

Next Generation Bioplastics Based on Renewable Resources and Their Potential Applications

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Challenges associated with the recyclability and end-of-life management of plastics are leading to a search for more environmentally friendly alternatives. The amount of conventional plastic that is recycled represents a tiny percentage of what is made. Most is sent to landfills or simply accumulates in the environment, which presents a challenge due to the generation of micro- and nanoplastics. Next-generation bioplastics have emerged as an option in recent years. Polyhydroxyalkanoates, polylactic acid, thermoplastic starch, lignocellulosic biocomposites, protein-based materials, seaweed, among others, can be regarded as promising alternatives to conventional plastics. These materials are innovative; some, such as polylactic acid and thermoplastic starch, are already established in the market, while others have recently gained ground in various sectors, including lignocellulosic biocomposites in the automotive industry and bioplastics based on marine algae for food packaging. However, this transition should not be limited to replacement. The study analyzes recent advances in next-generation bioplastics, including classification and potential applications. The study also explores key challenges and regulatory perspectives.

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INTRODUCTION

The end-of-life of assorted plastic materials has increasingly become a source of concern due to their environmental repercussions. Nevertheless, even with these drawbacks, the demand for and production of plastics worldwide continues to grow (Fig.1). Approximately 90% of global plastic production currently is based on fossil resources (European Bioplastics 2024). As shown in Fig. 1 (European Bioplastics 2024; OECD 2022; Plastics Europe 2024), from the beginning, there was a significant annual growth in fossil plastic production. Nowadays, production has reached almost 500 million tons, and it is expected to continue growing (OECD 2024).

The most significant production increases are expected to occur in Asia, mainly in China and India (Dokl *et al.* 2024). The increase in production is due to the characteristics of plastics: inexpensive, resistant (durable), lightweight, moldable, good stability, and suitable mechanical properties. Some application sectors include the packaging industry (bags/sacks, bottles, wrapping, rigid or flexible) with high growth forecast, automotive (dashboards, fuel system parts, electrical components, interior parts), healthcare and medical (bags, tubing, gloves, implants), construction (pipes, flooring, insulation panels,

window frames), electronics (laptops, phones, wire insulation, connectors), textile (sportswear, handbags, shoes, raincoats, jackets), agriculture (greenhouse and mulch films, drip irrigation systems), and aerospace (cabin interiors, aircraft windows, structural plane components) (Plastics Technology 2025).

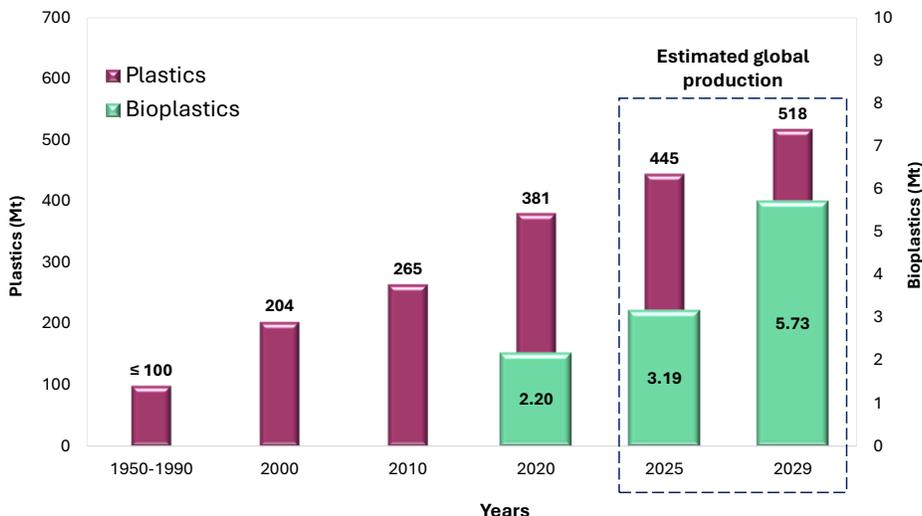


Fig. 1. Plastics and bioplastics production. Figure elaborated using data extracted from (European Bioplastics 2024; OECD 2022; Plastics Europe 2024)

Plastics are divided into thermoplastics (once formed, can be remolded) and thermosets (once formed, cannot be remolded). Thermoplastic materials include polyethylene (PE), polypropylene (PP), polystyrene (PS), styrene acrylonitrile, acrylonitrile butadiene styrene, polyamide, polyethylene terephthalate, polyvinylchloride, and polycarbonate. Fossil-based PE in all types (HDPE: high-density polyethylene, LDPE: low-density polyethylene, LLDPE: linear low-density polyethylene, ULDPE: ultra low-density polyethylene, *etc.*) is the most produced thermoplastic (26.2% from total produced) (Plastics Europe 2024). Final applications for PE derivatives include thin films, packaging containers, molded parts, bottles, liquid tanks, boxes, pipes, cables, toys, laboratory equipment, health and medical accessories, irrigation, mulch films, *etc.* (Burelo *et al.* 2023). PE can be obtained from fossil resources or from biomass; the latter is called bioPE and is considered to be a bioplastic. The second most produced thermoplastic is PP (19% of total production) (Plastics Europe 2024) and is usually applied to produce films, bags, food packaging, car parts, houseware, *etc.* (Sutkar and Dhulap 2025).

The plastic manufacturing industry transforms resins into rigid or flexible options according to the final applications. Some processing options include injection, extrusion, compression, blown, or rotational molding, calendering, thermoforming, casting, and 3D printing. The applications are diverse, and in some cases, plastics are for single use. From the total plastic generated globally, 50% ends up in landfills, 22% are either lost during collection or openly dumped, and only 9% undergoes proper recycling (OECD 2022). With global recycling rates below 10%, it is important to find new solutions, such as the use of bioplastics. Bioplastics are materials that meet one or both requirements: being biobased (obtained from biomass), and/or biodegradable (material that can be converted into water, carbon dioxide, and compost by microorganisms in the environment).

Currently, bioplastics account for less than 1% of plastics production. However, there are reasons to expect increasing trends (Fig.1), especially when considering emerging

regulations alongside conventional ones (European Bioplastics 2024). In recent years, next-generation bioplastics have emerged as an excellent option to reduce plastic pollution (Ehman and Area 2021), and specifically, some biobased and biodegradable options have a promising landscape. These include polylactic acid (PLA), polyhydroxyalkanoates (PHAs), thermoplastic starch (TPS), protein-based (from algae or animal origin), and cellulose-based materials.

BIOPLASTICS CLASSIFICATION

Figure 2 illustrates a gross classification of bioplastics based on their origin. Bioplastics can be classified according to their origin and degradability: fossil-based but biodegradable, biobased but non-biodegradable, or biobased and biodegradable (Ponce de León *et al.* 2025). The bioplastics industry is currently operating at just 60% of its production capacity. The market segments involve flexible and rigid packaging (45% of total applications), fibers, consumer goods, automotive and transport, agricultural, electrical, electronics, and coatings or adhesives, among others (European Bioplastics 2024). The bioplastics have attracted attention for their potential to mitigate environmental impact, although their integration into existing waste management systems remains complex.

The group of biobased bioplastics is composed of those whose carbon comes partially or totally from biomass (ASTM D6866, biobased content must be $\geq 50\%$) (ASTM D6866 2022), and whose chemical structure does not meet certified biodegradation standards (insufficient mineralization according to EN 13432 or ASTM D6400) (UNE 2001, ASTM D6400 2021).

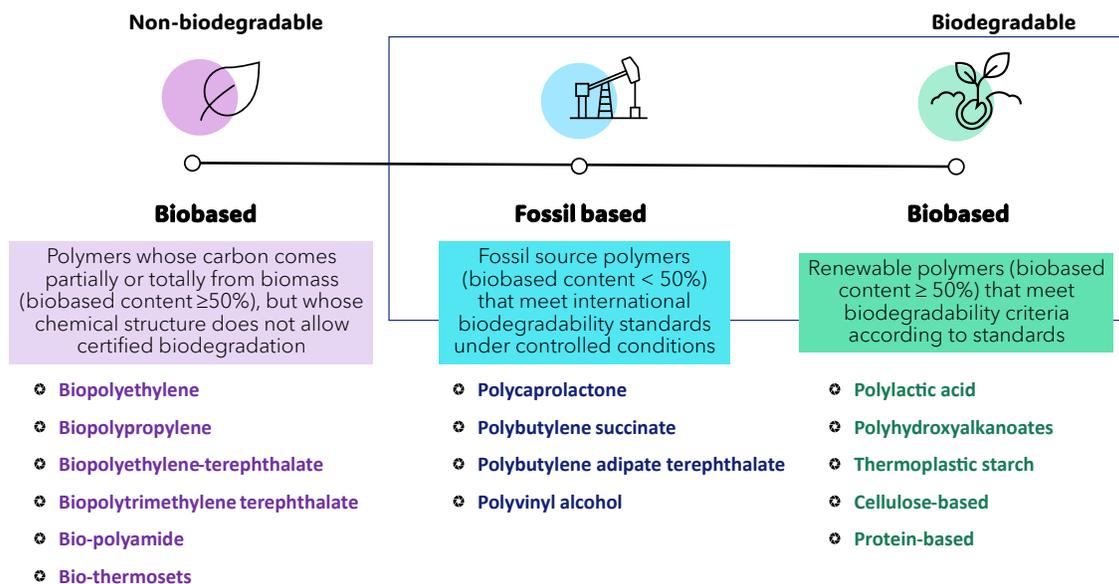


Fig. 2. Bioplastics according to source and biodegradation

BioPE is obtained from ethylene monomer. The monomer can be produced from bioethanol, a product obtained by fermentation of different biological feedstocks (sugar cane, sugar beet, crops, wheat or other grains, and lignocellulosic materials) (Mendieta *et al.* 2020). Subsequent polymerization of ethylene yields different types of bioPE with

properties similar to those of the conventional version (Siracusa and Blanco 2020). Biopolypropylene (bioPP) is obtained from isobutanol (also produced by fermentation), and the monomer is then synthesized by dehydration to bio-butylene. Finally, polymerization of bio-butylene produces bioPP (Siracusa and Blanco 2020). Biopolyethylene terephthalate (bioPET) is produced through the polymerization of two biobased monomers: biobased monoethylene glycol (from sugar cane) and terephthalic acid (a monomer obtained from p-xylene: isobutanol production *via* fermentation from biomass, followed by the three-step catalytic conversion of isobutanol to p-xylene *via* dehydration, dimerization, and dehydrocyclization). BioPET is highly versatile, as it can be processed and recycled using the same systems as standard PET (Louw *et al.* 2024). Biopoly(ethylene-co-isosorbide terephthalate) (bioPEIT) is a biobased polymer obtained from isosorbide (a biobased monomer derived from cellulose and starch), biobased ethylene glycol (from biobased bioethanol), and furanoic acid. Polymer is an excellent option for improving the mechanical and thermal properties of bioPET (Li *et al.* 2025).

