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# Eco-friendly plastics and development: A review article

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**Abstract** Biodegradable plastics or bioplastics are environmentally friendly plastics that break down naturally quickly. The development of bioplastics aims to minimize environmental pollution due to the current use of synthetic plastics. Biodegradable plastic has the same applications as synthetic plastic. However, after being used and thrown into the environment, this plastic can be decomposed by microorganisms into final products in the form of water and carbon dioxide gas. The advantage of using bioplastics is that they are cheap, can reduce existing packaging waste, reduce industrial waste, and prevent contamination from microorganisms. We are grouping bioplastics based on the era of development, namely "Old Economy" and "New Economy." In 2022, the global production capacity for new economic bioplastics was dominated by biodegradables, with biodegradable material types accounting for 55.6% and bio-based/non-biodegradable materials accounting for 44.4%. The market value of bioplastics worldwide is expected to continue. The main components of bioplastics are hydrocolloids, fats, and composites. The characteristics of bioplastics are divided into physical and mechanical properties. Physical characteristics include thickness, which indicates the ability of bioplastics to package products. In contrast, the mechanical characteristics of biodegradable plastics are plastic properties related to the material's response to the applied force, including tensile strength, elongation, and water absorption, which indicate the strength ability of bioplastics to withstand damage to materials during processing.

**Keywords:** Bioplastic, Biopolymer

## Introduction

The packaging that most people use today is plastic. Plastic is light, durable, does not break quickly, is resistant to bacteria and fungi, and is cheap. Therefore, plastic is widely used, especially as packaging for food products. Plastics are generally based on petrochemicals such as polyethylene, polypropylene, and so on (Cengristitama and Insan, 2020; Nayanathara Thathsarani Pilapitiya and Ratnayake, 2024). This plastic is non-biodegradable;

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biological processes cannot break it down, so they become waste and negatively impact the environment.

Synthetic polymers, as the main component in synthetic plastics, require tens to hundreds of years to decompose or degrade. When burned, the smoke produced from the plastic burning process results in carbon emissions, which can cause air pollution and climate change. Therefore, it is necessary to develop packaging that is environmentally friendly and biodegradable (easily decomposed by nature). Biodegradable plastic or bioplastic is an environmentally friendly plastic that quickly deteriorates naturally in a short period. Bioplastic development aims to minimize environmental pollution caused by the current use of synthetic plastics.

Bioplastics are made from renewable organic materials, such as carbohydrates obtained from plants, proteins, and animal lipids (Avérous and Pollet, 2012). The use of agro-industrial waste has great potential in the manufacture of bioplastics because the volume is relatively large and is rarely used, such as empty palm fruit bunches, cheese whey waste, and others. This article aimed to provide information related to bioplastics, which includes the definition of bioplastics, the raw materials used in making bioplastics, and important parameters that determine the quality of bioplastics.

***Bioplastic***

"Biodegradable" is defined as "capable of undergoing degradation into carbon dioxide, methane, water, inorganic compounds, and biomass" by ASTM standard D-5488-94d and European norm EN 13432, respectively. The primary mechanism is the enzymatic activity of microorganisms, which can be assessed by standard tests over a set amount of time and represent the disposal circumstances in place. Many media (liquid, inert, or compost medium) are available to assess biodegradability. Compostability is the ability of an item to decompose in compost (Avérous and Pollet, 2012).

In the 20$^{th}$ century, soybean/protein-based plastic was developed, which is biodegradable and environmentally friendly. Biodegradable plastic is formed from natural polymers derived from organic monomers such as starch, protein, rubber, cellulose, chitosan, and lignin. This natural polymer is widely distributed in nature, has good mechanical properties, and has added value. Biodegradable plastic has the same applications as synthetic plastic, but after being used and thrown into the environment, this plastic can be decomposed by microorganisms into final products in the form of water and carbon dioxide gas. Bioplastics can be degraded by algae, fungi, and bacteria (Das *et al*., 2018; Heikmat Zaki *et al*., 2017). In the decomposition process, there are two stages: defragmentation and biodegradation. Defragmentation is a catalysis method by heat, moisture, enzymes, and microbes. Biodegradation is a process in which large molecules are converted into more minor compounds by enzymes or acids naturally produced by microorganisms. According to Lavagnolo *et al.* (2024), biodegradable plastic breaks down into $CO_2$, methane, water, biomass, and inorganic components under aerobic and anaerobic conditions.

