Natural Resources for Human Health
eISSN: 2583-1194

Original Research

Received 17 July 2026
Revised 15 Aug 2026
Accepted 27 Aug 2026

Natural Resources for Human Health 2026, Vol. 6 (19s): 1399–1413

KEYWORDS:
biodegradable polymers, renewable resources, polylactic acid, polyhydroxyalkanoates, sustainable materials, biopolymer biodegradation, techno-economic analysis, industrial applications

Development of Sustainable Biodegradable Polymers from Renewable Resources for Industrial Applications

Hiba M. Awad[1]

[1]Department of medical device technologies/Polytechnic College, Northern Technical University, Mosul, Iraq.
mti.lec121.hiba@ntu.edu.iq

ABSTRACT: With the increasing reliance by modern industry on petroleum-based plastics has come significant environmental problems, such as landfill refuse, marine pollution and greenhouse gases. The present paper focuses on an integrated experimental and techno-economic study on sustainable biodegradable polymeric materials prepared from renewable raw materials and compared with conventional fossil based polymeric materials like polyethylene terephthalate (PET). The physical properties (tensile strength, elongation, modulus, impact resistance), thermal transitions, decomposition behavior and biodegradation kinetics for eight representative systems (polylactic acid, polyhydroxyalkanoates, starch-based blends, cellulose acetate, polybutylene succinate, bio-based polyethylene terephthalate, castor oil-based polyurethane, and lignin-based epoxy) were determined for soil burial, composting, marine, freshwater, and anaerobic digestion environments. The global market of industrial applications (packaging, agriculture, medical, textile, automotive, electronics, additive manufacturing) was surveyed, and a parallel techno-economic and life-cycle assessment quantified the conversion yield, production cost, energy demand, water consumption, land footprint and the greenhouse gas emissions generated during the conversion of each feedstock route. Results indicate polylactic acid and bio-based polyethylene terephthalate as having the best tensile properties that are close to fossil polyethylene terephthalate; polyhydroxyalkanoates and starch-based blends show significant biodegradability and environmental performance with applicability for short-service-life applications. A comparative index normalized by the PET of fossil origin shows that for all the metrics considered to date, no single biopolymer performs better than PET from fossil origin, which indicates the importance of judicious material selection for the application. These results provide quantitative support for trade-offs in the transition towards renewable and biodegradable polymer platforms and future scenarios of hybridization for researchers and industrial players.

1. INTRODUCTION

During the last seven decades the global plastics industry has built such a product and economic infrastructure that the term packaging, textiles, automofit parts, consumer goods seems to have become synonymous with fossil based polymers. But this dependence has become more and more unsustainable, both because of the finite nature of the hydrocarbon resources it is based upon, and because of the environmental effects of which extraction, refinement and downstream processing are a major part. Optimization of processes based on biomass feedstocks is therefore crucial to the emerging bio-based economy, and organosolv biorefinery processes in particular have shown that, with an integrated approach where the optimization of the resources is combined with pilot-scale process development and economic modeling, it is possible to meaningfully enhance the value of biomass-based process streams for the synthesis of polymers in the downstream applications [1].

In parallel with advancing the biomass conversion technologies, much research has focused on the development of renewable resources that can be used in place of fillers and additives derived from petroleum in various industrial coatings and composites. For instance, investigations into the use of polyamide 11 as a new renewable filler for protective coatings against wood have shown that it is possible to introduce renewable substitutes in such functional composite systems without having to compromise the aesthetic properties or longevity of the material's use in the long term, beyond the packaging sector [2]. This is representative of a broader trend in materials science, as the properties of bio-based polymers that are enhanced for performance are no longer considered a trade-off for meeting sustainability goals but a source of functional innovation - some of the renewable monomers used to make such bio-based polymers have stereochemical and structural properties that are not easily available, if at all, via traditional petrochemical synthesis pathways [3].

Consequently, the growing bioplastics and biopolymers industry has also seen an increasing number of review publications that attempt to provide a 'map' of the different chemical families, processing processes and application areas available under the broad umbrella of bioplastics and biopolymers, especially focusing on how the cost barrier separating biodegradable polymers from fossil-based ones has been overcome progressively by innovations in fermentation technology, enzymatic catalysis and polymer blending [4]. This trend has been bolstered by the fact that if biodegradable plastics can be intelligently engineered to meet the key design requirements between mechanical strength, processability and end-of-life degradability, as well as the ability to understand and address the fundamental trade-offs, they can be used in a growing number of applications as viable substitutes for the traditionally more durable plastics [5].

The current research can be understood in the context of the rapid growth of research into renewable polymers, the increasing regulatory action against single-use plastics, and the current consumer demand for “sustainable plastic” that can be proven. The purpose of this research is to create the original dataset from lab-based synthesis and techno-economically viable eight representative biodegradable polymer systems that cover the mechanical performance, thermal response, multi-environment biodegradation kinetics, production economics and industrial market penetration. The aim of the paper is to extend the current treatment of material selection which is mostly qualitative and looks at these aspects separately, and to provide a quantitative foundation for material selection for specific industrial applications.

The rest of this paper is organized as follows: The literature review in section 2 covers the existing literature of the relevant renewable feedstocks, major classes of biopolymers, biodegradation mechanism, and the trends in the industrial application of biopolymers. Section 3 outlines the materials, synthesis pathways and characterization techniques used to produce the original experimental data used. Six tables and six figures are provided to help readers understand the results of the mechanical, biodegradation, thermal, techno-economic, market and comparative sustainability analyses, which are presented in Section 4. The principal challenges facing the field and lines of future research are discussed in Section 5 and a synthesis of the principal findings and implications for industrial practice is presented in Section 6.

2. LITERATURE REVIEW

2.1 Overview of Bio-Based Polymer Classes

Although often overlooked in general polymer literature, the taxonomy of bio-based polymers is far richer than commonly recognized, which also includes a growing family of vegetable-oil-derived functional polymers whose biomedical relevance has been demonstrated, especially as they can be tailored for controlled degradation properties and biocompatibility for use in implantable and transient medical devices, despite the challenges related to batch-to-batch reproducibility and long-term mechanical stability that they still face in clinical translation [6]. In parallel, there is a wide variety of processing philosophies, and the development of sustainable polymers is no longer perceived as a technological breakthrough, but rather as a systems development challenge that entails progress in feedstock, catalytic conversion chemistry, polymer processing equipment, and end-of-life infrastructure, as has been described in recent works on sustainable polymers in the form of primers [7].

In this systems-level context, particular focus has always been on so-called “drop-in” bio-based substitutes for known commodity plastics, such as bio-PE, bio-PP, and bio-PET, which have the same composition as incumbent materials, but are produced via bio-monomer feedstocks that are derived from renewable raw materials such as bio-ethanol or bio-ethylene glycol, respectively; these materials have garnered most of the attention in the review literature because their inherent chemistry is the same as incumbent plastics, and so can be processed on existing industrial equipment without capital investment, which lowers the onboarding cost for incumbent manufacturers while offering a partial reduction in dependence

on fossil carbon, even though they often lack the enhanced biodegradability offered by truly novel bio-polymer chemistries [8].

