



## Biopolymers: Nature-Inspired Solutions for a Sustainable Industrial Future

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### Abstract

Today, the problem of accumulation and disposal of polymer waste is relevant for the environment. In this regard, there is a need to search for alternative ways to solve it, namely the transition to environmentally friendly materials that have the ability to biodegrade. Thus, biopolymers- an innovative class of materials is of increasing interest to researchers and specialists in various fields related to health care, environmental sustainability and industrial innovation. Further development of this topic requires joint research to fully understand both the fundamental properties and the practical application of biopolymer for new organic materials. Biopolymers are inherently flexible and versatile, as they can be produced using biological systems or derived from natural resources. They are typically categorized into two main types based on their origin: synthetic biopolymers and natural biopolymers. Categorizing biopolymers based on their sources, structures, and properties, and compares their characteristics and potentials in various fields. Currently, biocompatible and non-toxic biopolymers such as cellulose, starch, gelatin, chitosan, PCL, PHA, PLA and polyglutamic acids are being utilized to develop effective systems by providing safe, effective, and sustainable solutions. Grasping the fundamental characteristics of biopolymers, including their chemical, mechanical, physical, and thermal properties, is vital for exploring their practical uses. This review article explores biopolymers from both natural and synthetic sources, including applications in biomedical fields, food packaging, agriculture, and environmental remediation. By analyzing the advancements achieved in biopolymer research over recent decades, this article provides valuable insights into emerging trends and serves as reference for future investigations in this dynamic field.

### Introduction

The environment has emerged as a primary concern for researchers due to the significant impact of

human activities. The cumulative effects of these activities have led to devastating environmental consequences, contributing to the emergence of diseases and, ultimately, the loss of lives. Among the pressing

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challenges we face today, plastic pollution stands out as one of the most critical environmental issues. Its pervasive presence threatens ecosystems, wildlife, and human health, underscoring the urgent need for innovative solutions and sustainable practices to mitigate its impact (Evode et al., 2021; Horton, 2022).

The production of plastics plays a vital role in the global economy, with usage expanding rapidly over the years. Its versatility is particularly evident in the packaging industry, which alone accounts for approximately 47% of total plastic consumption. However, it is crucial to confront the environmental challenges associated with plastic production, as it significantly contributes to global warming and climate change, two of the most pressing issues of our time. This urgent concern has catalyzed advancements in various related fields, with marine litter being a prominent example. Alarming, between 50% and 100% of marine litter is composed of plastic, highlighting the exponential growth of plastic production and its catastrophic consequences for our oceans and ecosystems. Addressing this crisis requires immediate action and innovative solutions to reduce plastic waste and promote sustainability (Williams & Rangel-Buitrago, 2022).

Petroleum-based polymers are ubiquitous in a wide range of commercial products. However, their significant environmental drawbacks such as high levels of contamination and non-biodegradability render them increasingly undesirable. In response to these challenges, the development and utilization of biopolymers derived from natural sources present a promising solution. These environmentally friendly alternatives not only mitigate plastic waste but also promote sustainability by reducing our reliance on fossil fuels. By embracing natural polymers, we can move towards a greener future and minimize the ecological impact of our consumption patterns (Flórez et al., 2023). These biopolymers are characterized by their biocompatibility and biodegradability, making them highly valuable across a variety of applications. In the food industry, they are utilized to create edible films, emulsions, and sustainable packaging materials that enhance product preservation while reducing environmental impact. In the pharmaceutical sector, these versatile materials serve as effective drug delivery systems, as well as medical implants, tissue scaffolds, and wound healing dressings. Their inherent compatibility with biological systems further underscores their potential to revolutionize both food safety and healthcare solutions (Udayakumar et al., 2021).

Biopolymers, primarily sourced from polysaccharides and proteins, are subjected to various advanced production methods to enhance their properties and modify their chemical structures.

These techniques include solvent casting, coating, electrospinning, 3D printing, compression molding, and graft copolymerization. When implementing these methods, it is essential to consider various factors such as temperature, humidity, solvent selection, and processing duration, as these elements significantly impact the final product's characteristics. By optimizing these parameters, manufacturers can tailor the biopolymers to meet specific performance requirements, ensuring their suitability for diverse applications in fields such as food packaging, pharmaceuticals, and biomedical engineering (Flórez et al., 2023).

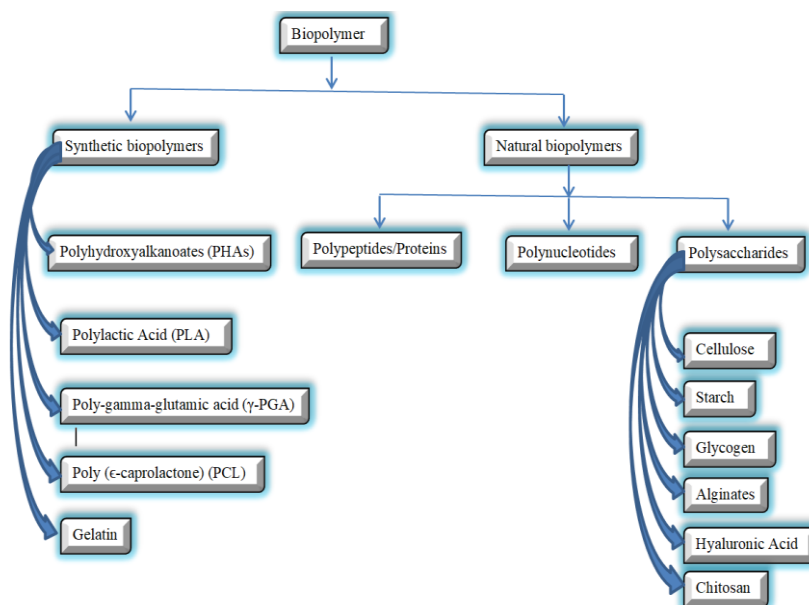
The global biopolymers market was valued at approximately \$13.7 billion in 2021 and is expected to exceed \$35.2 billion by 2030, reflecting a compound annual growth rate (CAGR) of 11.07%. Additionally, the marine biotechnology sector is anticipated to reach a value of \$5 billion globally by 2026 (Halaswamy et al., 2025). Their adaptability and sustainability make them essential contributors to the shift toward eco-friendly materials (Patra et al., 2024).

In this context, this review article aims to explore the key aspects of natural and synthetic biopolymers, emphasizing their applications and potential advancements in the field.

Based on a number of factors, such as their origin, degradability, and polymer backbone structure, biopolymers can be categorized into two primary categories: synthetic and natural biopolymers as shown in Fig. 1 (Samir et al., 2022).

### **Synthetic biopolymers**

A family of materials known as synthetic biopolymers combines the biological functioning of natural polymers with the characteristics of synthetic polymers (Shiva et al., 2023). They offer benefits like increased durability, adjustable characteristics, and ease of production, and are designed to resemble the structure and behavior of natural biopolymers (Galina Satchanska et al., 2024). Developments in materials science and biotechnology, as well as a growing need for sustainable substitutes for conventional petroleum-based polymers, have propelled the growth of synthetic biopolymers (Drishya et al., 2025).



**Fig. 1** Classification of biopolymers

New materials with better qualities and functions are being developed as a result of research into synthetic biopolymers. More effective production techniques are being made possible by advancements in fermentation and genetic engineering technologies (Fatima, 2024).

Recent developments in synthetic biopolymers highlight their industrial applications and sustainability. Polylactic acid (PLA), made from renewable resources like sugarcane and maize starch, is commonly used for biodegradable packaging and eco-friendly textiles, aiding sustainable fashion efforts (Mosomi et al., 2024; Patti & Acierno, 2022). Polyhydroxyalkanoates (PHAs), derived from microbial fermentation of sugars or lipids, serve as alternatives to traditional plastics in single-use products such as plates, bags, and cutlery. They are also biocompatible and biodegradable, making them suitable for medical applications like drug delivery systems and sutures (Ben Abdeladhim et al., 2024). Chitosan, sourced from chitin in crustacean shells, acts as a natural coating and preservative to enhance the shelf life of food products (Duan et al., 2019).

Polyester that is synthetic and biodegradable is called polycaprolactone (PCL). Because of its slow rate of disintegration and biocompatibility, it is frequently utilized in drug delivery systems and scaffolds for tissue engineering (Ntrivala et al., 2025).

## Natural biopolymers

Natural biopolymers are polymers obtained from renewable biological sources, including plants, animals, microbes, or biomass, they are biodegradable, nontoxic, and frequently composted (Kaur et al., 2024; Samir et al., 2022). These biopolymers are broadly classified into three categories based on their monomeric units and structure. These include collagen, fibrin, fibrinogen, gelatin, silk, elastin, myosin, keratin, and actin, which are polypeptides and proteins. Polysaccharide-based: cellulose, agarose, dextran, hyaluronic acid, chitin, chitosan, alginate, and glycosaminoglycan. DNA, RNA, and linear plasmid DNA are examples of polynucleotide-based (Hersh et al., 2021; Jabeen & Atif, 2023; Liu et al., 2022).

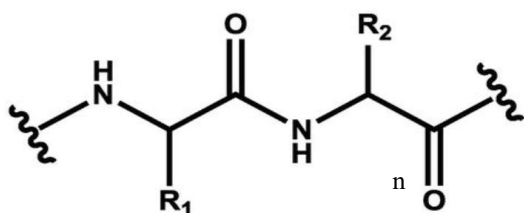
## Polypeptides and proteins

Recent years have seen a thorough investigation of peptides (short chain proteins) from several sources as viable biomaterials because of their remarkably diverse chemical, physical, and biological properties (Ganguly et al., 2020). Peptides are brief chains of amino acids joined by peptide bonds, which are covalent chemical bonds as shown in Fig. 2 (Giri & Giri, 2022).

Researches have reported that natural peptides have essential structural roles, providing support and

protection to the cells and organisms that produce them. Structural proteins like elastin, resilin, collagen, and silk have the remarkable ability to self-assemble into various materials, including silkworm cocoons, the extracellular matrix, nails; squid ring teeth, and the adhesive threads of mussels. These materials exhibit a diverse array of mechanical and structural characteristics ranging from soft to rigid, porous to densely packed, and dynamic to static while being composed of amide bonds (Shire et al., 2024).

Peptide functionalization can be accomplished through various methods. Chemical approaches include hydrolysis, oxidation, grafting, and aminolysis, while physical methods involve adsorption, entrapment, self-assembled monolayers, and layer-by-layer deposition. Peptides are simpler and more cost-effective to synthesize, easier to modify, and exhibit greater resistance to environmental conditions like temperature and pH (Klimek & Ginalska, 2020). These strategies enable modifications of biomaterials to improve their properties and functionalities (Ross et al., 2022).



**Fig. 2** Chemical structure of peptide

Source: Charan Giri (2022)

## Medical applications

### 1. Drug delivery system

Peptides possess several advantageous characteristics, including high affinity, low immunogenicity, a straightforward amino acid structure, and customizable molecular size. As a result, many peptides can be linked to drugs to create peptide-drug conjugates (PDCs), which serve as active pro-drugs. PDCs are considered promising drug delivery systems (DDS) due to their ability to enhance drug compatibility and stability in the body. Peptide-based DDSs are commonly utilized for delivering therapeutic agents, such as anti-cancer and nucleic acid-based drugs, as they help reduce drug degradation, maintain targeted drug concentrations, and extend the drugs' half-life in the body (Guo et al., 2024).

### 2. Tissue engineering and regenerative medicine

Peptides are widely used in tissue engineering due to their ability to mimic the extracellular matrix (ECM) and

promote cell adhesion, proliferation and differentiation (Chen et al., 2024b; Morwood et al., 2023). Significant developments include self-assembling peptide scaffolds that create a three-dimensional framework for the regeneration of tissues like bone, cartilage, and neural tissues (Jarecki et al., 2023). Additionally, bioactive peptides play a role in stimulating targeted cellular responses, such as angiogenesis (the creation of new blood vessels) and nerve regeneration, thereby speeding up the healing process (Md Fadilah et al., 2024).

## Application in food industries

### 1. Functional food ingredient

Peptides serve as bioactive components in functional foods, celebrated for their health-enhancing benefits. Examples include nutraceuticals like peptide-based supplements that bolster immune function, enhance gut health, and lower cholesterol levels. Additionally, protein hydrolysates sourced from milk, soy, or fish are abundant in bioactive peptides and are commonly incorporated into sports nutrition and health-oriented products (Wang et al., 2025).

### 2. Texture and stability enhancement

Peptides can enhance the texture, stability, and sensory characteristics of food products. For instance, gel-forming peptides are utilized in dairy alternatives, plant-based meats, and desserts to replicate the texture of conventional items (Liu et al., 2024; Siddiqui et al., 2024). Also, flavor-enhancing peptides play a crucial role in delivering umami taste and masking bitter flavors in processed foods (An et al., 2024).

## Application in industrial products

### 1. Anti-aging and skin repair

Peptides are commonly found in anti-aging products because they can boost collagen production, enhance skin elasticity, and lessen the visibility of wrinkles. Important applications include: signal peptides that encourage the synthesis of collagen and elastin, which helps to firm and revitalize the skin; carrier peptides that transport vital trace elements (such as copper) to the skin, supporting wound healing and tissue repair; and neurotransmitter-inhibiting peptides (like Argireline) that decrease muscle contractions, reducing the look of fine lines and wrinkles (Pintea et al., 2025; Nguyen et al., 2024; Veiga et al., 2023).