The advantage of using bioplastics is that they are cheap, can reduce existing packaging waste, reduce industrial waste, and prevent contamination from microorganisms. Bioplastics can barrier either gas, oil, or water. The water content of food is an important thing that must be maintained to ensure freshness, control the rate of microbial growth, obtain a good texture, and control water activity by releasing or receiving water. A comparison of various characteristics of plastic currently in circulation can be seen in Table 1.

**Table 1.** Differences in characteristics of synthetic, mixed, and bioplastic plastics

| **Characteristics** | **Synthetic plastic** | **Mixed plastic** | **Bioplastic** |
|---|---|---|---|
| Compiler | Synthetic polymer | Synthetic polymers and natural polymers | Natural polymer |
| Characteristics of raw materials | Hard to biodegradable | Some are biodegradable | Biodegradable |
| Mechanical properties | Very good and varied | Varies | Fine, varied, limited use |
| Biodegradability | - | Low | High |
| Compatibility | - | Low | High |
| Result of burning | Stable | Somewhat stable | Less stable |
| Example | - Polypropylene (PP)<br>- Polyethylene (PE)<br>- Polystyrene (PS) | - Polyethylene (PE) + starch<br>- Polyethylene (PE) + cellulose | - Poly Lactic Acid (PLA)<br>- Polycaprolactone (PCL) |

Bioplastics are very safe for the environment. *Pseudomonas sp., Streptococcus sp., Staphylococcus sp., Bacillus sp.,* and *Moraxella sp.* can degrade this plastic by breaking the polymer chains into oligomers and monomers (Folino *et al*., 2020). No dangerous chemical composites are formed when biodegradable plastic is burned. In addition, biodegradable plastics primarily induce positive effects on the decomposition of soil organic matter (Li *et al*., 2024). Figure 1 presents biopolymers (bioplastics) and their sources.

According to Hannover (2023), we are grouping bioplastics based on the era of development, namely “Old Economy” and “New Economy” Bioplastic (Figure 2). The first manufactured polymer materials were all based on modified natural materials (e.g., casein, gelatine, shellac, celluloid, cellophane, linoleum, rubber, etc.). That means they were bio-based since petrochemical materials were not yet available then. Since the middle of the 20$^{th}$ century, these early bio-based plastics, with a few exceptions (cellulose and rubber-based materials), have almost been replaced by petrochemical materials. Of particular interest today are new types of bioplastics, which were developed in the past 30 years. The publication presented here refers to the so-called "New Economy" bioplastics as opposed to "Old Economy" bioplastics, which indicate earlier materials developed before petrochemical bioplastics emerged yet still exist on the market today (e.g., rubber, cellophane, viscose, celluloid, cellulose acetate, linoleum).

