**International Journal of Academic and Applied Research (IJAAR)**
**ISSN: 2643-9603**
**Vol. 8 Issue 10 October - 2024, Pages: 84-104**

# Biodegradable Materials for Environmental Sustainability: A Review of Recent Developments

**Olabimtan Olabode.H*[1], Akinlotan Oluyinka. O[2], Zaid Abubakar[3], Yekeen Bayo.H[4],**
Adeshina Samuel[5].

*[1*] Department of Industrial and Environmental Pollution,*
*National Research Institute for Chemical Technology Zaria, Kaduna State, Nigeria.*
*[2] Department of Chemistry, Kogi State College of Education (Technical), Kabba Kogi State, Nigeria.*
*[3] Department of Engineering Materials Research,*
*Nigerian Building and Road Research Institute Northwest Zone, Fagge, Kano State, Nigeria.*
*[4] Department of Biological Science (Science Laboratory Technology),*
*Oke-Ogun Polytechnic Saki, Oyo State, Nigeria*
*[5] Department of Basic Medical Science,*
*Faculty of Medical and Health Sciences, Newgate University, Minna, Niger State, Nigeria.*

*Corresponding author: Olabode4angel@gmail.com*

***Abstract**: The increasing environmental impact of conventional plastics has driven the development of biodegradable materials as a sustainable alternative. This review article provides a comprehensive overview of recent advancements in biodegradable materials, focusing on their potential to address global environmental challenges. The paper examines a range of natural and synthetic biodegradable polymers, highlighting key properties, degradation mechanisms, and environmental benefits. The review also explores emerging biodegradable materials, such as polyhydroxyalkanoates (PHAs) and polylactic acid (PLA), alongside their applications in packaging, agriculture, medicine, and other industries. Additionally, the challenges related to the scalability, cost, and mechanical performance of biodegradable materials are discussed. The potential role of biodegradables in contributing to a circular economy and reducing plastic waste is emphasized, with an analysis of recent innovations in production techniques and environmental impact assessments. This review provides valuable insights into the latest trends, technologies, and future prospects for biodegradable materials, making a strong case for their adoption in promoting environmental sustainability.*

***Keywords:*** Biodegradable materials, Environmental sustainability, Biopolymers, Circular economy, Plastic waste reduction

## 1. INTRODUCTION

The global push towards environmental sustainability has significantly increased interest in biodegradable materials as a viable alternative to traditional plastics and other non-degradable substances. Biodegradable materials, by definition, are substances that can be broken down by microorganisms into water, carbon dioxide, methane, and biomass under natural environmental conditions [1]. These materials offer an eco-friendly solution to the growing problem of waste accumulation, which has been exacerbated by the widespread use of conventional plastics that persist in the environment for hundreds of years [2].

The importance of biodegradable materials lies in their potential to mitigate critical environmental challenges, including pollution and resource depletion. Traditional plastics, derived from petroleum-based products, contribute to both land and marine pollution, with over 8 million tons of plastic waste entering oceans annually [3]. In contrast, biodegradable materials, such as polylactic acid (PLA) and polyhydroxyalkanoates (PHA), are capable of decomposing naturally, thus reducing the overall environmental footprint [4]. The shift towards biodegradable alternatives can also address the issue of resource depletion by decreasing reliance on fossil fuels, which are finite and contribute to greenhouse gas emissions when processed for plastic production [5].

Also, the adoption of biodegradable materials supports the transition towards a circular economy, where materials are designed to return to the ecosystem without causing harm. This shift is critical in reducing the ecological impact of human activities and ensuring long-term sustainability [6].

Therefore, the increasing global interest in biodegradable materials reflects a broader commitment to addressing pressing environmental issues and promoting more sustainable production and consumption practices.

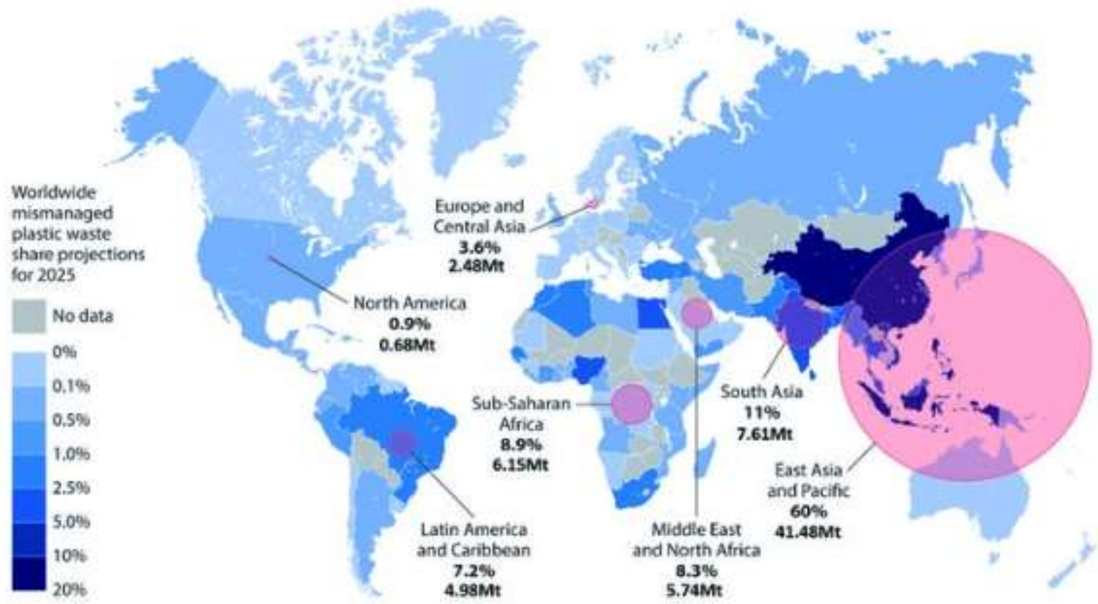


Figure 1: Global Plastic Waste Distribution [7]

The figure above highlights a significant disparity in mismanaged plastic waste shares across different regions. East Asia and the Pacific region are projected to have the highest share (60%), followed by South Asia (11%).

Many low-income regions, such as Sub-Saharan Africa and Latin America and the Caribbean, are also grappling with substantial amounts of mismanaged plastic waste.

The map indicates that data is unavailable for certain regions, suggesting the need for further research and data collection.

## 2. TYPES OF BIODEGRADABLE MATERIALS

Biodegradable materials can be broadly categorized based on their origin, distinguishing between natural and synthetic sources. This section provides detailed descriptions of each category, focusing on natural polymers, microbial polymers, and synthetic biodegradable polymers, all of which have distinct properties and applications relevant to sustainable material science.

### *2.1 Natural Polymers*

Natural polymers are derived from renewable biological sources and are biodegradable under natural environmental conditions. Some of the most commonly used natural polymers include cellulose, starch, and chitosan. Cellulose, the most abundant organic polymer on Earth, is derived from plant cell walls and is biodegradable through the action of microorganisms [8]. Starch, another widely available natural polymer, is extracted from crops like corn and potatoes. It is often used in combination with other materials to enhance its mechanical properties and biodegradability [9]. Chitosan, obtained from the exoskeletons of crustaceans, has gained attention due to its biodegradability, biocompatibility, and potential applications in medicine and packaging [10], [11].

### *2.2 Microbial Polymers*

Microbial polymers are produced by microorganisms through fermentation processes. One of the most studied groups of microbial polymers is polyhydroxyalkanoates (PHAs), which are biodegradable polyesters synthesized by bacteria. PHAs have garnered significant interest because they are fully biodegradable and biocompatible, making them suitable for various applications, including packaging, medical devices, and agriculture [12]. Among the PHAs, polyhydroxy butyrate (PHB) is the most commonly used and has

International Journal of Academic and Applied Research (IJAAR)
ISSN: 2643-9603
Vol. 8 Issue 10 October - 2024, Pages: 84-104

properties similar to petrochemical-derived plastics like polypropylene [13]. These materials can be broken down by a variety of microorganisms, thus contributing to waste reduction and reducing dependence on petroleum-based plastics [14].

### *2.3 Synthetic Biodegradable Polymers*

Synthetic biodegradable polymers, such as polylactic acid (PLA), are man-made materials designed to degrade under specific environmental conditions. PLA is synthesized from lactic acid, which can be derived from fermented plant sugars [15]. It is one of the most widely used synthetic biodegradable polymers due to its versatility, being employed in industries ranging from packaging to biomedical applications [16]. While PLA offers several advantages, including its compostability and low carbon footprint, it requires specific industrial composting conditions to degrade efficiently, limiting its biodegradability in natural environments [17]. Other synthetic biodegradable polymers include polycaprolactone (PCL) and polybutylene succinate (PBS), which also degrade over time when exposed to biological agents [18].

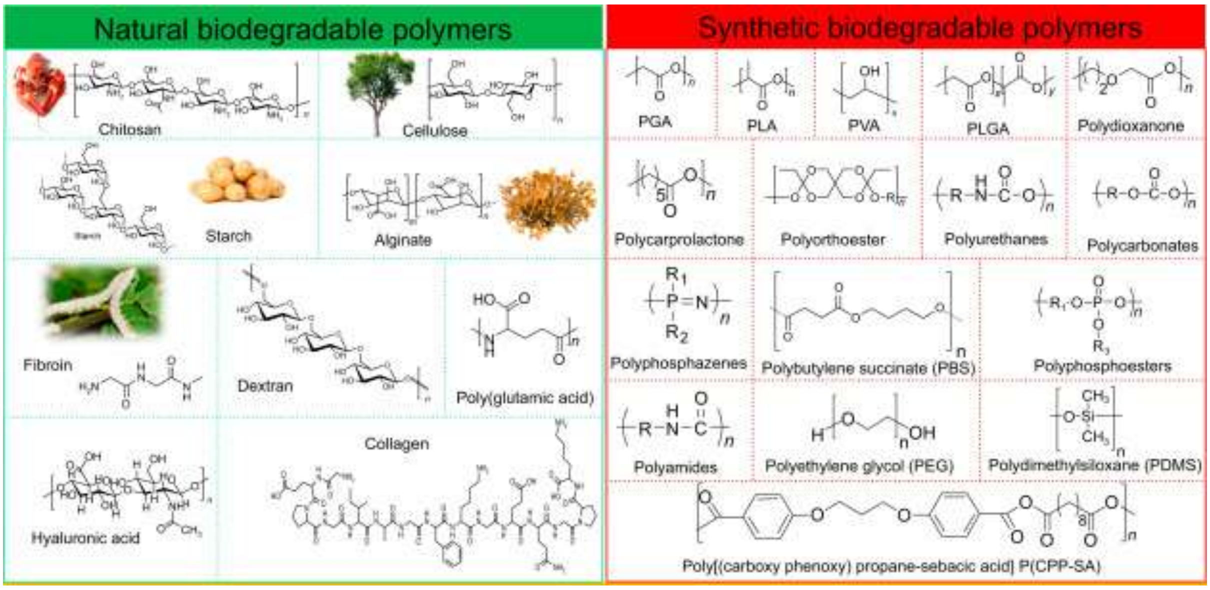


Figure 2: Chemical Structure of Major Synthetic Biodegradable Polymers [19].