Thermosets can also be obtained from biobased resources. Biobased epoxy resins have been produced from plant oils, linseed oil, lignin, vanillin, eugenol, resveratrol, tannic acid, magnolol, ferulic acid, *etc.* (Zhang *et al.* 2024). The cured epoxy resins derived from aromatic biobased compounds have been found to exhibit improved heat resistance compared to conventional epoxy resins (Bu *et al.* 2022; Zhang *et al.* 2024). Biopolyurethane (bioPUR) was also previously produced by a one-pot method from biobased polyol (from thermomechanical liquefaction of pinewood shavings and *Stipa tenacissima* grass) (Silva *et al.* 2023).

Also, when a fossil-based material (biobased content <50%, ASTM D6866 2022) complies with certified biodegradability according to EN 13432 (UNE 2001), ASTM D6400 (2021), or ISO 17088 (2021) ($\geq 90\%$ mineralization in industrial composting), it is considered biodegradable. Polycaprolactone (PCL) is an aliphatic, petroleum-derived, biodegradable, and biocompatible polyester. PCL is degraded by microorganisms under different environmental conditions (soil, compost, aquatic). Biocompatibility enables the use of PCL in biomedical applications (Ntrivala *et al.* 2025). Polybutylene succinate (PBS) is synthesized by polycondensation between succinic acid and butanediol. PBS exhibits higher mechanical properties (tensile strength, flexural modulus) but similar thermal behavior to LDPE (Jiang and Zhang 2017). Polybutylene adipate terephthalate (PBAT) is an aliphatic-aromatic copolyester that shows higher chain stiffness than entirely aliphatic polyesters such as PCL and PBS due to the presence of terephthalic groups. The applications involve the packaging and agriculture sectors (Jiang and Zhang 2017). PBAT and PBS have been combined with PLA to form ternary blends that improve processability and mechanical properties for 3D printing and blown film extrusion (Chuakhao *et al.* 2024). Also, blending PBAT with PLA, PS, PBS, PHBV, and PHB improves mechanical and thermal properties without compromising the biodegradability of the mixture. However, in some cases, polymer incompatibilities have been reported, which is why plasticizers and compatibilizers such as malleated PBAT, epoxy-based chain extender Joncryl® ADR 4368, and dicumyl peroxide bis(1-methyl-1-phenylethyl) have been used (Dammak *et al.* 2020). Poly(vinyl alcohol) (PVOH) is obtained from a fossil source but is biodegradable (Asano 2024). PVOH, which is a water-soluble and non-toxic polymer, presents good chemical and mechanical stability, tuned hydrophilicity, emulsifying and adhesive properties, and excellent film- and fiber-forming ability (Filimon *et al.* 2025). The applications of PVOH include films for packaging, adhesives, sizing agents in textiles,

coatings in the paper industry, wound dressings, drug delivery, tissue engineering, cement or concrete formulations (Asano 2024).

A third classification consists of biobased and biodegradable polymers. Biobased and biodegradable polymers are those renewable polymers that meet biodegradability criteria and offer technical improvements over conventional bioplastics (bio-based content $\geq 50\%$: ASTM D6866 (2022), and certified biodegradability: EN 13432 (UNE 2001) or ASTM D6400 (2022). Biobased and biodegradable options can be considered next-generation bioplastics for single-use applications because they can replace fossil-based plastics exhibiting similar physical, mechanical, thermal, and barrier properties but with high biodegradation.

NEXT-GENERATION BIOPLASTICS

A general classification involves two main categories: biomass-based bioplastics and those made from biological monomers, such as PLA (Pooja *et al.* 2023). Biomass-based sources (Fig. 3) include those derived from animal and vegetal proteins, polysaccharides, and microorganisms (most promising: PHAs).

Polysaccharides are naturally produced biopolymers that play essential roles in living organisms, serving as energy storage molecules and contributing to structural integrity. Polysaccharides from higher plants (starch and lignocellulosic) are the most used to produce bioplastics (Gamage *et al.* 2024). Polysaccharides also form a part of the structural component of the macroalgal cell wall and can be extracted using various techniques (Krishnan *et al.* 2024). Polysaccharide-based bioplastics have become promising alternatives to petroleum-derived plastics, demonstrating good film-forming performance with inherent biodegradability and susceptibility to enzymatic, microbial, and environmental degradation. In many cases, they are biocompatible, low-cost, widely available, present minimal environmental pollution at the end of their life cycle, rapidly degrade, or are even recyclable (Junaid *et al.* 2025). The most common derivatives of lignocellulosic products include biocomposites, although newer options involving chemical modifications to the main components (cellulose, lignin, hemicelluloses, extractives) are being explored.

Proteins are another option, and production involves extraction and purification followed by crosslinking, which can be physical, chemical, or enzymatic. Crosslinking modifies the mechanical and functional properties of protein-based bioplastics (Perez-Puyana *et al.* 2024). Animal protein sources have emerged as an excellent option because they can be obtained from cheese-production processes or from expired dairy products. The milk from cows and goats is composed primarily of 80% casein and 20% whey protein. In cheese production, casein is a key component; it coagulates, while the remaining whey is typically discarded (Chalermthai *et al.* 2019).

The third option is the microorganisms. PHAs accumulate in intracellular granules as typical intracellular products of secondary cellular metabolism. They serve as energy and carbon reserves, electron sinks, and protectors against stress when there is a high intracellular energy load, ample availability of natural sources of exogenous carbon, and a lack of additional growth factors such as nitrogen or phosphate sources. Therefore, PHAs increase, and the formation of catalytically active biomass is inhibited (Mukherjee and Koller 2023).

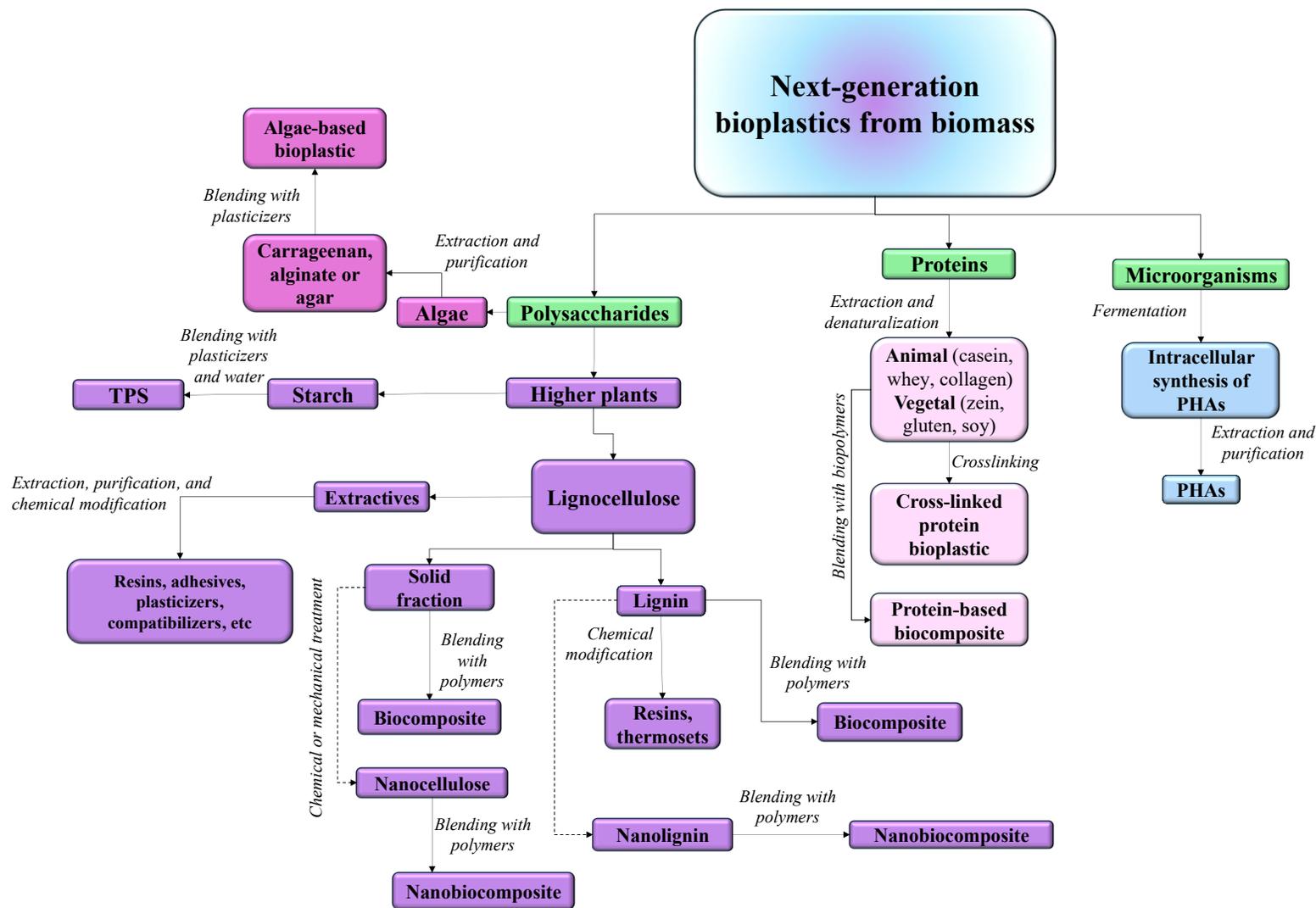


Fig. 3. Classification according to origin, routes, and obtained product for bioplastics from biomass