## 2. Hair care and scalp health

Peptides are utilized in hair care products to encourage hair growth, fortify hair strands, and enhance scalp health. Their applications include hair-growth stimulating peptides that activate hair follicles and prolong the growth phase of the hair cycle, keratin-strengthening peptides that mend damaged hair and minimize breakage, and scalp-soothing peptides that alleviate inflammation and irritation, creating a healthy environment for hair growth (Pappelbaum et al., 2024; Reihani & Ghourchian, 2025).

### Polysaccharide-based

Polysaccharide-based biopolymers are natural polymers composed of long chains of monosaccharide units (sugars) linked together by glycosidic bonds (Murphy et al., 2023). These biopolymers are biodegradable, renewable, and often exhibit unique physical and chemical properties, making them suitable for various applications in food, pharmaceuticals, cosmetics, and materials science (Behrooznia & Nourmohammadi, 2024; Benalaya et al., 2024).

### Cellulose

Cellulose is a crucial biopolymer known for its structural and functional roles in nature. It is made up of a linear chain of polysaccharides formed by repeating units of  $\beta$ -D-glucose linked by  $\beta(1 \rightarrow 4)$  glycosidic bonds (Wang et al., 2020a). This configuration results in a crystalline structure that contributes to its strength and rigidity. Furthermore, cellulose forms microfibrils that provide mechanical support to plants (Pedersen et al., 2023). It is primarily sourced from plant materials such as wood, cotton, and agricultural waste, though it can also be found in smaller amounts in certain algae and fungi (Femina & Asokan, 2024). As a biodegradable substance, cellulose can be decomposed by microorganisms, making it an environmentally friendly and sustainable material (Carolin et al., 2023).

Cellulose is a widely used biopolymer known for its abundance, biodegradability, and renewability (Jing et al., 2024). It is primarily applied in the production of biodegradable films and coatings for food packaging, reducing reliance on synthetic plastics. Cellulose derivatives, such as cellulose acetate and methylcellulose, are also used in edible packaging, offering an eco-friendly alternative to traditional plastic wraps (Hussain et al., 2024b).

Cellulose is transformed into fibers such as viscose, lyocell, and modal, which are favored in the textile industry for their softness, breathability, and biodegradability (Amjad, 2024). These fibers are gaining popularity in sustainable fashion as eco-friendly alternatives to synthetic materials.

In the pharmaceutical industry, cellulose derivatives like hydroxypropylmethylcellulose (HPMC) serve as excipients in formulations designed for controlled drug release. Also, microcrystalline cellulose (MCC) is frequently utilized as a binder and disintegrant in the production of tablets (Hadinugroho et al., 2023).

Other important application of cellulose as biopolymer include their use as skin products as a gentle exfoliant (Zhao et al., 2025). Additionally, its porosity and thermal stability make it suitable for use in super capacitors and flexible electronics. Cellulose derivatives are also employed in seed coatings to enhance germination and safeguard seeds (Wang et al., 2024b). Cellulose have also demonstrated its significance when integrated into bioplastic composites for construction purposes (Darmenbayeva et al., 2024).

### Starch

Starch is a complex carbohydrate polymer that is widely generated by plants, especially in agricultural crops. It consists of two primary components: amylose and amylopectin, both of which are formed from glucose units (Fig 3) connected by  $\alpha$ -1,4 and  $\alpha$ -1,6 glycosidic bonds (Apriyanto et al., 2022).

Starch is a widely available and cost-effective biopolymer (Onyeaka et al., 2022). However, native starches often fall short for certain industrial uses due to limitations such as brittleness, moisture sensitivity, and inadequate thermal and mechanical properties (Apriyanto et al., 2022; Zarski et al., 2021).

Starch is extensively utilized across different industries because of its biodegradable, renewable, and versatile nature (Rashwan et al., 2024). Major applications include serving as a thickening and gelling agent in soups, sauces, and desserts, as well as acting as stabilizers and binders in processed foods such as sausages and baked products (Shoukat et al., 2025). Additionally, it plays a crucial role in creating edible films and coatings for packaging, helping to prolong shelf life (Shoukat et al., 2025).

Starch-based adhesives find applications in the paper, packaging, and wood sectors (Lin & Catchmark,

2025). In water treatment, starch serves as a flocculant to eliminate contaminants (Ho et al., 2025). When combined with other polymers such as polylactic acid (PLA) or polyvinyl alcohol (PVA), starch is utilized to create biodegradable plastics (Tabassum et al., 2024). Additionally, it is employed in packaging materials, single-use cutlery, and agricultural mulch films (Ghasemlou et al., 2024).

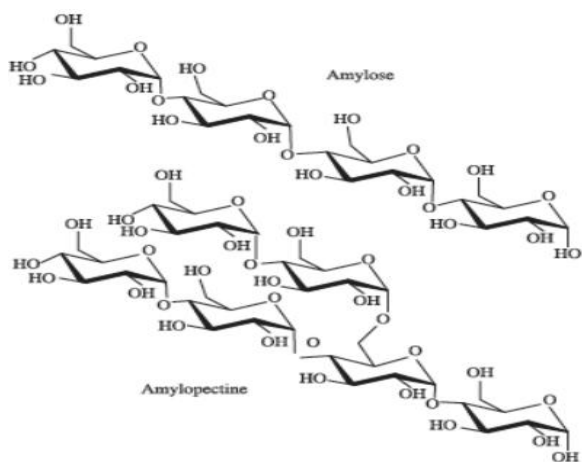


Fig. 3 Chemical structure of starch

Source: Begum et al. (2019)

## Glycogen

Glycogen is a polysaccharide commonly found in mammalian and non-mammalian cells, as well as microorganisms such as animals, fungi, and microbes (Tudu & Samanta, 2023). It is a primarily polymer of glucose units, with most glucose units linked together by  $\alpha$ -1,4-glucosidic linkages and a few  $\alpha$ -1,6 linkages (Paredes-Flores et al., 2024) (Fig. 4).

Glycogen is a heavily branched glucose polymer that serves as an energy reserve in animals, similar to starch in plants. Unlike starch, glycogen is not found in plant tissue and is instead concentrated in the liver, with smaller amounts in skeletal muscles. Despite its lower total amount, glycogen makes up a significant portion of muscle weight (Daghlaz & Rahimi, 2023).

Glycogen synthesis, known as glycogenesis, begins with a primer protein called glycogenin, which attaches glucose molecules to itself. This is followed by elongation, where glycogen synthase adds glucose units through  $\alpha$ -1,4-glucosidic bonds. The process concludes with branching, facilitated by the enzyme amylo- $\alpha$ -1, 4  $\rightarrow$ 1,6-transglucosidase, which introduces  $\alpha$ -1,6

glycosidic bonds, resulting in a highly branched structure (Tan et al., 2025).

Glycogen is commonly used in biochemical research as a standard or control for studying carbohydrate metabolism, enzymatic activity, and cellular energy dynamics (Pan et al., 2024).

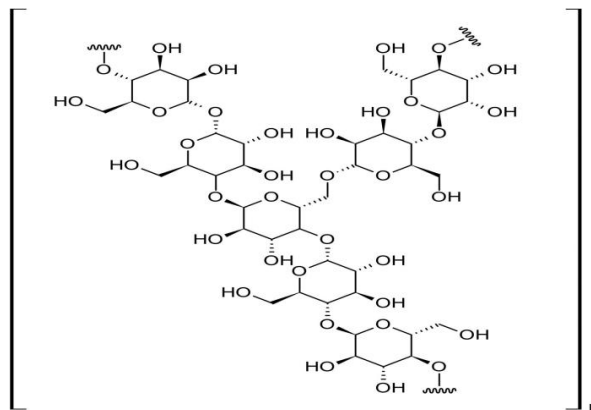


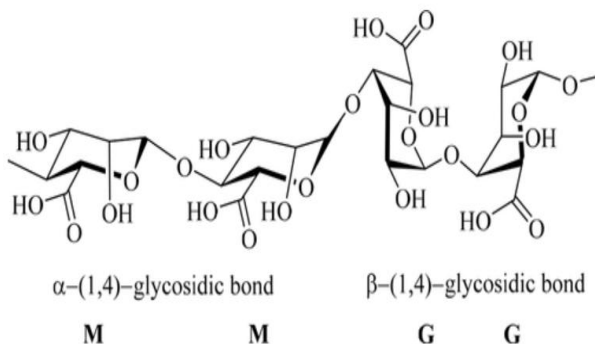
Fig. 4 Chemical structure of glycogen

Source: Abcam (2022)

## Alginates (ALGs)

Alginate is a natural hydrocolloid from algae, specifically brown algae, which is a group that includes many of the seaweeds, like kelps and an extracellular polymer of some bacteria that has garnered considerable interest as a sustainable biomaterial for various applications (Deniz et al., 2022; Chen et al., 2022). As shown (Fig. 5), alginates are composed of 1,4-linked  $\beta$ -d-mannuronate (M) and  $\alpha$ -l-guluronate (G) residues (Madsen et al., 2021). Over the past few decades, significant advancements have been made in modifying alginate to enhance its properties and expand its potential uses. Modified alginate can exhibit improved mechanical strength, increased biocompatibility, enhanced drug delivery capabilities, and greater stability, making it an attractive choice for applications in tissue engineering, wound healing, drug delivery systems, and food and beverage industries (Hariyadi & Islam, 2020; Kumar et al., 2021; Łętocha et al., 2022; Zhang & Zhao, 2020). This modification process involves the incorporation of different functional groups, cross-linking agents, or blending with other polymers to achieve the desired properties (Tan et al., 2023a). By tailoring the chemistry and structure of alginate, researchers are unlocking its

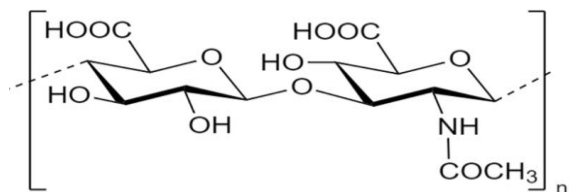
full potential, creating versatile materials with a wide range of applications while minimizing environmental impact (Guo et al., 2023a).



**Fig. 5** Chemical structure of alginate  
**Source:** Akshaya and Nathanael (2024)

### Hyaluronan/Hyaluronic acid

Hyaluronan (HA), a negatively charged polysaccharide, is abundant in extracellular matrices, epithelial tissues, soft connective tissues, and neuronal tissues (Tudu & Samanta, 2023). Its linear structure comprises N-acetyl glucosamine and glucuronic acid moieties, synthesized through cell membrane-bound enzymatic conjugation of monosaccharides (Fig. 6). HA has recently gained extensive attention across medicine, pharmaceuticals and cosmetics due to its versatile applications, including tissue engineering, wound healing, ophthalmology, and cancer therapy. Its biocompatible and cell-viable properties enable its use as a drug carrier in liposome and nanoparticle preparations (Buckley et al., 2022; Yasin et al., 2022; Zhu et al., 2019).

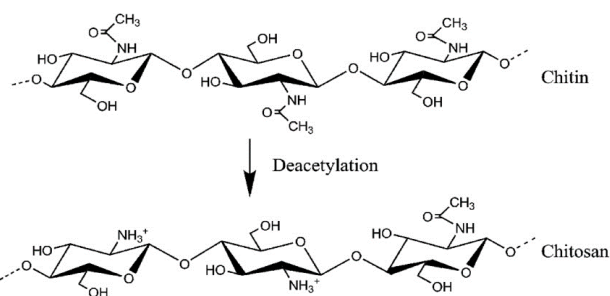


**Fig. 6** Chemical structure of hyaluronic acid  
**Source:** Gamage et al. (2024)

### Chitosan

Chitosan, the second most plentiful natural resource following cellulose, is generated through the deacetylation process applied to chitin, which is found in abundance in seafood waste (Wang et al., 2020b).

Chitin is a naturally occurring linear amino polysaccharide consisting of repeating units of poly- $\beta$ -(1-4)- N-acetyl-D-glucosamine (Fig. 7) (Hajji et al., 2014). Consequently, chitosan has garnered significant attention for its potential uses in various industries. Its versatility and effectiveness have been extensively recognized, making it a valuable biomaterial in numerous applications, such as wound healing, drug delivery, and tissue engineering. Chitosan's merits have been well-established, positioning it as a promising candidate for innovative solutions in biomedical sciences and beyond (Hisham et al., 2023).



**Fig. 7** Chemical structure of chitin and chitosan  
**Source:** Nilsen-Nygaard et al. (2015)

### Polynucleotide-based biopolymers

These macromolecules are vital components of biological systems, primarily made up of nucleotide monomers (Hakobyan et al., 2023). The main types of these biopolymers are DNA (deoxyribonucleic acid) and RNA (ribonucleic acid), both of which are crucial for the storage, transmission, and expression of genetic information (Moccia et al., 2023).

DNA is located in the nuclei of eukaryotic cells, as well as in mitochondria, chloroplasts, and the cytoplasm of prokaryotic cells. In contrast, RNA is found in both the cytoplasm and nucleus of cells, existing in various forms such as mRNA, tRNA, rRNA, and non-coding RNAs (Wang & Farhana, 2023).

