber is used in a multitude of automotive components such as engine mounts, seals, and wiper blades, where its damping properties help reduce vibrations and noise (Gupta et al., 2022). In the consumer sector, natural rubber's flexibility and safety are utilized in products ranging from waterproof footwear, such as boots and wetsuits, to sports equipment like hockey pucks and basketballs. Its elasticity and strength are also harnessed in industrial applications such as conveyor belts and bridge bearings, which require materials that can withstand high stresses and variable environmental conditions.

The environmental impact of natural rubber production is twofold. While rubber plantations can help in carbon sequestration, the expansion of these plantations has sometimes led to significant deforestation, especially in biodiverse regions like Southeast Asia. This deforestation not only leads to habitat loss but also increases the risk of badland formation, further endangering the remaining habitat. Sustainable rubber production practices are being promoted to mitigate these effects, including improved tapping techniques and the intercropping of rubber trees with other valuable plants to

maintain ecological balance. Health concerns associated with natural rubber primarily revolve around latex allergies, which can be severe. The proteins found in natural rubber latex can trigger allergic reactions ranging from skin rashes to anaphylactic shock (Hepner et al., 2003). This has led to stringent regulations in the medical field, particularly concerning the use of latex gloves and other medical devices where direct human contact occurs.

#### 2.5.2. Lignin and lignosulfonates

Lignin is a complex biopolymer found in the cell walls of most terrestrial plants, where it acts as a critical structural component that provides rigidity and resistance against pathogens (Shalini Yadav et al., 2023). It is primarily extracted from the wood used in the pulp and paper industry, with smaller amounts derived from agricultural residues. During the pulping process, especially in methods like kraft and sulfite pulping, lignin is separated from cellulose fibers through chemical treatment, resulting in large quantities of lignin as a by-product. In the case of lignosulfonates, these are specifically produced during the sulfite process where the lignin extracted from the wood is chemically modified to increase its solubility in water, facilitating its removal and subsequent utilization (Zevallos Torres et al., 2020).

Lignin is distinguished by its aromatic and highly branched structure, making it uniquely resistant to degradation and providing plants with compressive strength and waterproofing. It is inherently hydrophobic and binds with cellulose and hemicellulose in plants to form a robust, complex matrix. Lignosulfonates, derived from lignin through sulfonation, transform the polymer's inherent insolubility to become highly water-soluble (Ruwoldt, 2020). This transformation enhances their utility as dispersants and binding agents, enabling a wide range of industrial applications. The modified lignin retains the aromatic structure, which is useful in various chemical reactions and product formulations.

The versatility of lignin and lignosulfonates has led to their application across a spectrum of industries. In construction, lignosulfonates are used to improve the properties of concrete, acting as plasticizers that reduce water content while maintaining fluidity, thus saving energy during concrete production. They are also employed in dust control on unpaved roads, where their binding properties help to reduce surface erosion and maintain road stability. In the pulp and paper industry, lignosulfonates serve as effective binders and dispersants in the production of paper, improving sheet formation, strength, and the overall quality of the paper. Furthermore, the exploration of lignin in advanced materials such as carbon fibers, phenolic resins, and polyurethanes is expanding, highlighting its potential to replace petroleum-based materials in high-performance applications (Lai et al., 2023).

The utilization of lignin and lignosulfonates contributes positively to environmental sustainability. Their production and use help in reducing the dependency on fossil fuels by valorizing waste products from the wood and paper industries. This not only minimizes waste but also promotes the recycling of bio-based materials. The biodegradability of lignin and its derivatives ensures that these materials, when discarded, break down more readily in the environment compared to synthetic polymers, thus reducing long-term pollution and promoting a healthier ecosystem. Regarding health impacts, lignin and lignosulfonates are generally considered safe and non-toxic, which allows their use in a wide range of applications, including contact with food and in animal feed. However, the industrial processing of lignin can involve chemicals that require careful handling to prevent occupational exposure to dust and volatile compounds, ensuring safety in the workplace.

#### 2.5.3. Shellac

Shellac is a natural resin secreted by the female lac bug, *Kerria lacca*, found primarily in India and Thailand. These insects deposit lac resin on the branches of specific host trees, such as fig and acacia,

as part of their life cycle (Thombare et al., 2022). The raw shellac is harvested by scraping the resinous coating from the branches, then it is processed to remove impurities. This processing typically involves heating and filtering the raw lac to produce the refined shellac used in various applications (Ahuja et al., 2023). The traditional method of shellac production involves a sustainable harvesting approach that does not harm the trees and minimizes ecological disturbance, relying on natural cycles of lac production.

