Al-Rafidain Journal of Engineering Sciences

Journal homepage https://rjes.iq/index.php/rjes

ISSN 3005-3153 (Online)

Biodegradable Polymers: Environmental Sustainability, Challenges, and Considerations

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ARTICLE INFO

Article history:

Received	26 September	2024
Revised	26 September	2024
Accepted	12 October	2024
Available online	17 October	2024

Keywords:

Biodegradable polymers
Agro-waste
Sustainability
Environmentally friendly
Peel waste

ABSTRACT

The increasing global production of polymers and plastics has led to the development of a new environmentally friendly material that is degraded in the environment by enzymatic action and/or smaller units are created by the breakdown of microorganisms such as bacteria, fungi, and algae. In the present review, the analysis of biodegradable polymers was presented on the global production of these polymers and industrial and environmental applications. In addition, the work focuses on sustainability in the environment, because the biodegradable polymers have become spread as sustainable alternative options to the non-biodegradable polymers. Additionally, the study provided an explanation of how to produce biodegradable polymers using agricultural waste, including tomato pomace and pineapple peel waste. Generally, the creation and application of biodegradable polymers need to take into account their environmental effect and performance along with aspects like cost, availability, recyclability, and printing methods.

1. Introduction

Global plastic production has grown significantly over the past century, reaching more than 380 million tons in 2016. Within the next 20 years, plastics output is predicted to quadruple at the current rate of increase. Compared to other materials employed in building or packaging, which are plastics' two main application areas, none has achieved the remarkable success of plastics [1]. These polymeric materials last a long time and show high resistance in the environment (e.g. polyethene terephthalate - PET bottles have an expected lifetime of about 27 to 93 years [2] and conventional polymers are not biodegradation, consequently they produce pollution. For example: the plastic bags we use every day are made from polyethylene PE which is derived from petroleum products. Petroleum contains different compounds and heavy materials, thus petroleum is toxic and harmful to plants and animals [3]. In January 2018, the European Union (EU) suggested increasing more sustainable plastic industry. In addition, to plastic recycling, the EU discussed development the of biodegradable polymers (BPs) and used these kinds in several applications like medicine, tissues, plastic bags, etc [1].

Polymers are versatile compounds classified by various parameters, including their source, polymerization type, monomer composition, and molecular forces (Figure 1) [4]. each group has its advantages and offers spectrum

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https://doi.org/10.61268/yvq3rm27

applications. There are several biodegradable polymers for different applications [5].

The definition of "biodegradable polymers" is that polymers are disposed of by enzymatic action and/ or microorganisms such as bacteria, fungi and algae [6]. The BPs contain two groups; natural and synthetic. Oil and natural resources are the sources of synthetic and natural BPs, respectively. In contrast to synthetic BPs, which are produced chemically, natural BPs are obtained from biological or renewable sources, such as plants, animals, marine life, and microbes. They degraded into smaller units [7]. The degradation of BPs takes hours, days or maybe years according to the polymer structure [8], but they are supposed to break down into small biomass once they end up in the environment as shown in Figure 2. [9].