Applications of polynucleotide-based biopolymers include recombinant DNA technology, which is utilized to develop genetically modified organisms (GMOs) for use in agriculture, medicine, and industry (Hamdan & Tan, 2024; Khan et al., 2016). Research indicates that polynucleotides can be employed to deliver therapeutic genes aimed at treating genetic disorders, as well as serving as tools for genome editing (Huang et al., 2022; van der Oost & Patinios, 2023). Additionally, polynucleotides are used therapeutically; short strands can inhibit the

expression of genes responsible for diseases (Baylot et al., 2024). They can also be engineered into nanoscale structures for purposes such as drug delivery, biosensing, and molecular computing (Liang et al., 2024; Sun et al., 2024; Wang et al., 2023). In agriculture, polynucleotides are applied to introduce desirable traits such as pest resistance, drought tolerance, and enhanced nutritional content (Ding et al., 2021; Nagaraj et al., 2024; Vasileva et al., 2024).

### Synthetic biopolymer

These are class of polymers that are either derived from natural sources or synthesized to mimic natural polymers (Pinaeva & Noskov, 2024). They have gained significant attention in recent years due to their biocompatibility, biodegradability and versatility in applications ranging from medicine to environmental sustainability (Satchanska et al., 2024).

A variety of techniques can be used to produce synthetic biopolymers: chemical polymerization, which joins monomer units with chemical catalysts to achieve precise control over the molecular weight and structure of the polymer; enzymatic polymerization, which uses enzymes as catalysts and offers a high-specificity, environmentally friendly alternative; and recombinant DNA technology, which produces biopolymers by introducing genes encoding particular proteins into host organisms such as bacteria or yeast, resulting in the synthesis of the desired polymer (Getahun et al., 2024; Gkountela & Vouyiouka, 2022; Shire et al., 2024).

### Polyhydroxyalkanoates (PHAs)

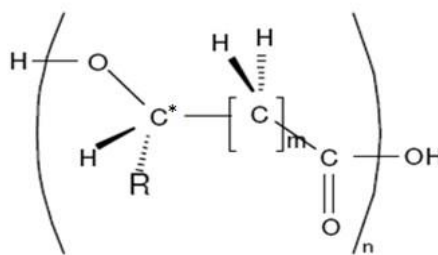
PHAs can be synthesized from a variety of carbon sources, which are typically classified into five categories: gases (including methane and carbon dioxide), alcohols (such as methanol, ethanol, glycerol, and octanol), carbohydrates (like glucose, fructose, sucrose, maltose, lactose, xylose, starch, and cellulose), fatty acids (including acetic acid, propionic acid, butyric acid, valeric acid, hexanoic acid, lauric acid, and oleic acid), and alkanes (such as hexane, octane, and dodecane) (Zhou et al., 2023).

PHA can be produced through several methods, such as microbial fermentation using either wild type or genetically modified microorganisms, in vitro techniques that utilize PHA synthase for catalysis, and synthesis involving genetically engineered plants (Poltronieri & Kumar, 2019).

Many microorganisms can store and break down polyhydroxyalkanoates (PHAs) due to the enzymes PHA synthase (PhaC) and PHA depolymerase (PhaZ). These enzymes facilitate the production and degradation of PHAs, enabling microorganisms to adapt to different environments and utilize PHAs for various functions (Chen et al., 2020; Zhou et al., 2023).

The synthesis of PHA faces several challenges, including high production costs that impact its scalability (Ilhami et al., 2025). Nevertheless, it is a valuable biopolymer with applications in various sectors (Thamarai et al., 2024). In the packaging industry, for instance, PHA is utilized to create biodegradable and compostable materials like bags, films, and containers (Cheng et al., 2024). These materials are safe for food contact and can help prolong the shelf life of perishable items (Kumar et al., 2023).

In the medical and pharmaceutical sectors, it is utilized to manufacture temporary medical implants like sutures, stents, and bone plates that naturally degrade within the body (Ben Abdeladhim et al., 2024; Pulingam et al., 2022). This adaptable biopolymer is also employed in agriculture for mulching films and as PHA coatings on fertilizers (Fig. 8), enabling a gradual release of nutrients, which enhances crop yields and minimizes environmental pollution (Acharjee et al., 2022).



**Fig. 8** Chemical structure of polyhydroxyalkanoate  
Source: Koller et al. (2012)

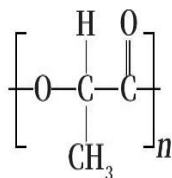
### Polylactic acid PLA

Polylactic acid (PLA) has garnered significant attention as a versatile polymer with vast potential for application in various industries, including chemistry, medicine, pharmaceuticals, and biotechnology. There are several potential methodologies for the production of polylactic acid (PLA), with a focus on enzymatic routes involving lipase enzymes. Lipases have shown promise in producing high-quality PLA with desirable mechanical and thermal properties (Fig. 9) (de Albuquerque et al., 2021).

Lactic acid (LA), a key monomer for producing PLA, is mainly produced through biological fermentation (Reshma et al., 2024). This necessitates an effective downstream separation process to keep production costs low and maintain high purity levels. The rising demand for PLA has led to significant growth in the global market for this biopolymer. Currently, PLA is the most widely used biopolymer in diverse sectors, including packaging, agriculture, and transportation (Swetha et al., 2023).

PLA has gained significant attention for its biocompatibility, biodegradability, and versatility (Hussain et al., 2024a). It is widely used in packaging for films, containers, and bottles, providing a biodegradable alternative to traditional plastics, especially for single-use items (O'Loughlin et al., 2023). It is utilized in medical applications due to its biocompatible nature, this material is used in absorbable sutures and stents, as it dissolves in the body over time (Yang et al., 2024). It is also a popular choice for 3D printing due to its ease of use, low melting temperature, and smooth finish, making it suitable for prototypes, models, and finished products across various industries (Joseph et al., 2023).

PLA are spun into textiles suitable for apparel and home furnishings, featuring moisture-wicking properties and biodegradability, making them ideal for sustainable fashion (Yang et al., 2021). The automobile industry is exploring PLA for lightweight interior components and non-structural parts to help reduce overall vehicle weight (Yan & Xu, 2025). PLA composites are being studied for construction applications to support sustainable building practices also, PLA can be utilized for biodegradable electronic casings and components, contributing to the reduction of electronic waste (Ye et al., 2024; Yedrissov et al., 2022).



**Fig. 9** Chemical structure of polylactic acid  
**Source:** Casalini et al. (2019)

### Poly- $\gamma$ -Glutamic Acid ( $\gamma$ -PGA)

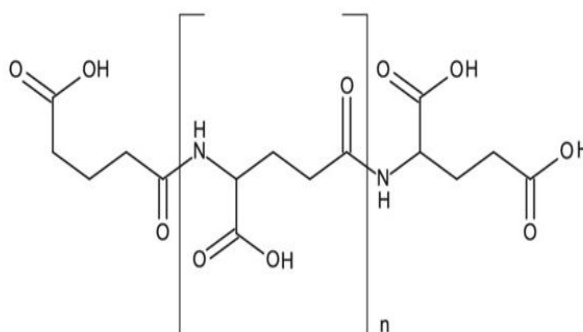
Poly- $\gamma$ -glutamic acid ( $\gamma$ -PGA) is a naturally occurring chiral biopolymer made up of l-glutamic acid, d-glutamic acid, or a combination of both in varying ratios (Fig. 10). Its properties, including conformational

states, enantiomeric characteristics, and molecular mass, can vary depending on the microbial producers used (Elbanna et al., 2024; Wang et al., 2022). It possesses several advantageous properties such as biodegradability, water solubility, environmental friendliness, and edibility, making it a versatile material with numerous industrial applications (Wang et al., 2022).

The microbial production of  $\gamma$ -PGA is considered a cost-effective and efficient approach. *Bacillus* species, in particular, have been thoroughly researched for their capacity to synthesize  $\gamma$ -PGA. The biosynthetic process of  $\gamma$ -PGA includes multiple metabolic stages such as racemization, polymerization, transfer, and catabolism. (Li et al., 2022).

It is used in different sphere of life; medical and pharmaceutical,  $\gamma$ -PGA is used as a carrier for controlling drug release due to its ability to encapsulate drug and degrade slowly (Cai et al., 2023). Its moisture-retention properties promote tissue regeneration and wound healing (Li et al., 2023). In tissue engineering,  $\gamma$ -PGA is employed as a scaffold for cell growth and tissue repair, as well as an anti-adhesion barrier (Suzuki et al., 2024; Wang et al., 2024b).

In the cosmetic and skincare industry,  $\gamma$ -PGA acts as a moisturizing agent and humectant, helping to retain skin moisture. This makes it an essential ingredient in anti-aging and hydrating products (Serra et al., 2024).  $\gamma$ -PGA serves as fertilizer carrier in the agricultural industries thereby enhancing nutrient absorption in plants by improving soil water retention (Elbanna et al., 2024; Guo et al., 2023b). It has been reported that it also promotes germination and plant growth (Dueñas et al., 2024; Zeng et al., 2024). The environmental application includes its use for wastewater treatment since it can absorb heavy metals and pollutant aiding in water purification (Chen et al., 2024a).



**Fig 10** Chemical structure of poly- $\gamma$ -glutamic acid ( $\gamma$ -PGA)  
**Source:** Balogun-Agbaje et al. (2021)

## Polycaprolactone

Polycaprolactone (PCL) is a synthetic polymer composed of repeating units sourced from caprolactone, a seven-membered cyclic ester. Due to its aliphatic structure, this features alternating ester linkages and methylene groups, this polymer exhibits hydrophobic characteristics (Bhadran et al., 2023).

PCL is a synthetic biodegradable polyester derived from petroleum-based monomers, classified as a biopolymer due to its biocompatibility and biodegradability (Fouad et al., 2023). It is produced through the ring-opening polymerization of  $\epsilon$ -caprolactone, resulting in a semi-crystalline structure with a low melting point (60°C) and high flexibility (Deshpande et al., 2023). PCL has a slow degradation rate of 2 to 3 years, making it versatile and valuable in various fields (Deshpande et al., 2023). PCL is used in diverse applications, including 3D printing of prototypes and medical implants due to its low processing temperature, which is ideal for custom devices and educational models (Kennedy et al., 2023). It serves as an eco-friendly adhesive and coating in textiles and electronics (Ferreira et al., 2022; Gadhav, 2022; Kim et al., 2023). Additionally, PCL enhances the biodegradability of conventional plastics, such as in PCL/starch blends (Surendren et al., 2022).

In medicine and pharmaceuticals, PCL is utilized in microspheres, nanoparticles, and implants for sustained drug release, including cancer therapies and hormonal treatments (Magill et al., 2023; Nwazojie et al., 2023). It plays a role in tissue engineering by providing 3D printed or electrospun scaffolds that support cell growth for bone, cartilage, and skin regeneration (Gharibshahian et al., 2023). Also, when blended with hydroxyapatite, PCL enhances bone repair (Lin et al., 2024). It is utilized in orthopedics for resorbable screws, pins, and bone fillers, which eliminates the need for secondary surgeries (Huang et al., 2023). In environmental applications, PCL is used for biodegradable packaging, compostable films, and containers, often blended with starch or PLA to enhance degradation (Dodda et al., 2023; Gürler et al., 2023; Westlake et al., 2023; Yang et al., 2022). Also, it serves as agricultural films that degrade after harvest, helping to reduce plastic waste (Mansoor et al., 2022).

## Gelatin

Gelatin is a natural biopolymer obtained through the partial breakdown of collagen, sourced from animal

tissues including skin, bones, and connective tissues (Julie Chandra et al., 2023). It consists of amino acids such as glycine, proline, and hydroxyproline (Gaspar-Pintilie et al., 2019). Gelatin is popular for its biocompatibility, biodegradability, and distinctive functional characteristics, including its ability to gel, emulsify, and form films (Eranda et al., 2024).

In the food industry gelatin is used as gelling ingredient used in desert like jelly, gummy candies and marshmallows also, as thickening agent it add texture to products like yoghurt, ice cream, and sauces (Himashree et al., 2022; Kadirvel & Narayana, 2023).

In pharmaceuticals and medicine, gelatin is used to create hard and soft capsules for oral drug delivery (vitamins and pain relievers), as well as in hydrogel dressings to promote healing and retain moisture (Cao et al., 2024; Chavarria-Rojas et al., 2021; Nezhad Mohseni et al., 2022). In tissue engineering, gelatin is used as scaffolds for 3D cell culture and regenerative medicine (e.g., skin grafting) (Asim et al., 2024; Quan et al., 2014).

Gelatin has a wide range of commercial applications, such as being used as an adhesive in glue sticks and animal-based glue, stabilizing fibers during weaving, and serving as a matrix for cell culture in biotechnology (Ahmetoglu et al., 2025; Mosleh et al., 2023; Song & Jang, 2023). It also helps to protect probiotics, enzymes, and nutrients in functional meals (Lomakina et al., 2012; Tan et al., 2023b; Wang et al., 2024a).