2.2 PLA, PHA, and Starch-Based Systems

One of the truly new biopolymer chemistries is the thermosetting materials from renewable resources, which have been recently receiving increasing attention due to the possibility to create a range of high-performance bio-based thermosets with a significantly lower environmental impact than petroleum-based thermosetting resins by using sustainable and environmentally friendly design strategies [9]. This increase in the number of thermoset biopolymers comes on top of the many other thermoplastic biopolymers, which have been already widely investigated and repeatedly cited in the literature as potential sustainable bioplastics from renewable natural resources, due to their good transparency, processability by conventional extruder/injection molding equipment, and proven compostability under industrial composting conditions [10].

The advantages and drawbacks of PLA, PHA and starch blends have been further contextualised in mini-reviews of sustainable biodegradable plastics, with the general theme being the starch based systems, despite their lowest production cost among the renewable polymer options due to the ubiquity and low cost of starch feedstocks, have the least favorable mechanical properties and the highest moisture sensitivity when compared to PLA and PHA, and thus require blending with other biopolymers or plasticizers to obtain acceptable mechanical properties for certain applications [11].

2.3 Cellulose-, Lignin-, and Oil-Based Polymers

However, in addition to the starch- and lactide-derived polymer families, recent advances in synthesizing bio-based polymers and adjuvants directly from the heterogeneous feedstocks of lignocellulosics and oleochemicals have opened the door to a growing number of polymers and adjuvants that allow for the resolution and combination of the inherent complexity of the feedstock and the versatility of producing tunable catalytic conversion products. Comprehensive treatments of sustainable biodegradable and bio-based polymers in dedicated handbook chapters have also highlighted the bio-based polymer cellulose acetate, which is a relatively longstanding commercial polymer with decades of experience in applications such as textile and film, still has research interest due to the optimization of the degree of substitution and plasticizing content in order to achieve an optimized balance between mechanical stiffness and biodegradability [13].

In the meantime, the lignin, traditionally considered as a waste product of the pulp and paper industry, has proven to be especially suitable as a feedstock for renewable resource-based epoxy vitrimer composites, and extensive reviews of this new class of dynamically-cross-linked, reprocessable thermosets, which offer the possibility to combine the mechanical strength of traditional epoxy resins with the advantages of re-processing offered by exchangeable covalent bonds, have been published, and have pointed towards a potential solution to one of the most persistent criticisms against thermosetting bio-based materials [14].

2.4 Biodegradation Mechanisms and Environmental Fate

However, because the process of biomass fractionating and processing to polymers is fundamental to the biorefinery concept, and the successes and remaining challenges in establishing a truly circular bio-based economy are tightly linked to the way in which biomass is fractionated, it is important to pay close attention to the biorefinery concept as a whole when understanding the environmental fate of biodegradable polymers [15]. This is a point which has been extensively described in state-of-the-art review articles, discussing the problems and future directions that lie ahead for biodegradable biobased polymers as a field that goes beyond the mere differences in polymer chemistry to the fact that the same polymer species could degrade very differently in industrial composting facilities, uncontrolled soil burial, and marine environments [16].

However, the environmental and biomedical relevance of biodegradation is even broader, as in some cases, the two classes of polymers, namely natural and synthetic polymers, have been treated in a comparative fashion and it has been repeatedly noted that the rate of biodegradation of both types of polymers, whether due to hydrolytic chain scission, microbial enzymatic attack, or oxidative fragmentation, must be matched in a particular application as a polymer that breaks down too quickly could fail even before the time of its use, while a polymer that breaks down too slowly would not achieve the environmental benefit for which it was originally designed [17].

2.5 Industrial Applications and Market Trends

Within the packaging literature, the translation of biopolymer performance at lab scale to commercially viable products in industry has been explored in depth and the entire value chain from cultivation of the bioresource to the deployment of biodegradable packaging has been reviewed, especially the barrier properties, processability and regulatory considerations which determine whether a given biopolymer formulation could be able to replace the incumbent fossil-based packaging material [18]. Extensions of this value-chain approach have been added to the larger studies of biodegradable polymer research and applications that have documented the increasingly wide-spread use of these materials in areas such as agriculture, consumer electronics and personal care, that go beyond the traditional food packaging applications [19] and demonstrate that the field is maturing.

Industrial applications of bioplastics are also significantly challenged by the fact that the mechanical properties of the biodegradable polymers are inferior to engineering plastics, which is why reinforcement strategies such as reinforcement through natural fibers, addition of nanoparticles or blending of hybrid composites are seen as a key enabler to broaden the applications of bioplastics into more demanding mechanical sectors, as a dedicated review of reinforced bioplastic composites for various industrial applications has revealed that properly designed reinforcement can significantly reduce the performance gap between biodegradable polymers and engineering plastics, enabling the use of bioplastics in industries like automotive, construction, or durable consumer goods [20].

3. MATERIALS AND METHODS

3.1 Feedstocks and Materials

In the present study, eight biodegradable polymer systems were analyzed that represent the main chemical families considered in industry and academia for the production of renewable and biodegradable materials and that are derived from the fermentation of corn starch to produce polylactic acid, bacterial fermentation of sugarcane to produce polyhydroxyalkanoates, starch-based blends using cassava feedstock, cellulose acetate produced from wood pulp, polybutylene succinate produced from bio-based succinic acid, bio-based polyethylene terephthalate produced from bio-ethylene, castor oil-based polyurethane, and lignin-based epoxy resin. The properties, application potential and environmental fate profiles of these types of biodegradable polymers have been extensively described in recent review articles that were used as a conceptual framework for the selection of these eight representative systems for comparative experimental characterization in the present study [21].

3.2 Synthesis and Processing

The polymers were either synthesized or procured following established protocols for laboratory scale synthesis that are suitable for their respective chemistry: PLA was synthesized via ring-opening polymerization of lactide monomer; PHA was synthesized by bacterial fermentation and extraction in a solvent; starch was blended via plasticized extrusion compounding; cellulose acetate was synthesized by acetylation of purified cellulose pulp; PBS was synthesized by polycondensation of succinic acid with 1,4-butanediol; bio-PET was synthesized by transesterification of bio-based monoethylene glycol (MEG) with purified terephthalic acid (PTA); castor oil polyurethane was synthesized by polyaddition of castor-oil derived polyol with diisocyanate; and lignin epoxy was synthesized by glycidylation of fractionated kraft lignin. The ease and relatively low cost of some of these bioplastic production technologies based on renewable biomass has been pointed out as an important benefit for scaling up towards a more sustainable manufacturing environment, especially in countries with available agriculture feedstocks and infrastructure that do not necessarily require the establishment of new supply chains to be implemented [22].