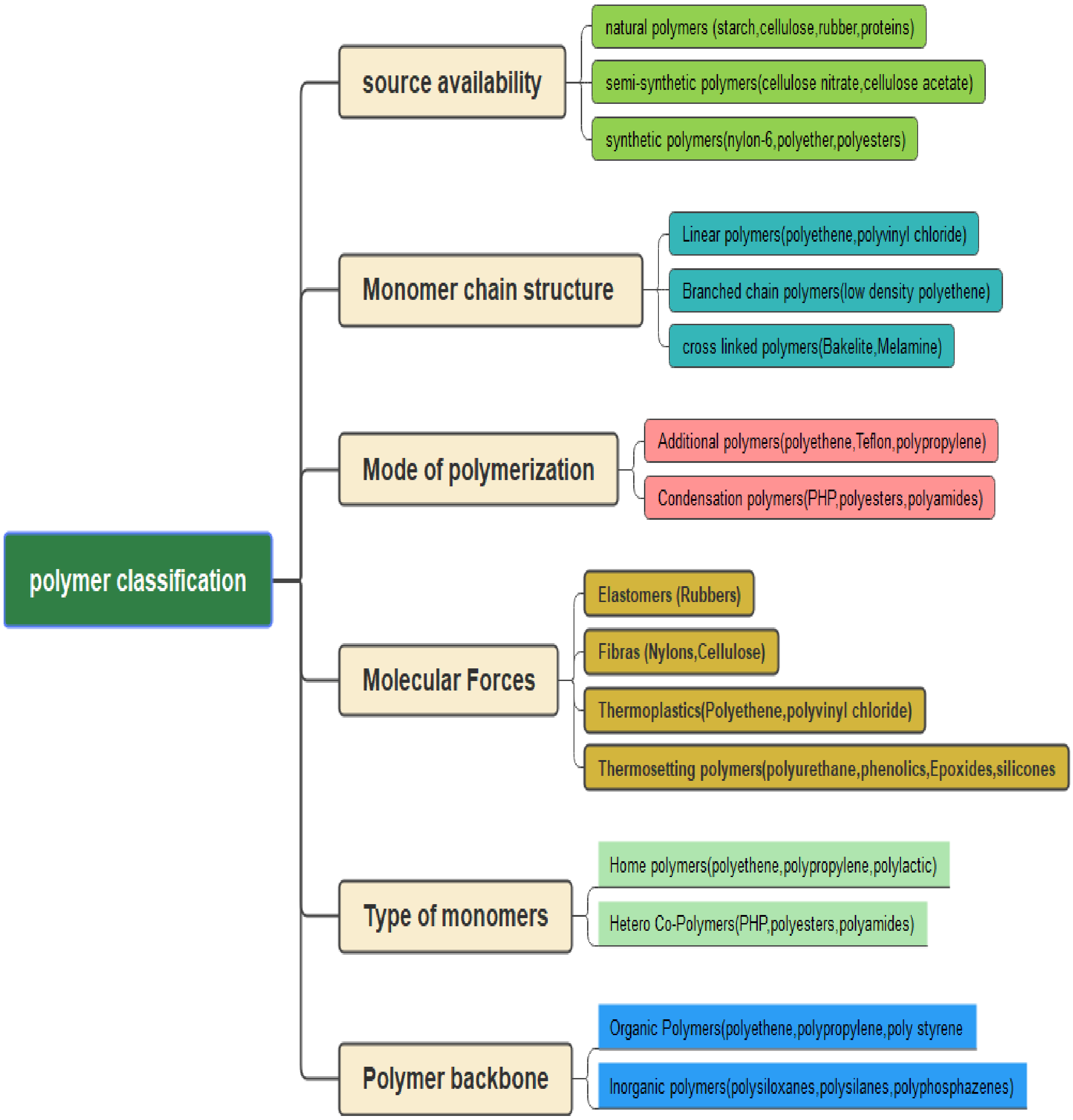

Figure 1. Classification of polymers based on various criteria [4]

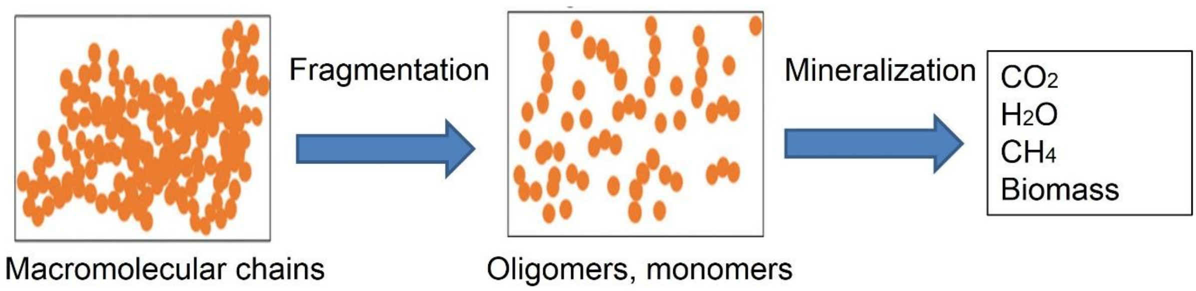

Figure 2. Degradation of BPs [9]