**Table 1. Natural Biodegradable Polymers**

| Polymer | Source | Examples | Biodegradability | Applications | References |
|---|---|---|---|---|---|
| **Chitosan** | Derived from chitin, found in crustacean shells | Chitosan derivatives, N-acetylglucosamine | Naturally biodegradable via enzymatic hydrolysis, producing non-toxic byproducts | Wound healing, drug delivery, water purification, tissue engineering | [20] |
| **Cellulose** | Plant cell walls, wood, cotton | Microcrystalline cellulose (MCC), bacterial cellulose | Biodegrades under aerobic or anaerobic conditions by microbial action | Packaging, bio composites, paper production, textiles | [21] |
| **Starch** | Plants such as corn, potatoes, wheat | Thermoplastic starch, starch-based blends | Biodegradable in soil and aquatic environments through enzymatic activity | Biodegradable plastics, packaging materials, agriculture | [22] |
| **Alginate** | Extracted from brown seaweed | Sodium alginate, calcium alginate | Biodegrades through microbial degradation in marine and | Wound dressings, drug delivery, cell encapsulation | [23] |

| | | | | | |
|---|---|---|---|---|---|
| | | | terrestrial ecosystems | | |
| **Fibroin** | Derived from silk produced by silkworms | Silk fibroin scaffolds, hydrogels | Biodegradable through proteolytic enzymes, with a controllable degradation rate | Tissue engineering, biomedical implants, drug delivery | [24] |
| **Collagen** | Animal connective tissues, primarily bovine or porcine | Collagen gels, sponges, membranes | Degraded by collagenase enzymes, producing harmless byproducts | Skin grafts, tissue scaffolds, wound healing, cosmetics | [25] |
| **Hyaluronic Acid** | Found in animal tissues, particularly in skin and cartilage | Hyaluronic acid gels, crosslinked HA | Degraded by hyaluronidase enzymes in the body, typically with a rapid degradation rate | Cosmetic fillers, wound healing, osteoarthritis treatments | [26] |
| **Dextran** | Produced by bacteria from sucrose | Dextran hydrogels, microcapsules | Biodegrades via enzymatic activity, primarily by dextranase enzymes | Drug delivery systems, tissue engineering, pharmaceutical applications | [27] |

Table 2. Synthetic Biodegradable Polymers

| **Polymer** | **Source** | **Examples** | **Biodegradability** | **Applications** | **References** |
|---|---|---|---|---|---|
| **Polylactic Acid (PLA)** | Derived from renewable resources (corn, sugarcane) | Polylactic acid blends, copolymers | Biodegrades into lactic acid through hydrolysis and microbial action in compostable environments | Biodegradable plastics, packaging, medical implants, 3D printing | [28] |
| **Polyglycolic Acid (PGA)** | Chemically synthesized from glycolic acid | PGA sutures, films, fibers | Biodegrades rapidly via hydrolysis into glycolic acid, especially in aqueous environments | Absorbable sutures, tissue engineering, drug delivery systems | [29] |
| **Polycaprolactone (PCL)** | Petroleum-based or derived from caprolactone monomers | PCL copolymers, blends, scaffolds | Slowly biodegrades through hydrolytic degradation, producing non-toxic byproducts | Long-term implants, tissue engineering, drug delivery | [30] |
| **Polyvinyl Alcohol (PVA)** | Petroleum-based synthetic polymer | PVA hydrogels, fibers, films | Biodegradable in aqueous environments via microbial activity and enzymatic hydrolysis | Biodegradable packaging, pharmaceuticals, water treatment | [31] |
| **Polylactide-co-Glycolide (PLGA)** | Copolymer of PLA and PGA | PLGA nanoparticles, films, sutures | Degrades into lactic and glycolic acids via hydrolysis and enzymatic action | Controlled drug release, tissue engineering scaffolds, sutures | [32] |

| | | | | | |
|---|---|---|---|---|---|
| **Polybutylene Succinate (PBS)** | Petroleum-based or synthesized from renewable resources | PBS films, fibers, foams | Biodegrades via microbial enzymatic action, with rates depending on environmental conditions | Biodegradable packaging, agricultural films, compostable plastics | [33] |
| **Polydioxanone (PDO)** | Petroleum-based synthetic polymer | PDO sutures, meshes | Biodegrades via hydrolysis into non-toxic byproducts, with a controllable degradation rate | Absorbable sutures, cardiovascular stents, tissue engineering | [34] |
| **Polyurethane (PU)** | Derived from polyols and diisocyanates | Biodegradable PU foams, coatings | Biodegradable under specific conditions (e.g., enzymes, hydrolysis) but slower than other synthetic polymers | Medical devices, coatings, adhesives, packaging | [35] |

## 3. PRODUCTION PROCESSES

The production of biodegradable materials involves a variety of methods, each contributing to the material's properties and environmental footprint. The most common processes include fermentation, polymerization, and composite material formation. This section critically examines these processes in terms of their efficiency, scalability, and environmental impact.

### *3.1 Fermentation*

Fermentation is primarily used in the production of microbial biodegradable polymers, such as polyhydroxyalkanoates (PHAs). In this process, microorganisms, typically bacteria, metabolize carbon sources like sugars or oils to produce PHAs. This method is considered efficient because it utilizes renewable feedstocks and produces biodegradable polymers in a relatively short timeframe [36]. However, the scalability of fermentation is limited by the high costs associated with feedstock, fermentation infrastructure, and downstream processing [37]. Despite these challenges, advances in metabolic engineering and optimization of microbial strains are improving both the yield and cost-effectiveness of fermentation-based production methods [38]. From an environmental perspective, fermentation has a lower carbon footprint compared to petrochemical processes, as it relies on renewable resources and generates biodegradable waste [39].

### *3.2 Polymerization*

Polymerization is a key process in the production of synthetic biodegradable polymers, such as polylactic acid (PLA). There are two main types of polymerization used in this context: condensation polymerization and ring-opening polymerization. PLA, for example, is typically produced through the ring-opening polymerization of lactide, a derivative of lactic acid [40]. Polymerization processes are efficient in terms of controlling molecular weight and polymer properties, allowing for the production of materials with specific characteristics tailored to various applications. However, the scalability of polymerization, particularly for biodegradable polymers, is heavily dependent on the availability of monomers like lactic acid, which are derived from agricultural crops [40]. While this presents an advantage in terms of using renewable resources, it also raises concerns about land use and competition with food production. Additionally, some polymerization processes require significant energy inputs, which can increase the overall environmental impact [41],[42]..

### *3.3 Composite Material Formation*

The formation of composite materials involves combining biodegradable polymers with natural fibers or other biodegradable materials to enhance mechanical strength, thermal stability, and biodegradability [43]. Common natural fibers used in composite formation include hemp, flax, and jute, which are renewable and biodegradable. The blending of polymers with natural fibers improves the material's performance and extends its range of applications, from packaging to automotive components [44]. Composite material formation is considered an efficient process because it allows for the utilization of agricultural by-products and reduces reliance on synthetic additives [45]. In terms of scalability, this process is widely adopted in industries due to its flexibility and compatibility with existing manufacturing systems [46]. However, the environmental impact of composite materials depends on the choice of fibers and the biodegradability of the polymer matrix. Fully biodegradable composites have the potential to

**International Journal of Academic and Applied Research (IJAAR)**
**ISSN: 2643-9603**
**Vol. 8 Issue 10 October - 2024, Pages: 84-104**

reduce plastic waste, but challenges remain in ensuring uniform degradation in various environmental conditions [47].

Table 3. Comparison of Polymerization Techniques

| **Polymerization Technique** | **Process Nature** | **Polymer Types** | **Reaction Conditions** | **Environmental Impact** | **References** |
|---|---|---|---|---|---|
| Condensation Polymerization | Step-growth, monomers join by eliminating a small molecule (e.g., water) | Polyesters, polyamides, polycarbonates | Moderate temperature and pressure, catalyst often required | Produces by-products, needs careful management of waste | [48] |
| Addition Polymerization | Chain-growth, monomers add to growing chain with no by-product | Polylactic acid (PLA), polyglycolic acid (PGA) | High temperatures, sometimes requires initiators or catalysts | No by-products, but can consume more energy due to higher temperatures | [49] |
| Ring-Opening Polymerization | Monomers with cyclic structures open to form long chains | Polycaprolactone (PCL), polylactide-co-glycolide (PLGA), polydioxanone (PDO) | Typically, lower temperatures, catalysts often required | Efficient process, generates minimal waste | [50] |
| Emulsion Polymerization | Free-radical polymerization in an emulsion system | Polyvinyl alcohol (PVA), polyhydroxyalkanoates (PHA) | Low temperatures, requires surfactants and initiators | Can involve toxic surfactants, but energy-efficient | [51] |
| Solution Polymerization | Polymerization in solution, monomer dissolved in a solvent | Polyethylene glycol (PEG), polybutylene succinate (PBS) | Moderate temperature, requires solvents and catalysts | Solvent disposal is critical for environmental safety | [52] |

## 4. APPLICATIONS OF BIODEGRADABLE MATERIALS

Biodegradable materials have a wide range of applications, making them an essential component in the shift toward more sustainable industries. This section categorizes these applications into key sectors, such as packaging, agriculture, and medical devices, and explores the associated benefits and challenges.