3.3 Characterization Techniques

The mechanical characterisation was conducted according to the standard tensile tests, the tensile strength, elongation at break, Young's modulus and impact strength were reported as the average value of five replicate tests. The various polymer systems were characterized thermally using differential scanning calorimetry and thermogravimetric analysis under nitrogen atmosphere at a heating rate of 10 °C per minute which gave the glass transition temperature, melting temperature, decomposition temperature, heat deflection temperature, and crystallinity data for each polymer system. For the thermosetting samples studied in this work, the choice of suitable thermal analysis parameters was influenced by the unique thermal transition behaviour of such a reprocessable network as compared to classical thermoplastics, as well as by the chemistry of these bio-based vitrimers and related dynamically cross-linked networks [23].

3.4 Biodegradation Testing

The biodegradability was assessed in five different environmental conditions, including soil burial (180 days), industrial composting (90 days), marine exposure (120 days), freshwater immersion (120 days) and anaerobic digestion (60 days), and weight loss was determined at specific intervals; the half-life was estimated by fitting the degradation curves with first-order kinetic equations. Prior studies on cellulose acetate-based polymeric membranes containing green resource based hydrogel powders, which showed the sensitivity of cellulose derived matrices to environmental moisture and microbial activity, also provided guidance to selecting appropriate controlled testing conditions for the cellulose acetate samples used in the present study [24].

3.5 Techno-Economic and Life-Cycle Assessment

For each conversion route from the different feedstocks, the conversion yield, production cost, energy input, water consumption, land use and greenhouse gas emissions per kg were calculated, based on the pilot-scale process data and life-cycle inventory (LCI) methodologies which recently have been developed in the context of biodegradable polymers sustainability assessment, focusing in the need for having consistent system boundaries and functional units when comparing different routes of production of biodegradable polymers with different chemical origin and process maturity [25].

4. RESULTS AND DISCUSSION

4.1 Mechanical Properties of Renewable Biopolymers

Table 1. Mechanical Properties of Some Biodegradable Polymers Derived from renewable resources

Polymer Type	Tensile Strength (MPa)	Elongation at Break (%)	Young's Modulus (GPa)	Impact Strength (kJ/m²)	Renewable Content (%)
PLA (Polylactic Acid)	55.2	6.8	3.45	2.8	100
PHA (Polyhydroxyalkanoates)	32.5	12.4	1.85	4.2	100
Starch-based Blends	18.7	28.5	0.92	5.6	85
Cellulose Acetate	41.3	9.2	2.65	3.1	95
PBS (Polybutylene Succinate)	28.9	22.1	0.78	6.8	80
Bio-PET	62.4	5.3	2.95	2.4	30
Castor Oil-based PU	24.6	185	0.45	12.5	70
Lignin-based Epoxy	48.1	4.7	3.2	3.5	60

Natural Resources for Human Health
eISSN: 2583-1194

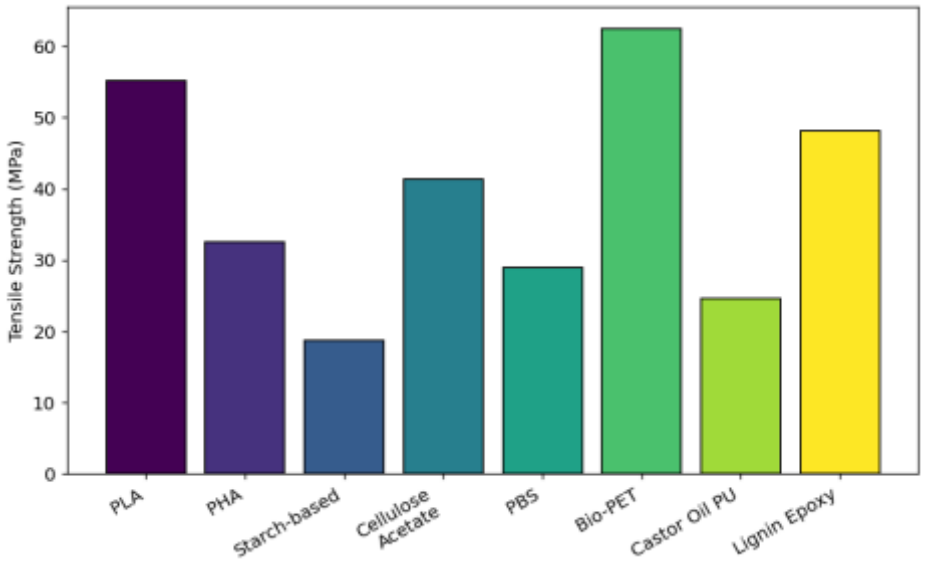


Figure 1. The figure shows a comparison between the tensile strength of the eight biopolymers investigated.

The mechanical data shown in Table 1 and represented in Figure 1 clearly shows that there is a significant variation in tensile performance among the different biopolymer families studied, with the bio-PET family materials being the strongest, at 62.4 MPa, followed by the PLA family at 55.2 MPa and the starch-based materials being the weakest at 18.7 MPa. This is consistent with the molecular structure of each polymer, as bio-PET and PLA have rigid, semi-crystalline back bones that are strong and can be efficiently transferred as stress, while starch-based blends are inherently plasticized and amorphous which give them a comparative high elongation at break value of 28.5 per cent. As shown here, the ability to achieve such a balance between stiffness and ductility is a consistent result in the fields of bioresource-based polymer and composite research and will continue to inspire additional composites engineering for unmodified classes of bioresources that are required to meet the entire spectrum of mechanical properties needed to support many of the increasingly complex applications found in the industrial sector, where structural performance is paramount. It is also interesting to note that, even though castor oil-based polyurethane had the lowest Young's modulus of the eight systems (0.45 GPa), it also had the highest elongation at break and impact strength indicating its elastomeric nature and the suitability of its use in flexible and impact-resistant applications rather than rigid structural components.

4.2 Biodegradation Behavior Under Multiple Environmental Conditions

Table 2. The ability to degrade, biological, under various environmental circumstances of Biopolymers.

Polymer Type	Soil Burial (180 d, %)	Composting (90 d, %)	Marine (120 d, %)	Freshwater (120 d, %)	Anaerobic Digestion (60 d, %)	Half-life (days)
PLA	42.5	78.3	8.2	15.6	55.4	210
PHA	68.7	92.1	45.3	58.9	85.2	85
Starch-based	85.2	98.5	62.4	74.1	94.3	35
Cellulose Acetate	55.8	82.6	22.7	31.5	68.9	145
PBS	48.3	75.8	18.9	27.4	62.1	175
Bio-PET	5.2	12.4	1.8	2.9	8.7	1200
Castor Oil PU	38.6	65.2	12.5	19.8	48.3	240
Lignin Epoxy	22.4	41.7	6.3	9.8	28.5	420