Some BPs are partially biodegradable, they are called "biobased" such as "bio-polypropylene" (bio-PP), "bio-polyethylene" (bio-PE), bio polyamide (bio-Pas) and "bio-polyethylene terephthalate" (bio-PET) [6]. The mechanical properties of biobased and biopolymer are the same biobased polyvinylchloride and bio-polyethylene both have good resistance against CO_2, O_2 and H_2O [10]. The most important BPs in the industry is polylactic acid which accounts for 24% of the global production (Figure 3) besides starch blends 44% and polyesters ("polybutylene succinate"-PBS and "polybutylene adipate terephthalate"-PBAT) which account for 23% [1]. According to the Nova Institute's projections, the global production of bioplastics is expected to reach 7.43 million tons by the year 2028 [11].

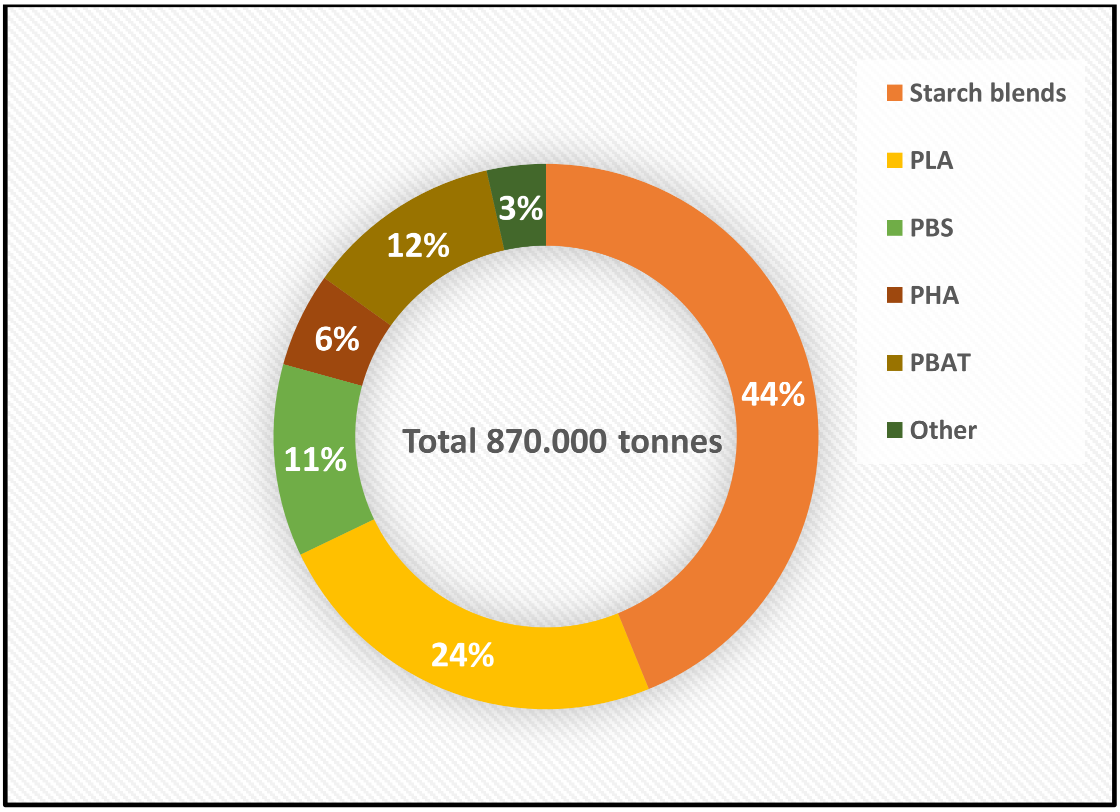

Figure 3. Global production of BPs according to European Bioplastics [2]