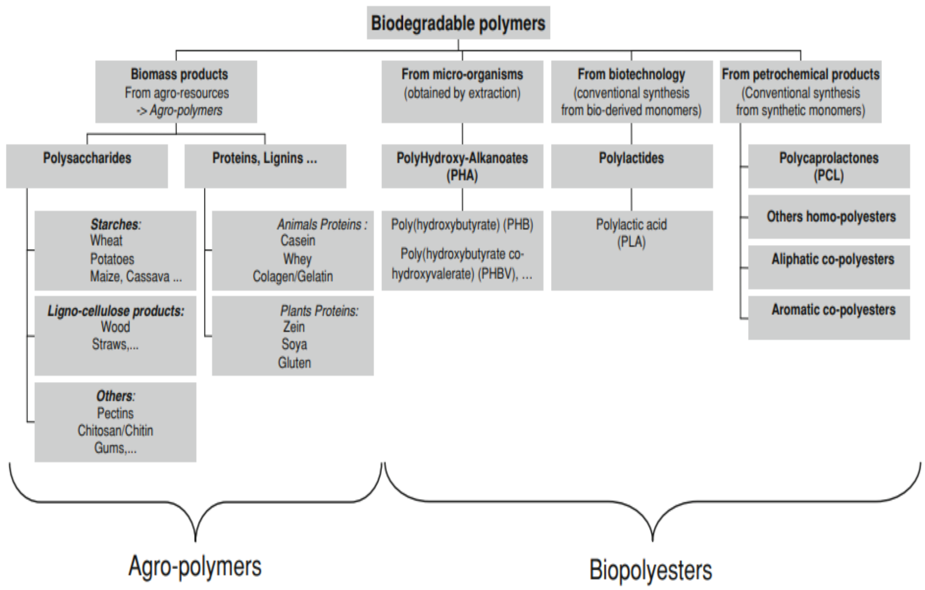


**Figure 1.** Classification of the main biodegradable polymers (Avérous and Pollet, 2012)

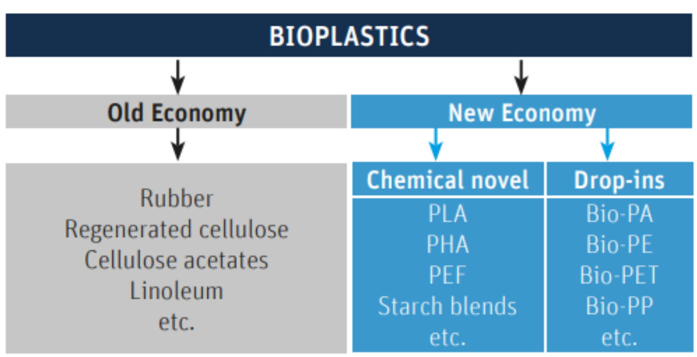


**Figure 2.** Old economy and new economy bioplastic

***Bioplastic forming biomass***

The main components of bioplastics are hydrocolloids, fats, and composites. Proteins, cellulose derivatives, alginate, pectin, and other polysaccharides are a group of hydrocolloids. The fat group includes wax, acylglycerols, and fatty acids, while the composite group is a mixture of hydrocolloid and fat groups (Safitri *et al*., 2016). The following are the components that make bioplastics:

***Hydrocolloid***

The hydrocolloids used in the manufacture of bioplastics are proteins or carbohydrates. Bioplastics formed from carbohydrates can be in starch, gum (alginate, pectin, and gum arabic), and chemically modified starch. The formation of bioplastics from protein can use casein, soy protein, wheat gluten, and corn protein. Hydrocolloid-based bioplastics have many benefits, including increased product resistance to lipids, carbon dioxide, and oxygen, improved structural integrity, and required mechanical qualities.

***Lipid***

Lipid-based bioplastics can be used as coating materials to lubricate convection products or protect products against water evaporation. The weakness of lipid-based bioplastics is their low integrity and durability, preventing their application in pure form. Wax, fatty acids, monoglycerides, and resins are lipids that are often used as bioplastics.

***Composite***

Composite bioplastics combine hydrocolloids and lipids, which can increase the advantages of hydrocolloids and lipids and reduce their weaknesses.

***Bioplastic additives***

**Plasticizers**

Plasticizers are organic solvents added to stiff or rigid solutions. Plasticizer is one aspect that influences the properties of composites in plastics. Plasticizers which help increase the flexibility and flexibility of polymers. Bioplastics tend to be stiff, so plasticizers must be added to increase the properties of the polymer, for example, heat resistance, low-temperature resistance, water resistance, good strength, more elasticity, and flexibility (Hamzah *et al*., 2021; Hidayati *et al*., 2019; Permata *et al*., 2024). Adding plasticizers is an effective approach to improving the mechanical performance of bioplastics (Zhao *et al*., 2023).

According to Ningsih (2015) plasticizers can increase flexibility and reduce intermolecular forces along the polymer chain, making bioplastics bendable. Adding plasticizers to bioplastics reduces brittleness caused by high intermolecular pressure. Plasticizers can also weaken the bonds between molecules along the polymer chain, making bioplastics more flexible and reducing their resistance to permeability. The greater the percentage of plasticizer added to the sample, the more solubility will increase, and the brittleness will decrease. Likewise, hydrophilic plasticizers can optimize the solubility and distance between primary molecules. A study Safitri *et al*., (2016) states that glycerol plasticizers can improve the elongation quality of biodegradable plastics. The greater the glycerol concentration, the higher the elongation value of the plastic formed.