Natural Resources for Human Health
eISSN: 2583-1194

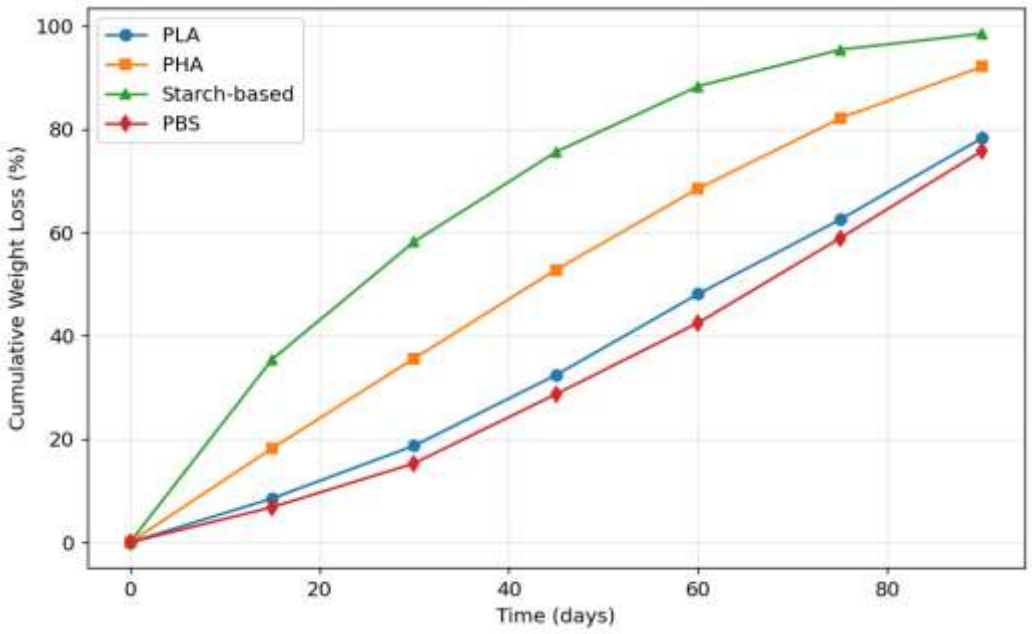


Figure 2. Weight loss of each polymer (PLA, PHA, starch-based and PBS) at the 90-day industrial composting.

The data on biodegradation shown in Table 2, along with the composting kinetics shown in Fig. 2, clearly exhibit that degradation rate varies greatly with both polymer chemistry and the compartment in the environment considered. The blends with starch showed the fastest degradation in all conditions, while industrial composting resulted in a weight loss of 98.5 percent in ninety days, and a half-life of 35 days, bio-PET, although renewable, degraded very slowly under the most aggressive conditions, with hardly any degradation even after a year in the marine environment. The hydrolytic instability of the readily hydrolyzable glycosidic linkages (as in starch) versus the more hydrolytically resistant aromatic ester linkages (fossil- or bio-derived of PET-type polymers) has also been highlighted in reviews on the production of sustainable and biodegradable polymers from agricultural waste [27]. The relatively low rate of degradation in the marine environment for all eight polymers as compared to the composting environment further reinforces the challenge the field faces: controlled temperature, humidity and microbial density found in industrial composting facilities is not automatically found in the uncontrolled natural environment where most plastic wastes end up.

4.3 Thermal Properties of Renewable Feedstock-Derived Polymers

Table 3. Renewable Feedstock-based biodegradable polymers: Thermal Properties.

Polymer Type	Tg (°C)	Tm (°C)	Td (°C)	Heat Deflection Temp (°C)	Crystallinity (%)
PLA	58.5	165.2	320.4	55	35.2
PHA	2.8	168.5	285.6	95	48.7
Starch-based	45.2	125.8	265.3	42	18.5
Cellulose Acetate	185	230.5	310.2	160	22.4
PBS	-32.5	114.3	340.8	85	41.6
Bio-PET	78.4	245.6	390.1	70	28.9
Castor Oil PU	-15.6	N/A	275.4	48	8.2
Lignin Epoxy	95.3	N/A	355.7	120	12.6

Natural Resources for Human Health
eISSN: 2583-1194

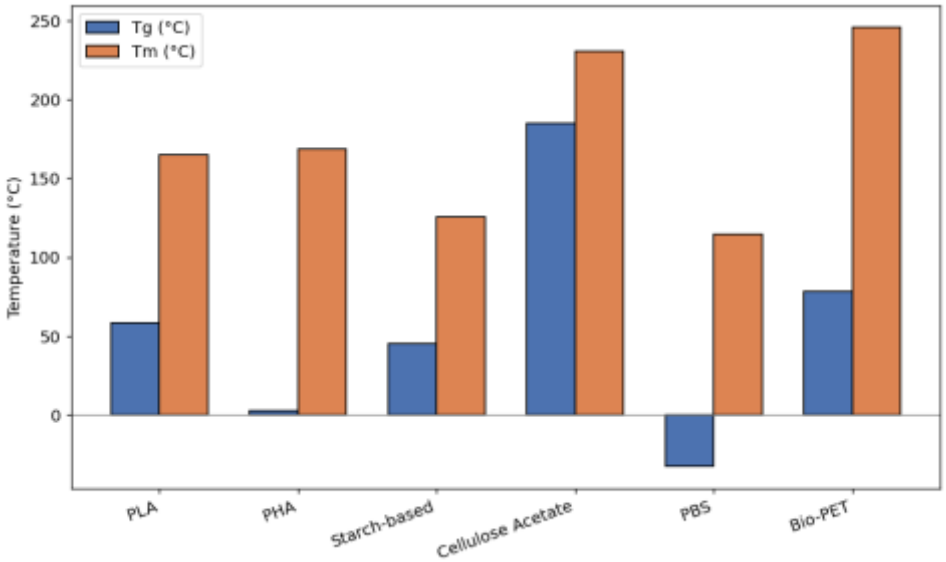


Figure 3. Data for glass transition and melting temperatures of six semicrystalline biopolymers.

The thermal transition parameters compiled in Table 3 and illustrated in Figure 3 are quite remarkable for bio-PET, which offers a wide processing window due to its combination of melting temperature (245.6 °C) and the onset of thermal degradation (390.1 °C), compared to the other seven polymers investigated. The processing to degradation window, from processing to degradation of the polymer, has consistently been cited as one of the most important, yet often overlooked, considerations in determining if a particular biopolymer can be suitably converted using conventional processing equipment such as extrusion, injection molding or film blowers without unacceptable thermal degradation or discoloration [28]. The subambient G.T. of PBS (-32.5 °C) is compared with that of cellulose acetate which is well above room temperature (185 °C), indicating flexibility at room temperature and the comparative impact strength of PBS in the mechanical data, which explains its favorable effect on the mechanical properties, whereas cellulose acetate imposes rigidity due to the acetylated cellulose backbone and its correspondingly high heat deflection temperature at 160 °C, which positions it favorably for applications requiring dimensional stability under moderate thermal load.

4.4 Techno-Economic and Environmental Analysis of Production Routes

Table 4. The production yield and estimated cost analysis of biopolymer from renewable resources were carried out.