### *4.1 Packaging*

One of the largest markets for biodegradable materials is the packaging industry, where they are seen as a sustainable alternative to conventional plastics [53]. Biodegradable polymers such as polylactic acid (PLA) and polyhydroxyalkanoates (PHAs) are increasingly used for producing films, containers, and coatings for food and beverage packaging. The key benefit of biodegradable packaging is its potential to significantly reduce plastic waste, which has become a critical environmental issue [54]. Unlike traditional petroleum-based plastics, biodegradable materials can decompose into natural elements under composting conditions, thus reducing the accumulation of plastic waste in landfills and oceans. However, the challenge lies in the limited infrastructure for industrial composting, as many biodegradable materials, including PLA, require specific conditions for degradation [55]. Also, the high cost of biodegradable materials compared to conventional plastics remains a barrier to widespread adoption [56].

### *4.2 Agriculture*

In agriculture, biodegradable materials are used in the production of mulching films, plant pots, and controlled-release fertilizers. Mulching films made from biodegradable polymers, such as starch-based films, have been developed to replace polyethylene films, which are widely used but problematic due to their non-degradability [57]. These biodegradable

International Journal of Academic and Applied Research (IJAAR)
ISSN: 2643-9603
Vol. 8 Issue 10 October - 2024, Pages: 84-104

alternatives help retain soil moisture, regulate temperature, and suppress weed growth, while eventually decomposing in the soil without leaving harmful residues [58]. This reduces the labor and cost associated with removing plastic mulch after harvest and minimizes environmental pollution. However, one of the challenges with biodegradable mulching films is ensuring that they degrade at the appropriate rate, which can vary depending on environmental conditions as the production of biodegradable agricultural products can be resource-intensive, raising concerns about their overall sustainability in comparison to more durable alternatives [59].

### *4.3 Medical Devices*

Biodegradable materials also have significant applications in the medical field, particularly in the development of temporary implants, drug delivery systems, and wound dressings. Biodegradable polymers such as polycaprolactone (PCL) and polyglycolic acid (PGA) are commonly used in medical devices because they can be designed to degrade safely within the body, eliminating the need for a second surgery to remove the device [60]. For instance, biodegradable sutures made from PLA and PGA have become the standard for wound closure, as they degrade naturally and reduce the risk of infection compared to non-biodegradable alternatives [61]. In drug delivery, biodegradable polymers can be engineered to control the release of medication over a specified period, improving treatment efficacy [62]. The main challenge in medical applications is the need to carefully control the degradation rate to ensure that the material functions effectively over its intended lifespan whilst the biocompatibility of these materials must be rigorously tested to prevent adverse reactions in the body [63].

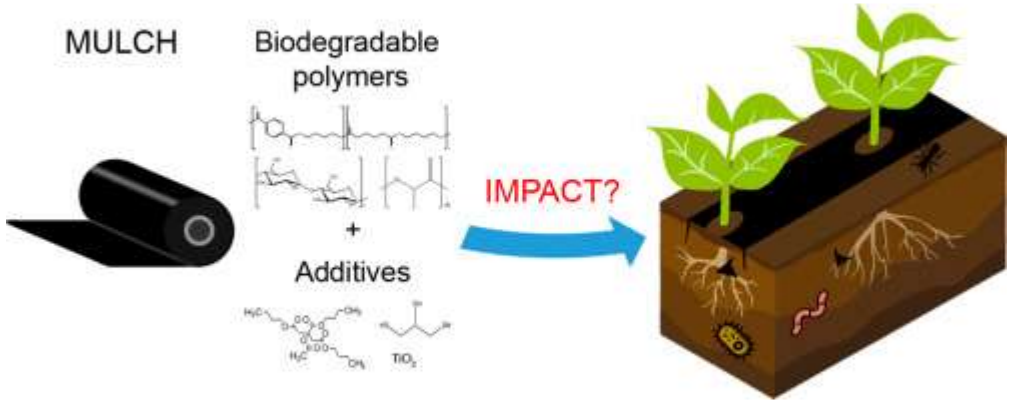


Figure 3: Applications of Biodegradable Mulch Films in Agriculture [64].

The figure presents a conceptual diagram illustrating the potential environmental impact of biodegradable mulch. The key components and interactions are as follows:

- Mulch: A biodegradable polymer-based material used as a ground cover in agriculture.
- Additives**:** Various additives, including $TiO_2$, may be incorporated into the mulch to enhance its properties or facilitate degradation.
- Soil Ecosystem**:** The mulch interacts with the soil ecosystem, affecting factors such as soil temperature, moisture retention, nutrient cycling, and microbial activity.

***Potential Impacts:***

*Soil Health***:** Biodegradable mulch can improve soil health by:

- o Reducing Erosion: Preventing soil erosion and loss of nutrients.
- o Enhancing Moisture Retention: Maintaining soil moisture levels, especially during dry periods.
- o Improving Soil Structure: Increasing soil organic matter and improving its structure.
- o Promoting Microbial Activity**:** Creating a favorable environment for beneficial soil microorganisms.

*Plant Growth:* Biodegradable mulch can positively influence plant growth by:

- o Providing Nutrients: Releasing nutrients into the soil as it degrades.
- o Suppressing Weeds: Reducing competition for resources from weeds.

- Protecting Against Pests**:** Deterring certain pests and diseases.

*Environmental Impact***:** The environmental impact of biodegradable mulch depends on several factors, including:

- Polymer Composition: The type of biodegradable polymer used can affect its degradation rate and potential toxicity.
- Additives: The presence and type of additives can influence the mulch's environmental impact.
- Soil Conditions**:** The soil type, climate, and microbial activity can affect the degradation process.

Table 3: Biodegradable Materials in Biomedical Applications

| Material | Biomedical Application | Advantages | Limitations | References |
|---|---|---|---|---|
| **Polylactic Acid (PLA)** | Tissue engineering scaffolds, drug delivery | Biocompatible, good mechanical properties, tunable degradation rates | Slow degradation, can lead to accumulation of acidic by-products causing localized inflammation | [65] |
| **Polyglycolic Acid (PGA)** | Sutures, tissue engineering scaffolds | Rapid degradation, high tensile strength, widely used in absorbable sutures | Hydrophilicity may limit applications in load-bearing tissues | [66] |
| **Polycaprolactone (PCL)** | Bone regeneration, soft tissue engineering | Long degradation time, good flexibility, suitable for long-term implants | Degradation is slow, limiting use in short-term biomedical applications | [67] |
| **Polylactide-co-glycolide (PLGA)** | Drug delivery systems, tissue scaffolds | Adjustable degradation rates, excellent biocompatibility | Degradation by-products (lactic and glycolic acids) can lead to pH changes and localized toxicity | [68] |
| **Chitosan** | Wound healing, drug delivery, antimicrobial coatings | Naturally derived, antimicrobial properties, promotes cell adhesion and proliferation | Limited mechanical strength, rapid degradation in aqueous environments | [69] |
| **Alginate** | Wound dressings, cell encapsulation, drug delivery | Biocompatible, non-toxic, gel-forming abilities, supports cellular encapsulation and wound healing | Poor mechanical strength, requires crosslinking agents to improve stability | [70] |
| **Collagen** | Skin grafts, wound dressings, tissue scaffolds | Promotes cell adhesion, natural extracellular matrix (ECM) component, excellent biocompatibility | Rapid degradation, potential for immune response in some patients | [71] |
| **Hyaluronic Acid (HA)** | Soft tissue augmentation, wound healing, drug delivery | Biocompatible, promotes cell migration and tissue regeneration | Short half-life, often requires chemical modification for controlled degradation | [72] |
| **Polyhydroxyalkanoates (PHA)** | Cardiovascular implants, tissue engineering | Biodegradable, biocompatible, potential for large-scale production | Expensive to produce compared to other biodegradable polymers | [73] |

## 5. ENVIRONMENTAL IMPACT AND CHALLENGES

While biodegradable materials are widely viewed as an environmentally friendly alternative to conventional plastics, their use is not without challenges. This section explores the environmental impact of biodegradable materials, focusing on their degradation behavior, the potential release of microplastics, and the energy consumption involved in their production. A comprehensive understanding of these factors is crucial for determining the overall sustainability of biodegradable materials.

### *5.1 Degradation Behavior*

One of the key environmental benefits of biodegradable materials is their ability to break down into natural components, such as water, carbon dioxide, and biomass, under certain conditions [74]. However, the degradation behavior of these materials varies significantly depending on the environment in which they are disposed of. For example, many biodegradable plastics, such as polylactic acid (PLA), require specific industrial composting conditions with high temperatures and humidity to degrade efficiently [75]. In natural environments, such as soil or water, these materials may degrade much more slowly, which can lead to accumulation similar to conventional plastics [76]. Moreover, biodegradable plastics that do not fully decompose in the environment can contribute to visual pollution and hinder ecosystems, calling into question their effectiveness in reducing plastic waste [77].

### *5.2 Potential Release of Microplastics*

While biodegradable materials are designed to break down, their incomplete degradation or fragmentation into smaller particles can result in the release of microplastics into the environment. Microplastics, defined as plastic particles smaller than 5 mm, pose significant ecological risks, as they can be ingested by marine organisms, enter the food chain, and cause harm to wildlife [78]. Some studies have shown that under suboptimal conditions, certain biodegradable plastics, such as polyhydroxyalkanoates (PHAs), can break down into microplastic particles rather than fully biodegrading [79]. This unintended consequence undermines the environmental benefits of biodegradable materials and suggests the need for more rigorous testing of their degradation pathways in various environmental contexts as also the persistence of microplastics in aquatic environments could exacerbate the current plastic pollution crisis if biodegradable materials are not managed properly.