Shellac is renowned for its excellent film-forming properties, creating a durable and high-gloss finish that is aesthetically pleasing and protective (Thombare et al., 2022). It is a thermoplastic substance, soluble in alcohol but not water, which makes it useful as a non-toxic coating and adhesive. Shellac forms hard, shiny films that dry quickly and can be easily layered, offering superior clarity and depth of finish (Tanasă et al., 2021). Its natural color ranges from pale yellow to a deep orange, depending on the type of tree and the time of harvest, and can be further refined to adjust its hue and transparency.

In the woodworking and furniture industry shellac is prized for its use as a wood finish that enhances the natural grain of wood while providing a protective coating against moisture and wear. In the food industry, shellac is used as a glazing agent on candies, fruits, and coffee beans, imparting a protective shine and extending shelf life (Rashid Sulthan et al., 2023). Additionally, shellac is employed in the cosmetics industry in products such as nail polish and hair spray for its film-forming and quick-drying characteristics (Sandewicz, 2017). It also serves as an insulating material in electronics and as a non-toxic, biodegradable binding agent in pharmaceuticals for coating pills to ensure controlled release of medication.

The environmental impact of shellac production is relatively low compared to synthetic alternatives. Since it is derived from a natural, renewable source, it contributes to the sustainability of the industries that use it, promoting less reliance on petroleum-based products (Mori, 2023). The harvesting process, when done sustainably, has minimal impact on the host trees and surrounding ecosystems. From a health perspective, shellac is considered safe for use in food and pharmaceutical applications as approved by regulatory bodies like the Food and Drug Administration (FDA). It is non-toxic and hypoallergenic, making it an excellent choice for use in products that come into direct contact with consumers. However, the alcohol-based solvents used with shellac in some applications can emit volatile organic compounds (VOCs), which require proper ventilation to ensure safety during application.

#### 2.5.4. Suberin and cutin

Suberin is primarily located in the cell walls of cork tissues and underground parts of plants, such as roots and tubers, acting as a barrier against water and solute movement. It is abundantly present in the bark of cork oak trees, from which commercial cork is harvested (Ranathunge et al., 2011). Cutin, on the other hand, is found in the cuticle, which covers the leaves, fruits, and other non-woody above-ground parts of plants, providing a protective, waxy coating (Buschhaus et al., 2011). The extraction of these biopolymers is more complex and not as commercially straightforward as materials like cellulose or lignin, typically involving chemical or enzymatic methods to break down plant tissues and isolate the desired compounds.

These two biopolymers are complex mixtures of fatty acids and glycerol, which grant them excellent hydrophobic properties. They are primarily known for their roles in plant biology as protective barriers. Suberin acts as a barrier against pathogens and helps regulate water flow in plants, while cutin minimizes water loss from the plant surface, aiding in drought resistance by reducing transpiration (Brunner et al., 2015). Both materials are highly resistant to degradation by environmental factors, which makes them particularly effective in their natural roles.

While not as widely used commercially as other biopolymers like cellulose, suberin and cutin have niche applications. Suberin, for

example, is explored for its use in the cork industry, where it contributes to the resilience and impermeability of cork products such as wine stoppers and cork flooring (Knapic et al., 2016). Research is ongoing into leveraging suberin's properties for developing natural water-resistant coatings and sealants for use in green building materials. Cutin is investigated for its potential in creating biodegradable films and coatings, particularly for agricultural applications where its natural water-resistant properties can be beneficial for protective seed coatings or slow-release fertilizers (Manrich et al., 2017).

The environmental impact of harvesting suberin and cutin is generally low, particularly in the case of suberin, which is harvested from cork oak trees in a sustainable manner. Cork oak forestry is considered environmentally beneficial, as it provides a renewable source of material without requiring the tree to be cut down; the bark regenerates over time. These practices enhance biodiversity and prevent desertification in regions like the Mediterranean. The use of suberin and cutin in industrial applications also supports the development of biodegradable and eco-friendly products, aligning with global sustainability goals. From a health perspective, both suberin and cutin are considered safe and non-toxic. They are naturally occurring in many fruits and vegetables and pose no known risks to human health, making them appealing for use in consumer products that require contact with food or skin.