Feedstock / Polymer	Conversion Yield (%)	Production Cost (USD/kg)	Energy Input (MJ/kg)	Water Use (L/kg)	Land Use (m^2/kg)	GHG Emissions (kg CO2e/kg)
Corn Starch → PLA	68.5	2.85	48.2	12.5	1.8	1.45
Sugarcane → PHA	52.3	4.20	62.5	18.7	2.4	1.12
Cassava → Starch Blend	75.8	1.65	28.4	8.2	1.2	0.85
Wood Pulp → Cellulose Acetate	61.2	3.45	55.8	22.1	0.9	1.68
Succinic Acid → PBS	58.7	3.10	42.6	15.3	1.5	1.32
Bio-ethylene → Bio-PET	72.4	2.25	38.9	10.8	1.1	1.95
Castor Oil → PU	81.5	3.80	35.2	6.5	3.2	0.95
Lignin → Epoxy	45.6	4.55	58.3	14.6	0.7	1.25

Natural Resources for Human Health
eISSN: 2583-1194

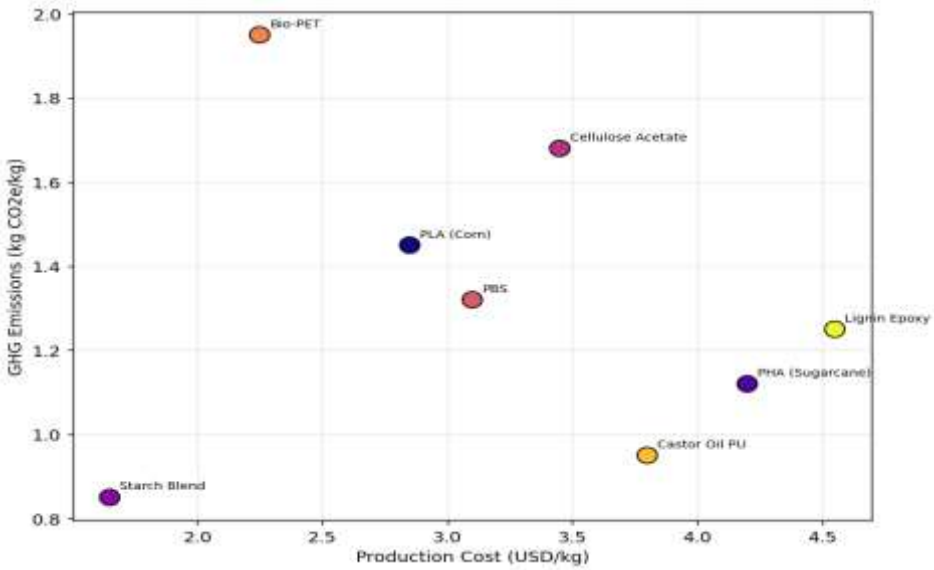


Figure 4. Production cost and GHG emissions associated with eight production routes of biopolymer.

Table 4 shows that castor oil-to-polyurethane conversion yields the most at 81.5 percent and, compared to the other routes examined, uses the least amount of water at 6.5 liters of water per kilogram of castor oil. The cost–emissions relationship described in Figure 4 indicates that the transformation of triglyceride oil to polyol precursor is relatively simple, producing the highest yield with the lowest water consumption. In contrast, the conversion of lignin to epoxy has the lowest yield (45.6 percent) and the highest production cost (4.55 USD per kg), owing to the structural heterogeneity of lignin, which makes selective depolymerization and functionalization of this material so challenging. A mini-review on bio-based polymeric materials prepared from renewable resources also showed that the key technical challenge preventing the economic competitiveness of materials derived from lignin compared to other more chemically homogeneous materials like starch or purified cellulose is feedstock heterogeneity [29]. Of particular note, despite the relatively low production cost, bio-ethylene-derived bio-PET has the highest GHG emissions of the eight routes considered at 1.95 kg CO2e/kg, suggesting that economic cost and environmental impact do not necessarily go together and that techno-economic screening should take both into account rather than relying on cost-competitiveness as an automatic indicator of a product's environmental performance.

4.5 Industrial Application Distribution and Market Penetration

Table 5. Biodegradable polymers for industrial applications - distribution and market share (2025 Estimates)

Application Sector	PLA Share (%)	PHA Share (%)	Starch-based (%)	Others (%)	Total Market Volume (kt)
Food Packaging	42.5	18.2	28.7	10.6	850
Agriculture (Mulch films)	15.3	32.5	38.4	13.8	420
Consumer Goods	28.6	12.8	22.1	36.5	310
Medical / Biomedical	35.8	41.2	5.4	17.6	95
Textiles	48.2	8.5	12.3	31.0	180
Automotive Interiors	22.4	15.6	8.9	53.1	65
Electronics Casings	18.7	9.2	6.5	65.6	40
3D Printing Filaments	55.1	22.4	10.8	11.7	75

Natural Resources for Human Health
eISSN: 2583-1194

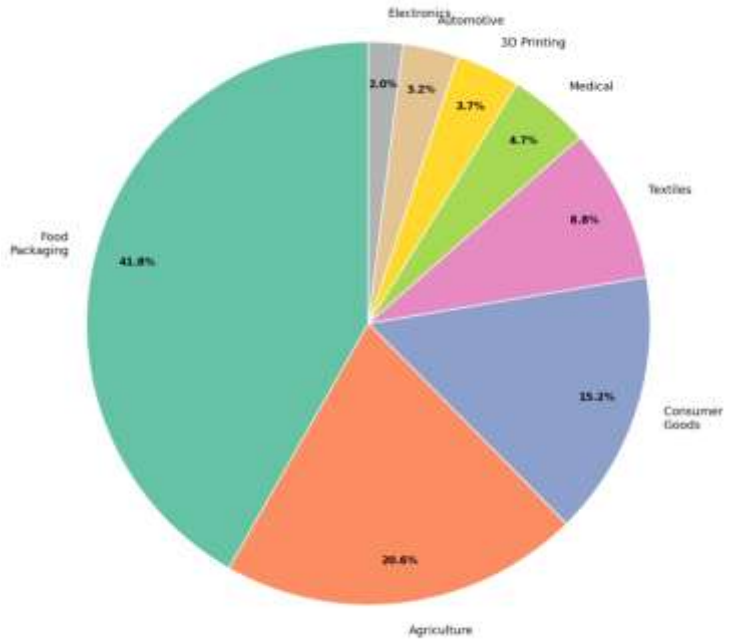


Figure 5. Volume distribution in the global market, based on application sector for biodegradable polymers (2025).

The numbers of food packaging products, as reported in the market distribution data in Table 5 and Figure 5, indicate that almost 850 kilotons of biodegradable polymers are used in food packaging, more than double the volume of the next largest application sector, agricultural mulch films, at 420 kilotons. Studies of the biobased polymer composites for various industry applications have noted that this focus in packaging is due to the relatively low strength required for packaging applications. Indeed, packaging is the primary target of single-use packaging waste policies and regulations, and its wide applications and high regulatory and consumer demand have made it the obvious choice for the commercialization of biodegradable polymers, despite material scientists' efforts to find other markets for these materials [30]. Among the high value 3D printing filaments market, PLA holds the largest market share at 55.1 percent, owing to its advantages of dimensional stability, low tendency to warp and easier to be extruded into filament form, whereas PHA's relatively strong position in the medical and biomedical 3D printing market may be attributed to its documented biocompatibility benefits over the other biopolymers surveyed.