### *5.3 Energy Consumption in Production*

The production of biodegradable materials, particularly synthetic biodegradable polymers like PLA and polybutylene succinate (PBS), involves significant energy consumption. The polymerization processes required to produce these materials often require high energy inputs, which can offset some of the environmental benefits gained from their biodegradability [80]. For instance, the production of PLA typically requires energy-intensive processes for the extraction and fermentation of sugars from crops like corn, followed by polymerization of lactic acid [81]. In comparison to the production of conventional plastics, the total carbon footprint of biodegradable plastics can be lower if renewable energy is used; however, if fossil fuels are the primary energy source, the environmental benefits may be diminished [82]. Moreover, concerns about land use for biopolymer feedstocks, such as the competition between agricultural land for food production and bioplastic production, also play a role in evaluating the sustainability of biodegradable materials [83].

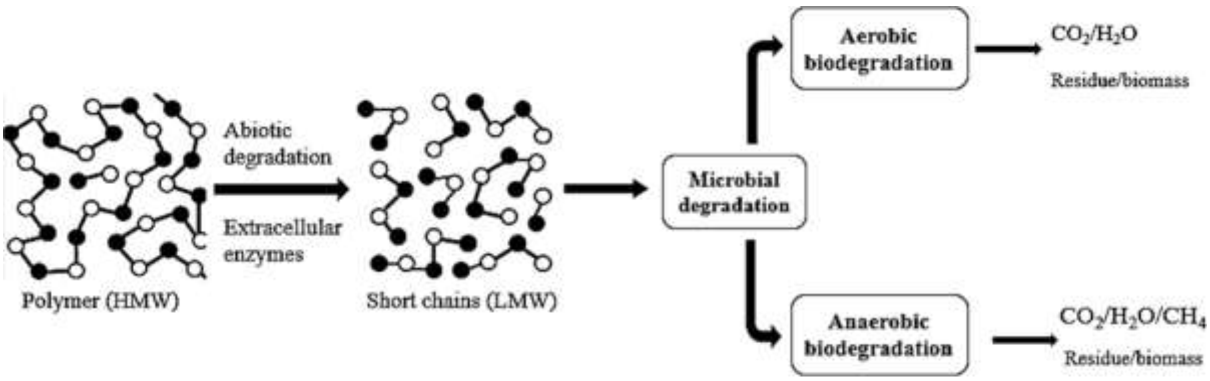


Figure 4: Degradation Pathways of Biodegradable Polymers [84].

International Journal of Academic and Applied Research (IJAAR)
ISSN: 2643-9603
Vol. 8 Issue 10 October - 2024, Pages: 84-104

The provided figure illustrates the various pathways through which polymers can undergo biodegradation. These pathways can be broadly categorized into abiotic and microbial degradation.

Abiotic Degradation:

- Physical and Chemical Processes**:** This pathway involves the breakdown of polymers due to physical factors like sunlight, heat, and water, or chemical reactions with environmental agents.
- Formation of Short Chains**:** Abiotic degradation often leads to the formation of shorter polymer chains (LMW).

Microbial Degradation:

- Extracellular Enzymes: Microorganisms secrete extracellular enzymes that can degrade polymers.
- Aerobic Biodegradation: In the presence of oxygen, aerobic microorganisms break down polymers, producing $CO_2$, $H_2O$, and biomass.
- Anaerobic Biodegradation**:** In the absence of oxygen, anaerobic microorganisms degrade polymers, producing $CO_2$, $H_2O$, $CH_4$ (methane), and biomass.

Key Takeaways:

- Multiple Pathways: Polymers can degrade through both abiotic and microbial pathways.
- Polymer Structure: The structure and composition of the polymer influence its susceptibility to degradation.
- Environmental Conditions: The presence of oxygen, temperature, and other environmental factors can affect the rate and pathway of biodegradation.
- End Products**:** The final products of biodegradation can vary depending on the type of polymer, the degradation pathway, and environmental conditions.

Implications:

- Sustainability: Understanding the biodegradation pathways of polymers is essential for developing sustainable materials and waste management strategies.
- Environmental Impact: The choice of polymer and its degradation pathway can influence the environmental impact of plastic waste.
- Bioremediation**:** Biodegradable polymers can be used for bioremediation purposes to clean up contaminated sites.

## 6.0 ENERGY CONSUMPTION AND CARBON FOOTPRINT

Although biodegradable materials are often promoted as environmentally friendly alternatives to conventional plastics, their production involves significant energy consumption and carbon emissions. This subsection examines the energy requirements and carbon footprint associated with manufacturing biodegradable materials, comparing them with traditional plastics to assess their overall environmental impact.

### *6.1 Energy Requirements*

The production of biodegradable materials, particularly synthetic polymers such as polylactic acid (PLA) and polybutylene succinate (PBS), is often energy-intensive. The manufacturing process for these materials typically involves multiple stages, including the extraction of raw materials, fermentation, polymerization, and sometimes compounding to enhance material properties [85]. For instance, the production of PLA involves fermenting plant-based sugars (such as those from corn or sugarcane) into lactic acid, which is then polymerized into PLA (Eugenio *et al*., 2023). Each stage of this process requires energy, often from non-renewable sources, which contributes to the overall energy demand of biodegradable plastic production.

In comparison to conventional plastics like polyethylene (PE) and polypropylene (PP), which are derived from petroleum-based feedstocks, the energy required for producing biodegradable plastics can be higher or lower depending on the specific material and production process [87]. For instance, while PLA production generally requires less fossil fuel energy compared to petroleum-based plastics, it often involves additional steps such as crop cultivation and processing, which increase its overall energy footprint [88]. In contrast, conventional plastic production tends to be more energy-efficient in terms of the polymerization process itself, but its reliance on fossil fuels is a significant drawback in terms of sustainability.

### *6.2 Carbon Footprint*

The carbon footprint of biodegradable materials is closely linked to their energy consumption. Since many biodegradable plastics are derived from renewable resources, such as corn or sugarcane, their carbon footprint is generally lower than that of traditional plastics, which are derived from fossil fuels (Narayan, 2010). For example, the production of 1 kg of PLA generates significantly less carbon dioxide ($CO_2$) emissions compared to the production of 1 kg of conventional plastic like polyethylene terephthalate (PET) [90]. Additionally, the cultivation of biomass for bioplastics has the potential to sequester $CO_2$, further reducing the overall carbon footprint [91].

However, this advantage is not without caveats. The total carbon footprint of biodegradable plastics depends on various factors, including land use for feedstock cultivation, agricultural inputs (such as fertilizers and pesticides), and the energy sources used in production [92]. For example, if the energy required for producing bioplastics comes from fossil fuels, this can negate some of the carbon savings achieved through the use of renewable feedstocks. Moreover, the growing demand for biomass feedstocks could lead to land-use changes, such as deforestation, which can contribute to increased $CO_2$ emissions [92]. This highlights the importance of considering the entire lifecycle of biodegradable materials when evaluating their carbon footprint.

### *6.3 Comparison to Conventional Plastics*

When comparing the overall environmental impact of biodegradable plastics to conventional plastics, the picture becomes more complex. Conventional plastics are produced from non-renewable resources, and their production releases significant amounts of $CO_2$ and other greenhouse gases [93]. However, because the production processes for traditional plastics are well-established and optimized, their energy efficiency is often higher than that of newer biodegradable materials. For example, the energy required to produce 1 kg of PET is lower than that required for 1 kg of PLA in some cases, depending on the energy source and the specific production technologies used [94]. Additionally, the production of conventional plastics does not require agricultural land, which can be a significant advantage in terms of minimizing land-use change and associated emissions.

Nevertheless, the disposal of conventional plastics represents a major environmental challenge, as they do not biodegrade and often accumulate in landfills or oceans, contributing to long-term environmental pollution [95]. In contrast, biodegradable plastics have the potential to reduce this waste problem, as they are designed to break down under specific conditions, thereby reducing their environmental impact at the end of their life cycle [96]. However, the actual environmental benefits of biodegradable plastics depend on proper waste management infrastructure, such as industrial composting facilities, which are not yet widely available in many parts of the world [97].

## 7.0 INNOVATIONS AND FUTURE PERSPECTIVES

The field of biodegradable materials is advancing rapidly, with innovations that address both the limitations of current materials and the growing demand for sustainable alternatives to conventional plastics. This section highlights key innovations, including the development of biodegradable composites and the use of genetic engineering to optimize microbial polymer production. These breakthroughs not only improve the performance and applicability of biodegradable materials but also enhance their environmental sustainability.

### *7.1 Development of Biodegradable Composites*

One of the most significant innovations in the field of biodegradable materials is the development of biodegradable composites, which combine biodegradable polymers with natural fibers or other bio-based additives to enhance material properties. These composites are designed to overcome some of the limitations of conventional biodegradable plastics, such as poor mechanical strength, thermal stability, and processability [99]. For example, the incorporation of natural fibers, such as cellulose, hemp, or flax, into biodegradable polymers like polylactic acid (PLA) or polyhydroxyalkanoates (PHA), results in composites that are stronger, more durable, and less prone to degradation under mechanical stress [100]. This development broadens the potential applications of biodegradable materials in sectors such as automotive, construction, and consumer goods, where material performance is critical [101].

Biodegradable composites also have the potential to reduce environmental impact by lowering the amount of polymer required in a given product and by enhancing the biodegradability of the composite as a whole. For instance, PLA-based composites with added natural fibers exhibit faster degradation rates in composting environments than pure PLA, making them more suitable for packaging and other short-life applications [102]. Furthermore, the use of bio-based fillers, such as lignin or starch, not only enhances the composite’s mechanical properties but also reduces reliance on fossil-based polymers, contributing to a reduction in carbon footprint [103]. This innovation represents a step forward in aligning biodegradable materials with circular economy principles by improving both performance and sustainability.