## Physical and chemical properties

The physicochemical characteristics of biopolymers are crucial for determining their application potential. Key measurable properties include mechanical Strength (such as tensile strength and elasticity) (Table 1), thermal stability (including glass transition temperature and melting point), barrier properties (pertaining to permeability to oxygen and water vapor), degradation kinetics (how quickly they break down under various conditions).

These properties vary based on the biopolymer's chemical makeup, molecular weight, and structural arrangement (Das et al., 2022; Flórez et al., 2023).

## Environmental impact and Degradation metrics

Biopolymers provide significant environmental benefits over traditional plastics due to their biodegradability and compostability, with degradation times ranging from

**Table 1** Tensile strength of some major biopolymer categories

| Biopolymer type               | Tensile strength (MPa) | References                 |
|-------------------------------|------------------------|----------------------------|
| Cellulose                     | 50 to 250              | Jakob et al. (2022)        |
| Chitosan                      | Up to 579              | Zhang et al. (2021)        |
| Starch                        | 5 to 8                 | Domene-López et al. (2019) |
| Gelatin                       | 46                     | Zaman et al. (2012)        |
| PLA                           | 39.9 to 52.5           | Gao et al. (2022)          |
| PHA                           | 40                     | Akinmulewo & Nwinyi (2019) |
| Polycaprolactone              | 3.4                    | Dwivedi et al. (2020)      |
| Poly- $\gamma$ -glutamic acid | 123.5                  | Yao et al. (2025)          |

**Table 2** Degradability properties of some major biopolymer categories

| Biopolymer type               | Degradation time    | References                 |
|-------------------------------|---------------------|----------------------------|
| Cellulose                     | 12 weeks            | Yadav & Hakkarainen (2021) |
| Chitosan                      | 12 weeks            | Boryniec et al. (1996)     |
| Starch                        | 3 Days to 12months  | Polman et al. (2021)       |
| Gelatin                       | Up 84 days          | Tondera et al. (2016)      |
| PLA                           | 1 week to 24 months | Grizzi et al. (1995)       |
| PHA                           | Days to 2 years     | Read et al. (2024)         |
| Polycaprolactone              | 2 to 3 years        | Deshpande et al. (2023)    |
| Poly- $\gamma$ -glutamic acid | 20 to 30 days       | Fan et al. (1996)          |

weeks to years based on material composition and environmental conditions (Table 2). They break down into natural byproducts like carbon dioxide, water, and biomass (Cheng et al., 2024). Biopolymers have a much lower carbon footprint, reducing greenhouse gas emissions compared to petroleum-based plastics, largely due to the use of renewable materials and biomass carbon sequestration (Islam et al., 2024). Degradation rates depend on factors such as molecular structure and environmental conditions; under optimal composting conditions, many biopolymers can fully degrade within a few months, while degradation in marine environments can take a longer time (Dintcheva, 2024; Feijoo et al., 2025; Payanthoth et al., 2024).

### Sustainability of biopolymers for industries

The relationship between biopolymers and industries is mutually beneficial, as a sustainable industry establishes the necessary framework, renewable energy sources, circular waste management systems, and ethical sourcing policies to ensure the truly sustainable production and use of biopolymers (Haq et al., 2025). In return, biopolymers offer the foundational materials that enable industries to meet their key sustainability goals: decreasing reliance on fossil fuels, closing the carbon loop, and eliminating waste (Gonçalves et al., 2025; Kamran et al., 2025). The ultimate objective is not merely to substitute one material for another, but to redesign systems so that materials are utilized or maintained for

as long as possible and to restore natural systems at the end of their lifecycle.

### Conclusion

The increasing significance of biopolymers across various industries is closely linked to sustainability, as they offer a practical alternative to conventional petroleum-based plastics. The connection between biopolymers and a sustainable industrial future can be examined through several key aspects, such as the utilization of renewable materials that lessen dependence on fossil fuels and aid in combating climate change. This aligns with the principles of a sustainable industrial future that emphasize resource efficiency. Additionally, many biopolymers possess biodegradable properties, allowing them to break down naturally in the environment, which helps reduce pollution and waste accumulation. This characteristic is vital for tackling the global plastic waste crisis. Furthermore, the production of biopolymers typically results in lower greenhouse gas emissions compared to traditional plastics.

Biopolymers contribute to the development of a circular carbon economy by absorbing carbon from the atmosphere via photosynthesis. The growth of biopolymer technologies promotes innovation and offers up new market opportunities, resulting in job creation and economic development. Sustainable industrial practices usually include investing in local communities and supporting fair trade initiatives.

Sustainable practices frequently use life cycle assessments (LCA) to evaluate the environmental impact of items over their full life cycle, from manufacturing to disposal. Biopolymers outperform traditional materials in LCAs because they have a reduced environmental impact.

Biopolymers can also be employed in circular economy frameworks, which aim to reduce waste and reuse or recycle resources. This technique promotes sustainability by ensuring that resources are utilized.

Biopolymers have enormous promise for a more sustainable future, but their manufacturing and widespread adoption face considerable constraints and hurdles. These challenges can be divided into three categories: technical, economic, and systemic. The most significant limitations and problems of biopolymers include economic viability and high manufacturing costs, as feedstock such as maize, sugarcane, and potatoes are agricultural commodities vulnerable to price volatility

due to weather, harvest yields, and competition in the food market. It is also influenced by economies of scale, which demonstrate how the petrochemical plastic sector has evolved over a century, with massively optimized production plants. The biopolymer sector is young and operates on a smaller scale, resulting in higher per-unit costs.

Certain biopolymers have inherent characteristics that limit their use. These qualities include thermal stability, durability, mechanical strength, and barrier properties.

The competition with food crops also raises ethical considerations and resource allocation dilemmas ("Food vs. Fuel").

However, biopolymers also hold industrial potential in sectors such as textiles, automotive, and construction, where their lightweight and durable properties provide sustainable alternatives to traditional materials. However, to fully realize their potential, ongoing research is needed to enhance their properties, such as thermal stability and mechanical strength, and to optimize production costs for broader industrial adoption. This shift toward biopolymers represents a crucial step in addressing environmental challenges and promoting sustainable development.

A prioritized research agenda should encompass the synthesis and modification of biopolymers, energy storage and conversion technologies, as well as life cycle assessment (LCA) and sustainability metrics.

### Conflict of interest

There is no conflict of interest.

### Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript the author(s) Grammarly was used to enhance clarity. The final content was reviewed and edited by the Moses Edache Entonu and Artem Malinin, who takes full responsibility for the accuracy and integrity of the publication. This declaration is not required for the use of standard tools for checking grammar, spelling, or formatting.

### References

Abcam. (2022). *Glycogen, polymer of glucose* (ab146544). <https://www.abcam.co.jp/products/biochemicals/glycogen-polymer-of-glucose-ab146544.html>

- Acharjee, S.A., Bharali, P., Gogoi, B., Sorhie, V., Walling, B., & Alemtoshi. (2022). PHA-based bioplastic: A potential alternative to address microplastic pollution. *Water, Air, & Soil Pollution*, 234(1), 21. <https://doi.org/10.1007/S11270-022-06029-2>
- Ahmetoglu, U., Gungor, M., & Kilic, A. (2025). Alginate/gelatin blend fibers for functional high-performance air filtration applications. *International Journal of Biological Macromolecules*, 294, 139389. <https://doi.org/10.1016/j.ijbiomac.2024.139389>
- Akinmulewo, A.B., & Nwinyi, O.C. (2019). Polyhydroxyalkanoate: A biodegradable polymer (a mini review). *Journal of Physics: Conference Series*, 1378(4), 042007. <https://doi.org/10.1088/1742-6596/1378/4/042007>
- Akshaya, S., & Nathanael, A.J. (2024). A review on hydrophobically associated alginates: Approaches and applications. *ACS Omega*, 9(4), 4246–4262. <https://doi.org/10.1021/acsomega.3c08619>
- Amjad, A.I. (2024). Bamboo fibre: A sustainable solution for textile manufacturing. *Advances in Bamboo Science*, 7, 100088. <https://doi.org/10.1016/j.bamboo.2024.100088>
- An, J., Wicaksana, F., Woo, M.W., Liu, C., Tian, J., & Yao, Y. (2024). Current food processing methods for obtaining umami peptides from protein-rich foods: A review. *Trends in Food Science & Technology*, 153, 104704. <https://doi.org/10.1016/j.tifs.2024.104704>
- Apriyanto, A., Compart, J., & Fettke, J. (2022). A review of starch, a unique biopolymer—structure, metabolism and in planta modifications. *Plant Science*, 318, 111223. <https://doi.org/10.1016/j.plantsci.2022.111223>
- Asim, S., Hayhurst, E., Callaghan, R., & Rizwan, M. (2024). Ultra-low content physio-chemically crosslinked gelatin hydrogel improves encapsulated 3D cell culture. *International Journal of Biological Macromolecules*, 264, 130657. <https://doi.org/10.1016/j.ijbiomac.2024.130657>
- Balogun-Agbaje, O.A., Odeniyi, O.A., & Odeniyi, M.A. (2021). Drug delivery applications of poly- $\gamma$ -glutamic acid. *Future Journal of Pharmaceutical Sciences*, 7(1), 125. <https://doi.org/10.1186/s43094-021-00280-w>
- Baylot, V., Le, T.K., Taïeb, D., Rocchi, P., & Colleaux, L. (2024). Between hope and reality: treatment of genetic diseases through nucleic acid-based drugs. *Communications Biology*, 7(1), 489. <https://doi.org/10.1038/s42003-024-06121-9>
- Begum, M.H.A., Hossain, M.M., Gafur, M.A., Kabir, A.N. M.H., Tanvir, N.I., & Molla, M.R. (2019). Preparation and characterization of polyvinyl alcohol–starch composites reinforced with pulp. *SN Applied Sciences*, 1(9), 1091.
- Behrooznia, Z., & Nourmohammadi, J. (2024). Polysaccharide-based materials as an eco-friendly alternative in biomedical, environmental, and food packaging. *Giant*, 19, 100301. <https://doi.org/10.1016/j.giant.2024.100301>
- Ben Abdeladhim, R., Reis, J.A., Vieira, A.M., & de Almeida, C.D. (2024). Polyhydroxyalkanoates: Medical applications and potential for use in dentistry. *Materials*, 17(22), 5415. <https://doi.org/10.3390/ma17225415>