Poly(lactic acid)

PLA is a biobased and industrially compostable (EN 13432 and ASTM D6400 standards) polymer derived from lactic acid. This building block molecule is produced by microbial fermentation or chemical synthesis (Ramezani Dana and Ebrahimi 2023). There are two established routes for the synthesis of PLA from lactic acid: ring-opening polymerization and polycondensation.

Ring-opening polymerization occurs through cationic, anionic, coordination, or free-radical polymerization. Condensation polymerization, on the other hand, involves the elimination of small molecules such as water (Maharana *et al.* 2009). There are three forms of lactic acid: L-lactic acid, D-lactic acid, and racemic mixtures. Optically pure individual components are considered more valuable than racemic mixtures. Optically highly pure L-lactic acid is the most used form and the primary precursor of PLA. Then, the addition of optically pure D-lactic acid can modify the mechanical properties of PLA (Huang *et al.* 2021).

Based on D-lactic acid content, PLA is divided into three categories: poly(D-lactic acid) (PDLA), poly(L-lactic acid) (PLLA), and poly(DL-lactic acid) (PDLA). PDLA is amorphous, and PLLA is semicrystalline. By increasing PLA crystallinity and decreasing molecular chain mobility, the elongation at break of the material decreases, while its tensile strength and modulus increase (Wu *et al.* 2023). PLLA has low D-content (<5%) (Wang *et al.* 2015), better thermal properties (Wu *et al.* 2023), and higher tensile and burst strength (Pölöskei *et al.* 2020). PLLA is recommended for injection molding and 3D printing. Commercial options (NatureWorks Ltd.) are 3100HP and 3260HP (both with D-content < 2%), 3251D (D-content: 1.4), 4032D (D-content: 1.4-2%) (Standau *et al.* 2020).

Figure 4 shows different PLA grades from NatureWorks (Mihai and Gendron 2016; Piontek *et al.* 2020; Standau *et al.* 2020; Xie *et al.* 2021; NatureWorks 2025a). Different grades are observed, with one showing an increase in melt flow rate (MFR, corresponding to a decrease in PLA's molecular weight) and the other showing an increase in the crystalline melting temperature (which in turn reflects a decrease in the D isomer).

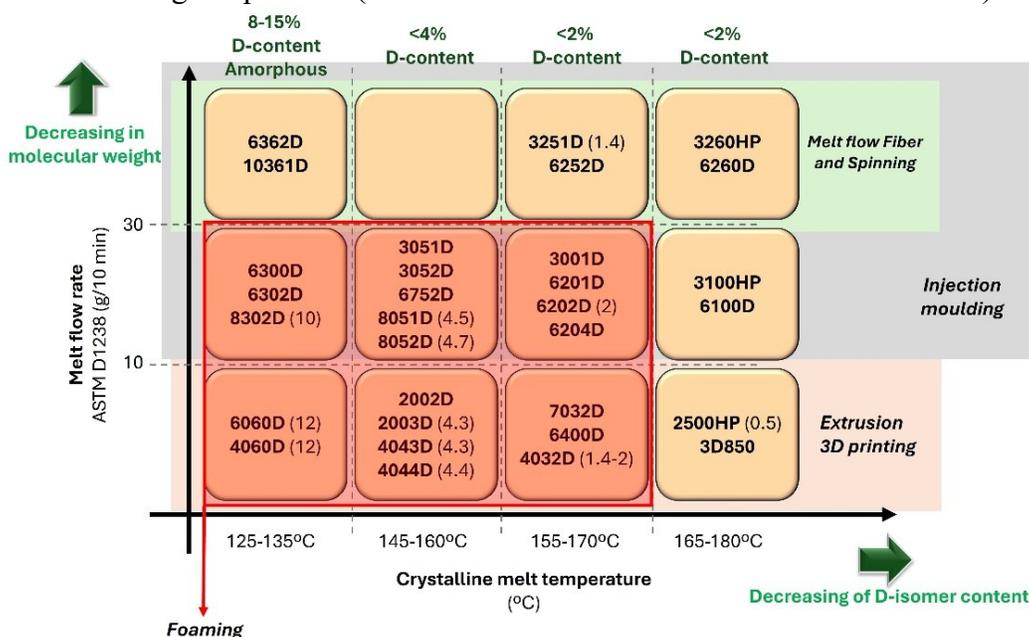


Fig. 4. NatureWorks PLA products and their common processing. Adapted from (Mihai and Gendron 2016; Piontek *et al.* 2020; Standau *et al.* 2020; Xie *et al.* 2021; NatureWorks 2025a)

The range follows from the amorphous component to the semicrystalline (low D content). For lower MFR (MFR<10), processability includes extrusion applications, stretch blow molding, bottle-grade fiber melt spinning, 3D printing monofilaments, oriented films, thermoforming, and, at some temperatures, foaming applications.

Then, as the MFR increases, applications shift towards injection molding (MFR>10), melt flow fiber, and spinning (MFR>30) (Mihai and Gendron 2016; NatureWorks 2025a; Piontek *et al.* 2020; Standau *et al.* 2020; Xie *et al.* 2021).

PLA is the most produced bioplastic in the world (910.000 tons per year, 37.1% of the total bioplastics produced). Packaging, textiles, medical supplies, agricultural products, and electronics are among the main applications of PLA (European Bioplastics 2024). This wide versatility is due to its properties. PLA has a specific gravity of 1.20 to 1.25 g/cm³, melting temperatures between 120 and 170 °C, hardness of 80 to 90 HRA, elongations up to 10%, tensile strength between 50 and 70 MPa, *etc.* (Farah *et al.* 2016; Aloyaydi and Sivasankaran 2020; NatureWorks 2025b). Furthermore, the material is industrially compostable, biocompatible, and safe for food contact (Priyanka *et al.* 2023).

Poly(hydroxyalkanoates)

PHAs are a biobased, biocompatible, and biodegradable polyester family produced by microorganisms. The family group can be divided into two categories: short-chain (5 or fewer carbon atoms) and long-chain PHAs (6 to 14 carbon atoms) (Mai *et al.* 2024). The length of the chains confers the physical, mechanical, and biological characteristics. PHAs' family is composed of those molecules with short-chain polyhydroxybutyrate (PHB) and polyhydroxybutyrate-co-valerate (PHBV), and those with long-chain molecules such as polyhydroxyoctanoate (PHO), and polyhydroxybutyrate-co-hexanoate (PHBH).

Short-chain PHAs are typical thermoplastics with high tensile strength, low elongation at break, and crystallinity (excepting those with a high fraction of 4-hydroxybutyrate monomer, which is achiral). Long-chain PHAs are potential flexible elastomers and adhesive resins with low crystallinity, melting points close to room temperature (below the boiling point of water), and a remarkably low glass transition temperature, also below the freezing point of water (Koller *et al.* 2025).

The PHAs are produced from different prokaryotic microorganisms (Koller *et al.* 2010) (Fig. 5). PHB is the most representative molecule from the PHA family. It is highly crystalline and has limited processability. The limited processability is attributed to the proximity of the decomposition temperature (≈ 270 °C) to the melting point (≈ 180 °C).

However, these characteristics can be modified through the addition of alternative monomeric units, such as (R)-3-hydroxyvalerate (3HV) or achiral blocks 4-hydroxybutyrate (4HB), and 5-hydroxyvalerate (5HV). The achiral and building blocks confer potentially desirable characteristics to the polymer. The addition of building blocks into polyester chains requires expensive co-substrates (precursors) (Koller *et al.* 2010). These precursors are often toxic to the PHA-producing strain, and the dosage must be controlled. Poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV), poly(3-hydroxybutyrate-co-3-hydroxyhexanoate) (PHBHHX), and poly(-3-hydroxybutyrate-co-4-hydroxybutyrate) (P3HB4HB) are the main PHAs copolymers (Koller *et al.* 2010).

Carbon sources for PHAs production have been widely studied, and the type of PHA obtained depends primarily on the source used. The sources involve gases (methane, carbon dioxide), n-alcohols (methanol, ethanol, glycerol, octanol), n-alkanes (hexane, octane, dodecane), carbohydrates (glucose, fructose, sucrose, maltose, lactose, xylose,

starch, cellulose), and n-alkanoic acids (acetic acid, propionic acid, butyric acid, valeric acid, hexanoic acid, lauric acid, oleic acid) (Zhou *et al.* 2023).