### *7.2 Genetic Engineering for Microbial Polymer Production*

Another key innovation driving the advancement of biodegradable materials is the use of genetic engineering to optimize microbial polymer production, particularly for biopolymers like polyhydroxyalkanoates (PHAs). PHAs are a class of biodegradable polymers produced by certain bacteria as intracellular storage compounds under nutrient-limited conditions [104]. However, traditional methods of PHA production are costly and inefficient due to the limited yield and slow production rates of naturally occurring microbial strains [105].

Recent breakthroughs in genetic engineering have focused on enhancing the efficiency of microbial strains to produce PHAs more rapidly and in higher quantities. By introducing specific genes or modifying metabolic pathways, researchers have been able to engineer bacteria that can convert various carbon sources, such as agricultural waste or industrial by-products, into PHAs more efficiently [106]. Sohn et al, genetically engineered strains of *Cupriavidus necator* and *Escherichia coli* have been developed to produce high yields of PHAs from inexpensive feedstocks, such as lignocellulosic biomass, which significantly reduces production costs [107].

In addition to improving production efficiency, genetic engineering has also been used to modify the physical and chemical properties of PHAs, enabling the development of tailor-made biopolymers with specific characteristics, such as increased flexibility, toughness, or thermal stability [108]; [109]. This innovation opens up new possibilities for the application of PHAs in industries such as packaging, agriculture, and biomedical devices, where material properties must meet stringent performance criteria [110].

### *7.3 Emerging Materials and Techniques*

Beyond biodegradable composites and microbial polymer production, researchers are exploring other novel materials and techniques to advance the field of biodegradable plastics. For instance, the development of nanocomposites, which incorporate nanoparticles into biodegradable polymers, has shown promise in enhancing the barrier properties, strength, and biodegradability of materials [111]. Nanoclay and nanocellulose are commonly used as reinforcing agents in these nanocomposites, offering improvements in mechanical performance and thermal stability while maintaining biodegradability [112]. These advancements are particularly important for applications in food packaging, where high barrier properties are essential to extend the shelf life of products while reducing plastic waste [113].

Another emerging technique is the use of bio-based plasticizers, which are added to biodegradable polymers to enhance their flexibility and processability without compromising biodegradability. Traditional plasticizers, such as phthalates, are often toxic and non-biodegradable, but new bio-based alternatives, such as epoxidized soybean oil and citrates, offer a safer and more sustainable option for modifying the properties of biodegradable plastics [114]. These innovations further expand the range of applications for biodegradable materials, making them more competitive with conventional plastics in various industries.

## 8.0 CONCLUSION

This review highlights the significant progress made in the development and application of biodegradable materials, emphasizing their potential to address pressing environmental challenges such as plastic pollution and resource depletion. Key findings from the analysis demonstrate that biodegradable materials, including natural polymers, microbial polymers, and synthetic biodegradable plastics, offer promising alternatives to conventional plastics, particularly when integrated with innovative production processes such as genetic engineering and composite formation.

The review also underscores the environmental benefits of biodegradable materials, particularly in terms of their potential to reduce plastic waste and carbon emissions. However, it acknowledges that the adoption of biodegradable materials is not without challenges, including concerns related to energy consumption, carbon footprint, and the infrastructure required for their proper disposal. Furthermore, the review identifies the need for more comprehensive research to fully understand the lifecycle impacts of these materials, including their degradation behavior in various environments and the potential release of microplastics.

To achieve the widespread adoption of biodegradable materials and realize their full environmental potential, continued research and innovation are crucial. Emerging technologies, such as the development of biodegradable composites and the use of genetic engineering to enhance microbial polymer production, will play a key role in improving material performance and sustainability. Moreover, addressing the challenges associated with energy consumption and production costs will be essential for making biodegradable materials more accessible and competitive with conventional plastics on a global scale.

The review concludes by calling for interdisciplinary collaboration between researchers, industry leaders, and policymakers to accelerate the development and deployment of biodegradable materials. Such collaboration will be essential in fostering innovation, creating supportive regulatory frameworks, and ensuring that biodegradable materials are produced and disposed of in a manner that maximizes their environmental benefits. Policy support at both national and international levels will also be critical in facilitating the transition to more sustainable material systems, including investment in infrastructure for composting and recycling, as well as incentives for research and development. Only through collective efforts can biodegradable materials contribute meaningfully to achieving global environmental sustainability.

**Conflicts of Interest**

None

**REFERENCES**

1. Taofeeq D. Moshood, Gusman Nawanir, Fatimah Mahmud, Fazeeda Mohamad, Mohd Hanafiah Ahmad, Airin AbdulGhani. Sustainability of biodegradable plastics (2022). New problem or solution to solve the global plastic pollution, *Current Research in Green and Sustainable Chemistry*, Volume 5,2022,100273, ISSN 2666-0865, https://doi.org/10.1016/j.crgsc.2022.100273.

2. Crystal Xue Er Thew, Zhi Sen Lee, Penjit Srinophakun, Chien Wei Ooi. (2023). Recent advances and challenges in sustainable management of plastic waste using biodegradation approach, *Bioresource Technology*, Volume 374, 2023, 128772, ISSN 0960-8524, https://doi.org/10.1016/j.biortech.2023.128772.

3. Shivika Sharma, Vikas Sharma, Subhankar Chatterjee (2023). Contribution of plastic and microplastic to global climate change and their conjoining impacts on the environment - *A review, Science of The Total Environment,* Volume 875,2023,162627, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2023.162627.

4. Boey, J., Mohamad, L., Khok, Y., Tay, G., & Baidurah, S. (2021). A Review of the Applications and Biodegradation of Polyhydroxyalkanoates and Poly (lactic acid) and Its Composites. *Polymers*, 13. https://doi.org/10.3390/polym13101544.

5. Pacheco-López, A., Lechtenberg, F., Somoza-Tornos, A., Graells, M., & Espuña, A. (2021). Economic and Environmental Assessment of Plastic Waste Pyrolysis Products and Biofuels as Substitutes for Fossil-Based Fuels., 9. https://doi.org/10.3389/fenrg.2021.676233 .

6. Wojnarowska, M., Sołtysik, M., & Guzik, M. (2021). Socio-economic Importance of Biomaterials in the Transition to the Circular Economy Model. *SHS Web of Conferences*. https://doi.org/10.1051/SHSCONF/20219205029.

7. Watt, E., Picard, M., Maldonado, B., Abdelwahab, M. A., Mielewski, D. F., Drzal, L. T., Mohanty, A. K. (2021). Ocean plastics: environmental implications and potential routes for mitigation – *a perspective. RSC Advances, 11(35), 21447–21462.* doi:10.1039/d1ra00353d

8. Sun, Y., Mazzotta, M., Miller, C., Apprill, A., Izallalen, M., Mazumder, S., Perri, S., Edwards, B., Reddy, C., & Ward, C. (2023). Distinct microbial communities degrade cellulose diacetate bioplastics in the coastal ocean. *Applied and Environmental Microbiology*, 89. https://doi.org/10.1128/aem.01651-23.

9. Gamage, A., Thiviya, P., Mani, S., Ponnusamy, P., Manamperi, A., Evon, P., Merah, O., & Madhujith, T. (2022). Environmental Properties and Applications of Biodegradable Starch-Based Nanocomposites. *Polymers*, 14. https://doi.org/10.3390/polym14214578.

10. Thambiliyagodage, C., Jayanetti, M., Mendis, A., Ekanayake, G., Liyanaarachchi, H., & Vigneswaran, S. (2023). Recent Advances in Chitosan-Based Applications—A

Review. *Materials*, 16. https://doi.org/10.3390/ma16052073.

11. Desai, N., Rana, D., Salave, S., Gupta, R., Patel, P., Karunakaran, B., Sharma, A., Giri, J., Benival, D., & Kommineni, N. (2023). Chitosan: A Potential Biopolymer in Drug Delivery and Biomedical Applications. *Pharmaceutics*, 15. https://doi.org/10.3390/pharmaceutics15041313.
12. Kaniuk, Ł., & Stachewicz, U. (2021). Development and Advantages of Biodegradable PHA Polymers Based on Electrospun PHBV Fibers for Tissue Engineering and Other Biomedical Applications. *ACS Biomaterials Science & Engineering*, 7, 5339 - 5362. https://doi.org/10.1021/acsbiomaterials.1c00757.
13. Kang, S., Liang, J., Yuan, H., Lin, F., Deng, D., & Fu, J. (2022). Tailored recycling chemicals and fuels from poly-3-hydroxybutyrate: A review. *Biofuels*, 16. https://doi.org/10.1002/bbb.2371.
14. Ahsan, W., Hussain, A., Lin, C., & Nguyen, M. (2023). Biodegradation of Different Types of Bioplastics through Composting—A Recent Trend in Green Recycling. *Catalysts*. https://doi.org/10.3390/catal13020294.
15. Weng, Y., Dunn, C., Qiang, Z., & Ren, J. (2023). Immobilization of Protease K with ZIF-8 for Enhanced Stability in Polylactic Acid Melt Processing and Catalytic Degradation. *ACS applied materials & interfaces*. https://doi.org/10.1021/acsami.3c11979.
16. Sharma, S., Sudhakara, P., Singh, J., Ilyas, R., Asyraf, M., & Razman, M. (2021). Critical Review of Biodegradable and Bioactive Polymer Composites for Bone Tissue Engineering and Drug Delivery Applications. *Polymers*, 13. https://doi.org/10.3390/polym13162623.
17. Borelbach, P., Kopitzky, R., Dahringer, J., & Gutmann, P. (2023). Degradation Behavior of Biodegradable Man-Made Fibers in Natural Soil and in Compost. *Polymers*, 15. https://doi.org/10.3390/polym15132959.
18. Rosato, A., Romano, A., Totaro, G., Celli, A., Fava, F., Zanaroli, G., & Sisti, L. (2022). Enzymatic Degradation of the Most Common Aliphatic Bio-Polyesters and Evaluation of the Mechanisms Involved: An Extended Study. *Polymers*, 14. https://doi.org/10.3390/polym14091850.
19. E.S. Hosseini, S. Dervin, P. Ganguly, R. Dahiya, Biodegradable materials for sustainable health monitoring devices, ACS Appl. Bio Mater. 4 (2021) 163–194. https://doi.org/10.1021/acsabm.0c01139,
20. Velásquez, C. (2023). Chitosan and its applications in oenology. *OENO One*. https://doi.org/10.20870/oeno-one.2023.57.1.7262.
21. Erdal, N., & Hakkarainen, M. (2022). Degradation of Cellulose Derivatives in Laboratory, Man-Made, and Natural Environments. *Biomacromolecules*, 23, 2713 - 2729. https://doi.org/10.1021/acs.biomac.2c00336.
22. Yu, X., Chen, L., Jin, Z., & Jiao, A. (2021). Research progress of starch-based biodegradable materials: a review. *Journal of Materials Science*, 56, 11187 - 11208. https://doi.org/10.1007/s10853-021-06063-1.
23. Hurtado, A., Aljabali, A., Mishra, V., Tambuwala, M., & Serrano-Aroca, Ã. (2022). Alginate: Enhancement Strategies for Advanced Applications. *International Journal of Molecular Sciences*, 23. https://doi.org/10.3390/ijms23094486.
24. Giannelli, M., Guerrini, A., Ballestri, M., Aluigi, A., Zamboni, R., Sotgiu, G., & Posati, T. (2022). Bioactive Keratin and Fibroin Nanoparticles: An Overview of Their Preparation Strategies. *Nanomaterials*, 12. https://doi.org/10.3390/nano12091406.
25. Irastorza, A., Zarandona, I., Andonegi, M., Guerrero, P., & Caba, K. (2021). The versatility of collagen and chitosan: From food to biomedical applications. *Food Hydrocolloids*. https://doi.org/10.1016/J.FOODHYD.2021.106633.