Many factors affect the biodegradation process such as the structure of the polymer. When the polymer contains both hydrophobic and hydrophilic structures, it degrades more easily than polymers with either hydrophilic or hydrophobic structures."Polymer morphology"; by increasing the melting point, the degradation of the polymer reduces. Also, the enzymatic degradation in the amorphous regions in the polymer is more easily than in crystalline regions. Furthermore, as the molecular weight of the polymer increases, the capacity for polymer degradation decreases [12, 13]. This viewpoint article addresses the current state of environmental acceptability of biodegradable polymers, exploring the sustainability challenges and opportunities. It also details the production of biodegradable polymers from agricultural waste. The development and use of biodegradable polymers should consider their environmental impact and performance, as well as factors like cost, availability, recyclability, and printing methods.

2. Literature review

Researchers in their recent works focused on the production of biopolymers. Some of these materials are used in a lot of safe and friendly products for the environment, especially in medicine, engineering, textile and agriculture [14]. Various datasets have been used to evaluate global interest, knowledge, and research on BPs. Firstly, the number of documents published by various countries has been studied using the 'Biodegradable AND Polymer AND Plastic' keyword; the first fifteen countries with the published papers are explain in Figure 4. China, have the highest number of documents (around 1800) among countries, followed by the USA and India. Secondly, documents published by year have been investigated by choosing the ‘BPs and bio-based plastics’ keyword as illustrate in Figure 5. Displays that from the last 25 years of analysis, interest has grown in BPs, continuously increasing. The first technical bioplastic was published in 1947. As a result of the growing trend and interest in BPs, the greatest number of papers were published by the end of 2023. This growth in the number of publications reflects the attention to biodegradable polymers which coincides with development the of environmental stability and global concerns about sustainability [15]. Many researchers investigated polylactides over the next 50 years, such as PLA which is produced and derived from lactic acid biologically by fermentation [14].

Some research published another suggestion for sustainability and the management of solid plastics. In 2022 Kumari *et al.* converted the solid plastic wastes into activated carbon fibres (ACFs). The produced AFCs have high adsorption capacity for several pollutants [16]. In 2016 in Iceland, a student suggested using algae bottles instead of polyethene bottles by mixing powdered agar with water. This new bottle is very important for a sustainable environment because people can chew this bottle [3].