### 3. Navigating the economic landscape

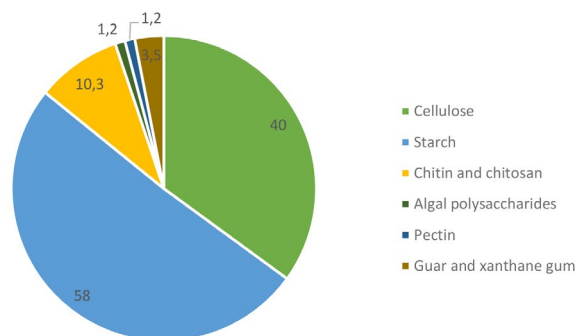
This section explores the economic dynamics and market trends influencing the adoption and development of biopolymers. It delves into detailed analyses of market size, growth projections, and the economic viability of various natural and synthetic biopolymers, highlighting challenges and opportunities within the industry. Technological advancements and their impacts on production costs and market penetration are also discussed, providing a comprehensive overview of the economic factors driving biopolymer industries.

#### 3.1. Polysaccharides

Polysaccharides such as cellulose, starch, chitin, and alginate have been fundamental to various industries due to their abundant natural occurrence and renewable nature. The global market for polysaccharides is expanding robustly, especially for cellulose and starch. As of 2023, the total polysaccharide market was valued at approximately \$114.2 billion with a projected average compound annual growth rate (CAGR) of around 6.1 % through 2028 with the highest share in market growth for starch and cellulose, respectively (Research Nester, 2024; Grand View Research, 2024c). These polysaccharides dominate their market segment due to their widespread availability and relatively low production costs. Moreover, rising demand for chitin and its derivative chitosan in niche markets like water treatment and biomedical applications is evident, driven by their biocompatibility and non-toxicity. At the Figure 2 are given market shares for all polysaccharides that are subject of this review, given values represent share in the market in billions of dollars (Research Nester, 2024; Grand View Research, 2024c; 2024b; Fact. MR, 2024; Polaris Market Research, 2024).

Technological advancements have significantly influenced the economic viability of polysaccharides by reducing production costs and enhancing functionality. The cost of producing these biopolymers can vary widely, influenced by the choice of raw materials and production technologies. For instance, the cost of producing industrial-grade cellulose ranges from \$900 to \$1,500 per ton, dependent on factors such as plant capacity and geographic location. Costs for starch derivatives, like modified starches, tend to be higher due to the complexity of the chemical modifications required. Beyond raw material costs, the scalability of production processes presents significant economic challenges, as scaling up biopolymer production often involves complex

bioengineering which can escalate costs.



**Fig. 2.** Estimated global market size\* in billions of US dollars for most industrial applied polysaccharides in 2023

Polysaccharides face several technical challenges that limit their broader application. For example, the moisture sensitivity of starch and cellulose can adversely affect their physical properties and durability, posing challenges in moisture-rich environments. Additionally, variability in molecular weight and chain length due to natural source differences can lead to product performance inconsistencies. To address these issues, considerable research has focused on the chemical modification or blending of polysaccharides with other materials, such as synthetic polymers, to enhance their water resistance and mechanical strength. However, these modifications can complicate recycling or composting processes, potentially diminishing the environmental benefits these materials offer.

While derived from abundant and renewable resources, the commercial extraction and purification of polysaccharides can be resource-intensive and costly, especially for high-purity products required in pharmaceutical applications (Fact.MR, 2024; Polaris Market Research, 2024). Competition with food supply, particularly for starch and cellulose, can also affect market prices and availability, posing an economic barrier to broader adoption. Furthermore, the lack of established supply chains for novel polysaccharides in some regions can inhibit market penetration compared to well-established synthetic polymers. The infrastructure for producing, processing, and distributing biopolymers is still developing, requiring significant investment from stakeholders across the value chain.