The quality of the bioplastic that will be produced depends on the type of plasticizer used. Plasticizers that are often used in making bioplastics are monosaccharides, disaccharides, polyols (glycerol, sorbitol, glyceryl derivatives, polyethylene glycol), and lipids and their derivatives. The compatibility of the plasticizer with the material to be plasticized determines the choice of plasticizer. The ideal plasticizer for polysaccharide bioplastics, which are usually water-based, is a hydrophilic plasticizer with hydroxyl groups because it is very similar to the structure of polysaccharides. Glycerol, sorbitol, xylitol, mannitol, polyethylene glycol, ethylene glycol, and propylene glycol are plasticizers commonly used in polysaccharide films. The higher the concentration of plasticizer used, the more solubility will also increase (Coniwanti *et al*., 2014).

**Filler**

A filler is a mineral aggregate with a size that is generally 200 mesh. A sieve will fill the cavities between the coarse aggregate particles on the bioplastic film frame to minimize the cavities' size, maximize density, and improve the balance of the resulting bioplastic mass. The air cavities in the bioplastic films are filled with coarse aggregate particles, so the air cavities in the bioplastic films become smaller, and the mass density will be higher. Filler, also known as filler, which is often used in the manufacture of bioplastics, is calcium carbonate ($CaCO_3$). $CaCO_3$ contains calcium, which has strong properties so that optimal plastic stiffness is obtained and overcomes bioplastics brittleness and tearing power. Not only that, $CaCO_3$ is also difficult to dissolve in water, so the level of resistance to water in the resulting bioplastic is higher. Apart from $CaCo_3$, several fillers that are often used in making biodegradable plastics are ZnO, CMC, CNF, MCC, chitosan, clay, and empty oil palm fruit bunch fiber (Abral *et al*., 2018).

***The development of new economic bioplastics***

According to Hannover (2023), in 2022, the global production capacity for new economic bioplastics will be dominated by biodegradables (Figure 3), with biodegradable material types accounting for 55.6% and bio-based/non-biodegradable materials accounting for 44.4% (Figure 4). Asia has the highest production capacity (Figure 5) and market segment in flexible packaging (Figure 6).