- Benalaya, I., Alves, G., Lopes, J., & Silva, L.R. (2024). A review of natural polysaccharides: sources, characteristics, properties, food, and pharmaceutical applications. *International Journal of Molecular Sciences*, 25(2), 1322. <https://doi.org/10.3390/ijms25021322>
- Bhadran, A., Shah, T., Babanyinah, G.K., Polara, H., Taslimy, S., Biewer, M.C., & Stefan, M.C. (2023). Recent advances in polycaprolactones for anticancer drug delivery. *Pharmaceutics*, 15(7), 1977. <https://doi.org/10.3390/pharmaceutics15071977>
- Boryniec, S., Ratajska, M., & Strobin, G. (1996). Biodegradation of chitosan. *Polimery*, 41(10), 564–567.
- Buckley, C., Murphy, E.J., Montgomery, T.R., & Major, I. (2022). Hyaluronic acid: A review of the drug delivery capabilities of this naturally occurring polysaccharide. *Polymers*, 14(17), 3442. <https://doi.org/10.3390/polym14173442>
- Cai, M., Han, Y., Zheng, X., Xue, B., Zhang, X., Mahmut, Z., ... Sun, J. (2023). Synthesis of poly- $\gamma$ -glutamic acid and its application in biomedical materials. *Materials*, 17(1), 15. <https://doi.org/10.3390/ma17010015>
- Cao, H., Wang, J., Hao, Z., & Zhao, D. (2024). Gelatin-based biomaterials and gelatin as an additive for chronic wound repair. *Frontiers in Pharmacology*, 15, 1398939. <https://doi.org/10.3389/fphar.2024.1398939>
- Carolin C, F., Kamalesh, T., Kumar, P.S., Hemavathy, R.V., & Rangasamy, G. (2023). A critical review on sustainable cellulose materials and its multifaceted applications. *Industrial Crops and Products*, 203, 117221. <https://doi.org/10.1016/j.indcrop.2023.117221>
- Charan Giri, N. (2022). Protein and peptide drug delivery. In Ahmad, U., Haider, Md.F., & Akhtar, J. (Eds.), *Smart Drug Delivery* (pp. 39–74), IntechOpen. <https://doi.org/10.5772/intechopen.99608>
- Chavarria-Rojas, M., Acuña-Amador, D., & Madrigal-Redondo, G.L. (2021). Gelatin and non-gelatin soft gel capsules: A review. *Journal of Excipients and Food Chemicals*, 12(2), 19–29.
- Chavarria-Rojas, M., Acuña-Amador, D., & Madrigal-Redondo, G.L. (2021). Gelatin and non-gelatin soft gel capsules: A review. *Journal of Excipients and Food Chemicals*, 12(2), 19–29. <https://doi.org/10.66617/001c.25162>
- Chen, F., Zhao, Y., Zhao, H., Zhou, X., & Liu, X. (2024a). Heavy metal removal from wastewater using poly (gamma-glutamic acid)-based hydrogel. *Gels*, 10(4), 259. <https://doi.org/10.3390/gels10040259>
- Chen, G.Q., Chen, X.Y., Wu, F.Q., & Chen, J.C. (2020). Polyhydroxyalkanoates (PHA) toward cost competitiveness and functionality. *Advanced Industrial and Engineering Polymer Research*, 3(1), 1–7. <https://doi.org/10.1016/j.aiepr.2019.11.001>
- Chen, Z., Du, C., Liu, S., Liu, J., Yang, Y., Dong, L., ... Lei, Y. (2024b). Progress in biomaterials inspired by the extracellular matrix. *Giant*, 19, 100323. <https://doi.org/10.1016/j.giant.2024.100323>
- Chen, Z., Wei, W., & Ni, B.J. (2022). Algae-based alginate biomaterial: Production and applications. In Ngo, H., Guo, W., Pandey, A., Chang, J.S., & Lee, D.J. (Eds.), *Biomass, Biofuels, and Biochemicals* (pp. 37–66), Elsevier. <https://doi.org/10.1016/b978-0-323-96142-4.00004-x>
- Cheng, J., Gao, R., Zhu, Y., & Lin, Q. (2024). Applications of biodegradable materials in food packaging: A review. *Alexandria Engineering Journal*, 91, 70–83. <https://doi.org/10.1016/j.aej.2024.01.080>
- Daghlas, S.A., & Rahimi, N. (2023). *Biochemistry, Glycogen. StatPearls*. <https://www.ncbi.nlm.nih.gov/books/nbk539802/>
- Darmenbayeva, A., Zhussipnazarova, G., Rajasekharan, R., Massalimova, B., Zharlykapova, R., Nurlybayeva, A., ... & Shinibekova, A. (2024). Applications and advantages of cellulose–chitosan biocomposites: Sustainable alternatives for reducing plastic dependency. *Polymers*, 17(1), 23. <https://doi.org/10.3390/polym17010023>
- Das, A., Ringu, T., Ghosh, S., & Pramanik, N. (2022). A comprehensive review on recent advances in preparation, physicochemical characterization, and bioengineering applications of biopolymers. *Polymer Bulletin*, 80, 7247–7312. <https://doi.org/10.1007/s00289-022-04443-4>
- de Albuquerque, T.L., Marques Júnior, J.E., de Queiroz, L.P., Ricardo, A.D.S., & Rocha, M.V.P. (2021). Polylactic acid production from biotechnological routes: A review. *International Journal of Biological Macromolecules*, 186, 933–951. <https://doi.org/10.1016/j.ijbiomac.2021.07.074>
- Deniz, I., Imamoglu, E., & Keskin-Gundogdu, T. (Eds.). (2022). *Properties and Applications of Alginates*. IntechOpen. <https://doi.org/10.5772/intechopen.94635>
- Deshpande, M.V., Girase, A., & King, M.W. (2023). Degradation of poly ( $\epsilon$ -caprolactone) resorbable multifilament yarn under physiological conditions. *Polymers*, 15(18), 3819. <https://doi.org/10.3390/polym15183819>
- Deshpande, M.V., Girase, A., & King, M.W. (2023). Degradation of poly( $\epsilon$ -caprolactone) resorbable multifilament yarn under physiological conditions. *Polymers*, 15(18), 3819. <https://doi.org/10.3390/polym15183819>
- Ding, T., Song, G., Liu, X., Xu, M., & Li, Y. (2021). Nucleotides as optimal candidates for essential nutrients in living organisms: A review. *Journal of Functional Foods*, 82, 104498. <https://doi.org/10.1016/j.jff.2021.104498>
- Dintcheva, N.T. (2024). Overview of polymers and biopolymers degradation and stabilization towards sustainability and materials circularity. *Polymer*, 306, 127136. <https://doi.org/10.1016/j.polymer.2024.127136>
- Dodda, J.M., Azar, M.G., Bělský, P., Šlouf, M., Gajdošová, V., Kasi, P.B., ... Kovářík, T. (2023). Bioresorbable films of polycaprolactone blended with poly (lactic acid) or poly (lactic-co-glycolic acid). *International Journal of Biological Macromolecules*, 248, 126654. <https://doi.org/10.1016/j.ijbiomac.2023.126654>
- Domene-López, D., García-Quesada, J.C., Martín-Gullón, I., & Montalbán, M.G. (2019). Influence of starch composition and molecular weight on physicochemical properties of biodegradable films. *Polymers*, 11(7), 1084. <https://doi.org/10.3390/polym11071084>
- Drishya, P.K., Reddy, M.V., Mohanakrishna, G., Sarkar, O., Isha, Rohit, M.V., ... Chang, Y.C. (2025). Advances in microbial and plant-based biopolymers: Synthesis and applications in next-generation materials. *Macromol*, 5(2), 21. <https://doi.org/10.3390/macromol5020021>

- Duan, C., Meng, X., Meng, J., Khan, M.I.H., Dai, L., Khan, A., ... Ni, Y. (2019). Chitosan as a preservative for fruits and vegetables: A review on chemistry and antimicrobial properties. *Journal of Bioresources and Bioproducts*, 4(1), 11–21. <https://doi.org/10.21967/jbb.v4i1.189>
- Dueñas, C., Calvio, C., Slamet-Loedin, I.H., Susanto, U., & Macovei, A. (2024). Seed priming with poly-gamma-glutamic acid ( $\gamma$ -PGA) improves rice germination performance under drought conditions. *Agriculture*, 14(6), 926. <https://doi.org/10.3390/agriculture14060926/s1>
- Dwivedi, R., Kumar, S., Pandey, R., Mahajan, A., Nandana, D., Katti, D.S., & Mehrotra, D. (2020). Polycaprolactone as biomaterial for bone scaffolds: Review of literature. *Journal of Oral Biology and Craniofacial Research*, 10(1), 381. <https://doi.org/10.1016/j.jobcr.2019.10.003>
- Elbanna, K., Alsulami, F.S., Neyaz, L.A., & Abulreesh, H.H. (2024). Poly ( $\gamma$ ) glutamic acid: A unique microbial biopolymer with diverse commercial applicability. *Frontiers in Microbiology*, 15, 1348411. <https://doi.org/10.3389/fmicb.2024.1348411>
- Eranda, D.H.U., Chaijan, M., Panpipat, W., Karnjanapratum, S., Cerqueira, M.A., & Castro-Muñoz, R. (2024). Gelatin-chitosan interactions in edible films and coatings doped with plant extracts for biopreservation of fresh tuna fish products: A review. *International Journal of Biological Macromolecules*, 280, 135661. <https://doi.org/10.1016/j.ijbiomac.2024.135661>
- Evode, N., Qamar, S.A., Bilal, M., Barceló, D., & Iqbal, H.M.N. (2021). Plastic waste and its management strategies for environmental sustainability. *Case Studies in Chemical and Environmental Engineering*, 4, 100142. <https://doi.org/10.1016/j.csee.2021.100142>
- Fan, K., Gonzales, D., & Sevoian, M. (1996). Hydrolytic and enzymatic degradation of poly ( $\gamma$ -glutamic acid) hydrogels and their application in slow-release systems for proteins. *Journal of Environmental Polymer Degradation*, 4(4), 253–260. <https://doi.org/10.1007/bf02070694/metrics>
- Fatima, S.N. (2024). Microbial biopolymers: A sustainable alternative to traditional petroleum-based polymers for a greener future. *Materials Today Communications*, 40, 109846. <https://doi.org/10.1016/j.mtcomm.2024.109846>
- Feijoo, P., Marín, A., Sánchez-Safont, E., Tena-Medialdea, J., García-March, J.R., Gámez-Pérez, J., & Cabedo, L. (2025). Marine degradation of plastics in western mediterranean sea: Comparison between biodegradable and conventional polymers. *Polymer Degradation and Stability*, 234, 111222. <https://doi.org/10.1016/j.polymdegradstab.2025.111222>
- Femina, K.S., & Asokan, A. (2024). Extraction of cellulose. In Thomas, S., Hosur, M., Pasquini, D., & Jose Chirayil, C. (Eds.), *Handbook of Biomass* (pp. 485–512), Springer. [https://doi.org/10.1007/978-981-99-6727-8\\_20/figures/9](https://doi.org/10.1007/978-981-99-6727-8_20/figures/9)
- Ferreira, E.F., Mouro, C., Silva, L., & Gouveia, I.C. (2022). Sustainable packaging material based on PCL nanofibers and lavandula luisieri essential oil, to preserve museological textiles. *Polymers*, 14(3), 597. <https://doi.org/10.3390/polym14030597>
- Flórez, M., Cazón, P., & Vázquez, M. (2023). Selected biopolymers' processing and their applications: A review. *Polymers*, 15(3), 641. <https://doi.org/10.3390/polym15030641>
- Fouad, F.A., Youssef, D.G., Refay, F.A., & Heakal, F.E.T. (2023). Biocompatibility of nanomaterials reinforced polymer-based nanocomposites. In Ali, G.A.M., Makhoul, A.S.H. (Eds.), *Handbook of Biodegradable Materials* (pp. 351–390), Springer. [https://doi.org/10.1007/978-3-031-09710-2\\_17](https://doi.org/10.1007/978-3-031-09710-2_17)
- Gadhav, R.V. (2022). Lactic acid-sustainable raw material for biodegradable hot melt adhesive: Review. *Open Journal of Organic Polymer Materials*, 12(3), 31–45. <https://doi.org/10.4236/ojopm.2022.123003>
- Gamege, A., Liyanapathirana, A., Manamperi, A., Gunathilake, C., Mani, S., Merah, O., & Madhujith, T. (2022). Applications of starch biopolymers for a sustainable modern agriculture. *Sustainability*, 14(10), 6085. <https://doi.org/10.3390/su14106085>
- Ganguly, A., Sharma, K., & Majumder, K. (2020). Peptides as biopolymers—Past, present, and future. In K. Pal, I. Banerjee, P. Sarkar, D. Kim, W.-P. Deng, N.K. Dubey, & K. Majumder (Eds.), *Biopolymer-based formulations* (pp. 87–104). Elsevier. <https://doi.org/10.1016/B978-0-12-816897-4.00004-7>
- Gao, G., Xu, F., Xu, J., & Liu, Z. (2022). Study of material color influences on mechanical characteristics of fused deposition modeling parts. *Materials*, 15(19), 7039. <https://doi.org/10.3390/ma15197039>
- Gaspar-Pintilie, A., Stefan, L.M., Anton, E.D., Berger, D., Matei, C., Negreanu-Pirjol, T., & Moldovan, L. (2019). Physicochemical and biological properties of gelatin extracted from marine snail rapana venosa. *Marine Drugs*, 17(10), 589. <https://doi.org/10.3390/md17100589>
- Getahun, M.J., Kassie, B.B., & Alemu, T.S. (2024). Recent advances in biopolymer synthesis, properties, & commercial applications: A review. *Process Biochemistry*, 145, 261–287. <https://doi.org/10.1016/j.procbio.2024.06.034>
- Gharibshahian, M., Salehi, M., Beheshtizadeh, N., Kamalabadi-Farahani, M., Atashi, A., Nourbakhsh, M.S., & Alizadeh, M. (2023). Recent advances on 3D-printed PCL-based composite scaffolds for bone tissue engineering. *Frontiers in Bioengineering and Biotechnology*, 11, 1168504. <https://doi.org/10.3389/fbioe.2023.1168504>
- Ghasemlou, M., Barrow, C.J., & Adhikari, B. (2024). The future of bioplastics in food packaging: An industrial perspective. *Food Packaging and Shelf Life*, 43, 101279. <https://doi.org/10.1016/j.fpsl.2024.101279>
- Gkountela, C.I., & Vouyiouka, S.N. (2022). Enzymatic polymerization as a green approach to synthesizing bio-based polyesters. *Macromol*, 2(1), 30–57. <https://doi.org/10.3390/macromol2010003>
- Gonçalves, R., Serra, J., Reizabal, A., Correia, D.M., Fernandes, L.C., Brito-Pereira, R., ... Lanceros-Méndez, S. (2025). Biobased polymers for advanced applications: Towards a sustainable future. *Progress in Polymer Science*, 162, 101934. <https://doi.org/10.1016/j.progpolymsci.2025.101934>