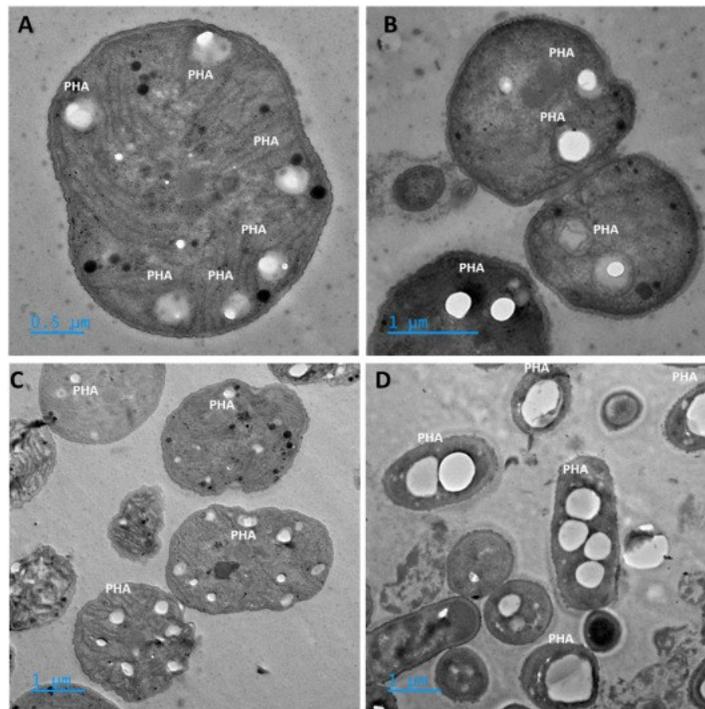


Fig. 5. Images obtained by transmission electron microscopy of PHA granules accumulated inside the cytoplasm of different cyanobacteria. Extracted from (Pham *et al.* 2024). CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>)

Thermoplastic Starch

TPS, or plasticized starch, is a next-generation bioplastic manufactured by plasticizing starch (corn, potato, tapioca, *etc.*) with plasticizers under high temperature and shear pressure. Starch plasticization is performed to improve its processability. Pure starch is not considered a thermoplastic polymer due to the strong inter- and intramolecular hydrogen bonds in amylose and amylopectin molecules. Therefore, when it is combined with plasticizers at temperatures between 90 and 180 °C and low shear stress, the granular starch is destroyed by breaking hydrogen bonds, along with partial depolymerization of the starch backbone. As a result, the TPS melts and exhibits viscoelastic behavior, enabling processability during extrusion, injection, or blown molding (Zhang *et al.* 2014a). Plasticizers are added to pure starch in small quantities to ensure successful plasticization; below a minimum amount, there is what is called antiplasticization (which increases Young's modulus and tensile strength, and decreases elongation), resulting in a more brittle material. Water, polyols, sugars, glycols, urea, amides, and amino acids can be used as plasticizers (Zhang and Han 2006).

TPS has potential as a next-generation bioplastic. It is biobased, biodegradable, non-toxic, presents easy processability, and is biocompatible. TPS exhibits oxygen barrier properties comparable to those of LDPE and ethyl vinyl alcohol, but poor mechanical properties (Müller *et al.* 2009; Bastarrachea *et al.* 2011; Zhang *et al.* 2014a).

Moisture absorption and retrogradation are also significant challenges in the material. These lower values limit the application of plasticized starch in industry. To

overcome these challenges, some options include selecting starch sources with a higher amylose content, using more efficient plasticizers, adding nanoclay or fiber, and blending with other polymers (Zhang *et al.* 2014b). The amylose/amylopectin ratio influences mechanical properties, film-forming capacity, oxygen and water vapor permeability, moisture absorption, and retrogradation (Zhang *et al.* 2014b).

Applications of TPS are in medical and pharmaceutical fields, packaging solutions, agriculture, and the food industry. Flexible TPS can be produced by solvent casting and extrusion-blown molding, whereas rigid TPS items can be made using extrusion-injection molding, thermoforming, and trough foams techniques (Surendren *et al.* 2022).

Lignocellulosic Biomass Derivatives

For years, lignocellulosic biomass components have been an alternative to conventional plastics. Paper and cardboard packaging, molded pulp, cellulose acetate, and microcrystalline cellulose have played a key role in numerous applications. However, the use of lignocellulosic derivatives shows additional potential through new products.

Derivatives of lignocellulosic components can be divided into their primary components: cellulose, lignin, hemicellulose, and extractives. Cellulose-based products involve several materials, including fiber pulp, cellulose acetate, methyl cellulose, regenerated cellulose, carboxymethyl cellulose, microcrystalline cellulose, hydroxypropyl cellulose, nanocellulose (Peranidze *et al.* 2023), biocomposites, and glucose as a precursor for ethylene (Mendieta *et al.* 2020), lactic, succinic, itaconic, levulinic, and glucaric acids (Deng *et al.* 2016).

Lignin-based derivatives include lignin nanoparticles, phenolic resins, polyurethanes, epoxy thermosets, biocomposites, nanocomposites, foams, and adhesives (Alinejad *et al.* 2019). Hemicellulose-based derivatives can involve xylans and galactomannans with modified structure (Bigand *et al.* 2011). The xylose is a precursor for 2,5-furandicarboxylic and muconic acids, whereas arabinose is a precursor for ferulic, gallic, and coumaric acids; mannose is a precursor for lactic and succinic acids; and galactose is a precursor for lactic and itaconic acids (Deng *et al.* 2016). Finally, extractives-based derivatives are terpenes and condensed polyphenols (resins and adhesives). These include abietic acid (polyesters), phenols (epoxy monomers), oleic (plasticizers), gallic acid (crosslinkers), and stearyl alcohol (compatibilizer) (Fernández Sosa *et al.* 2024).

Cellulose is the most abundant polymer. It consists of D-glucopyranose units (10,000 to 15,000 units) linked by a covalent β -1,4-glycosidic bond *via* the -OH groups of the C4 and C1 carbon atoms, forming a linear, high-molecular-weight homopolymer. The -OH groups form intra- and intermolecular bonds, resulting in a semicrystalline structure. The molecular structure can adopt four crystalline forms (I, II, III, and IV) depending on the material source and the treatments applied. Cellulose I is sourced from plants, algae, tunicates, and bacteria. Cellulose II, the most stable form, can be produced by either regeneration or mercerization. Cellulose II has a monoclinic structure and is used to produce cellophanes, Rayon, and Tencel. Alkaline treatments of cellulose I and II obtain cellulose III. Cellulose IV is obtained by thermal treatment of cellulose III (Peranidze *et al.* 2023).

Nanocellulose

Nanocellulose refers to all varieties of cellulose-based nanomaterials obtained by bottom-up and top-down methods. The bottom-up method involves building the nanostructure from small molecules, as is the case with bacterial cellulose, while the top-

down method starts with macroscale cellulose and uses various chemical or mechanical methods to produce a nanomaterial (Dufresne 2012). This review only discusses nanocellulose obtained through top-down methods (these allow the valorization of lignocellulosic biomass). Nanocellulose obtained by the top-down method is divided mainly into three types: cellulose nanocrystals, nanofibrillated cellulose, and microfibrillated cellulose.

Cellulose nanocrystals (CNC), also named as nanocrystalline cellulose (NCC), are a type of cellulose nanowhiskers presenting a pure crystalline structure, 3 to 10 nanometers (nm) wide and an aspect ratio >5 (TAPPI 2012). CNC can be produced by top-down processes from lignocellulosic resources (cellulose pulps, dissolving pulps, microcrystalline cellulose, or agricultural or industrial wastes). The conventional method for producing CNC involves acid hydrolysis (with strong mineral acids) treatment followed by ultrasonication. This treatment results in a highly crystalline nanostructure (Dagnino *et al.* 2025).

Nanofibrillated cellulose (NFC), also called cellulose nanofibrils (CNFs), is a type of cellulose that contains both crystalline and amorphous regions, with a width of 5 to 30 nm and an aspect ratio of > 50 (TAPPI 2012). NFCs are obtained by pure mechanical treatment or a combination of chemical and mechanical treatments. Oxidation of pulps with NaClO and NaBr, catalyzed by 2,2,6,6-tetramethylpiperidin-1-yl)oxyl (TEMPO), has been widely studied as a pretreatment to produce CNFs. The TEMPO-oxidation introduces carboxylate groups by substitution of -OH groups, thereby enhancing surface charge, dispersibility, and mechanical strength (Saito and Isogai 2004). In some cases, pure mechanical treatment results in a suspension with a majority of microfibrillated material and a smaller amount of nanofibrillar material. This material is called microfibrillated cellulose (MFC) or, in some cases, cellulose microfibril (CMF) (Lavoine *et al.* 2012). Figure 6 shows the methodology to produce MFC by mechanical fibrillation using a simple disk refiner.