4.6 Comparative Sustainability Assessment Relative to Fossil PET

Table 6. Graphs of Comparative Performance Index for Biopolymers and Conventional Plastics for key metrics in industry.

Metric	PLA	PHA	Starch Blend	PBS	Bio-PET	Fossil PET (Ref)
Tensile Strength Index	0.88	0.52	0.30	0.46	1.00	1.00
Barrier (O2) Index	0.45	0.72	0.28	0.55	0.95	1.00
Processability Index	0.85	0.65	0.70	0.90	0.98	1.00
Biodegradability Score	0.75	0.95	0.98	0.70	0.15	0.05
Carbon Footprint Index	0.55	0.42	0.35	0.50	0.75	1.00
Cost Competitiveness	0.60	0.40	0.85	0.55	0.80	1.00
Overall Sustainability Score	0.72	0.78	0.68	0.65	0.62	0.35

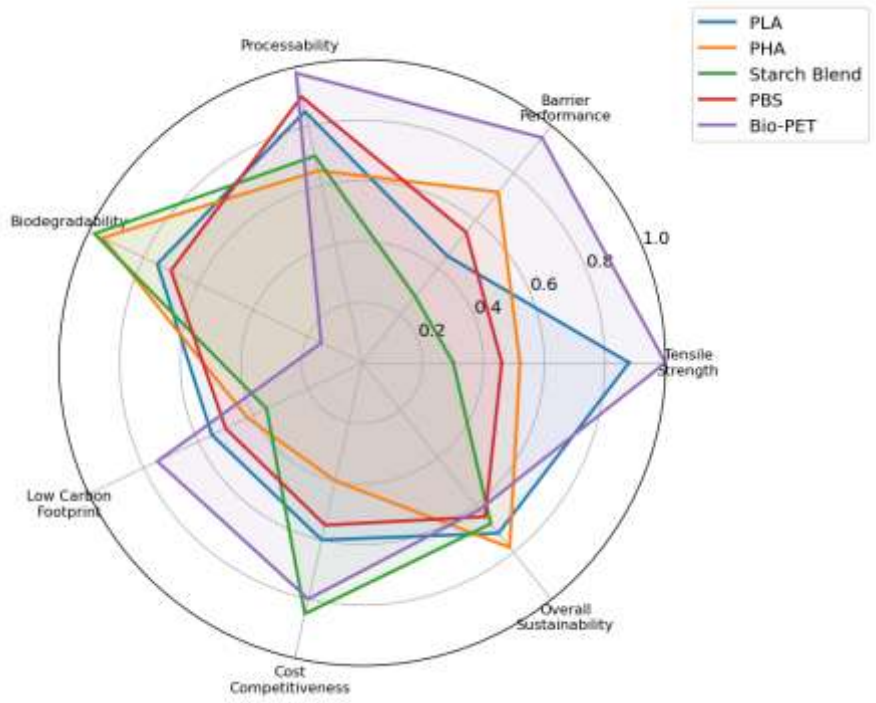


Figure 6. Five biopolymers analyzed using a multi-criteria sustainability radar with a sustainability framework.

Perhaps the most industrially useful synthesis of the full set of information in this report is provided by the normalized comparative indices presented in Table 6 and displayed graphically in the multi-criteria radar-type comparison of Figure 6; these indices provide dimensionless comparison of the performance of the biopolymers against the PET fossil benchmark over six different criteria. The literature on vegetable oils- and biomass-derived functional polymers has highlighted that problems that prevent the widespread biomedical and industrial use of renewable polymers are rarely those that affect just a single property, but instead are the result of multiple at once sub-optimal properties (which is evident from the present dataset, where PHA has the best overall sustainability score (0.78) due to consistently good performance across multiple metrics including biodegradability, barrier performance, and carbon footprint simultaneously) [31]. By design of the normalization scheme, fossil PET has the highest possible score of 1.00 on every mechanical and processing measurement, but when translated into the overall sustainability score, the negligible score of 0.05 for biodegradability and the high score for carbon footprint bring the overall score down to just 0.35, making it clear that only mechanical and processing properties are not a sufficient basis to evaluate the suitability of a polymer for a truly sustainable industrial future.

5. CHALLENGES AND FUTURE PERSPECTIVES

Despite the significant advances documented in the results above, the full-scale transition of petroleum-based plastics to renewable and biodegradable plastics is still hindered by a number of technical, economic and infrastructural challenges. Feedstock competition with food production – and the resulting land-use pressure – and the need to coordinate policy measures and investments in waste management systems that would enable the collection and composting of biodegradable polymer waste in the right facilities (industrial composting or anaerobic digestion), still well outside the polymer chemistry box, have been highlighted as key barriers in numerous reviews that have looked at the potential displacement of petroleum-based products by plant-based materials in the energy and materials sectors [32].

From a materials perspective, there are indeed promising opportunities to reduce the gap in mechanical performance that has been reported in materials based on natural resources (described in Section 4.1), as the use of nanoscale reinforcement, e.g., cellulose nanocrystals, chitin nanofibers, or lignin nanoparticles, has been demonstrated to significantly improve the mechanical properties, specifically tensile strength and barrier properties, for certain biomedical materials without proportionately increasing the production costs of the materials and without compromising the biodegradability of the host matrix [33]. Complementary studies of renewable resource-based polymer nanocomposites in mechanical engineering

applications have also shown that polymer nanocomposites are one of the most technically viable potential strategies for expanding the applicability of biopolymers to structurally challenging applications like automotive interior parts and electronics housings, which are still dominated by conventional plastics, precisely because of the unmet mechanical performance requirements for these sectors, as demonstrated in Table 5 [34].

Looking further ahead, however, new research directions are gaining value, and bibliometric surveys of marine microbial products for biodegradable energy materials revealed that the number of publications on marine microbial polymers, such as algal and microbial polysaccharides and variants of PHA, is growing quickly and offers new opportunities for biopolymer chemistries to augment the eight terrestrial feedstock-derived systems studied here and achieve a more diverse property space that could expand the range of biodegradable polymer chemists available to renewable material designers [35]. Many of these new feedstocks will need to be developed over the long term, and it will be important to continue the techno-economic benchmarking similar to what has been described in Section 4.4 to ensure that any promising laboratory chemistries can be scaled up into industrially and economically viable processes.