- Grizzi, I., Garreau, H., Li, S., & Vert, M. (1995). Hydrolytic degradation of devices based on poly (dl-lactic acid) size-dependence. *Biomaterials*, 16(4), 305–311. [https://doi.org/10.1016/0142-9612\(95\)93258-f](https://doi.org/10.1016/0142-9612(95)93258-f)
- Guo, H., Qin, Q., Chang, J.S., & Lee, D.J. (2023a). Modified alginate materials for wastewater treatment: Application prospects. *Bioresource Technology*, 387, 129639. <https://doi.org/10.1016/j.biortech.2023.129639>
- Guo, J., Zhang, J., Zhang, K., Li, S., & Zhang, Y. (2023b). Effect of  $\gamma$ -PGA and  $\gamma$ -PGA SAP on soil microenvironment and the yield of winter wheat. *PLoS One*, 18(7), e0288299. <https://doi.org/10.1371/journal.pone.0288299>
- Guo, S., Wang, J., Wang, Q., Wang, J., Qin, S., & Li, W. (2024). Advances in peptide-based drug delivery systems. *Heliyon*, 10(4), e26009. <https://doi.org/10.1016/j.heliyon.2024.e26009>
- Gürler, N., Pekdemir, M.E., Torğut, G., & Kök, M. (2023). Binary PCL–waste photopolymer blends for biodegradable food packaging applications. *Journal of Molecular Structure*, 1279, 134990. <https://doi.org/10.1016/j.molstruc.2023.134990>
- Hadinugroho, W., Martodihardjo, S., Fudholi, A., Riyanto, S., & Prasetyo, J. (2023). Hydroxypropyl methylcellulose as hydrogel matrix and citric acid-locust bean gum as negative matrix for controlled release tablet. *ACS Omega*, 8(8), 7767–7778. <https://doi.org/10.1021/acsomega.2c07432>
- Hajji, S., Younes, I., Ghorbel-Bellaaj, O., Hajji, R., Rinaudo, M., Nasri, M., & Jellouli, K. (2014). Structural differences between chitin and chitosan extracted from three different marine sources. *International Journal of Biological Macromolecules*, 65, 298–306. <https://doi.org/10.1016/j.ijbiomac.2014.01.045>
- Hakobyan, K., Noble, B.B., & Xu, J. (2023). The current science of sequence-defined macromolecules. *Progress in Polymer Science*, 147, 101754. <https://doi.org/10.1016/j.progpolymsci.2023.101754>
- Halaswamy, D., Borehalli Mayegowda, S., Brijesh, H., & Bheemappa, M. (2025). Economic aspects of marine biopolymers. In S. Ahmed & A. Soundararajan (Eds.), *Marine biopolymers* (pp. 989–1007). Elsevier. <https://doi.org/10.1016/B978-0-443-15606-9.00033-4>
- Hamdan, M.F., & Tan, B.C. (2024). Genetic modification techniques in plant breeding: A comparative review of CRISPR/Cas and GM technologies. *Horticultural Plant Journal*, 11(5), 1807–1829. <https://doi.org/10.1016/j.hpj.2024.02.012>
- Haq, F., Kiran, M., Khan, I.A., Mehmood, S., Aziz, T., & Haroon, M. (2025). Exploring the pathways to sustainability: A comprehensive review of biodegradable plastics in the circular economy. *Materials Today Sustainability*, 29, 101067. <https://doi.org/10.1016/j.mtsust.2024.101067>
- Hariyadi, D.M., & Islam, N. (2020). Current status of alginate in drug delivery. *Advances in Pharmacological and Pharmaceutical Sciences*, 2020, 8886095. <https://doi.org/10.1155/2020/8886095>
- Hersh, J., Broyles, D., Capcha, J.M.C., Dikici, E., Shehadeh, L.A., Daunert, S., & Deo, S. (2021). Peptide-modified biopolymers for biomedical applications. *ACS Applied Bio Materials*, 4(1), 229–251. <https://doi.org/10.1021/acsbm.0c01145>
- Himashree, P., Sengar, A.S., & Sunil, C.K. (2022). Food thickening agents: Sources, chemistry, properties and applications-A review. *International Journal of Gastronomy and Food Science*, 27, 100468. <https://doi.org/10.1016/j.ijgfs.2022.100468>
- Hisham, F., Maziati Akmal, M.H., Ahmad, F., Ahmad, K., & Samat, N. (2023). Biopolymer chitosan: Potential sources, extraction methods, and emerging applications. *Ain Shams Engineering Journal*, 15(2), 102424. <https://doi.org/10.1016/j.asej.2023.102424>
- Ho, K., Lau, S.Y., Ting, L.H., Zahir, A., Lam, M.K., Choy, S.Y., Lim, S., & Shi, T.I. (2025). Review of starch-based coagulants for water treatment: Mechanisms, extraction and surface modification. *Next Sustainability*, 5, 100083. <https://doi.org/10.1016/j.nxsust.2024.100083>
- Horton, A.A. (2022). Plastic pollution: When do we know enough? *Journal of Hazardous Materials*, 422, 126885. <https://doi.org/10.1016/j.jhazmat.2021.126885>
- Huang, B., Yang, M., Kou, Y., & Jiang, B. (2023). Absorbable implants in sport medicine and arthroscopic surgery: A narrative review of recent development. *Bioactive Materials*, 31, 272–283. <https://doi.org/10.1016/j.bioactmat.2023.08.015>
- Huang, C., Li, Q., & Li, J. (2022). Site-specific genome editing in treatment of inherited diseases: possibility, progress, and perspectives. *Medical Review*, 2(5), 471–500. <https://doi.org/10.1515/mr-2022-0029>
- Hussain, M., Khan, S.M., Shafiq, M., & Abbas, N. (2024a). A review on PLA-based biodegradable materials for biomedical applications. *Giant*, 18, 100261. <https://doi.org/10.1016/j.giant.2024.100261>
- Hussain, S.A., Yadav, M.P., Sharma, B.K., Qi, P.X., & Jin, T.Z. (2024b). Biodegradable food packaging films using a combination of hemicellulose and cellulose derivatives. *Polymers*, 16(22), 3171. <https://doi.org/10.3390/polym16223171>
- Ilhami, S., Rahman, S. N. S. A., Iqhrammullah, M., Hamid, Z., Chai, Y. H., & Lam, M. K. (2025). Polyhydroxyalkanoates production from microalgae for sustainable bioplastics: A review. *Biotechnology Advances*, 79, 108529. <https://doi.org/10.1016/j.biotechadv.2025.108529>
- Islam, M., Xayachak, T., Haque, N., Lau, D., Bhuiyan, M., & Pramanik, B.K. (2024). Impact of bioplastics on environment from its production to end-of-life. *Process Safety and Environmental Protection*, 188, 151–166. <https://doi.org/10.1016/j.psep.2024.05.113>
- Jabeen, N., & Atif, M. (2023). Polysaccharides based biopolymers for biomedical applications: A review. *Polymers for Advanced Technologies*, September, 35(1), e6203. <https://doi.org/10.1002/pat.6203>

- Jakob, M., Mahendran, A.R., Gindl-Altmutter, W., Bliem, P., Konnerth, J., Müller, U., & Veigel, S. (2022). The strength and stiffness of oriented wood and cellulose-fibre materials: A review. *Progress in Materials Science*, 125, 100916. <https://doi.org/10.1016/j.pmatsci.2021.100916>
- Jarecki, J., Waško, M.K., Widuchowski, W., Tomczyk-Warunek, A., Wójciak, M., Sowa, I., & Blicharski, T. (2023). Knee cartilage lesion management—current trends in clinical practice. *Journal of Clinical Medicine*, 12(20), 6434. <https://doi.org/10.3390/jcm12206434>
- Jing, L., Shi, T., Chang, Y., Meng, X., He, S., Xu, H., ... Liu, J. (2024). Cellulose-based materials in environmental protection: A scientometric and visual analysis review. *Science of the Total Environment*, 929, 172576. <https://doi.org/10.1016/j.scitotenv.2024.172576>
- Joseph, T.M., Kallingal, A., Suresh, A.M., Mahapatra, D.K., Hasanin, M.S., Haponiuk, J., & Thomas, S. (2023). 3D printing of polylactic acid: recent advances and opportunities. *The International Journal of Advanced Manufacturing Technology*, 125(3), 1015–1035. <https://doi.org/10.1007/s00170-022-10795-y>
- Julie Chandra, C.S., Sasi, S., & Bindu Sharmila, T.K. (2023). Material applications of gelatin. In Thomas, S., AR, A., Jose Chirayil, C., & Thomas, B. (Eds.), *Handbook of Biopolymers* (pp. 1–34), Springer. [https://doi.org/10.1007/978-981-19-0710-4\\_28](https://doi.org/10.1007/978-981-19-0710-4_28)
- Kadirvel, V., & Narayana, G. P. (2023). Edible gums—An extensive review on its diverse applications in various food sectors. *Food Bioengineering*, 2(4), 384–405. <https://doi.org/10.1002/fbe2.12067>
- Kamran, F., Afshar, H., & Shahi, F. (2025). Recent advances and applications of sustainable and recyclable polymers. *Polymer Engineering & Science*, 65(8), 3845–3879. <https://doi.org/10.1002/pen.27257>
- Kaur, R., Pathak, L., & Vyas, P. (2024). Biobased polymers of plant and microbial origin and their applications: A review. *Biotechnology for Sustainable Materials*, 1(1), 1–21. <https://doi.org/10.1186/s44316-024-00014-x>
- Kennedy, S. W., Roy Choudhury, N., & Parthasarathy, R. (2023). 3D printing soft tissue scaffolds using poly (caprolactone). *Bioprinting*, 30, e00259. <https://doi.org/10.1016/j.bprint.2023.e00259>
- Khan, S., Ullah, M. W., Siddique, R., Nabi, G., Manan, S., Yousaf, M., & Hou, H. (2016). Role of recombinant DNA technology to improve life. *International Journal of Genomics*, 2016, 2405954. <https://doi.org/10.1155/2016/2405954>
- Kim, J.W., Park, S., Park, K., & Kim, B.K. (2023). Non-toxic natural additives to improve the electrical conductivity and viscosity of polycaprolactone for melt electrospinning. *Applied Sciences*, 13(3), 1844. <https://doi.org/10.3390/app13031844>
- Klimek, K., & Ginalska, G. (2020). Proteins and peptides as important modifiers of the polymer scaffolds for tissue engineering applications—A review. *Polymers*, 12(4), 844. <https://doi.org/10.3390/polym12040844>
- Koller, M., Salerno, A., Muhr, A., Reiterer, A., Chiellini, E., Casella, S., ... Braunegg, G. (2012). Whey lactose as a raw material for microbial production of biodegradable polyesters. In H.E.D.M. Saleh (Ed.), *Polyester* (pp. 51–92). InTech. <https://doi.org/10.5772/48737>
- Kumar, A., Bhatt, A.N., Singh, L.R.K., Karim, Z., & Ansari, M.S. (2021). Alginate-based hydrogels for tissue engineering. In S.A. Bhawani, Z. Karim, & M. Jawaaid (Eds.), *Polysaccharide-Based Nanocomposites for Gene Delivery and Tissue Engineering* (pp. 59–69). Elsevier. <https://doi.org/10.1016/b978-0-12-821230-1.00002-5>
- Kumar, N., Pratibha, Prasad, J., Yadav, A., Upadhyay, A., Neeraj, Shukla, S., Petkoska, A.T., Heena, Suri, S., Gniewosz, M., & Kieliszek, M. (2023). Recent trends in edible packaging for food applications—Perspective for the future. *Food Engineering Reviews*, 15(4), 718–747. <https://doi.org/10.1007/s12393-023-09358-y>
- Łętocha, A., Miastkowska, M., & Sikora, E. (2022). Preparation and characteristics of alginate microparticles for food, pharmaceutical and cosmetic applications. *Polymers*, 14(18), 3834. <https://doi.org/10.3390/polym14183834>
- Li, D., Hou, L., Gao, Y., Tian, Z., Fan, B., Wang, F., & Li, S. (2022). Recent advances in microbial synthesis of poly-γ-glutamic acid: A review. *Foods*, 11(5), 739. <https://doi.org/10.3390/foods11050739>
- Li, M., Li, J., Xiong, X., Wang, Y., Jia, Y.G., Shi, X., & Fu, X. (2023). Heparinized PGA host-guest hydrogel loaded with paracrine products from electrically stimulated adipose-derived mesenchymal stem cells for enhanced wound repair. *Engineered Regeneration*, 4(3), 225–237. <https://doi.org/10.1016/j.engreg.2023.03.002>
- Liang, Q., Ye, J., Wang, Y., Wen, J., Zhang, Y., Xu, Z., ... Zhao, X. (2024). An enzyme-free and ratiometric biosensor for single nucleotide polymorphism with portable electrochemical system. *Sensors and Actuators B: Chemical*, 412, 135745. <https://doi.org/10.1016/j.snb.2024.135745>
- Lin, R.H., Hung, H.S., Tang, C.M., Tsou, H.K., Chen, P.H., Yueh, C.Y., & Wang, H.M.D. (2024). *In vitro* biocompatibility of polycaprolactone/hydroxyapatite nanocomposite membranes modified by oleic acid for bone regeneration. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 688, 133576. <https://doi.org/10.1016/j.colsurfa.2024.133576>
- Lin, W.S., & Catchmark, J.M. (2025). Improved starch adhesives for packaging and wood products. *Polymer Engineering & Science*, 65(4), 1682–1692. <https://doi.org/10.1002/pen.27077>
- Liu, W., Giaveri, S., Ortiz, D., & Stellacci, F. (2022). DNA as a recyclable natural polymer. *Advanced Functional Materials*, 32(21), 2109538. <https://doi.org/10.1002/adfm.202109538>
- Liu, Y., Aimutis, W.R., & Drake, M.A. (2024). Dairy, plant, and novel proteins: Scientific and technological aspects. *Foods*, 13(7), 1010. <https://doi.org/10.3390/foods13071010>