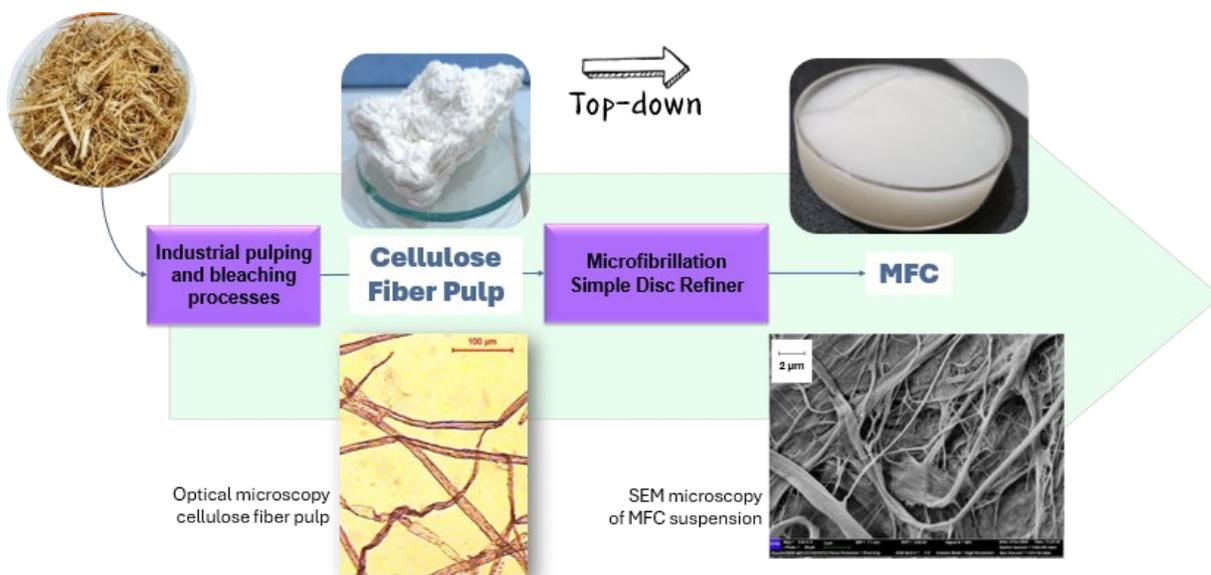


Fig. 6. Methodology to produce MFC using a disk refiner

The suspension contains fibrils of different sizes; in addition, residual fiber is observed, indicating the coexistence of various sizes in the system. In addition to the disc refiner for micro- and nanofibrillation, other widely used equipment includes a high-pressure homogenizer, a MASUKO grinder, high-speed agitation with an Ultraturrax, and a colloid mill (Boufi *et al.* 2016).

Nanocellulose derivatives have high potential for use in several applications due to their surface functionalization, high reactivity, excellent mechanical strength, high hydrophilicity, and biocompatibility.

Cellulose-based thermoplastic composites

Cellulose-based biocomposites are materials that combine a thermoplastic matrix with lignocellulosic fibers or nanofibers, either as is or chemically modified. Also, other components can be added to optimize the mixture according to the final application: cellulose, nanocellulose (Ehman *et al.* 2025), silanes, maleic anhydride, and isocyanates (Lu *et al.* 2005), glycerol, sorbitol, citrate, or cellulose esters (Ahokas *et al.* 2025; Immonen *et al.* 2021), melt flow modifiers (Mazzanti and Mollica 2020), thermal retardants, calcium carbonate, kaolin clay, titanium oxide (Gwon *et al.* 2012), UV stabilizers, colors, pigments, antioxidants, and water repellence additives. Cellulose/nanocellulose primarily acts as a biobased mechanical reinforcement agent, enhancing dimensional stability, stiffness, tensile, impact, and compression strength (Table 1).

Table 1. Changes of Polymer Properties after Cellulose/nanocellulose Addition

Positive Effects	Negative Effects
<p>Higher mechanical performance Increases in impact, compression, and tensile strength with the addition of fibers for rigid packaging. Improvements in polymer elongation by adding CNFs</p>	<p>High water absorption Not suitable for long-term applications in humid environments or containers in contact with moisture or liquids</p>
<p>Biobased content Increase in biobased content if the polymer is a fossil-based material</p>	<p>Decrease in melt flow rate Key property for the transformation stage (blow molding, injection molding, passing the material through extruders)</p>
<p>Increase in dimensional stability Lower molecular mobility and better resistance to external changes</p>	<p>Compatibility and dispersion issues Between matrix and reinforcement (but can be solved by adding compatibilizers or modifying the surface of the fiber or nanocellulose)</p>
<p>Reinforce can act as a nucleating agent Influence on the cooling stage: shorter cooling times are required, achieving better dimensional and thermal stability</p>	<p>Increased stiffness Greater material fragility</p>
<p>Biodegradability Improved biodegradation in compost due to the nature of the fiber (may vary if there is chemical modification)</p>	<p>Increase in aging rate Ideal for single-use applications. Not suitable for long-term applications</p>
	<p>Recycling Challenges A recovery system is required for multicomponent systems</p>

The addition of 40% lignocellulosic fiber fillers to virgin or recycled HDPE, PP, or LDPE has increased mechanical strength (Samadam *et al.* 2022; Rodríguez-Fabià *et al.* 2023; Albedah *et al.* 2024). The strengths further increase with the addition of coupling agents or compatibilizers, as these agents improve matrix-fiber adhesion, leading to greater mechanical stability and reduced water absorption (Méndez *et al.* 2007). which may not be beneficial in extrusion lines. In some cases, some lubricants can also be added to increase the MFR. Fatty acids, esters, stearates, and silicones are common lubricants (Mazzanti and Mollica 2020). Factors from the masterbatch that influence the rheological behavior of biocomposites are cellulose fiber load and sizes, matrix molecular weight, temperature, lubricants, coupling additives, and other additives (Mazzanti and Mollica 2020).

A challenge in cellulose-based biocomposites is water absorption due to the hydrophilic nature of cellulose and its limited compatibility with polar polymers (Mohammed *et al.* 2022). Surface modification of cellulose/nanocellulose (physical and chemical) or the incorporation of water-repellent additives, such as hydrophobic agents, are some options to reduce water absorption. This aspect is interesting for applicability, especially if the biocomposite will be in contact with water or humidity.

In extrusion lines, cellulose fibers must be dried before the extrusion line entrance, and pulling a vacuum on the compounding extruder can help reduce moisture and volatile components that cause odor and, in some cases, color changes in the biocomposites (Markarian 2024a).

Protein-based Bioplastics

In the current market, with widespread interest in PHAs and PLA production, as well as new alternatives based on cellulose and starch, proteins have re-emerged with new options that can be adapted to the market. This is of considerable importance, as many organic wastes contain substantial amounts of protein, offering a strategic opportunity for their valorization. Protein-based bioplastics are produced from plant and animal resources. Emerging options include proteins derived from microalgae and insects, even industrial waste (Pastrana-Pastrana *et al.* 2025). Examples can be found in the oil industry (soybeans, canola, rapeseed, sunflower, peanuts, sesame, black cumin and cottonseed), dairy industry (cheese whey), animal processing (porcine blood plasma, fish skin gelatin, chicken feather keratin, fish myofibrillar protein), and cereal-based byproducts (corn gluten meal, rice protein, wheat dried distillers 'grain, brewery spent grain) (Qazanfarzadeh and Kumaravel 2023). Proteins can be combined with other renewable materials to obtain maximized properties for flexible packaging (Fig. 7).

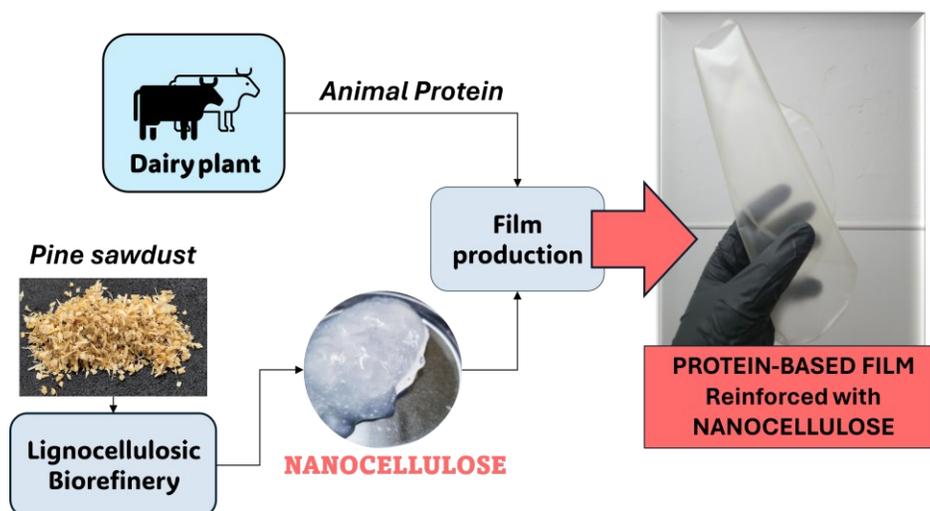


Fig. 7. Protein-based films reinforced with nanocellulose obtained in PROCYP. Film image courtesy Eng. Agustina Ponce de León

Proteins are composed of amino acids. They are synthesized and broken down by enzymes, and to obtain water-resistant protein bioplastics, it is necessary to cross-link amino acids with a specific enzyme (Basit *et al.* 2025). In addition, proteins can be combined with plasticizers, such as glycerol. The range of potential raw materials suitable to produce protein-based bioplastics is extensive. They produce biodegradable, edible, flexible, and thermoformable films (Cruz *et al.* 2022).

Table 2 summarizes the types, sources, commercial options, applications, and some advantages and limitations when protein-based materials are used. Protein films exhibit high biodegradability and good mechanical properties, though these are lower than those of many polysaccharide-based polymers such as starch and cellulose derivatives. Protein can form a good barrier to vapor permeation, but it has high water solubility, which limits its application in humid environments. It has good forming capacity and, being biocompatible, can be used in edible films for food (Bhaskar *et al.* 2023; Purewal *et al.* 2023).