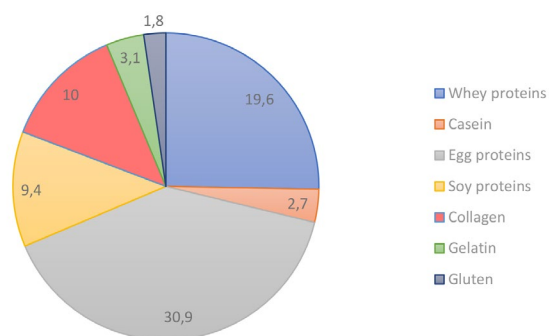
Regulatory frameworks also vary widely by country, impacting the development and adoption of polysaccharide-based products. In some regions, stringent regulations on the use of genetically modified organisms (GMOs) can restrict the use of genetically engineered microbes or plants that could otherwise help produce polysaccharides more efficiently and sustainably. Environmental concerns are significant, particularly regarding the agricultural practices used to grow raw materials for polysaccharide production. Issues like deforestation, pesticide use, and water consumption are critical as they can offset the environmental benefits of using renewable materials. Ensuring that polysaccharide production enhances rather than harms sustainability efforts remain a continuing challenge.

#### 3.2. Proteins

Protein-based biopolymers such as whey, casein, egg proteins, soy proteins, collagen, and gelatin are pivotal to various industries including food, pharmaceuticals, and cosmetics, due to their functional properties and biocompatibility. The global market for these proteins is experiencing robust growth, driven by health-conscious consumers and advancements in biotechnology. As of 2023, the market for protein-based biopolymers was valued at approximately \$77.5 billion, with a projected compound annual growth rate (CAGR) of around 6.4%

\* The real estimated global market size is even larger since some markets are not covered by certain reports

through 2033 (Research Reports World, 2024). Egg and whey proteins, in particular, hold significant shares due to their nutritional value and versatility in food and beverage applications. Collagen and soy proteins also contribute notably to the market, particularly in pharmaceutical and cosmetic products due to their skin and joint health benefits. At the Figure 3 are presented market shares for selected proteins that are subject of this review, values present in the chart represent market cap in billions of dollars (Research Reports World, 2024; Future Market Insights, 2024a; Fortune Business Insights, 2024; IMARC Group, 2024e; Future Market Insights, 2024b; IMARC Group, 2024a; Grand View Research, 2024a).



**Fig. 3.** Estimated global market size\*\* in billions of US dollars for key protein-based biopolymers in 2023

Technological advancements have significantly influenced the economic viability of these proteins by enhancing their functional properties and reducing production costs. The cost of extracting and purifying these proteins varies, influenced by factors such as source quality and processing technology. For instance, the production costs for high-purity whey protein can range from \$5,000 to \$8,000 per ton, depending on the degree of processing and the functional characteristics desired (Future Market Insights, 2024b). Costs for collagen and gelatin, derived from animal tissues, are influenced by the availability and cost of raw materials, such as hides and bones, and the complexity of extraction and purification processes (IMARC Group, 2024a; Fortune Business Insights, 2024).

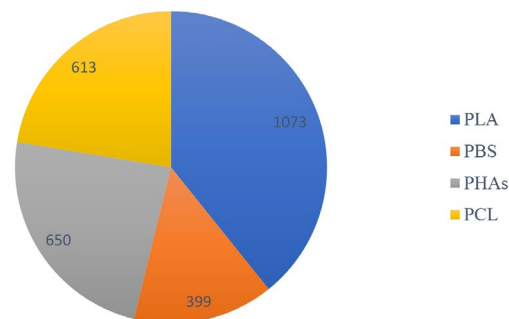
Protein-based biopolymers face several technical challenges that restrict their broader application. Sensitivities such as denaturation at high temperatures for whey proteins, or hygroscopic properties for soy proteins, can limit their use in various environmental conditions or processing methods. Additionally, variability in protein structure and composition due to natural source differences can affect product consistency and performance. To overcome these limitations, extensive research has been directed towards developing advanced modification techniques such as enzymatic hydrolysis or cross-linking, which enhance solubility, thermal stability, and mechanical properties. However, these modifications may complicate the recycling or biodegradation processes, potentially reducing the environmental benefits.

Despite being derived from renewable resources, the extraction and purification processes for these proteins can be energy-intensive and costly, particularly when high purity is required for pharmaceutical or food-grade applications. Competition for raw materials, especially in the case of soy and whey proteins, can also impact market prices and availability, presenting economic barriers to widespread adoption. Moreover, the lack of established supply chains for novel proteins in some regions can restrict market penetration when compared to more established synthetic alternatives. The development of infrastructure for producing, processing, and distributing these biopolymers is essential, necessitating significant investment and collaboration across various stakeholders.