- Lomakina, G.Y., Bezrukikh, A.E., & Ugarova, N.N. (2012). Effect of gelatin on properties of *Luciola mingrellica* firefly luciferase. *Moscow University Chemistry Bulletin*, 67(1), 8–12. <https://doi.org/10.3103/s0027131412010051>
- Madsen, M., Westh, P., Khan, S., Ipsen, R., Almdal, K., Aachmann, F.L., & Svensson, B. (2021). Impact of alginate mannuronic-guluronic acid contents and pH on protein binding capacity and complex size. *Biomacromolecules*, 22(2), 649–660. <https://doi.org/10.1021/acs.biomac.0c01485>
- Magill, E., Demartis, S., Gavini, E., Permana, A.D., Thakur, R.R.S., Adrianto, M.F., ... Larrañeta, E. (2023). Solid implantable devices for sustained drug delivery. *Advanced Drug Delivery Reviews*, 199, 114950. <https://doi.org/10.1016/j.addr.2023.114950>
- Mansoor, Z., Tchuengbou-Magaia, F., Kowalczyk, M., Adamus, G., Manning, G., Parati, M., ... Khan, H. (2022). Polymers use as mulch films in agriculture—A review of history, problems and current trends. *Polymers*, 14(23), 5062. <https://doi.org/10.3390/polym14235062>
- Md Fadilah, N.I., Shahabudin, N.A., Mohd Razif, R.A., Sanyal, A., Ghosh, A., Baharin, K.I., ... Fauzi, M.B. (2024). Discovery of bioactive peptides as therapeutic agents for skin wound repair. *Journal of Tissue Engineering*, 15, 1–31. <https://doi.org/10.1177/20417314241280359>
- Moccia, M., Pascucci, B., Saviano, M., Cerasa, M.T., Terzidis, M.A., Chatgililoglu, C., & Masi, A. (2024). Advances in nucleic acid research: Exploring the potential of oligonucleotides for therapeutic applications and biological studies. *International Journal of Molecular Sciences*, 25(1), 146. <https://doi.org/10.3390/ijms25010146>
- Morwood, A.J., El-Karim, I.A., Clarke, S.A., & Lundy, F.T. (2023). The role of extracellular matrix (ECM) adhesion motifs in functionalised hydrogels. *Molecules*, 28(12), 4616. <https://doi.org/10.3390/molecules28124616>
- Mosleh, Y., van Die, M., Gard, W., Breebaart, I., van de Kuilen, J.W., van Duin, P., & Poulis, J.A. (2023). Gelatine adhesives from mammalian and fish origins for historical art objects conservation: How do microstructural features determine physical and mechanical properties? *Journal of Cultural Heritage*, 63, 52–60. <https://doi.org/10.1016/j.culher.2023.07.012>
- Mosomi, E.K., Olanrewaju, O.A., & Adeosun, S.O. (2024). Pivotal role of polylactide in carbon emission reduction: A comprehensive review. *Engineering Reports*, 6(8), e12909. <https://doi.org/10.1002/eng2.12909>
- Murphy, E.J., Fehrenbach, G.W., Abidin, I.Z., Buckley, C., Montgomery, T., Pogue, R., ... Rezoagli, E. (2023). Polysaccharides—Naturally occurring immune modulators. *Polymers*, 15(10), 2373. <https://doi.org/10.3390/polym15102373>
- Nagaraj, S., Rajasekaran, R., Palaniappan, J., Rangasamy, S., Narayanasamy, C., & Narayanan, M.B. (2024). Emerging technological developments to address pest resistance in Bt cotton. *Journal of Cotton Research*, 7(1), 30. <https://doi.org/10.1186/s42397-024-00192-z>
- Nezhad Mohseni, M., Najafpour Darzi, G., Ramezani, R., & Jahani, A. (2022). A developed composite hard-gelatin capsules: Delayed-release enteric properties. *Heliyon*, 8(12), e12265. <https://doi.org/10.1016/j.heliyon.2022.e12265>
- Nguyen, T.T.M., Yi, E.J., Jin, X., Zheng, Q., Park, S.J., Yi, G.S., ... Yi, T.H. (2024). Sustainable dynamic wrinkle efficacy: non-invasive peptides as the future of botox alternatives. *Cosmetics*, 11(4), 118. <https://doi.org/10.3390/cosmetics11040118>
- Ntrivala, M.A., Pitsavas, A.C., Lazaridou, K., Baziakou, Z., Karavasili, D., Papadimitriou, M., ... Bikiaris, D.N. (2025). Polycaprolactone (PCL): The biodegradable polyester shaping the future of materials—A review on synthesis, properties, biodegradation, applications and future perspectives. *European Polymer Journal*, 234, 114033. <https://doi.org/10.1016/j.eurpolymj.2025.114033>
- Nwazojie, C.C., Obayemi, J.D., Salifu, A.A., Borbor-Sawyer, S.M., Uzonwanne, V.O., Onyekanne, C.E., ... Soboyejo, W.O. (2023). Targeted drug-loaded PLGA-PCL microspheres for specific and localized treatment of triple negative breast cancer. *Journal of Materials Science: Materials in Medicine*, 34(8), 41. <https://doi.org/10.1007/s10856-023-06738-y>
- O'Loughlin, J., Doherty, D., Herward, B., McGleenan, C., Mahmud, M., Bhagabati, P., ... Gaughran, J. (2023). The potential of bio-based polylactic acid (PLA) as an alternative in reusable food containers: A review. *Sustainability*, 15(21), 15312. <https://doi.org/10.3390/su152115312>
- Onyeaka, H., Obileke, K., Makaka, G., & Nwokolo, N. (2022). Current research and applications of starch-based biodegradable films for food packaging. *Polymers*, 14(6), 1126. <https://doi.org/10.3390/polym14061126>
- Pan, Y., Hatano, A., Ohno, S., Morita, K., Kokaji, T., Bai, Y., ... Kuroda, S. (2024). Time and dose selective glucose metabolism for glucose homeostasis and energy conversion in the liver. *npj Systems Biology and Applications*, 10(1), 1–22. <https://doi.org/10.1038/s41540-024-00437-2>
- Pappelbaum, K.I., Virgilio, N., Epping, L., van der Steen, B., Jimenez, F., Funk, W., ... Bertolini, M. (2024). Revealing novel insights on how oral supplementation with collagen peptides may prevent hair loss: Lessons from the human hair follicle organ culture. *Journal of Functional Foods*, 116, 106124. <https://doi.org/10.1016/j.jff.2024.106124>
- Paredes-Flores, M.A., Rahimi, N., & Mohiuddin, S.S. (2024). *Biochemistry, Glycogenolysis*. StatPearls. <https://www.ncbi.nlm.nih.gov/books/NBK554417/>
- Patra, N., Ramesh, P., Donthu, V., & Ahmad, A. (2024). Biopolymer-based composites for sustainable energy storage: Recent developments and future outlook. *Journal of Materials Science: Materials in Engineering*, 19(1), 34. <https://doi.org/10.1186/S40712-024-00181-9>
- Patti, A., & Aciermo, D. (2022). Towards the sustainability of the plastic industry through biopolymers: Properties and potential applications to the textiles world. *Polymers*, 14(4), 692. <https://doi.org/10.3390/polym14040692>

- Payanthoth, N.S., Mut, N.N.N., Samanta, P., Li, G., & Jung, J. (2024). A review of biodegradation and formation of biodegradable microplastics in soil and freshwater environments. *Applied Biological Chemistry*, 67, 110. <https://doi.org/10.1186/s13765-024-00959-7>
- Pedersen, G.B., Blaschek, L., Frandsen, K.E.H., Noack, L.C., & Persson, S. (2023). Cellulose synthesis in land plants. *Molecular Plant*, 16(1), 206–231. <https://doi.org/10.1016/j.molp.2022.12.015>
- Pinaeva, L.G., & Noskov, A.S. (2024). Biodegradable biopolymers: Real impact to environment pollution. *Science of The Total Environment*, 947, 174445. <https://doi.org/10.1016/j.scitotenv.2024.174445>
- Pintea, A., Manea, A., Pintea, C., Vlad, R., Birsan, M., Antonoaea, P., ... Ciurba, A. (2025). Peptides: Emerging candidates for the prevention and treatment of skin senescence: A Review. *Biomolecules*, 15(1), 88. <https://doi.org/10.3390/biom15010088>
- Polman, E.M.N., Gruter, G.J.M., Parsons, J.R., & Tietema, A. (2021). Comparison of the aerobic biodegradation of biopolymers and the corresponding bioplastics: A review. *Science of The Total Environment*, 753, 141953. <https://doi.org/10.1016/j.scitotenv.2020.141953>
- Poltronieri, P., & Kumar, P. (2019). Polyhydroxyalkanoates (PHAs) in industrial applications. In Martinez, L., Kharissova, O., & Kharisov, B. (Eds.), *Handbook of Ecomaterials* (pp. 2843–2872), Springer. [https://doi.org/10.1007/978-3-319-68255-6\\_70](https://doi.org/10.1007/978-3-319-68255-6_70)
- Pulingam, T., Appaturi, J.N., Parumasivam, T., Ahmad, A., & Sudesh, K. (2022). Biomedical applications of polyhydroxyalkanoate in tissue engineering. *Polymers*, 14(11), 2141. <https://doi.org/10.3390/POLYM14112141>
- Quan, R., Zheng, X., Xu, S., Zhang, L., & Yang, D. (2014). Gelatin-chondroitin-6-sulfate-hyaluronic acid scaffold seeded with vascular endothelial growth factor 165 modified hair follicle stem cells as a three-dimensional skin substitute. *Stem Cell Research & Therapy*, 5, 118. <https://doi.org/10.1186/srct508>
- Rashwan, A.K., Younis, H.A., Abdelshafy, A.M., Osman, A.I., Eletmany, M.R., Hafouda, M.A., & Chen, W. (2024). Plant starch extraction, modification, and green applications: A review. *Environmental Chemistry Letters*, 22(5), 2483–2530. <https://doi.org/10.1007/s10311-024-01753-z>
- Read, T., Chaléat, C., Laycock, B., Pratt, S., Lant, P., & Chan, C.M. (2024). Lifetimes and mechanisms of biodegradation of polyhydroxyalkanoate (PHA) in estuarine and marine field environments. *Marine Pollution Bulletin*, 209, 117114. <https://doi.org/10.1016/j.marpolbul.2024.117114>
- Reihani, N., & Ghourchian, H. (2025). Synergy of keratin peptides and natural oils embedded in nanostructured lipid carriers to protect and restore human hair structure. *Journal of Molecular Liquids*, 422, 126957. <https://doi.org/10.1016/j.molliq.2025.126957>
- Reshma, C.S., Remya, S., & Bindu, J. (2024). A review of exploring the synthesis, properties, and diverse applications of poly lactic acid with a focus on food packaging application. *International Journal of Biological Macromolecules*, 283, 137905. <https://doi.org/10.1016/j.ijbiomac.2024.137905>
- Ross, A., Sauce-Guevara, M.A., Alarcon, E.I., & Mendez-Rojas, M.A. (2022). Peptide biomaterials for tissue regeneration. *Frontiers in Bioengineering and Biotechnology*, 10, 893936. <https://doi.org/10.3389/fbioe.2022.893936>
- Royal Society of Chemistry. (n.d.). *Polylactic acid: Inspirational chemistry book*. <https://edu.rsc.org/resources/polylactic-acid/4018499.article>
- Shiva, S., R.G., A.P., Bajaj, G., John, A.E., Chandran, S., Kumar, V.V., & Ramakrishna, S. (2023). A review on the recent applications of synthetic biopolymers in 3D printing for biomedical applications. *Journal of Materials Science: Materials in Medicine*, 34, 62. <https://doi.org/10.1007/s10856-023-06765-9>
- Samir, A., Ashour, F.H., Hakim, A.A.A., & Bassyouni, M. (2022). Recent advances in biodegradable polymers for sustainable applications. *npj Materials Degradation*, 6, 68. <https://doi.org/10.1038/s41529-022-00277-7>
- Satchanska, G., Davidova, S., & Petrov, P.D. (2024). Natural and synthetic polymers for biomedical and environmental applications. *Polymers*, 16(8), 1159. <https://doi.org/10.3390/polym16081159>
- Serra, M., Gudina, E., Botelho, C., Teixeira, J.A., & Barros, A.N. (2024). Polyglutamate: Unleashing the versatility of a biopolymer for cosmetic industry applications. *Cosmetics*, 11(3), 76. <https://doi.org/10.3390/cosmetics11030076>
- Shahbaz, U., Basharat, S., Javed, U., Bibi, A., & Yu, X. Bin. (2023). Chitosan: A multipurpose polymer in food industry. *Polymer Bulletin*, 80(4), 3547–3569. <https://doi.org/10.1007/s00289-022-04269-0>
- Shire, E., Coimbra, A.A.B., Barba Ostria, C., Rios-Solis, L., & López Barreiro, D. (2024). Molecular design of protein-based materials—state of the art, opportunities and challenges at the interface between materials engineering and synthetic biology. *Molecular Systems Design & Engineering*, 9(12), 1187–1209. <https://doi.org/10.1039/d4me00122b>
- Shoukat, R., Cappai, M., Pilia, L., & Pia, G. (2025). Rice starch chemistry, functional properties, and industrial applications: A review. *Polymers*, 17(1), 110. <https://doi.org/10.3390/polym17010110>
- Siddiqui, S.A., Khalifa, I., Yin, T., Morsy, M.K., Khoder, R.M., Salauddin, M., ... Khalid, N. (2024). Valorization of plant proteins for meat analogues design—a comprehensive review. *European Food Research and Technology*, 250, 2479–2513. <https://doi.org/10.1007/s00217-024-04565-1>
- Song, H., & Jang, H. (2023). The effect of gelatin-coating on embryonic stem cells as assessed by measuring young's modulus using an atomic force microscope. *Journal of Animal Reproduction and Biotechnology*, 38(3), 121–130. <https://doi.org/10.12750/jarb.38.3.121>