26. Buckley, C., Murphy, E., Montgomery, T., & Major, I. (2022). Hyaluronic Acid: A Review of the Drug Delivery Capabilities of This Naturally Occurring Polysaccharide. *Polymers*, 14. https://doi.org/10.3390/polym14173442.

27. Barzkar, N., Babich, O., Das, R., Sukhikh, S., Jahromi, S., & Sohail, M. (2022). Marine Bacterial Dextranases: Fundamentals and Applications. *Molecules*, 27. https://doi.org/10.3390/molecules27175533.

28. Ilyas, R., Zuhri, M., Aisyah, H., Asyraf, M., Hassan, S., Zainudin, E., Sapuan, S., Sharma, S., Bangar, S., Jumaidin, R., Nawab, Y., Faudzi, A., Abral, H., Asrofi, M., Syafri, E., & Sari, N. (2022). Natural Fiber-Reinforced Polylactic Acid, Polylactic Acid Blends and Their Composites for Advanced Applications. *Polymers*, 14. https://doi.org/10.3390/polym14010202.

29. Kundak, H., & Bilisik, K. (2023). Development of Three-Dimensional (3D) Biodegradable Polyglycolic Acid Fiber (PGA) Preforms for Scaffold Applications: Experimental Patterning and Fiber Volume Fraction-Porosity Modeling Study. *Polymers*, 15. https://doi.org/10.3390/polym15092083.

30. Dias, J., Sousa, A., Augusto, A., Bártolo, P., & Granja, P. (2022). Electrospun Polycaprolactone (PCL) Degradation: An In Vitro and In Vivo Study. *Polymers*, 14. https://doi.org/10.3390/polym14163397.

31. Rivera-Hernández, G., Antunes-Ricardo, M., Martínez-Morales, P., & Sánchez, M. (2021). Polyvinyl alcohol based-drug delivery systems for cancer treatment. *International journal of pharmaceutics*, 120478. https://doi.org/10.1016/j.ijpharm.2021.120478.

32. Danhier, F., Ansorena, E., Silva, J., Coco, R., Breton, A., & Préat, V. (2012). PLGA-based nanoparticles: an overview of biomedical applications. *Journal of controlled release: official journal of the Controlled Release Society*, 161 2, 505-22. https://doi.org/10.1016/j.jconrel.2012.01.043.

33. Aliotta, L., Seggiani, M., Lazzeri, A., Gigante, V., & Cinelli, P. (2022). A Brief Review of Poly (Butylene Succinate) (PBS) and Its Main Copolymers: Synthesis, Blends, Composites, Biodegradability, and Applications. *Polymers*, 14. https://doi.org/10.3390/polym14040844.

34. Erben, J., Blatonova, K., Kalous, T., Capek, L., Běhálek, L., Borůvka, M., & Chvojka, J. (2022). The Injection Molding of Biodegradable Polydioxanone—A Study of the Dependence of the Structural and Mechanical Properties on Thermal Processing Conditions. *Polymers*, 14. https://doi.org/10.3390/polym14245528.

35. Akindoyo, J., Beg, M., Ghazali, S., Islam, M., Jeyaratnam, N., & Yuvaraj, A. (2016). Polyurethane types, synthesis and applications – a review. *RSC Advances*, 6, 114453-114482. https://doi.org/10.1039/C6RA14525F.

36. Wang, J., Liu, S., Huang, J., & Qu, Z. (2021). A review on polyhydroxyalkanoate production from agricultural waste Biomass: Development, Advances, circular Approach, and challenges. *Bioresource technology*, 342, 126008. https://doi.org/10.1016/j.biortech.2021.126008.

37. Fackler, N., Heijstra, B., Rasor, B., Brown, H., Martin, J., Ni, Z., Shebek, K., Rosin, R., Simpson, S., Tyo, K., Giannone, R., Hettich, R., Tschaplinski, T., Leang, C., Brown, S., Jewett, M., & Köpke, M. (2021). Stepping on the Gas to a Circular Economy: Accelerating Development of Carbon-Negative Chemical Production from Gas Fermentation. *Annual review of chemical and biomolecular engineering*. https://doi.org/10.1146/annurev-chembioeng-120120-021122.

38. Parekh, S., Vinci, V., & Strobel, R. (2000). Improvement of microbial strains and fermentation processes. *Applied Microbiology and Biotechnology*, 54, 287-301. https://doi.org/10.1007/s002530000403.

39. Dahiya, S., Chatterjee, S., Sarkar, O., & Mohan, S. (2020). Renewable hydrogen production by dark-fermentation: Current status, challenges and perspectives. *Bioresource technology*,

124354. https://doi.org/10.1016/j.biortech.2020.124354.

40. Balla, E., Daniilidis, V., Karlioti, G., Kalamas, T., Stefanidou, M., Bikiaris, N., Vlachopoulos, A., Koumentakou, I., & Bikiaris, D. (2021). Poly (lactic Acid): A Versatile Biobased Polymer for the Future with Multifunctional Properties—From Monomer Synthesis, Polymerization Techniques and Molecular Weight Increase to PLA Applications. *Polymers*, 13. https://doi.org/10.3390/polym13111822.

41. Yadav, P., Ismail, N., Essalhi, M., Tysklind, M., Athanassiadis, D., & Tavajohi, N. (2021). Assessment of the environmental impact of polymeric membrane production. *Journal of Membrane Science*. https://doi.org/10.1016/J.MEMSCI.2020.118987.

42. Haque, F., Ishibashi, J., Lidston, C., Shao, H., Bates, F., Chang, A., Coates, G., Cramer, C., Dauenhauer, P., Dichtel, W., Ellison, C., Gormong, E., Hamachi, L., Hoye, T., Jin, M., Kalow, J., Kim, H., Kumar, G., LaSalle, C., Liffland, S., Lipinski, B., Pang, Y., Parveen, R., Peng, X., Popowski, Y., Prebihalo, E., Reddi, Y., Reineke, T., Sheppard, D., Swartz, J., Tolman, W., Vlaisavljevich, B., Wissinger, J., Xu, S., & Hillmyer, M. (2022). Defining the Macromolecules of Tomorrow through Synergistic Sustainable Polymer Research. *Chemical reviews*. https://doi.org/10.1021/acs.chemrev.1c00173.

43. R, A., Mr, S., Kushvaha, V., Khan, A., Seingchin, S., & Dhakal, H. (2022). Modification of Fibres and Matrices in Natural Fibre Reinforced Polymer Composites: A Comprehensive Review. *Macromolecular rapid communications*, e2100862. https://doi.org/10.1002/marc.202100862.

44. Dolza, C., Fages, E., Gonga, E., Gómez-Caturla, J., Balart, R., & Quiles-Carrillo, L. (2021). Development and Characterization of Environmentally Friendly Wood Plastic Composites from Biobased Polyethylene and Short Natural Fibers Processed by Injection Moulding. *Polymers*, 13. https://doi.org/10.3390/polym13111692.

45. Suffo, M., Mata, M., & Molina, S. (2020). A sugar-beet waste based thermoplastic agro-composite as substitute for raw materials. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2020.120382.

46. Gola, A., Pastuszak, Z., Relich, M., Sobaszek, Ł., & Szwarc, E. (2021). Scalability analysis of selected structures of a reconfigurable manufacturing system taking into account a reduction in machine tools reliability. *Eksploatacja I Niezawodnosc-maintenance and Reliability*, 23, 242-252. https://doi.org/10.17531/EIN.2021.2.4.

47. Maiti, S., Islam, M., Uddin, M., Afroj, S., Eichhorn, S., & Karim, N. (2022). Sustainable Fiber-Reinforced Composites: A Review. *Advanced Sustainable Systems*, 6. https://doi.org/10.1002/adsu.202200258.

48. Lang, M., & Kumar, K. (2021). Simple and General Approach for Reversible Condensation Polymerization with Cyclization. *Macromolecules*. https://doi.org/10.1021/acs.macromol.1c00718.

49. Tanaka, J., Archer, N., Grant, M., & You, W. (2021). Reversible-Addition Fragmentation Chain Transfer Step-Growth Polymerization. *Journal of the American Chemical Society*. https://doi.org/10.1021/jacs.1c07553.