\*\* The real estimated global market size is even larger since some markets are not covered by certain reports

### 3.3. Natural polyesters

The market for natural polyesters such as PLA, PHAs, PBS and PCL is demonstrating vigorous growth driven by a global shift towards sustainable materials. As of 2023, this market was valued at approximately \$2.67 billion, and it's projected to experience a compound annual growth rate (CAGR) of 4.2% through 2033 (Grand View Research, 2024e; IMARC Group, 2024b; Grand View Research, 2024d; IMARC Group, 2024c). PLA remains at the forefront due to its broad applicability in compostable packaging and disposable items, where its biodegradability under commercial composting conditions is a significant advantage. The market for PLA alone is expected to reach around \$1.07 billion by 2028, catalyzed by expanding regulatory mandates for sustainable packaging solutions across North America and Europe. PHAs are rapidly gaining ground, particularly valued in the medical sector for producing biocompatible and absorbable sutures, meshes, and implants. This segment's growth is bolstered by an increased focus on medical sustainability and the reduction of hospital-generated plastic waste. PBS, with its balance of biodegradability and mechanical strength, is becoming a preferred material in agricultural applications such as mulch films, which degrade in the soil, reducing agricultural waste. The market for PBS is projected to expand particularly in regions like Asia-Pacific, where agriculture utilizes extensive plastic materials. PCL's niche but growing segment is propelled by its unique properties suitable for long-term implantable devices and controlled drug release systems. The market for PCL is expected to grow particularly in the biomedical sector, driven by advancements in drug delivery technology and regenerative medicine. Pie chart of market size and share for those natural polyesters are given by Figure 4, the values given in the Figure represent estimated market share in millions of dollars (IMARC Group, 2024c; Grand View Research, 2024d; IMARC Group, 2024b; Grand View Research, 2024e).



**Fig. 4.** Estimated global market size\*\*\* (millions of US dollars) for key natural polyesters in 2023

Innovations in fermentation technology, especially for PHAs, are reducing production costs and improving material properties by utilizing renewable feedstocks like agricultural residues. Advanced catalysis and polymerization techniques have similarly enhanced the synthesis of PLA and PBS, allowing for better control over molecular weights and improved performance characteristics. For PCL, developments in synthesis from bio-based monomers are expanding its applications in environmentally friendly products.

The production costs of natural polyesters remain a challenge compared to synthetic polymers. For instance, PLA can cost around \$2,200 to \$2,800 per ton, with similar ranges for other polyesters depending on the processing technology and feedstock costs. These costs are influenced by the volatile prices of agricultural commodities and the energy-intensive nature of polymer processing (Grand View Research, 2024e). PHAs are more expensive to produce, typically

\*\*\* The real estimated global market size is even larger since some markets are not covered by certain reports



costing between \$3,000 to \$5,000 per ton due to the need for precise fermentation conditions and the cost of microbial feedstocks, which often include refined sugars (Grand View Research, 2024d). Advances in using waste streams as feedstocks are helping to reduce costs but have yet to be implemented on a large scale. PBS and PCL also face similar cost issues. The production costs for PBS are influenced by the price of succinic acid and butanediol, with ongoing research into bio-based routes expected to reduce costs in the future (IMARC Group, 2024b). PCL, being a specialty polymer, often commands higher prices, justified by its applications in high-value medical devices and long-term implants (IMARC Group, 2024c).

Natural polyesters face several challenges that restrict their broader application. The mechanical and thermal properties of these materials can be less favorable than those of traditional plastics, often requiring them to be blended with other materials to achieve the desired performance. This need can complicate the recycling or composting processes, potentially undermining the environmental benefits. Furthermore, the variability in feedstock quality can lead to inconsistencies in the final product, impacting broader industrial adoption.

### 3.4. Polyamides

The market for natural polyamides is not only significant but also expanding due to their irreplaceable roles in both traditional and innovative applications. In 2023, the global market for natural polyamides was estimated at about \$57.8 billion with projections indicating a CAGR of 3.5% up to 2028, fueled by luxury fashion and high-end consumer goods where silk's luster and feel are unmatched (Mordor Intelligence, 2024; IMARC Group, 2024d; Market Research Intellect, 2024). Technological advancements are pivotal in driving these growth trends. For instance, biotechnological enhancements in silk production include genetically modified silkworms that can produce silk with modified properties such as enhanced strength or intrinsic coloration, reducing the need for post-treatment dyeing and thus aligning with sustainability goals. Wool processing has seen innovations that allow for the production of lighter, less allergenic wool products, broadening its use beyond traditional clothing into active wear and technical applications. Elastin has benefited from advanced genetic engineering techniques allowing for increased yield and purity, crucial for its expanding use in high-precision medical applications. In the Figure 5 are given market size for subjected natural polyamides, the values given within the chart pie present market share in billions of dollars (Mordor Intelligence, 2024; IMARC Group, 2024d; Market Research Intellect, 2024).