- Sun, X., Setrerrahmane, S., Li, C., Hu, J., & Xu, H. (2024). Nucleic acid drugs: Recent progress and future perspectives. *Signal Transduction and Targeted Therapy*, 9, 316. <https://doi.org/10.1038/s41392-024-02035-4>
- Surendren, A., Mohanty, A.K., Liu, Q., & Misra, M. (2022). A review of biodegradable thermoplastic starches, their blends and composites: recent developments and opportunities for single-use plastic packaging alternatives. *Green Chemistry*, 24(22), 8606–8636. <https://doi.org/10.1039/d2gc02169b>
- Suzuki, T., Konishi, H., Suzuki, A., Katsumata, T., Fukuda, Y., Miyamoto, K., ... Nemoto, S. (2024). Role of intermediate water in alleviating postsurgical intrapericardial adhesion. *Surgery Today*, 55, 847–856. <https://doi.org/10.1007/s00595-024-02953-4>
- Swetha, T.A., Ananthi, V., Bora, A., Sengottuvelan, N., Ponnuchamy, K., Muthusamy, G., & Arun, A. (2023). A review on biodegradable polylactic acid (PLA) production from fermentative food waste - Its applications and degradation. *International Journal of Biological Macromolecules*, 234, 123703. <https://doi.org/10.1016/j.ijbiomac.2023.123703>
- Tabassum, N., Rafique, U., Qayyum, M., Mohammed, A.A.A., Asif, S., & Bokhari, A. (2024). Kaolin–polyvinyl alcohol–potato starch composite films for environmentally friendly packaging: Optimization and Characterization. *Journal of Composites Science*, 8(1), 29. <https://doi.org/10.3390/jcs8010029>
- Tan, J., Luo, Y., Guo, Y., Zhou, Y., Liao, X., Li, D., ... Liu, Y. (2023a). Development of alginate-based hydrogels: Crosslinking strategies and biomedical applications. *International Journal of Biological Macromolecules*, 239, 124275. <https://doi.org/10.1016/j.ijbiomac.2023.124275>
- Tan, X., Testoni, G., Sullivan, M.A., López-Soldado, I., Vilaplana, F., Gilbert, R.G., ... Duran, J. (2025). Glycogenin is dispensable for normal liver glycogen metabolism and body glucose homeostasis. *International Journal of Biological Macromolecules*, 291, 139084. <https://doi.org/10.1016/j.ijbiomac.2024.139084>
- Tan, Y., Zi, Y., Peng, J., Shi, C., Zheng, Y., & Zhong, J. (2023b). Gelatin as a bioactive nanodelivery system for functional food applications. *Food Chemistry*, 423, 136265. <https://doi.org/10.1016/j.foodchem.2023.136265>
- Thamarai, P., Vickram, A.S., Saravanan, A., Deivayanai, V.C., & Evangeline, S. (2024). Recent advancements in biosynthesis, industrial production, and environmental applications of polyhydroxyalkanoates (PHAs): A review. *Bioresource Technology Reports*, 27, 101957. <https://doi.org/10.1016/j.biteb.2024.101957>
- Tondera, C., Hauser, S., Krüger-Genge, A., Jung, F., Neffe, A.T., Lendlein, A., ... Pietzsch, J. (2016). Gelatin-based hydrogel degradation and tissue interaction in vivo: Insights from multimodal preclinical imaging in immunocompetent nude mice. *Theranostics*, 6(12), 2114. <https://doi.org/10.7150/thno.16614>
- Tudu, M., & Samanta, A. (2023). Natural polysaccharides: Chemical properties and application in pharmaceutical formulations. *European Polymer Journal*, 184, 111801. <https://doi.org/10.1016/j.eurpolymj.2022.111801>
- Udayakumar, G.P., Muthusamy, S., Selvaganesh, B., Sivarajasekar, N., Rambabu, K., Banat, F., ... Show, P.L. (2021). Biopolymers and composites: Properties, characterization and their applications in food, medical and pharmaceutical industries. *Journal of Environmental Chemical Engineering*, 9(4), 105322. <https://doi.org/10.1016/j.jece.2021.105322>
- van der Oost, J., & Patinios, C. (2023). The genome editing revolution. *Trends in Biotechnology*, 41(3), 396–409. <https://doi.org/10.1016/j.tibtech.2022.12.022>
- Vasileva, Y., Zhulanov, A., Chertov, N., Sboeva, Y., Boronnikova, S., Pechenkina, V., ... Kalendar, R. (2024). Identification of SNPs associated with drought resistance in hybrid populations of *Picea abies* (L.) H. Karst.–*P. obovata* (Ledeb.). *Genes*, 15(11), 1440. <https://doi.org/10.3390/genes15111440>
- Veiga, E., Ferreira, L., Correia, M., Pires, P.C., Hameed, H., Araújo, A.R., ... Paiva-Santos, A.C. (2023). Anti-aging peptides for advanced skincare: Focus on nanodelivery systems. *Journal of Drug Delivery Science and Technology*, 89, 105087. <https://doi.org/10.1016/j.jddst.2023.105087>
- Wang, B.T., Hu, S., Yu, X.Y., Jin, L., Zhu, Y.J., & Jin, F.J. (2020a). Studies of cellulose and starch utilization and the regulatory mechanisms of related enzymes in fungi. *Polymers*, 12(3), 530. <https://doi.org/10.3390/polym12030530>
- Wang, D., & Farhana, A. (2023). *Biochemistry, RNA structure*. StatPearls. <https://www.ncbi.nlm.nih.gov/books/NBK558999/>
- Wang, F., Li, Q., & Fan, C. (2023). The evolution of DNA-based molecular computing. In Jonoska, N., & Winfree, E. (Eds.), *Natural Computing Series* (pp. 31–45), Springer. [https://doi.org/10.1007/978-981-19-9891-1\\_3](https://doi.org/10.1007/978-981-19-9891-1_3)
- Wang, L., Chen, S., & Yu, B. (2022). Poly-γ-glutamic acid: Recent achievements, diverse applications and future perspectives. *Trends in Food Science & Technology*, 119, 1–12. <https://doi.org/10.1016/j.tifs.2021.11.009>
- Wang, L., Zhong, X., Li, S., Liu, X., Wang, K., Cai, R., ... Wang, Z. (2024a). Probiotics encapsulated by gelatin and hyaluronic acid via layer-by-layer assembly technology for enhanced viability. *Food Hydrocolloids*, 153, 109967. <https://doi.org/10.1016/j.foodhyd.2024.109967>
- Wang, S., Wang, X., Luo, Y., & Liang, Y. (2025). A comprehensive review of conventional and stimuli-responsive delivery systems for bioactive peptides: from food to biomedical applications. *Advanced Composites and Hybrid Materials*, 8, 12. <https://doi.org/10.1007/s42114-024-01053-8>
- Wang, W., Meng, Q., Li, Q., Liu, J., Zhou, M., Jin, Z., & Zhao, K. (2020b). Chitosan derivatives and their application in biomedicine. *International Journal of Molecular Sciences*, 21(2), 487. <https://doi.org/10.3390/ijms21020487>

- Wang, Y., Yu, X., He, H., Zhu, W., Yuan, X., & Wang, H. (2024b). Engineering high-performance and multifunctional seed coating agents from lignocellulosic components. *Industrial Crops and Products*, 222, 119768. <https://doi.org/10.1016/j.indcrop.2024.119768>
- Westlake, J.R., Tran, M.W., Jiang, Y., Zhang, X., Burrows, A.D., & Xie, M. (2023). Biodegradable biopolymers for active packaging: Demand, development and directions. *Sustainable Food Technology*, 1(1), 50–72. <https://doi.org/10.1039/d2fb00004k>
- Williams, A.T., & Rangel-Buitrago, N. (2022). The past, present, and future of plastic pollution. *Marine Pollution Bulletin*, 176, 113429. <https://doi.org/10.1016/j.marpolbul.2022.113429>
- Yadav, N., & Hakkarainen, M. (2021). Degradable or not? Cellulose acetate as a model for complicated interplay between structure, environment and degradation. *Chemosphere*, 265, 128731. <https://doi.org/10.1016/j.chemosphere.2020.128731>
- Yan, L., & Xu, H. (2025). Lightweight composite materials in automotive engineering: State-of-the-art and future trends. *Alexandria Engineering Journal*, 118, 1–10. <https://doi.org/10.1016/j.aej.2024.12.002>
- Yang, N., Ying, L., Li, K., Chen, F., Zhao, F., Sun, Z., ... Liu, J. (2022). Biodegradable mulching films based on polycaprolactone and its porous structure construction. *Polymers*, 14(24), 5340. <https://doi.org/10.3390/polym14245340>
- Yang, Y., Zhang, M., Ju, Z., Tam, P.Y., Hua, T., Younas, M.W., ... Hu, H. (2021). Poly (lactic acid) fibers, yarns and fabrics: Manufacturing, properties and applications. *Textile Research Journal*, 91(13–14), 1641–1669. <https://doi.org/10.1177/0040517520984101>
- Yang, Z., Yin, G., Sun, S., & Xu, P. (2024). Medical applications and prospects of polylactic acid materials. *iScience*, 27(12), 111512. <https://doi.org/10.1016/j.isci.2024.111512>
- Yao, Y., Hsu, Y.I., & Uyama, H. (2025). Schiff base crosslinked poly ( $\gamma$ -glutamic acid) composite films with high mechanical strength and remoldability. *Polymer Degradation and Stability*, 240, 111450. <https://doi.org/10.1016/j.polymdegradstab.2025.111450>
- Yasin, A., Ren, Y., Li, J., Sheng, Y., Cao, C., & Zhang, K. (2022). Advances in hyaluronic acid for biomedical applications. *Frontiers in Bioengineering and Biotechnology*, 10, 910290. <https://doi.org/10.3389/fbioe.2022.910290>
- Ye, G., Zhang, X., & Bi, H. (2024). Construction of high-performance and sustainable polylactic acid composites for 3D printing applications with plasticizer. *International Journal of Biological Macromolecules*, 269, 132162. <https://doi.org/10.1016/j.ijbiomac.2024.132162>
- Yedrissov, A., Khrustalev, D., Alekseev, A., Khrustaleva, A., & Vetrova, A. (2022). New composite material for biodegradable electronics. *Materials Today: Proceedings*, 49, 2443–2448. <https://doi.org/10.1016/j.matpr.2020.11.053>
- Zaman, H.U., Khan, M.A., & Khan, R.A. (2012). Studies on the thermo-mechanical properties of gelatin based films using 2-hydroxyethyl methacrylate by gamma radiation. *Open Journal of Composite Materials*, 2012(2), 15–21. <https://doi.org/10.4236/ojcm.2012.21003>
- Zarski, A., Bajer, K., & Kapuśniak, J. (2021). Review of the most important methods of improving the processing properties of starch toward non-food applications. *Polymers*, 13(5), 832. <https://doi.org/10.3390/polym13050832>
- Zeng, W., Hou, Y., Ao, C., & Huang, J. (2024). Effects of PGPR and  $\gamma$ -PGA on maize growth and rhizosphere microbial community in saline soil. *Agricultural Water Management*, 295, 108736. <https://doi.org/10.1016/j.agwat.2024.108736>
- Zhang, M., & Zhao, X. (2020). Alginate hydrogel dressings for advanced wound management. *International Journal of Biological Macromolecules*, 162, 1414–1428. <https://doi.org/10.1016/j.ijbiomac.2020.07.311>
- Zhang, Q., Chen, Y., Wei, P., Zhong, Y., Chen, C., & Cai, J. (2021). Extremely strong and tough chitosan films mediated by unique hydrated chitosan crystal structures. *Materials Today*, 51, 27–38. <https://doi.org/10.1016/j.mattod.2021.10.030>
- Zhao, X., Zhang, Y., Lv, Z., Ding, Z., Wang, Y., Yang, H., ... Chen, H. (2025). Nanocellulose and its composites toward flexible supercapacitor. *Advanced Materials Technologies*, 10(10) 2401709. <https://doi.org/10.1002/admt.202401709>
- Zhou, W., Bergsma, S., Colpa, D.I., Euverink, G.J.W., & Krooneman, J. (2023). Polyhydroxyalkanoates (PHAs) synthesis and degradation by microbes and applications towards a circular economy. *Journal of Environmental Management*, 341, 118033. <https://doi.org/10.1016/j.jenvman.2023.118033>
- Zhu, Y., Kruglikov, I.L., Akgul, Y., & Scherer, P.E. (2019). Hyaluronan in adipogenesis, adipose tissue physiology and systemic metabolism. *Matrix Biology*, 78–79, 284–291. <https://doi.org/10.1016/j.matbio.2018.02.012>