Table 2. Advantages and Limitations of Protein-based Bioplastics

Protein Types	Soy, zein, gluten, casein, gelatin, whey
Sources	Soybean, corn, dairy products, by-products from wheat starch and cheese industry, fish, chicken, eggs
Advantages	High tensile strength, transparency, and superior oxygen and moisture barrier; High biodegradability, limited antimicrobial and antioxidant activity
Limitations	Poor performance at high temperatures or in humid environments; Viscosity is highly sensitive to humidity and when it is too high, the performance can be improved with the use of plasticizers; Edible films cost 10 to 50 times more than conventional packaging (plastic)
Applications	Films/coatings to preserve fruits and vegetables; Adhesives; Tissue regeneration; Gene delivery
Cost Comparisons	Protein costs vary depending on the type of protein, with gelatin being the cheapest. Protein can be combined with other, less expensive, biodegradable polymers. Costs can be further reduced by utilizing by-products from the dairy industry.
Reference	Chalermthai <i>et al.</i> 2020; Bhaskar <i>et al.</i> 2023; Purewal <i>et al.</i> 2023; Tassinari <i>et al.</i> 2023

Like polysaccharide-based biopolymers, protein films offer ecological benefits, but their cost and scalability challenges pose threats that hinder market expansion. The evaluation of costs associated with whey protein bioplastics was around 4 USD/Kg, lower than PHB costs (5-11 USD/Kg) but higher than conventional plastic values (1.20 to 2 USD/Kg) (Chalermthai *et al.* 2020; Tassinari *et al.* 2023). A sensitivity analysis for whey protein bioplastic production concluded that the unit plastic selling price was the most sensitive parameter, followed by the amount of feedstock whey protein concentrate, and the number of batches in the process (Chalermthai *et al.* 2020).

Seaweed-based Materials

As renewable resources, seaweeds are a potential source for producing next-generation bioplastics due to their non-toxicity, biodegradability in the environment, antioxidant properties, and ability to form films (Kajla *et al.* 2024). Seaweed has a high content of hydrocolloids (agar, carrageenan, and alginate, which have gelling and film-forming properties) and a low content of cellulose and starch, but lacks lignin. The selection of seaweed species to use as a source depends on the characteristics searched: green seaweeds contain mainly starch and ulvan (a sulfated polysaccharide), brown seaweeds have mainly alginate, and red seaweed contain carrageenan and agar (Torrejon *et al.* 2025).

ADVANCES IN APPLICATIONS

The applications of next-generation plastics are currently being studied as replacements for conventional plastics. Some are still under investigation, while others are already emerging products on the market. This section provides the latest developments for each option.

Progress in PLA and PHAs Solutions

PLA has gained a place in the market with industrially compostable (packaging sector) and durable applications (good in automotive and electronics). The leading producers of PLA worldwide are NatureWorks LLC (USA), TotalEnergies Corbion (The Netherlands and Thailand), BASF SE (Germany), Futamura Group (Japan), and Biome Bioplastics (UK). Around early 2028, a collaboration between Emirates Biotech (UAE) and Sulzer is also expected to produce around 80,000 t/year of PLA. TotalEnergies Corbion, in partnership with Useon, announced the production of expanded PLA (EPLA) molded products for foam packaging applications. NatureWorks also announced a new grade of biaxially oriented PLA (BOPLA). BOPLA stretches up to 7 times its transverse axis in equipment designed initially for PP and can be used for food packaging (Markarian 2025).

Current applications for PLA include food packaging, the medical sector, textile fibers, 3D printing, agricultural solutions, thermoforming, construction, automotive, and toys, among others. The characteristics of PLA define its specific applications; for example, PDLA is used in 3D printing, and PLLA in medical implants. PLA has been used in the manufacture of 3D printing filaments, combined with reinforcing additives such as cellulose, pigments to impart color, additives to improve thermal resistance, and even minerals to reduce cost. Some objects that can be obtained include medical orthotic components, architectural prototypes, and custom-specified parts (Futero 2025).

PLA/PHB blends have been applied to cosmetic packaging and even bottle caps. Despite the higher production cost of PLA compared to fossil-based plastics, companies have increased production for specific applications. Such a trend also has been observed, on a smaller scale, in the production of PHAs. In the flexible solutions space, Lummus and RWDC Industries have made progress in PHA production and are preparing the technology for global licensing (Eldridge 2024). Some applications for PHAs include medical devices, drug delivery systems, food packaging films, cosmetics, and agricultural solutions. The main characteristic of PHAs is their biodegradability in both soil and marine environments. However, their mechanical properties and thermal resistance are low; therefore, the incorporation of additives is necessary. In these cases, it is crucial to evaluate the influence of additives on biodegradation. A previous study on the biodegradation of 3D structures formed with PHB and cellulose fibers demonstrated that the addition of 20% thermomechanical cellulose fibers does not negatively affect their biodegradation (Ehman *et al.* 2021).

TPS in Agriculture and Food Packaging

The ease of processing and rapid biodegradation of TPS make it a good option in flexible and rigid applications. Table 3 summarizes some commercially available TPS-based products. These include pouches, bags, edible films, silage wraps, and mulch films are the commonly found options. Novamont (Italy) is the largest producer of TPS, with the MATER-Bi® family. The MATER-Bi® line of products is designed for packaging, agriculture, and waste-separation bags (Novamont 2025). The product is organized into series and grades, each for certain applications. For example, MATER-Bi® EF04P pellets (MFI:4g/10min) are recommended for flexible film blowing applications (Novamont 2019), while Mater-Bi® SE52F0 pellets (MFI:3g/10min) are recommended for sheet extrusion and thermoforming applications, including plates and food trays (Novamont 2025). A product with a higher MFI value, such as Mater-Bi® EI02A2 (MFI:17g/10min), is applied for injection molding applications (Novamont 2019b).

Table 3. Some Commercially Available TPS Products

Manufacturer	Product	Characteristics	Reference
Novamont S.p.A. (Versalis)	MATER-BI®	TPS pellets for several applications	(Novamont 2025)
AGRANA STARCH	AMITROPLAST®	TPS pellets and additives	(AGRANA STARCH 2021)
	AGENACOMP® F30, F40, F50, F51, and F61	TPS + biodegradable polymer + additives	(AGRANA STARCH 2025)
BioLogiQ	NuPlastiQ CG® 1000, 1005, 2030, 2031, 2040, and 2041	Pure TPS, pellets with density 1.4 g/cm ³ , and several MFI: 0.6, 4, 6, 6.5, 8, and 9 g/10min	(BioLogiQ 2025)
Rodenburg Biopolymers	Solanyl®	TPS pellets. Series C1, C2, and C8	(Rodenburg Biopolymers 2025)
BIOTEC	BioPlast GS	Mostly pellets for flexible solutions	(BIOTEC 2025)
Biome Bioplastics	BiomeHT, BioMesh, BiomeCord, BiomeEP, BiomeEasyFlow	Series designed for flexible and rigid applications	(Biome Bioplastics 2025)
Cardia Bioplastics	Biohybrid™ BL-F02	TPS and PE (MFI: 1.2 g/10 min)	(Cardia Bioplastics 2025)
	Compostable B-F12	TPS and PBAT (MFI < 3.8 g/10min)	

Another producer of TPS bioplastics is AGRANA STARCH (Europe, USA), with its family composite product AGENACOMP®, a combination of AMITROPLAST® (TPS) and biodegradable polymers (*e.g.*, PBAT) for flexible packaging films, injection mulch films, or 3D printing. The manufacturer demonstrated that a film composed of 50% TPS and 50% PBAT is biodegradable under home compost conditions (28 °C or lower) (AGRANA STARCH 2021). The AGENACOMP® family includes several products: F30 (comparable to PE, recommended for mulch films), F40 (biobased content 33%), F50 (biobased content 40%), F51 (biobased content >50%), and F61 (biobased content >60%) (AGRANA STARCH 2025). AMITROPLAST® is also recommended for injection molding: food trays, cutlery, agricultural clips and guides, sanitary products, 3D printing, and plant plots (AGRANA STARCH 2021).

NuPlastiQ CG®, a family of products manufactured by BioLogiQ (Asia and USA) are based on TPS and recommended for blending with several biodegradable and non-biodegradable polymers: PLA, PHAs, PBAT, LLDPE, and PP. The differences between the different NuPlastiQ CG® marketed products are based on MFI (determined by ASTM D1238), for example, the NuPlastiQ CG® 1000 has an MFI of 6 g/10 min (170 °C, 21.6 Kg) while the NuPlastiQ CG® 2040 has an MFI of 0.6 g/10 min (150 °C, 10 Kg) (BioLogiQ 2025). A higher MFI is recommended for injection molding applications, while a lower MFI is ideal for extrusion and blow molding.

Rodenburg Bioplastics (The Netherlands) produces Solanyl®, FlourPlast® (masterbatches), and Optinyl® (compatibilizers). Solanyl® is based on TPS from starch recovered from secondary streams of the potato processing industry and on resources derived from grain, root, or seed flour. Solanyl® C1 is recommended for injection or compression molding; C2 for sheet or profile extrusion; and C8 for blown or cast film extrusion (Rodenburg Biopolymers 2025). BIOTEC (Germany) also produces the Bioplast GS family from potato starch, including TPS-based formulations combined with other polymers. Bioplast includes series for flexible film production, vertical form/film seals, blown film extrusion, coextrusion, flexible applications dedicated as core layers in coextrusion, *etc.* (BIOTEC 2025). Biome Bioplastics (UK) offers TPS resins derived from potato starch for mono- and co-ex blown film lines, injection molding, sheet extrusion, thermoforming, and coatings (Biome Bioplastics 2025). Cardia Bioplastics (Australia) designs hybrid TPS formulations to increase the biobased carbon content in conventional polymers. For example, Cardia Biohybrid™ BL-F02, a homogeneous blend of TPS and PE, is recommended for thin- and thick-gauge film and blown-molding applications. Also, a Cardia Compostable B-F12 version is a blend of TPS and PBAT (Cardia Bioplastics 2025).