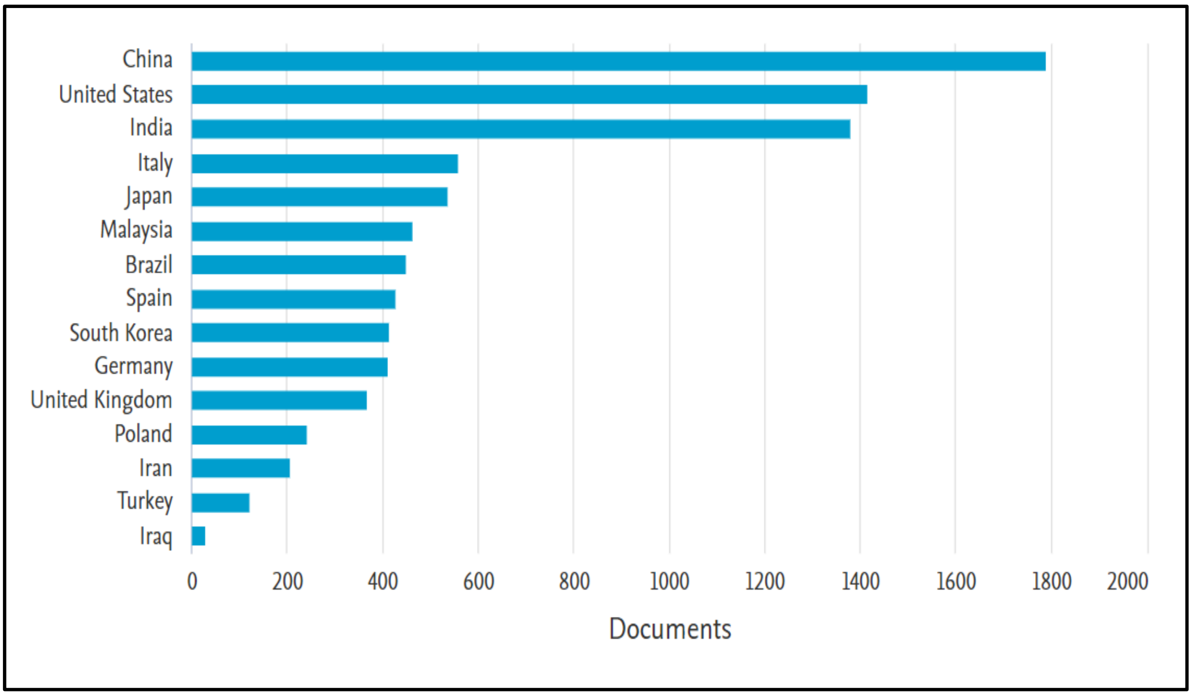

Figure 4. Papers published per country in ScienceDirect

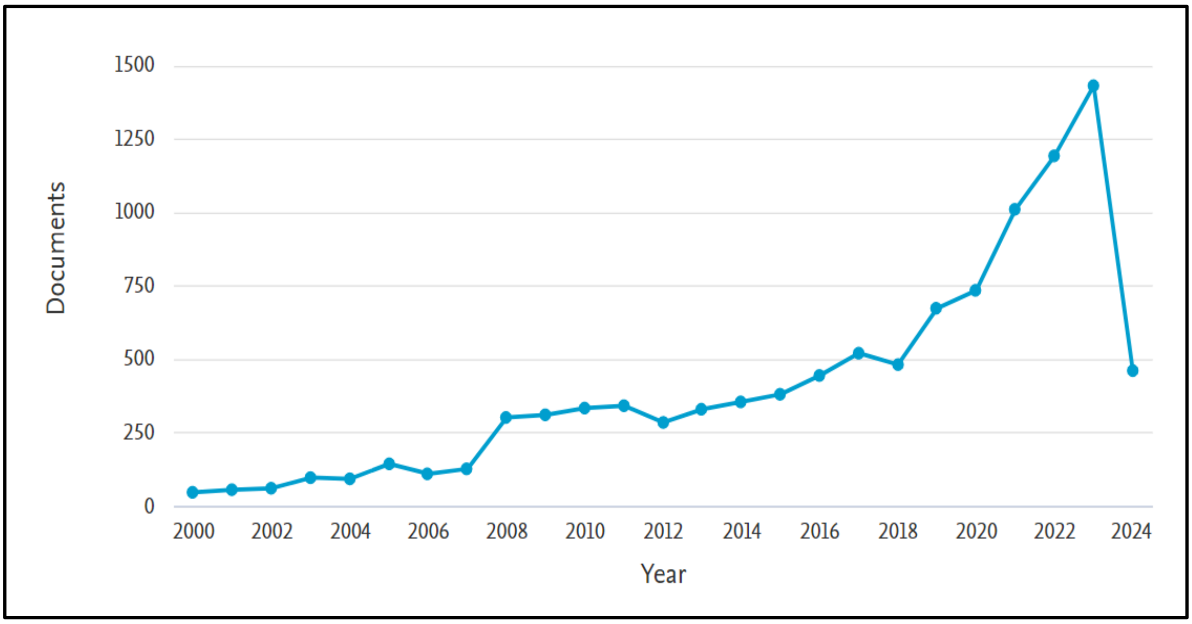

Figure 5. Publication of BPs by year

3. Application of biodegradable polymers

The Nobel Prize in chemistry was given to Hermann Staudinger in 1953 for his research on macromolecules. Since that time polymers have been used in everything in everyday life, so he was called the "father of polymer science" [8]. There are several applications for all types of BPs including pharmaceutical, medical, agriculture and food packing [15]. Figure 6. Summarize the various supplication of BPs materials [13].