Despite their burgeoning markets, natural polyamides face significant economic hurdles primarily due to the intensive labor and complex processes required for their production. Silk and wool, both derived from animal sources, involve costly stages from animal rearing to fiber processing. Silk, for example, requires extensive labor in both the rearing of silkworms and the delicate process of reeling silk from cocoons (IMARC Group, 2024d). Wool, while less labor-intensive than silk, still requires substantial investment in terms of sheep farming, shearing, and subsequent fiber processing (Mordor Intelligence, 2024). Elastin's economic challenges are marked by its complex extraction process from tissues, requiring high levels of purification to meet medical-grade standards, making its production expensive and limiting its accessibility (Market Research Intellect, 2024).

The application of natural polyamides is often limited by their intrinsic properties. For example, silk and wool's sensitivity to environmental factors like moisture and sunlight can degrade their quality and longevity, posing challenges in their use in outdoor or harsh environments without significant treatment. Elastin, while biocompatible and highly elastic, suffers from issues related to scalability of production. Its high cost of extraction and purification makes large-scale applications challenging. The variability inherent in

natural sources also affects the consistency and predictability of these materials. Genetic and environmental factors can significantly influence the quality of silk and wool, impacting the uniformity required for high-standard applications. Additionally, the technical limitations of working with natural polyamides, such as their processing sensitivity and compatibility with other materials, necessitate ongoing research and technological innovation to broaden their application scope. Economic barriers further complicate the widespread adoption of these materials. The costs associated with sustainable and ethical production practices are often higher than those for synthetic alternatives. The market for natural polyamides is also affected by fluctuations in global economies, changes in consumer preferences, and the pace of innovation within the textile and biomedical sectors.

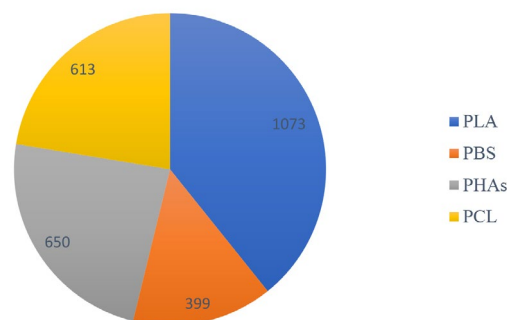


Fig. 5. Estimated global market size\*\*\*\* (billions of US dollars) for key natural polyamides in 2023

### 3.5. Other biopolymers

Dominating the elastomer market, natural rubber is vital for industries ranging from automotive to consumer goods. The global natural rubber market is projected to reach approximately \$30.9 billion by 2033, growing from its 2023 valuation of about \$18.3 billion (Future Market Insights, 2024b). This growth is primarily driven by increasing demand in emerging economies, where rapid industrialization is boosting the automotive and manufacturing sectors. As byproducts of the paper and pulp industry, lignin and its derivatives hold a unique position in the biopolymer market. The lignosulfonates market alone is expected to reach \$3.1 billion by 2033, growing at a CAGR of 3.8% from 2020 (Precision Business Insights, 2024). The use of lignosulfonates in concrete admixtures and as a binding agent in animal feed significantly contributes to this growth, supported by increasing awareness of sustainable construction materials. While niche, the shellac market remains steady, primarily supported by the food and pharmaceutical industries, where it is used as a coating agent. The market size for shellac is expected to exceed \$183 million by 2032, growing at a modest rate (Zion Market Research, 2024). Traditional uses in high-quality wood finishes and furniture continue to sustain demand, particularly in South Asia and artisanal markets globally. Although not commercially significant yet, the potential market for suberin and cutin is growing, especially in sustainable materials research. Their unique properties could lead to breakthroughs in biodegradable films and barriers, positioning them as future contenders in packaging and agricultural applications (Lecart et al., 2023).