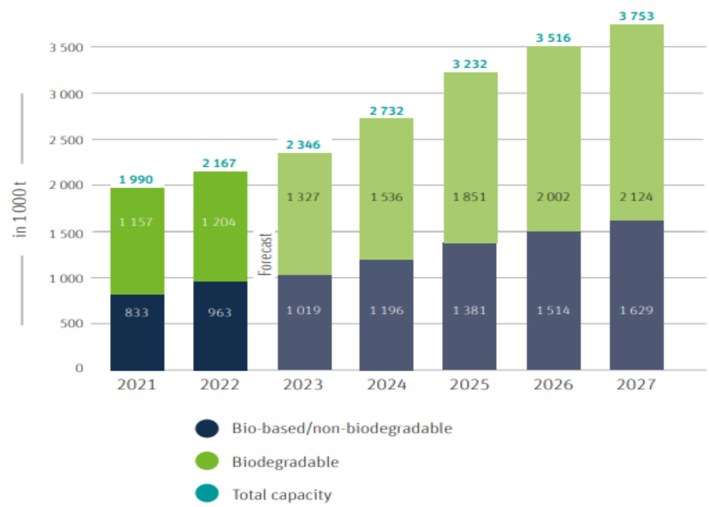


**Figure 3.** New economy bioplastics global production capacities

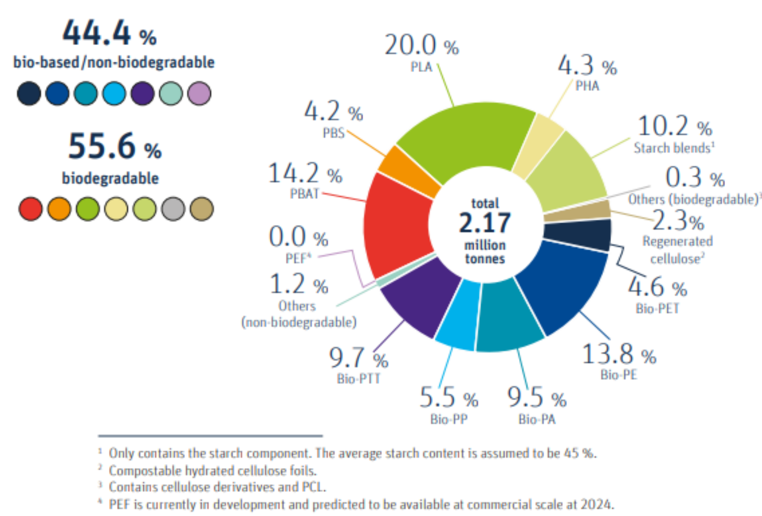


**Figure 4.** New Economy bioplastics production capacities by material type

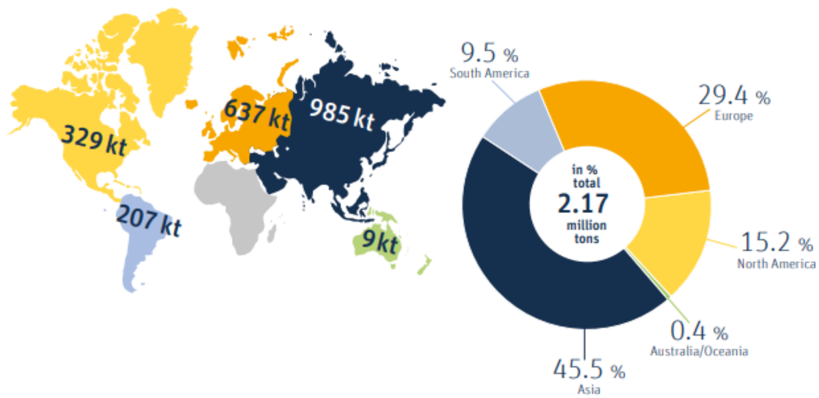


**Figure 5.** New Economy bioplastics production capacities by region

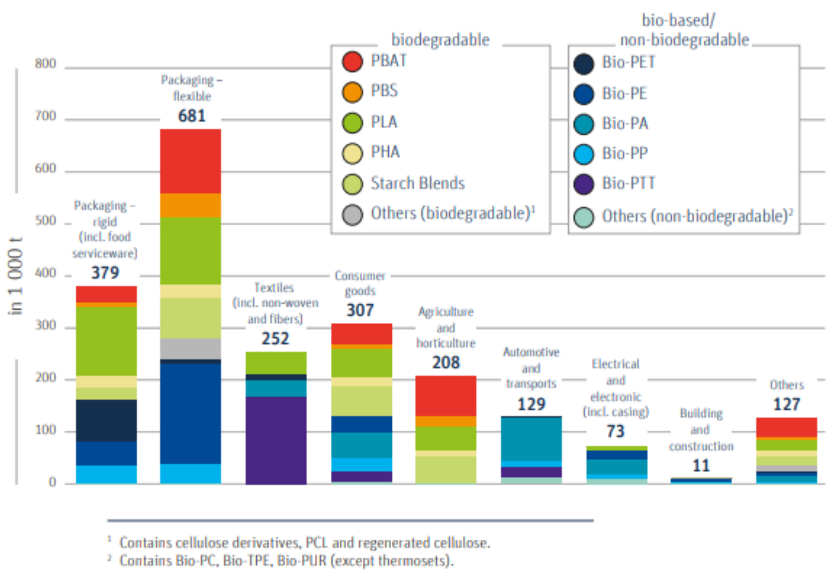


**Figure 6.** New economy bioplastics production capacities by market segment

***Characteristics of biodegradable plastics***

The characteristics of bioplastics are divided into physical and mechanical properties. Physical characteristics include thickness, which indicates the ability of bioplastics to package products. In contrast, mechanical characteristics of biodegradable plastics are plastic properties related to the response of the material to the applied force, including tensile strength, elongation, and water absorption, which indicate the strength ability of bioplastics to withstand damage to materials during processing.

**Thickness**

Thickness is one of the observations made to determine the characteristics of biodegradable plastic samples. Plastic thickness was measured using a screw micrometer with an accuracy of 0.001 mm. Thickness will affect the gas permeability level and involve plastic use. The thicker the biodegradable plastic, the lower the air permeability and the better the plastic's ability to protect its packaged product. Thickness also affects the mechanical properties of plastics, such as tensile strength and elongation. During use, the thickness of the plastic must be adjusted to the product to be packaged. Factors that can affect the thickness of bioplastics are the concentration of dissolved solids in the formation of bioplastics and the size of the printing plate. The higher the concentration of dissolved solids, the thickness of the bioplastic will increase. The bioplastic should possess even thickness throughout the area, the variation in thickness may reduce the stability and strength of the bioplastic (Marichelvam *et al*., 2019).