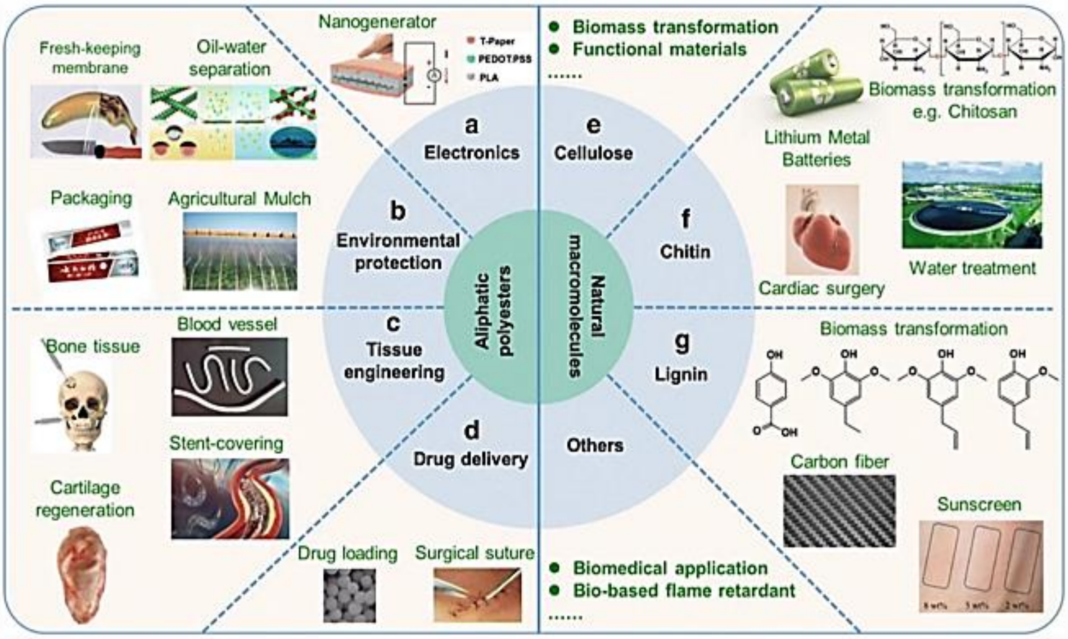

Figure 6. Application of biodegradable polymers [13]

3.1 Medical applications:

BPs have diverse medical applications, including gloves, blood containers, and medical equipment, due to their biodegradability, allowing them to decompose without additional removal procedures. [17]. Polyhydroxyalkanoates – PHA is a widely used polymer in medical approaches, PHA is highly valued for its ability to biodegrade, its biocompatibility, and its capacity to break down through surface erosion. Additionally, PHA serves as an effective drug carrier. Certain PHA monomers can even be utilized in the production of carbapenem antibiotics and macrolides [18].

3.2 Food packing:

Converting waste into useful packaging materials is now a key priority for reducing the environmental impact of synthetic plastics. BPs are a new type of polymer used in industry, differing from traditional polymers, and require high resistance to water and oxygen for food packaging applications[19]. PLA can used for packing various materials such as cups, bottles, films and containers [15].

4. Biodegradable polymers in the environment

Biodegradation is a process by which microorganisms convert organic materials into inorganic chemicals, such as biopolymers used in plastic materials. This process involves mineralizing carbon, consuming it for microorganisms' development and reproduction, and leaving the rest as a polymeric residue. Anaerobic conditions also contribute to the production of CO_2 and CH_4, as well as other microorganisms.

Organic recycling converts bio-waste into compost for agriculture. Three strategies include industrial composting, home composting, and anaerobic digestion. Industrial composting uses plastic materials, home composting uses less bio-waste, and anaerobic digestion decomposes without oxygen, producing biogas and digestate.

Biopolymer-based applications in soil improvement are rapidly growing. Industrial compost, made from biopolymers, is used to adjust soil texture, water content, organic matter, pH, temperature, oxygen, sunlight, and other factors for optimal microbial activity.

Despite all the useful applications of polymers, polymers today are considered harmful materials because of their negative effects on the environment, because of the long backbone of -C-C- bonds with high molar mass which last in the environment for a long time, therefore, the biodegradable polymers were discussed as the most important solution to protect the environment from the polymers pollution [19]. Synthetic polymers should not affect the environment or human health. Although the BPs are environmentally friendly, the production of these kinds of materials faces several challenges [15].