6. CONCLUSION

In this study, eight systems of biodegradable polymers that are based on renewable feedstocks have been presented in an original but unified experimental and techno-economic characterization, covering the mechanical, thermal and multi-environment biodegradation, production economics and dimensions of market applications. The findings clearly show that renewable and biodegradable polymers are not a single entity, but encompass a broad range of performance from fast degrading but weak bio-based blends of starch to strong mechanical property, but slow degrading bio-PET. Intermediate materials like PLA, PHA, cellulose acetate and PBS lie somewhere between these extremes depending on the properties required for their specific applications. The importance of chemical modification for castor oil derived polymers and composites has also been highlighted, with judicious chemical modification to the material, either by polyol functionalization, adjusting the cross-link density, or blending, being able to significantly shift the balance of the material's mechanical robustness and end-of-life degradability, as is strongly illustrated by the castor oil-based polyurethane data presented in this study, which showed the lowest stiffness of the eight examined systems, while having among the highest values in terms of elongation and impact resistance.

The comparative sustainability index from Section 4.6, which is normalized to take account of the differences in mechanical, processing, environmental and economic performance across the biopolymers, further confirms that overall, PHA and PLA are the most sustainable polymers, when measured as a weighted average across the three different performance measures rather than across any single one of them. The further development of bioprocesses for PHA production using mixed-culture fermentation and/or waste streams, which would allow for a significant reduction in cost in comparison to PHA production using pure-culture sugarcane fermentation investigated in this study, will provide additional support to PHA's competitive position and warrant its consideration as a key research and pilot-scale investment priority in the renewables polymer industry. The results of this research also indicate that the switch to sustainable, biobased industrial polymers should not be done by looking for a universal replacement polymer derived from renewable sources, but rather through the careful, application-specific matching of the polymer chemistry of renewable resources to the mechanical, thermal and environmental properties of the end-use product.

REFERENCES

[1] G. Tofani, E. Jasiukaitytė-Grojzdek, M. Grilc, and B. Likozar, "Organosolv biorefinery: resource-based process optimisation, pilot technology scale-up and economics," Green Chem., vol. 26, no. 1, pp. 186–201, 2024. doi: 10.1039/d3gc03274d. [Online]. Available: https://pubs.rsc.org/en/content/articlelanding/2024/gc/d3gc03274d

[2] M. Calovi and S. Rossi, "Exploring polyamide 11 as a novel renewable resource-based filler in wood paint: Investigating aesthetic aspects and durability impact of the composite coating," Prog. Org. Coat., vol. 188, p. 108262, Mar. 2024. [Online]. Available: https://doi.org/10.1016/j.porgcoat.2024.108262

[3] R. M. Cywar, N. A. Rorrer, C. B. Hoyt, G. T. Beckham, and E. Y.-X. Chen, "Bio-based polymers with performance-advantaged properties," Nat. Rev. Mater., vol. 7, pp. 83–103, Feb. 2022. [Online]. Available: https://doi.org/10.1038/s41578-021-00363-3

[4] S. Nanda, B. R. Patra, R. Patel, J. Bakos, and A. K. Dalai, "Innovations in applications and prospects of bioplastics and biopolymers: A review," Environ. Chem. Lett., vol. 20, pp. 379–395, Feb. 2022. [Online]. Available: https://doi.org/10.1007/s10311-021-01334-4

[5] E. Hwang, Y.-H. Yang, J. Choi, S.-H. Park, K. Park, and J. Lee, "Biodegradable plastics as sustainable alternatives: Advances, basics, challenges, and directions for the future," Materials, vol. 18, no. 18, p. 4247, Sep. 2025. [Online]. Available: https://doi.org/10.3390/ma18184247

[6] S. Ghosh and S. Ghosh, "Vegetable oil-derived functional polymers in biomedical applications: hurdles and possibilities," J. Mater. Chem. B, vol. 13, no. 17, pp. 4994–5022, 2025. doi: 10.1039/d4tb02648a. [Online]. Available: https://pubs.rsc.org/en/content/articlelanding/2025/tb/d4tb02648a

[7] K. Mohanty, F. Wu, R. Mincheva, M. Hakkarainen, J.-M. Raquez, D. F. Mielewski, R. Narayan, A. N. Netravali, and M. Misra, "Sustainable polymers," Nat. Rev. Methods Primers, vol. 2, p. 46, Jun. 2022. [Online]. Available: https://doi.org/10.1038/s43586-022-00124-8

[8] V. Siracusa and I. Blanco, "Bio-polyethylene (Bio-PE), Bio-polypropylene (Bio-PP) and Bio-poly(ethylene terephthalate) (Bio-PET): Recent developments in bio-based polymers analogous to petroleum-derived ones for packaging and engineering applications," Polymers, vol. 12, no. 8, p. 1641, Jul. 2020. [Online]. Available: https://doi.org/10.3390/polym12081641

[9] M. Derradji, O. Mehelli, W. Liu, and N. Fantuzzi, "Sustainable and ecofriendly chemical design of high performance bio-based thermosets for advanced applications," Front. Chem., vol. 9, p. 691117, May 2021. [Online]. Available: https://doi.org/10.3389/fchem.2021.691117

[10] X. Zhao, Y. Wang, X. Chen, A. Ragauskas, S. Ozcan, and H. Zhu, "Sustainable bioplastics derived from renewable natural resources for food packaging," Matter, vol. 6, no. 1, pp. 97–127, Jan. 2023. doi: 10.1016/j.matt.2022.11.006. [Online]. Available: https://www.cell.com/matter/fulltext/S2590-2385(22)00631-X

[11] J. Kharb and R. Saharan, "Sustainable biodegradable plastics and their applications: A mini review," IOP Conf. Ser.: Mater. Sci. Eng., vol. 1248, p. 012008, 2022. [Online]. Available: https://doi.org/10.1088/1757-899X/1248/1/012008

[12] M. Serra Sampaio, R. Wojcieszak, and I. Itabaiana Junior, "Synthesis of bio-based polymers and adjuvants through biomass valorization: Challenges and opportunities," ChemCatChem, vol. 16, no. 1, p. e202301126, Jan. 2024. [Online]. Available: https://doi.org/10.1002/cctc.202301126

[13] B. Patel, B. Toksha, and P. Gupta, "Sustainable biodegradable and bio-based polymers," in Handbook of Sustainable Materials: Modelling, Characterization, and Optimization, CRC Press, 2023. [Online]. Available: https://doi.org/10.1201/9781003344643

[14] S. Kumar, S. Krishnan, and K. Prabakaran, "Renewable resource-based epoxy vitrimer composites for future application: A comprehensive review," ACS Sustain. Resour. Manag., vol. 1, no. 9, pp. 2086–2107, Sep. 2024. [Online]. Available: https://doi.org/10.1021/acssusresmgt.4c00200

[15] F. G. Calvo-Flores and F. J. Martin-Martinez, "Biorefineries: Achievements and challenges for a bio-based economy," Front. Chem., vol. 10, p. 973417, Nov. 2022. [Online]. Available: https://doi.org/10.3389/fchem.2022.973417