**Tensile strength**

According to Abral *et al*. (2018), the tensile strength test determines the tensile strength or maximum tensile force when measuring bioplastic films. The greater the power that occurs on the plastic film, the greater the tensile force of the plastic. During testing, the material is stretched until the material breaks.

Tensile strength testing is a type of testing method for biodegradable plastic materials. The test method is also straightforward, relatively inexpensive, and standardized worldwide, such as ASTM D638 type I in America and JIS 224 in Japan. Through the release of the material, it can be seen how the material responds to the tensile force and how long the tested material extends. The test equipment used in tensile testing must have a firm grip and a high degree of rigidity (very stiff). The tensile strength measurement results are related to the amount of plasticizer added in manufacturing. The addition of excessive plasticizers will produce bioplastic with low tensile strength. Tensile strength testing involves placing materials under specific stresses to determine how strong a material is. The mechanical quality of a material is more substantial when it has a high tensile test than when it has a low tensile test.

**Elongation**

Elongation is the most significant force found in plastic films because of the tensile strength, which causes an increase in the length of the plastic film. This test is essential to determine the ability of the plastic to withstand the applied load before the plastic sample breaks or breaks. In simple terms, elongation is the maximum elongation of bioplastic when it starts to tear. Elongation is the percentage change in the length of the bioplastic when the bioplastic is pulled until it breaks. One can determine percent lengths by comparing the length of the film at the break to the length of the bioplastic before being pulled (Sofiah *et al*., 2019). Adding more significant amounts of addictive material can stretch the intermolecular space of the bioplastic and reduce the number of internal hydrogen bonds, thereby decreasing the brittleness of the bioplastic and increasing the percent elongation (Safitri *et al*., 2016).

**Elasticity**

Elasticity is the ability of a material to return to its original shape after the force acting on the object stops. Elasticity is also referred to as a measure of the stiffness of a material. Elasticity is calculated by comparing the tensile strength with elongation.

**Water resistance**

According to Ismaya *et al*. (2019), the composite's water absorption capacity is the composite's ability to absorb water over a certain period of time. The water absorption test aims to determine the resistance of bioplastics to water so that the results of the water absorption test can be used to determine the proper packaging for a product to be packaged. Percent water absorption is the percent of dry weight of bioplastic that dissolves after being immersed in water for 30 minutes. All primary composites absorb water over time. All polymer composites absorb water when exposed to moisture or immersed in water. Synthetic plastic is usually used as a food or drink container because of its high water resistance. Tests for water resistance or absorption are carried out to identify whether the properties of biodegradable plastics are similar to conventional plastics. Swelling tests determine the water resistance property of biodegradable plastics, specifically the percentage swelling of the plastic in the presence of water. This test aims to see the reality of bonds that occur in the polymer and the degree of order in the polymer, which is known from the percentage of weight gain of the polymer after swelling. Low water content has implications for preserving food, including extending its shelf life, because low water content can inhibit microbial activity.

**Biodegradability**

Biodegradation testing aims to determine the time required for biodegradable plastic to decompose in nature. The technique used in biodegradation testing is the soil burial test technique. The soil burial test technique is a technique that uses microorganisms in the soil for the degradation process. The degradation processes that occur can include hydrolysis (chemical degradation), enzymatic degradation (enzymes), degradation by bacteria/fungi, mechanical degradation (wind and abrasion), and photodegradation (light). This process can also occur anaerobically or aerobically. Biodegradable plastics are tested for their biodegradable properties by placing bioplastic samples on the soil surface and leaving them exposed to air. In the degradation process, the process of destroying bioplastic samples is influenced by the sample's contact with air and microorganisms, hydrophobic properties, additives, polymer structure, production process, and the molecular weight of the sample. Testing for bioplastics is carried out by weighing bioplastics before and after burial in the soil to determine the shrinkage weight of bioplastics. The ideal biodegradable plastic materials are completely degradable into smaller molecules of $CO_2$ and $HO_2$. Commercial biodegradable polymers must have a product mass of 50% organic molecules and not include more heavy metals that are safe for human health. Additionally, the product must be able to decay (by >90% in 6 months) in a controlled setting (Din *et al*., 2020).