50. Tran, H., Toland, A., Stellmach, K., Paul, M., Gutekunst, W., & Ramprasad, R. (2022). Toward Recyclable Polymers: Ring-Opening Polymerization Enthalpy from First-Principles. *The journal of physical chemistry letters*, 4778-4785. https://doi.org/10.1021/acs.jpclett.2c00995.

51. Lovell, P., & Schork, F. (2020). Fundamentals of Emulsion Polymerization. *Biomacromolecules*. https://doi.org/10.1021/acs.biomac.0c00769.

52. Xu, W., Su, Y., Shang, M., Lu, X., & Lu, Q. (2020). Rapid synthesis of polyimide precursors by solution polymerization using Continuous-flow microreactors. *Chemical Engineering*

*Journal*, 397, 125361. https://doi.org/10.1016/j.cej.2020.125361.

53. Shaikh, S., Yaqoob, M., & Aggarwal, P. (2021). An overview of biodegradable packaging in food industry. *Current Research in Food Science*, 4, 503 - 520. https://doi.org/10.1016/j.crfs.2021.07.005.

54. Gupta, P., Toksha, B., & Rahaman, M. (2022). A Review on Biodegradable Packaging Films from Vegetative and Food Waste. *The Chemical Record*, 22. https://doi.org/10.1002/tcr.202100326.

55. Fogašová, M., Figalla, S., Danišová, L., Medlenová, E., Hlaváčiková, S., Vanovčanová, Z., Omaníková, L., Baco, A., Horváth, V., Mikolajová, M., Feranc, J., Bočkaj, J., Plavec, R., Alexy, P., Repiská, M., Přikryl, R., Kontárová, S., Báreková, A., Sláviková, M., Koutný, M., Fayyazbakhsh, A., & Kadlečková, M. (2022). PLA/PHB-Based Materials Fully Biodegradable under Both Industrial and Home-Composting Conditions. *Polymers*, 14. https://doi.org/10.3390/polym14194113.

56. Bartolucci, L., Cordiner, S., Maina, E., Kumar, G., Mele, P., Mulone, V., Igliński, B., & Piechota, G. (2023). Sustainable Valorization of Bioplastic Waste: A Review on Effective Recycling Routes for the Most Widely Used Biopolymers. *International Journal of Molecular Sciences*, 24. https://doi.org/10.3390/ijms24097696.

57. Menossi, M., Cisneros, M., Alvarez, V., & Casalongué, C. (2021). Current and emerging biodegradable mulch films based on polysaccharide bio-composites. A review. *Agronomy for Sustainable Development*, 41. https://doi.org/10.1007/s13593-021-00685-0.

58. Wang, X., Shrestha, S., Tymon, L., Zhang, H., Miles, C., & DeVetter, L. (2022). Soil-biodegradable mulch is an alternative to non-biodegradable plastic mulches in a strawberry-lettuce double-cropping system., 6. https://doi.org/10.3389/fsufs.2022.942645.

59. Griffin-LaHue, D., Ghimire, S., Yu, Y., Scheenstra, E., Miles, C., & Flury, M. (2021). In-field degradation of soil-biodegradable plastic mulch films in a Mediterranean climate. *The Science of the total environment*, 806 Pt 1, 150238. https://doi.org/10.1016/j.scitotenv.2021.150238.

60. Magazzini, L., Grilli, S., Fenni, S., Donetti, A., Cavallo, D., & Monticelli, O. (2021). The Blending of Poly (glycolic acid) with Polycaprolactone and Poly(l-lactide): Promising Combinations. *Polymers*, 13. https://doi.org/10.3390/polym13162780.

61. Agubata, C., Mbah, M., Akpa, P., & Ugwu, G. (2021). Application of self-healing, swellable and biodegradable polymers for wound treatment. *Journal of wound care*, 30 Sup9a, IVi-IVx. https://doi.org/10.12968/jowc.2021.30.Sup9a.IV.

62. Tsung, T., Tsai, Y., Lee, H., Chen, Y., & Lu, D. (2023). Biodegradable Polymer-Based Drug-Delivery Systems for Ocular Diseases. *International Journal of Molecular Sciences*, 24. https://doi.org/10.3390/ijms241612976.

63. Brito, J., Andrianov, A., & Sukhishvili, S. (2022). Factors Controlling Degradation of Biologically Relevant Synthetic Polymers in Solution and Solid State. *ACS applied bio materials*. https://doi.org/10.1021/acsabm.2c00694.

64. Serrano-Ruiz, H., Martin-Closas, L., & Pelacho, A. M. (2020). *Biodegradable plastic mulches: Impact on the agricultural biotic environment. Science of The Total Environment, 141228.* doi: 10.1016/j.scitotenv.2020.1412

65. Li, G., Zhao, M., Xu, F., Yang, B., Li, X., Meng, X., Teng, L., Sun, F., & Li, Y. (2020). Synthesis and Biological Application of Polylactic Acid. *Molecules*, 25. https://doi.org/10.3390/molecules25215023.

66. Budak, K., Sogut, O., & Sezer, U. (2020). A review on synthesis and biomedical applications of polyglycolic acid. *Journal of Polymer Research*, 27, 1-19. https://doi.org/10.1007/s10965-020-02187-1.

67. Ilyas, R., Zuhri, M., Norrrahim, M., Misenan, M., Jenol, M., Samsudin, S., Nurazzi, N., Asyraf, M., Supian, A., Bangar, S., Nadlene, R., Sharma, S., & Omran, A. (2022). Natural Fiber-Reinforced Polycaprolactone Green and Hybrid Biocomposites for Various Advanced Applications. *Polymers*, 14. https://doi.org/10.3390/polym14010182.

68. Rocha, C., Gonçalves, V., Silva, M., Bañobre-López, M., & Gallo, J. (2022). PLGA-Based Composites for Various Biomedical Applications. *International Journal of Molecular Sciences*, 23. https://doi.org/10.3390/ijms23042034.

69. Ojeda-Hernández, D., Canales-Aguirre, A., Matías-Guiu, J., Gómez-Pinedo, U., & Mateos-Díaz, J. (2020). Potential of Chitosan and Its Derivatives for Biomedical Applications in the Central Nervous System. *Frontiers in Bioengineering and Biotechnology*, 8. https://doi.org/10.3389/fbioe.2020.00389.

70. Dodero, A., Alberti, S., Gaggero, G., Ferretti, M., Botter, R., Vicini, S., & Castellano, M. (2021). An Up-to-Date Review on Alginate Nanoparticles and Nanofibers for Biomedical and Pharmaceutical Applications. *Advanced Materials Interfaces*, 8. https://doi.org/10.1002/admi.202100809.

71. Ghomi, E., Nourbakhsh, N., Kenari, M., Zare, M., & Ramakrishna, S. (2021). Collagen-based biomaterials for biomedical applications. *Journal of biomedical materials research. Part B, Applied biomaterials*. https://doi.org/10.1002/jbm.b.34881.

72. Le, H., & Cerf, D. (2022). Colloidal Polyelectrolyte Complexes from Hyaluronic Acid: Preparation and Biomedical Applications. *Small*, e2204283. https://doi.org/10.1002/smll.202204283.

73. Kalia, V., Patel, S., & Lee, J. (2023). Exploiting Polyhydroxyalkanoates for Biomedical Applications. *Polymers*, 15. https://doi.org/10.3390/polym15081937.

74. Rai, P., Mehrotra, S., Priya, S., Gnansounou, E., & Sharma, S. (2021). Recent advances in the sustainable design and applications of biodegradable polymers. *Bioresource technology*, 124739. https://doi.org/10.1016/j.biortech.2021.124739.

75. Maragkaki, A., Malliaros, N., Sampathianakis, I., Lolos, T., Tsompanidis, C., & Manios, T. (2023). Evaluation of Biodegradability of Polylactic Acid and Compostable Bags from Food Waste under Industrial Composting. *Sustainability*. https://doi.org/10.3390/su152215963.

76. Beltrán-Sanahuja, A., Benito-Kaesbach, A., Sánchez-García, N., & Sanz-Lázaro, C. (2021). Degradation of conventional and biobased plastics in soil under contrasting environmental conditions. *Science of The Total Environment*, 787, 147678. https://doi.org/10.1016/J.SCITOTENV.2021.147678.

77. Manfra, L., Marengo, V., Libralato, G., Costantini, M., Falco, F., & Cocca, M. (2021). Biodegradable polymers: A real opportunity to solve marine plastic pollution. *Journal of hazardous materials*, 416, 125763. https://doi.org/10.1016/j.jhazmat.2021.125763.

78. Vázquez, O., & Rahman, M. (2021). An ecotoxicological approach to microplastics on terrestrial and aquatic organisms: A systematic review in assessment, monitoring and biological impact. *Environmental toxicology and pharmacology*, 103615. https://doi.org/10.1016/j.etap.2021.103615.

79. Wei, X., Bohlén, M., Lindblad, C., Hedenqvist, M., & Hakonen, A. (2021). Microplastics generated from a biodegradable plastic in freshwater and seawater. *Water research*, 198, 117123. https://doi.org/10.1016/j.watres.2021.117123.

80. Kosmalska, D., Janczak, K., Raszkowska-Kaczor, A., Stasiek, A., & Ligor, T. (2022). Polylactide as a Substitute for Conventional Polymers—Biopolymer Processing under Varying Extrusion Conditions. *Environments*. https://doi.org/10.3390/environments9050057.

81. Eugenio, L., Murguiondo, C., Galea-Outon, S., Prieto, A., & Barriuso, J. (2023). Fungal–Lactobacteria Consortia and Enzymatic Catalysis for Polylactic Acid Production. *Journal of Fungi*, 9. https://doi.org/10.3390/jof9030342.

82. Agarwal, P., Soni, R., Kaur, P., Madan, A., Mishra, R., Pandey, J., Singh, S., & Singh, G. (2022). Cyanobacteria as a Promising Alternative for Sustainable Environment: Synthesis of Biofuel and Biodegradable Plastics. *Frontiers in Microbiology*, 13. https://doi.org/10.3389/fmicb.2022.939347.