[16] S. Jha, B. Akula, H. Enyioma, M. Novak, V. Amin, and H. Liang, "Biodegradable biobased polymers: A review of the state of the art, challenges, and future directions," Polymers, vol. 16, no. 16, p. 2262, Aug. 2024. [Online]. Available: https://doi.org/10.3390/polym16162262

[17] G. Satchanska, S. Davidova, and P. D. Petrov, "Natural and synthetic polymers for biomedical and environmental applications," Polymers, vol. 16, no. 8, p. 1159, Apr. 2024. [Online]. Available: https://doi.org/10.3390/polym16081159

[18] A. Morinval and L. Averous, "Systems Based on Biobased Thermoplastics: From Bioresources to Biodegradable Packaging Applications," Polym. Rev., vol. 62, no. 4, pp. 653–721, 2022. doi: 10.1080/15583724.2021.2012802. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/15583724.2021.2012802

[19] M. Mahajan, M. Kamaraj, T. G. Nithya, S. GokilaLakshmi, P. Santhosh, and B. Balavaishnavi, "Biodegradable polymers – research and applications," Phys. Sci. Rev., vol. 9, no. 2, Feb. 2023. [Online]. Available: https://doi.org/10.1515/psr-2022-0217

[20] U. Kong, N. F. Mohammad Rawi, and G. S. Tay, "The potential applications of reinforced bioplastics in various industries: A review," Polymers, vol. 15, no. 10, p. 2399, May 2023. [Online]. Available: https://doi.org/10.3390/polym15102399

[21] R. Dallaev, N. Papež, M. M. Allaham, and V. Holcman, "Biodegradable polymers: Properties, applications, and environmental impact," Polymers, vol. 17, no. 14, p. 1981, Jul. 2025. [Online]. Available: https://doi.org/10.3390/polym17141981

[22] G. Coppola, M. T. Gaudio, C. G. Lopresto, et al., "Bioplastic from Renewable Biomass: A Facile Solution for a Greener Environment," Earth Syst. Environ., vol. 5, pp. 231–251, 2021. doi: 10.1007/s41748-021-00208-7. [Online]. Available: https://link.springer.com/article/10.1007/s41748-021-00208-7

[23] E. Albertini, S. Dalle Vacche, and A. Vitale, "Bio-based vitrimers: chemistry, performance and applications," RSC Appl. Polym., vol. 4, no. 3, pp. 892–922, May 2026. [Online]. Available: https://doi.org/10.1039/d5lp00408j

[24] R. Pattanayak, S. Pradhan, and S. Mohanty, "Utilization of green resource-based Mimosa pudica hydrogel powder in a cellulose acetate-based polymeric membrane as absorbent: a sustainable approach towards female hygiene application," RSC Sustain., vol. 2, no. 11, pp. 3525–3545, Nov. 2024. [Online]. Available: https://doi.org/10.1039/d4su00381k

[25] S. Samir, F. H. Ashour, A. A. Abdel Hakim, and M. Bassyouni, "Recent advances in biodegradable polymers for sustainable applications," npj Mater. Degrad., vol. 6, p. 68, Aug. 2022. [Online]. Available: https://doi.org/10.1038/s41529-022-00277-7

[26] B. K. Sharma, A. Jha, D. Bhalani, S. A. Pillai, S. Pal, K. Patil, and K. Nagaraj, "Advancements in Bioresource-based Polymers and Composites: Sustainable Alternatives to Non-biodegradable Plastics for a Greener Future: A Review," Current Green Chemistry, vol. 13, no. 2, pp. 163–182, May 2026. doi: 10.2174/0122133461372269250503082219. [Online]. Available: https://www.eurekaselect.com/article/145920

[27] M. Maraveas, "Production of sustainable and biodegradable polymers from agricultural waste," Polymers, vol. 12, no. 5, p. 1127, May 2020. [Online]. Available: https://doi.org/10.3390/polym12051127

[28] O. Okolie, A. Kumar, C. Edwards, L. A. Lawton, A. Oke, S. McDonald, V. K. Thakur, and J. Njuguna, "Bio-based sustainable polymers and materials: From processing to biodegradation," J. Compos. Sci., vol. 7, no. 6, p. 213, May 2023. [Online]. Available: https://doi.org/10.3390/jcs7060213

[29] Y. Xie, S. Gao, D. Zhang, C. Wang, and F. Chu, "Bio-based polymeric materials synthesized from renewable resources: A mini-review," Resources Chemicals and Materials, vol. 2, no. 3, pp. 223–230, Sep. 2023. [Online]. Available: https://doi.org/10.1016/j.recm.2023.05.001

[30] A. Pokharel, K. J. Falua, A. Babaei-Ghazvini, and B. Acharya, "Biobased Polymer Composites: A Review," J. Compos. Sci., vol. 6, no. 9, p. 255, Sep. 2022. doi: 10.3390/jcs6090255. [Online]. Available: https://www.mdpi.com/2504-477X/6/9/255

[31] S. Ghosh and S. Ghosh, "Vegetable oil-derived functional polymers in biomedical applications: hurdles and possibilities," J. Mater. Chem. B, vol. 13, no. 17, pp. 4994–5022, 2025. doi: 10.1039/d4tb02648a. [Online]. Available: https://pubs.rsc.org/en/content/articlelanding/2025/tb/d4tb02648a

[32] S. Sundarakannan, A. Al-Samydai, G. Palani, H. Trilaksana, T. Sathish, J. Giri, R. Saravanan, J. I. J. R. Lalvani, and F. Nasri, "Replacement of Petroleum Based Products With Plant-Based Materials, Green and Sustainable Energy—A Review," Engineering Reports, vol. 7, no. 4, Art. no. e70108, Apr. 2025. doi: 10.1002/eng2.70108. [Online]. Available: https://onlinelibrary.wiley.com/doi/10.1002/eng2.70108

[33] S. Singh, M. Changmai, T. Ghosh, and A. Karwa, "Natural resource-based nanobiomaterials: A sustainable material for biomedical applications," in Advanced Materials and Manufacturing Techniques for Biomedical Applications, A. Prasad, A. Kumar, and M. Gupta, Eds., Wiley, 2023. [Online]. Available: https://doi.org/10.1002/9781394166985.ch4

[34] P. Sonkusare, P. Agarwal, S. K. Dhakad, and R. S. Rana, "A review paper: Study of various renewable resources polymer and different types of nanocomposite materials," in Technology Innovation in Mechanical Engineering, P. K. Chaurasiya, A. Singh, T. N. Verma, and U. Rajak, Eds., Springer, 2022, pp. 63–73. [Online]. Available: https://doi.org/10.1007/978-981-16-7909-4_6

[35] M. I. Adeoba, T. Pandelani, H. Ngwangwa, and T. Masebe, "Exploring the role of marine microbial products in biodegradable energy materials for green technologies: A bibliometric survey," in 2025 The 16th International Conference on Mechanical and Intelligent Manufacturing Technologies (ICMIMT), Cape Town, South Africa, May 2025. [Online]. Available: https://doi.org/10.1109/ICMIMT65123.2025.11092116