Lignocellulosic Biocomposites

The production of biocomposites combining polymers with lignocellulosic materials has increased in recent years. Cellulose fibers, nanocellulose, and lignin are versatile when combined with HDPE, LDPE, PP, PLA, PHAs, and other polymers. Masterbatches based on high cellulose fiber loads are currently combined with virgin or recycled PP and PLA.

Skylo processes plastic and paper waste from industries and municipalities, then separates it into different fractions. The paper waste is subsequently converted into reinforcing additives for masterbatches used in the plastics industry. Syklocomp pellets are composed of 60 to 70% recycled cellulose fibers (Skylo 2025). FlexForm Technologies produces biocomposites based on PP and 50% natural fibers from annual crops to produce

automotive parts, including doors, consoles, ceilings, and other panels (FlexForm Technologies 2025). Norske Skog produces pellets composed of 60% thermomechanical fibers from Norway spruce, combined with rPP and PLA, in a 300 ton/year pilot plant for injection molding, 3D printing, and extrusion applications. UPM also produces UPM Formi biocomposite, with 50% of cellulose filler content and PLA for injection molding, extrusion, and 3D printing applications (Markarian 2024a).

Depending on the type of matrix polymer used, biocomposite pellets can be used for short- or long-term products. In some cases, the goal is to reduce water absorption for a specific application. In these cases, the OH groups in cellulose can be chemically modified by esterification or grafting with hydrophobic reagents (Markarian 2024a). UPM developed a combination of thermoplastics and thermosets, such as BioMotion™, a renewable functional filler. These additives are produced inside UPM biorefinery (Germany), an establishment that also produces renewable monoethylene glycol and monopropylene glycol from hardwoods. The additive can be incorporated into thermoplastics as a masterbatch for injection molding, compression molding, blow molding, thermoforming, film blowing, and 3D printing (Markarian 2024a; UPM 2025). Lignin powder was also combined with PLA at 30% on a pilot scale (adapted for KraussMaffei Extrusion) to produce pellets with enhanced flexural, tensile modulus, and thermal properties. Lignin Industries produces Renol® lignin masterbatches for combination with LDPE, polypropylene, and ABS in applications such as flexible packaging, electronics, and construction (Markarian 2025).

Additives used in biocomposites are mainly derived from fossil sources. Therefore, a challenge for producers of next-generation bioplastics is to develop bio-based, biodegradable solutions. The need has been observed in PLA, which requires additives to enhance its melt strength for plastic conversion processes, as well as its flexibility and impact strength for end-use applications. For example, in PLA and other bioplastics, some options include BYK's SCONA TPPL-grafted PLA and BioStrength Arkema (Markarian 2024a). Ourobio (USA) uses residual sugars and proteins from food and agricultural processing streams as raw materials to co-produce PHAs and biodegradable pigments in a fermentation bioreactor.

The researchers found that during PHA production, a secondary reaction occurred: the proteins were converted into pigment precursors and, ultimately, into indigo pigments. The microbes can be modified to produce a full palette of colors. Indigo and its derivatives are thermostable at the temperatures used in plastics processing, and in initial benchtop twin-screw extruder tests, they were able to blend the pigments into PHA mixtures, producing red, blue, and purple, along with the PHAs. Therefore, an alternative pigment emerges to replace existing inorganic ones (Markarian 2024b).

Success Stories from Lab to the Market: Protein and Seaweed-based

Flexible and rigid packaging, edible films, and paper coatings are some of the most common applications of protein-based plastics (Fig. 8). Several producers of protein-based plastics have transitioned from laboratory scale to market, achieving success stories but also facing challenges that remain.

Xampla (UK) uses plant-based proteins (peas, potatoes, and rapeseed) to produce water-soluble edible films and paper coating (Morro™). Morro is ready to replace polyvinyl alcohol plastic films with dishwasher tablets and detergent pods, and food container films. Furthermore, it can be used as a coating on paperboard (Xampla 2025). Traceless (Germany) produces a plastic-replacement product made from proteins extracted

from vegetal waste (Traceless®). The product can be processed in standard injection molding machines, achieving good flowability at low temperatures to produce rigid packaging, as a coating on paper, and in familiar cast- and blow-film production lines (Traceless 2025). CareTips® pellets are made by Lactips (France) from casein and are suitable for injection molding, blown extrusion, and extrusion (Lactips 2025).

Notpla, B'Zeos, Noriware, and Kelpi are successful examples of seaweed-based packaging. Notpla has redesigned liquid packaging solutions through encapsulation with a completely edible material (NotPla 2025).

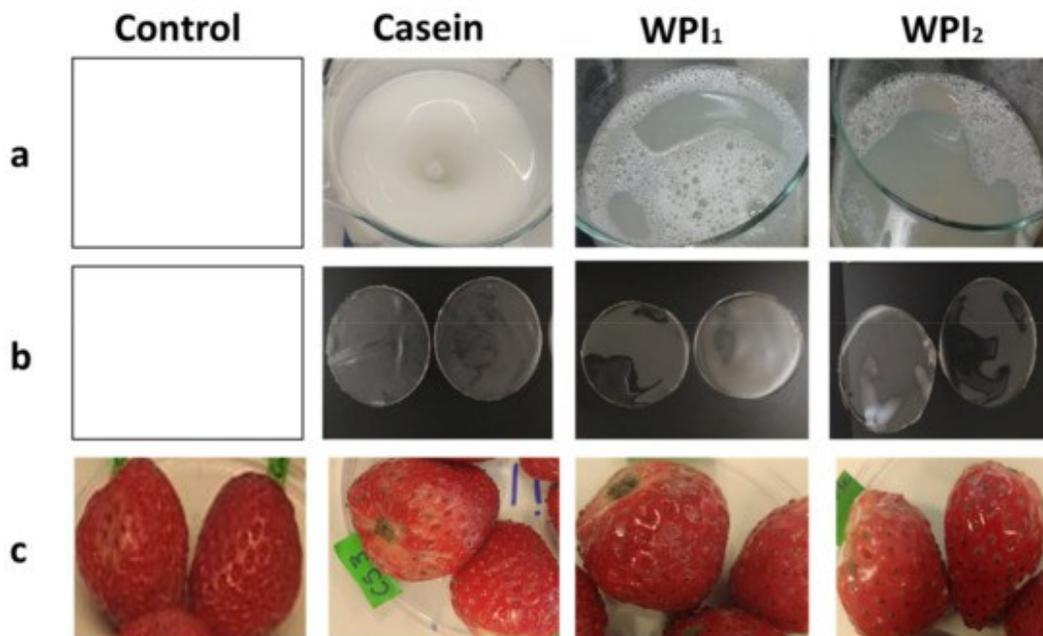


Fig. 8. (a) Solutions from casein and whey proteins, (b) films prepared from the solutions, and (c) strawberries coated with solutions. Extracted from (Fematt-Flores *et al.* 2022): CC BY license. (<https://creativecommons.org/licenses/by/4.0/>)

TOWARDS A PARADIGM SHIFT IN BIOPLASTICS

The paradigm shift in next-generation bioplastics not only involves replacing materials, but also reconfiguring an entire system: production, consumption, and waste management. The participation of all stakeholders (society, industry, and government) is crucial. Innovation and industry through development of scalable technologies and products, society from knowledge and responsible practices, and finally government using regulatory frameworks, development of integral systems (promoting circularity), and incentives to the society and industry.

Reconfiguration Instead of Replacement

Bioplastics have been developed as replacements for conventional plastics, reducing the use of fossil resources while maintaining their properties. Now, considering the possibility that bioplastics can act as a catalyst to reorganize or reconfigure systems opens new horizons in systems design. One strategy for achieving this reconfiguration is to consider the current challenges associated with bioplastics. The first significant

challenge for bioplastics production is that higher production costs are incurred to achieve products with properties similar to those of a fossil based one. The replacement strategy focuses on scaling up production and supporting it with regulations or subsidies to balance prices. However, if the goal includes system reconfiguration, it should head towards expanding the functionality of the bioplastic. Bioplastics should not only replicate the role of fossil plastics but also provide new properties. For example, expanded functionality at the end of the life cycle, such as controlled biodegradation in single-use options, nutrient release in agriculture, and integration with the human body in medical solutions.

Another challenge is environmental problems associated with fossil-based, non-biodegradable plastics. Replacement is the use of biobased, compostable, or biodegradable plastics. Reconfiguration is the design of a closed production cycle (waste is reintegrated into the process, emissions are minimized, and new value chains are fostered through circularity). This approach transforms the linear model into a circular one. In the case of single-use packaging, it is not enough to choose biodegradable options; it is important also to consider packaging designed for industrial composting, single-material recycling, and resource recovery (compost, energy). If the material returns to the soil or water, then one should aim for controlled biodegradation in environments that provide nutrients. For example, such a strategy could be used for difficult-to-manage medical and agricultural waste. Functional reconfigurations could involve implants that degrade in the body, bioabsorbable sutures, mulching films that nourish the soil, and slow-release fertilizer capsules.

Challenges posed by fossil dependence are addressed through biobased sources. But the reconfiguration promotes the integration of agro/forest-industrial wastes into existing production lines. It diversifies raw material sources and leverages previously discarded byproducts.

The Role of Innovation in the Paradigm Shift

Innovation in the reconfiguration of the system for the inclusion of bioplastics encompasses not only technological and productive development but also influences of actors in society, including political and regulatory aspects. In this respect, it is possible to visualize the most critical actors in each case: research centers (universities, institutes), the government, society, and the productive sector. Innovation appears in the development of new bioplastics, the use of new resources, and the optimization of methodologies to produce these products.