The production of natural rubber is labor-intensive and highly sensitive to weather conditions and diseases, which can cause significant price volatility. For instance, the cost of natural rubber can range significantly, influenced by geopolitical events and environmental policies. Efforts to improve rubber crop yields and disease resistance through biotechnological advancements are crucial for maintaining economic viability (Future Market Insights, 2024b). Economically,

\*\*\*\* The real estimated global market size is even larger since some markets are not covered by certain reports



lignin is gaining value as industries seek to utilize waste products effectively. The cost of processing lignin into lignosulfonates or other valuable derivatives is offset by the revenue generated from these products. Investments in refining technologies that can convert lignin into high-value chemicals like vanillin or carbon fibers are enhancing its economic appeal (Precision Business Insights, 2024). Economic challenges for shellac include its labor-intensive harvesting and vulnerability to synthetic alternatives. However, its non-toxic, renewable nature continues to justify the higher cost in specific markets, such as pharmaceuticals and luxury food coatings, where safety and quality are paramount (Zion Market Research, 2024). Currently, the high costs associated with extracting and processing suberin and cutin from plant tissues make them less competitive. However, research into cost-effective extraction methods and the development of applications that can leverage their natural properties could improve their economic outlook (Lecart et al., 2023).

Natural rubber is challenged by environmental concerns related to deforestation and biodiversity loss in rubber plantations. Additionally, the rise of synthetic alternatives continues to pressure the natural rubber industry to innovate and improve sustainability practices. Lignin and Lignosulfonates struggle with consistency and quality issues, which can affect their broader application in high-performance areas. Technological advancements are needed to enhance their properties and expand their use beyond current limitations. Shellac faces challenges from synthetic alternatives that can mimic its properties at a lower cost. Moreover, the labor-intensive nature of its production limits scaling opportunities, keeping it within more traditional or niche applications. Suberin and Cutin are limited by a lack of research and development focused on their commercial extraction and application. Their potential in industrial applications remains largely speculative without significant technological breakthroughs to harness their properties economically.

#### 4. Conclusion

This comprehensive review underscores the pivotal role of biopolymers in fostering sustainable practices across various industries. Biopolymers, including polysaccharides, proteins, polyesters, and polyamides—emerge as crucial alternatives to conventional non-renewable, petroleum-based materials due to their inherent biodegradability and derivation from renewable resources. These attributes not only align with increasing regulatory demands and consumer preferences for environmentally conscious products but also address global environmental challenges such as climate change, pollution, and resource depletion.

The versatility of biopolymers is evident in their wide-ranging applications, from biodegradable packaging and eco-friendly textiles to advanced medical technologies like drug delivery systems and biocompatible implants. These applications demonstrate the significant potential of biopolymers to enhance environmental sustainability while meeting diverse industrial requirements.

However, the review also highlights several challenges impeding the widespread adoption of biopolymers. Key obstacles include the scalability of production processes, elevated manufacturing costs, and performance inconsistencies stemming from natural source variability. Overcoming these barriers is essential for biopolymers to effectively compete with synthetic materials, which currently dominate the market due to their cost-effectiveness and material uniformity.

Looking ahead, the expansion of the biopolymer market hinges on advancements in enhancing their mechanical and chemical properties to satisfy specific industry demands without compromising their environmental benefits. Innovations in genetic engineering, fermentation technology, and nanotechnology present promising pathways to improve biopolymer functionality and reduce production costs. Additionally, the development of integrated biorefineries capable of efficiently converting biomass into a variety of valuable bioproducts could significantly boost both productivity and sustainability within the

biopolymer sector.

Furthermore, creating a supportive regulatory and economic framework is crucial for the advancement and adoption of biopolymers. Implementing incentives for sustainable material usage, providing subsidies for research and development, and enforcing stricter regulations on non-degradable plastics can stimulate market growth. Educational initiatives and awareness campaigns are also vital in shifting consumer and industrial behaviors towards embracing sustainable materials.

In conclusion, while biopolymers have made substantial progress in various applications, their future success is intrinsically linked to continued technological innovation, economic support, and regulatory facilitation. As the global community intensifies its pursuit of sustainable solutions, biopolymers are well-positioned to become fundamental components of sustainable development, transforming material production and utilization in harmony with environmental preservation. This review emphasizes the necessity for ongoing research, interdisciplinary collaboration, and innovative strategies to fully realize the potential of biopolymers as cornerstone materials in a sustainable future.

#### Acknowledgement:

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