### *Advantages of bioplastics*

#### Eco- friendly

Plastics are made from unsustainable fossil fuels. In addition, the production of fossil fuels causes a lot of damage to the natural environment. On the other hand, bioplastics are produced from biomass such as trees and even from plant waste, which is completely biodegradable. Therefore, bioplastics are completely made from renewable resources. The engineering of materials also causes a lot of pollution; for example, producing PVC factories release dioxins, which accumulate in humans and wildlife and are linked to reproductive and immune diseases (Porta *et al*., 2011). Burning fossil fuels increases the amount of $CO_2$ in the atmosphere, which increases the average temperature (greenhouse effect). Scientists see a clear link between increasing $CO_2$ in the atmosphere and increasing the number of thunderstorms and droughts. Climate protection is essential to environmental policy because climate change can have significant negative consequences. Governments and organizations are working with concentrated resources against this menace (Weiss *et al*., 2012).

#### Easy to decompose

Conventional plastics take thousands of years to decompose and end up at the bottom of the ocean. These plastics cause the most environmental damage including inhibiting development and destroying natural habitats. On the other hand, bioplastics take less time to decompose. For some bioplastics, this decomposition can be done at home, and even for bioplastics that require specific conditions, the time required for complete decomposition is significantly reduced. This relieves a lot of pressure on our current landfills (Sarasa *et al*., 2009).

**Toxicity**

Some plastics decompose quickly in the oceans, and many harmful chemicals are released into the waters that enter the food chain and harm animals, plants and humans. Bioplastics are completely safe and contain no chemicals or pollutants. They decompose harmlessly and dissolve in the soil. This benefit of bioplastics is especially important because the burden of toxic plastics on Earth is mounting, and at this rate, it will cause generalized problems for future generations (Witt *et al*., 2001).

**Low energy consumption**

Many companies still use fossil fuels to produce bioplastics. However, bioplastics use much less power for their production. For example, making polylactic acid involves much less energy consumption than other plastics.

**Market value of bioplastics**

According to Statista Research Department (2023), the global bioplastics market value is estimated to reach 7.6 billion US dollars. The market value of bioplastics is expected to reach US$15.55 billion by 2028. In contrast to the bioplastics market, which typically expanded year-on-year from 2017 to 2019, the COVID-19 pandemic had a detrimental impact, causing a decline of 5.02 percent in 2020 (Figure 7). By 2022, 2.2 million metric tons of bioplastics will be produced globally. Biodegradable bioplastic capacity in 2022 is 1.14 million metric tons. Future expansion is expected to continue (Figure 8).

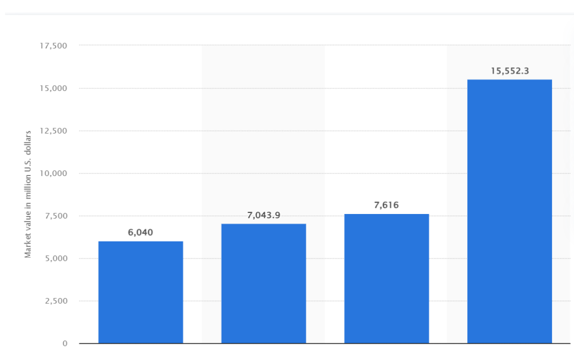


**Figure 7.** Market value of bioplastics worldwide from 2018 to 2021, with a forecast for 2028

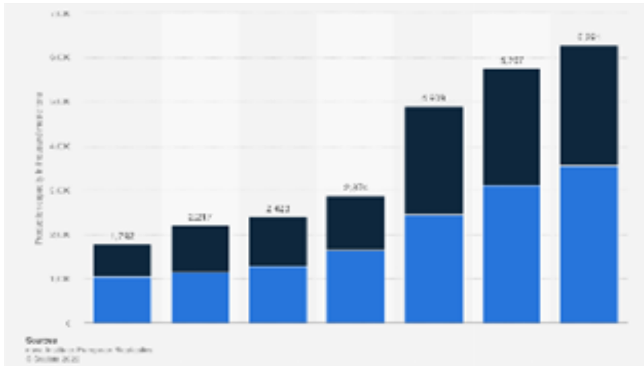

**Figure 8.** Global market value of bioplastics from 2018 to 2021

Bioplastics are plastics that quickly decompose naturally. The polymers that makeup bioplastics can come from biomass products, microorganisms, biotechnology, and petrochemical products. The main parameters observed from bioplastics are physical, chemical, and biodegradation. In the future, the demand for bioplastics will increase.

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