83. Patel, N., Feofilovs, M., & Blumberga, D. (2022). Agro Biopolymer: A Sustainable Future of Agriculture – State of Art Review. *Environmental and Climate Technologies*, 26, 499 - 511. https://doi.org/10.2478/rtuect-2022-0038.

84. Samir, A., Ashour, F.H., Hakim, A.A.A. (2022). Recent advances in biodegradable polymers for sustainable applications. *npj Mater Degrad* **6**, 68 (2022). https://doi.org/10.1038/s41529-022-00277-7

85. Mehrpouya, M., Vahabi, H., Barletta, M., Laheurte, P., & Langlois, V. (2021). Additive manufacturing of polyhydroxyalkanoates (PHAs) biopolymers: Materials, printing techniques, and applications. *Materials science & engineering. C, Materials for biological applications*, 127, 112216. https://doi.org/10.1016/j.msec.2021.112216.

86. Ali, S., Elsamahy, T., Koutra, E., Kornaros, M., El-sheekh, M., Abdelkarim, E., Zhu, D., & Sun, J. (2021). Degradation of conventional plastic wastes in the environment: A review on current status of knowledge and future perspectives of disposal. *The Science of the total environment*, 771, 144719. https://doi.org/10.1016/j.scitotenv.2020.144719.

87. Fonsêca, A., Ramalho, E., Gouveia, A., Figueiredo, F., & Nunes, J. (2023). Life Cycle Assessment of PLA Products: A Systematic Literature Review. *Sustainability*. https://doi.org/10.3390/su151612470.

88. Singh, S., Pereira, J., Brandão, T., Oliveira, A., & Poças, F. (2022). Recycling of polypropylene (PP) by supercritical $CO_2$ for extraction of contaminants from beverage cups. A comparison with polyethylene terephthalate (PET) and polylactic acid (PLA). *Journal of the science of food and agriculture*. https://doi.org/10.1002/jsfa.12213.

89. Monjurul Islam, Tu Xayachak, Nawshad Haque, Deborah Lau, Muhammed Bhuiyan, Biplob Kumar Pramanik (2024). Impact of bioplastics on environment from its production to end-of-life, *Process Safety and Environmental Protection*, Volume 188, 2024, Pages 151-166, ISSN 0957-5820.https://doi.org/10.1016/j.psep.2024.05.113.

90. Agarwal, P., Soni, R., Kaur, P., Madan, A., Mishra, R., Pandey, J., Singh, S., & Singh, G. (2022). Cyanobacteria as a Promising Alternative for Sustainable Environment: Synthesis of Biofuel and Biodegradable Plastics. *Frontiers in Microbiology*, 13. https://doi.org/10.3389/fmicb.2022.939347.

91. Lomwongsopon, P., & Varrone, C. (2022). Contribution of Fermentation Technology to Building Blocks for Renewable Plastics. *Fermentation*. https://doi.org/10.3390/fermentation8020047.

92. Jeswani, H., Perry, M., Shaver, M., & Azapagic, A. (2023). Biodegradable and conventional plastic packaging: Comparison of life cycle environmental impacts of poly (mandelic acid) and polystyrene. *The Science of the total environment*, 166311. https://doi.org/10.2139/ssrn.4348390.

93. Louw, J., Farzad, S., & Görgens, J. (2022). Polyethylene furanoate: technoeconomic analysis of biobased production. *Biofuels*, 17. https://doi.org/10.1002/bbb.2430.

94. Wojnowska-Baryła, I., Bernat, K., & Zaborowska, M. (2022). Plastic Waste Degradation in Landfill Conditions: The Problem with Microplastics, and Their Direct and Indirect Environmental Effects. *International Journal of Environmental Research and Public Health*, 19. https://doi.org/10.3390/ijerph192013223.

95. Kim, M., Chang, H., Zheng, L., Yan, Q., Pfleger, B., Klier, J., Nelson, K., Majumder, E., & Huber, G. (2023). A Review of Biodegradable Plastics: Chemistry, Applications, Properties, and Future Research Needs. *Chemical reviews*. https://doi.org/10.1021/acs.chemrev.2c00876.

96. Huang, S., Wang, H., Ahmad, W., Ahmad, A., Vatin, N., Mohamed, A., Deifalla, A., & Mehmood, I. (2022). Plastic Waste Management Strategies and Their Environmental Aspects: A Scientometric Analysis and Comprehensive Review. *International Journal of Environmental Research and Public Health*, 19. https://doi.org/10.3390/ijerph19084556.

97. Sun, D., Gu, T., Mao, Y., Huang, C., Qi, X., Yang, J., & Wang, Y. (2022). Fabricating High-Thermal-Conductivity, High-Strength, and High-Toughness Polylactic Acid-Based Blend Composites via Constructing Multioriented Microstructures. *Biomacromolecules*. https://doi.org/10.1021/acs.biomac.2c00067.

98. Injorhor, P., Trongsatitkul, T., Wittayakun, J., Ruksakulpiwat, C., & Ruksakulpiwat, Y. (2023). Biodegradable Polylactic Acid-Polyhydroxyalkanoate-Based Nanocomposites with Bio-Hydroxyapatite: Preparation and Characterization. *Polymers*, 15. https://doi.org/10.3390/polym15051261.

99. Kharb, J., & Saharan, R. (2022). Sustainable Biodegradable Plastics and their Applications: A Mini Review. *IOP Conference Series: Materials Science and Engineering*, 1248. https://doi.org/10.1088/1757-899X/1248/1/012008.

100. Momeni, S., Craplewe, K., Safder, M., Luz, S., Sauvageau, D., & Elias, A. (2023). Accelerating the Biodegradation of Poly (lactic acid) through the Inclusion of Plant Fibers: A Review of Recent Advances. *ACS sustainable chemistry & engineering*, 11 42, 15146-15170. https://doi.org/10.1021/acssuschemeng.3c04240.

101. Machado, M., Hofmann, M., Garrido, M., Correia, J., Bordado, J., & Rosa, I. (2023). Incorporation of Lignin in Bio-Based Resins for Potential Application in Fiber–Polymer Composites. *Applied Sciences*. https://doi.org/10.3390/app13148342.

102. Afreen, R., Tyagi, S., Singh, G., & Singh, M. (2021). Challenges and Perspectives of Polyhydroxyalkanoate Production from Microalgae/Cyanobacteria and Bacteria as Microbial Factories: An Assessment of Hybrid Biological System. *Frontiers in Bioengineering and Biotechnology*, 9. https://doi.org/10.3389/fbioe.2021.624885.

103. Estévez-Alonso, Á., Loosdrecht, M., Kleerebezem, R., & Werker, A. (2021). Simultaneous nitrification and denitrification in microbial community-based polyhydroxyalkanoate production. *Bioresource technology*, 337, 125420. https://doi.org/10.1016/j.biortech.2021.125420.

104. Jia, D., He, M., Tian, Y., Shen, S., Zhu, X., Wang, Y., Zhuang, Y., Jiang, W., & Gu, Y. (2021). Metabolic Engineering of Gas-Fermenting Clostridium ljungdahlii for Efficient Co-production of Isopropanol, 3-Hydroxybutyrate, and Ethanol. *ACS synthetic biology*. https://doi.org/10.1021/acssynbio.1c00235.

105. Sohn, Y., Son, J., Jo, S., Park, S., Yoo, J., Baritugo, K., Na, J., Choi, J., Kim, H., Joo, J., & Park, S. (2021). Chemoautotroph

Cupriavidus necator as a potential game-changer for global warming and plastic waste problem: A review. *Bioresource technology*, 340, 125693. https://doi.org/10.1016/j.biortech.2021.125693.

106. Santolin, L., Thiele, I., Neubauer, P., & Riedel, S. (2023). Tailoring the HHx monomer content of P(HB-co-HHx) by flexible substrate compositions: scale-up from deep-well-plates to laboratory bioreactor cultivations. *Frontiers in Bioengineering and Biotechnology*, 11. https://doi.org/10.3389/fbioe.2023.1081072.

107. Choi, S., Rhie, M., Kim, H., Joo, J., Cho, I., Son., J., Jo, S., Sohn, Y., Baritugo, K., Pyo, J., Lee, Y., Lee, S., & Park, S. (2020). Metabolic engineering for the synthesis of polyesters: A 100-year journey from polyhydroxyalkanoates to non-natural microbial polyesters. *Metabolic engineering*. https://doi.org/10.1016/j.ymben.2019.05.009.

108. Bunster, G., & Pavez, P. (2022). Novel Production Methods of Polyhydroxyalkanoates and Their Innovative Uses in Biomedicine and Industry. *Molecules*, 27. https://doi.org/10.3390/molecules27238351.

109. Iglesias-Montes, M., Soccio, M., Siracusa, V., Gazzano, M., Lotti, N., Cyras, V., & Manfredi, L. (2022). Chitin Nanocomposite Based on Plasticized Poly (lactic acid)/Poly(3-hydroxybutyrate) (PLA/PHB) Blends as Fully Biodegradable Packaging Materials. *Polymers*, 14. https://doi.org/10.3390/polym14153177.

110. Hussin, F., Wahab, R., & Attan, N. (2020). Nanocellulose and nanoclay as reinforcement materials in polymer composites: A review. *Malaysian Journal of Fundamental and Applied Sciences*, 16, 145-153. https://doi.org/10.11113/MJFAS.V16N2.1430.

111. Versino, F., Ortega, F., Monroy, Y., Rivero, S., López, O., & García, M. (2023). Sustainable and Bio-Based Food Packaging: A Review on Past and Current Design Innovations. *Foods*, 12. https://doi.org/10.3390/foods12051057.

112. Frank, C., Emmerstorfer-Augustin, A., Rath, T., Trimmel, G., Nachtnebel, M., & Stelzer, F. (2023). Bio-Polyester/Rubber Compounds: Fabrication, Characterization, and Biodegradation. *Polymers*, 15. https://doi.org/10.3390/polym15122593