Innovation also allows for the reconfiguration of industrial processes, making them more flexible in producing these products, developing technologies, creating infrastructure or systems proper at the end of the product life cycle, and generating public-private partnerships.

The government can improve consumer trust by using transparent labeling, controlling greenwashing, using regulatory frameworks, and evaluating producers and consumer responsibility. Finally, it promotes and educates citizens, enabling them to participate actively in the transition.

Investment and Flexibility in Industry

The opportunities for conventional plastics industries to produce bioplastics can follow a temporal distribution and will depend on the level of investment required. In some cases, existing machinery can be used, with only modifications to the operating conditions;

therefore, this is considered a short-term change. For example, HDPE films can be converted into PLA.

In the medium term, modifications to current equipment are required, while in medium- to long-term scenarios, adaptation involves both adjustments and the incorporation of existing machinery. This group, for example, could include industries that use recycled resins and wish to incorporate lignocellulosic fibers. In that case, they will require specific equipment for fiber drying and additional hopper systems to feed the materials into the extruder. Finally, in the long term, plastic substitutions require the development of more complex, automated, custom-designed equipment.

Regulatory Perspectives: What's Regulated and What's Missing

Currently, regulatory perspectives present several challenges, including a lack of specific definitions, inconsistent international standards, poor management of materials after their useful life, and environmental concerns.

The standards differ across countries and even jurisdictions, creating confusion among consumers. This aspect is more evident in low-income countries, underscoring the need to develop international standards. The EU has demonstrated a rational integration in the development of terms and definitions among its member countries. Some countries use these definitions in their regional regulations.

Also, the lack of knowledge about the components involved in bioplastic materials is another existing gap, particularly regarding the damage to the environment and the human body. The EU has regulations on the import of components containing bioplastics and conventional plastics into its member states. In other countries, regulations are more focused on food packaging. Many countries base their rules on EU standards and even FDA guidelines.

The inefficient handling of materials at the end of their useful life cycle is another existing problem. Inadequate composting or recycling systems, especially in low-income countries, limit the effectiveness of bioplastics systems. In some cases, problems arise from inconsistent labeling rules that lead to greenwashing and contamination of recycling streams. Policies that integrate bioplastics into circular-economy strategies could create an efficient system. Governments are exploring Extended Producer Responsibility (EPR) schemes, subsidies to communes, and education to address this problem. This last point is of relative importance considering a growing market for bioplastics.

SUMMARY OF COMPARATIVE LIFE CYCLE ASSESSMENT

The evaluation of Life Cycle Assessment (LCA) for next-generation materials is particularly relevant because it enables a comprehensive assessment of their overall sustainability, avoiding conclusions based solely on their biobased and biodegradable characteristics. In LCA, the environmental impact categories are expressed as specific category indicators (like characterization factors) for quantification. Several studies have evaluated the LCAs of next-generation plastics such as PLA, PHAs, TPS, cellulose-based biocomposites, *etc.*, against conventional plastics, assessing the different impacts such as global warming potential (GWP) or carbon footprint, eutrophication, potential acidification, photochemical oxidant formation, aquatic/terrestrial ecotoxicity, human toxicity, cumulative energy demand, abiotic resource use, biotic resource use, and ozone depletion potential (Banerjee and Ray 2022).

An interesting study in the packaging sector was conducted by Desole *et al.* 2024, who evaluated fresh pasteurized milk bottles using LCA analysis. The evaluation compared a PET (bottle: PET, cap: HDPE, and label: LDPE) and PLA (bottle: PLA, cap: PLA, and label: PLA) options (500 mL bottle). The cradle-to-gate impacts showed that the PLA bottle reduced cumulative energy demand (by 30.9%) and net GWP (by 9.7%) compared to the fossil-based bottle. These advantages depend largely on how biogenic carbon is accounted for and the agricultural impacts associated with corn cultivation. When agricultural emissions are included and CO₂ credits are excluded, the environmental superiority of PLA decreases significantly (with the GWP being 15% higher for the PLA bottle), revealing that its performance is not inherently better than PET, that it is necessary to optimize the processes, and that the actual sustainability of biopolymers depends as much on agriculture as on the methodological decisions of the LCA. The effect of process optimization is also observed in PHAs, where the material shows good end-of-life performance. However, its cradle-to-gate impact can be high if biotechnological processes are not optimized, leading to high energy consumption (Desole *et al.* 2024).

A comparative study between PLA and PHAs demonstrated that PLA generally shows better cradle-to-gate results because its industrial production is more optimized and consumes less energy. However, its dependence on crops can increase impacts on land use and eutrophication. PHAs stand out for their actual biodegradability in natural environments and for their excellent end-of-life performance. On the contrary, their production is more expensive and energy-intensive, which can increase their environmental footprint in the early stages (Álvarez-Chávez *et al.* 2012).

Another interesting study was performed by Surendren *et al.* (2024), who evaluated the comparative LCA of different plasticization and co-plasticization processes of corn starch. The aim was to identify how plasticizers affect the environmental performance of the entire process. The analysis considered both the production of the plasticizing agents and the energy stages involved in starch transformation. The cradle-to-gate analysis evaluated for 4 routes: 1) used glycerol and water as plasticizers (conventional ones), 2) used glycerol, water, and urea (co-plasticizer), 3) used glycerol, water, and citric acid (co-plasticizer), and 4) used glycerol, water, and succinic anhydride (co-plasticizer). Glycerol-citric acid and glycerol-succinic anhydride systems exhibited environmental profiles like those of the traditional glycerol process, positioning them as viable alternatives from a sustainability perspective. However, the glycerol-urea process resulted in significant environmental impacts, primarily associated with its elaboration and additional energy consumption. The energy sensitivity analysis also showed that qualitative reductions in energy consumption significantly decrease the impacts on GWP, carcinogenicity, ecotoxicity, and fossil fuel depletion. Therefore, the results showed that plasticizer selection and energy efficiency are critical variables in the sustainable design of starch-based materials (Surendren *et al.* 2024).

Cradle-to-gate LCA was also performed in a protein system (Chalermthai *et al.* 2021). An LCA analysis of whey protein obtained from dairy wastes evaluated the impacts associated with several process stages: obtaining the residual whey, protein recovery and purification, chemical modification or polymerization, and shaping of the bioplastic. The study focused on the environmentally advantageous alternative of using whey protein as a raw material, rather than conventional dairy waste management, and finally, the production of plastics derived from fossil fuels. The analysis considered GWP, energy use, eutrophication, acidification, and toxicity. The use of whey to produce biopolymers has significantly reduced the environmental burden associated with its disposal as waste.

However, the pretreatment, protein purification, and polymerization processes have significant impacts, primarily due to energy consumption, and therefore require optimization (Chalermthai *et al.* 2021).

Lignocellulosic biocomposites LCAs have been extensively studied in recent years due to a growing interest from the industry to incorporate lignocellulosic fibers as a reinforcement agent in thermoplastic matrices. Foroughi *et al.* (2021) identified that cellulose can be positioned as a low-carbon material. However, its performance depends critically on the biomass source, the energy intensity of processing, forest or agricultural management, and integration into circular systems. In nanocellulose production, the authors found that the most significant impacts are primarily concentrated in the cultivation/extraction stages, the chemical/mechanical pretreatments, and in the energy-intensive refining processes (Foroughi *et al.* 2021). Banerjee and Ray (2022) noted that lignocellulosic fibers incorporated into fossil and biobased polymers have significantly lower environmental impacts than synthetic reinforcements. The reason is attributed to their renewable origin and, in many cases, their availability as industrial byproducts. The authors reported that these lignocellulosic fibers can improve the environmental performance of thermoplastic composites by lowering the carbon footprint per functional unit, particularly when combined with biobased matrices. However, their sustainability also depends on factors such as the type of pretreatment, the biomass source, and the processing efficiency (optimize the energy and water consumption) (Banerjee and Ray 2022).

FUTURE OUTLOOK

Despite numerous studies on next-generation bioplastics, some challenges and gaps remain. In PLA bioplastics, improving end-of-life management, reducing the agricultural impact of carbon sources, and achieving greater energy efficiency in production are some current challenges. These issues can be addressed by improving regulations for recycling and composting management systems, optimizing production processes through integration, such as the application of biorefineries, and using agricultural or forestry biomass waste as a carbon source. In the case of PHAs, it is still important to reduce the impact of pretreatment/biomass and process energy. This will enable future profitability during scale-up and reduce product costs, making it more competitive. For biomass-derived bioplastics, challenges related to production and polymer properties still need to be addressed. Reducing energy and water consumption, along with enhancing fractionation, extraction, and purification, can be achieved through integrated systems such as biorefineries, which not only produce bioplastics but also generate other high-value products. The moisture resistance in biomass-derived bioplastics, such as starch or cellulose derivatives, can be increased by mixing them with other more hydrophobic polymers or through chemical modifications.

FINAL REMARKS

Next-generation bioplastics are a key alternative for reducing the consumption of fossil-based plastics. Despite the promising biobased and biodegradable options, it is

essential to understand that this shift isn't simply about replacement, but rather a paradigm shift across the entire supply chain and involving all stakeholders.

The materials offer advantages in carbon footprint, but their impact on agriculture remains significant. Furthermore, the availability of composting and recycling infrastructure is limited, reducing their true environmental potential, which demonstrates the need for a shift in the current paradigm. Optimizing processes, using lignocellulosic waste as raw material, incorporating renewable energy into production, and implementing more robust end-of-life management systems are viable solutions.

Challenges remain, but collaborative action between society, regulatory bodies, and industry will enable significant changes and improved management to support the growing market for these materials.

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