Biodegradability doesn't mean that the polymer disposes at the same speed in each environment, but it depends on several conditions like soil, pH, water, sunlight and type of microorganisms [9]. For example, the most commercial BP is polylactic acid – PLA with a glass transition temperature of about (Tg = 60 ℃). The degradation of this polymer in soil lasts about 11 months under field conditions [9].

Figure 7 shows the biodegradability in soil, water and compost. Above Tg, the degradation of PLA will increase, because the chains of the polymer become more flexible. The humidity in compost is high which also increases the degradation of PLA. On the other hand, the degradation of PLA in soil takes about 1 year because the temperature usually doesn't exceed 30℃ [2].

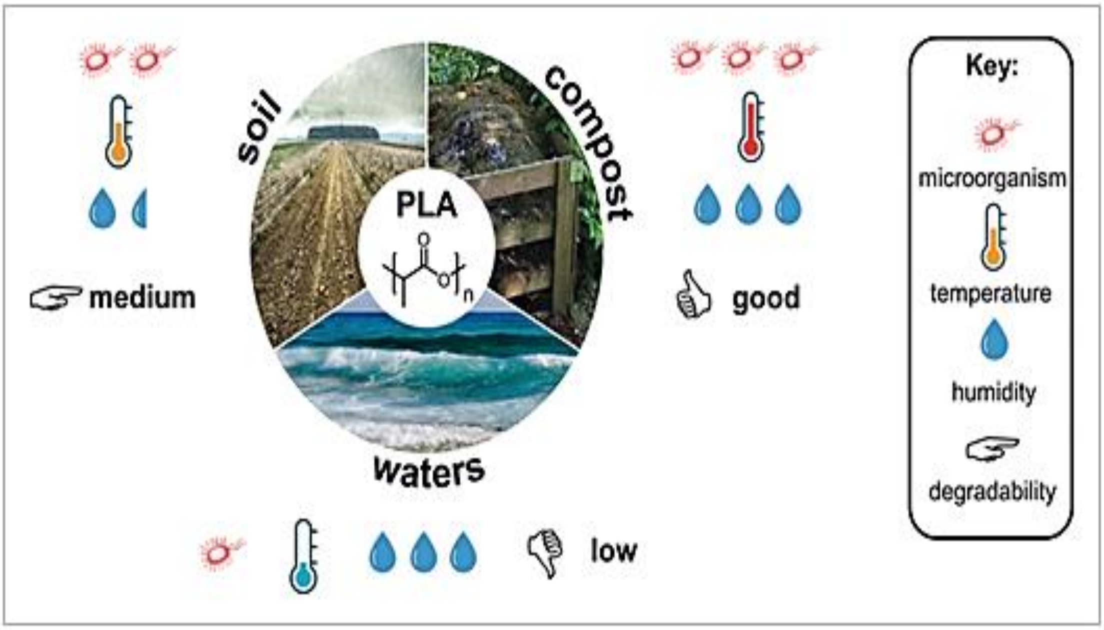

Figure 7. The biodegradation of PLA in different environments [2]

Another example of BPs is starch which is used as a blend with different conventional polymers as bio-based polymers. This bio-polymer is very important to use because it has high biodegradability in the environment [10].

5. Sustainability

Sustainability involves balancing, economic, social and environmental factors. "The UN World Commission on "Environment and Development in Our Future" linked sustainability with renewability and development, The inclusion of renewable biomass in a comprehensive carbon cycle can be a highly intricate process. The carbon in this cycle transfers between four reservoirs on the planet [20, 21].

Because of increasing the amount of CO_2 and the generation of greenhouse gases and CFCs in the atmosphere that are responsible for global warming, people make efforts to make carbon cycle re-balancing. One of the solutions to re-balance the carbon cycle is developing industries based on biodegradable polymers [14], [20].

The BPs have become spread as sustainable alternative options to non-biodegradable polymers and they become so popular in several industries because they are non-polluting products. The sustainable development goals are making a balance between developing society and respecting the environment [10].

Figure 7. Sustainable product development [10]

The selection of suitable agro-waste depends on several considerations such as starch content, bioavailability, biodegradation, impact on agriculture supply chains and food security [22].

In 2016 Vega *et al.* produced Polyhydroxyalkanoates Various fermentation conditions were employed to process pineapple peel waste, resulting in different outcomes during the fermentation process [23]. Using similar methods to produce bio-based polymers, bioplastics are made from agricultural waste from tomato pomace. Aliphatic polyesters were synthesized at different temperatures (125, 150, and 175 °C) [23]. A matrix of potato peel and bacterial cellulose was used for biodegradable food packing which was formed as films [24].

Biopolymers made from agricultural waste provide a long-term remedy for the negative aspects of petroleum-based polymers. Biopolymers made from agricultural waste provide a long-term remedy for the negative aspects of petroleum-based polymers. Agro-food wastes in the supply chain can be repurposed as feedstock for biopolymer production, decreasing fossil fuel dependency and enhancing resource recovery and waste management [25]. On the other hand, starch, cellulose, and chitin are examples of agricultural waste that can be used to produce bioplastics, such as polylactic acid, thermoplastic starch, and chitosan bioplastic [26]. Waste from the sugarcane industry includes lignocellulosic biomass, which serves as a storehouse for lignin, hemicellulose, and cellulose [27]. Agricultural waste may provide enormous amounts of cellulose, and it can also be simply used to extract xylan and cutin [28].

The primary result of the seafood sector's waste is chitin/chitosan, while fish, poultry, and tannery industry waste may be used to separate collagen and gelatin. [29],[30]. Each of these biopolymers may be used as a raw material in many sectors, such as the food packaging sector, to create environmentally friendly packaging [31]. The multidisciplinary research, which combines engineering and biological science, provides new approaches for rethinking biosynthesis pathways and converting biomass into useful products like biopolymers that increase economic efficiency [32] (Table 1). Furthermore, utilising food waste through fermentation can lead to the production of biopolymers, such as xanthan gum and polyhydroxyalkanoates, which can be tailored for specific applications by modifying their chemical structure [33].

Microbial enrichment approaches using mixed microbial communities present great potential in producing a wide range of microbial biopolymers from organic waste. This reduces production costs and turns waste into a valuable resource [34]. Finally, the use of agricultural waste for the production of biopolymers is a developing field with potential for commercialization and environmental benefits [35].

Table 1: Main BPs developed from agro-waste and applications

Bio-waste	BP type	Application	References
Potato peel	Starch	Packaging industry	[40][41]
Tomato peel	Cutin	Wastewater removal	[42][43]
Corn waste	Starch	Textile and packaging industry	[40]
Eggshells	Gelatin	Wastewater removal Industrial application Biomedical implant materials	[45]
Sugarcane	Hemicellulose	Packaging industry Biodegradable plates	[28]
Rice Straw	Xylan	Packaging industry Biodegradable plates	[40]
Banana peel	Cellulose nanofiber	Biodegradable plates Biomedical materials	[38][39]
Sheep wool	Gelatin	Textile and packaging industry	[44]
Watermelon	PHA	Food and packaging industry	[46]

7. Conclusion

Biodegradable polymers encounter challenges during their development and implementation, particularly their high cost and limited availability compared to conventional petroleum-based plastics. Accordingly, biodegradable polymers are discussed as an alternative solution for environmental sustainability because they are disposed by enzymatic action and/ or microorganisms into smaller units. BPs, commonly PLA and PHA, are widely used in applications like food packaging and drug delivery. Recently work has focus on the production of biopolymers which are used in safe and friendly products for the environment and some researchers developed green materials from agricultural waste.. However, emerging technologies such as heat-assisted digital light processing and volumetric printing offer potential solutions to these challenges. Furthermore, the development of biodegradable, water-soluble and water-dispersible polymers as alternatives to non-biodegradable polymers is the focus of industry interest. In general, the development and use of biodegradable polymers requires addressing factors such as cost, availability, recyclability, and printing techniques while taking into account their environmental impact and performanc

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