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BIOPLASTICS AND THEIR BIODEGRADATION IN NATURAL ENVIRONMENTS

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Abstract: Bioplastics are kind of plastics produce from natural and renewable raw materials biomass sources such as sugarcane, corn starch, wood, waste paper, vegetable oils and fats, bacteria, algae, etc. As an alternative to conventional petrochemical plastics, bioplastics are naturally degraded in the environment, and are not harmful to nature environment because it can decompose back into carbon dioxide. Thus, the products made from bioplastics are renewable, biodegradable, compostable and environmentally friendly. The aims of this short review are to present classifications of bioplastic, their advantages and disadvantages, processing, applications and the process of biodegradation.
Key words: bioplastic, biodegradation, environment

INTRODUCTION

Plastic is considered the most useful material during the last century, playing a fundamental role in modern life. Petrochemical plastics, such as polyethylene (PE), polypropylene (PP), Polyvinyl chloride (PVC), Polystyrene (PS), and polyethylene terephthalate (PET), find extensive application in various fields, including electronics, packaging, construction, and aviation [1]. These synthetic plastic materials have high strength, light weight, resistance to corrosion, and low toxicity, also are inexpensive, easy to manipulate and easily formed into diverse products [2]. The major drawback of petroleum-derived plastics is their limited degradability, guiding to the persistence of plastic content in the environment for many years. More than 34 million tons of plastic wastes are generated each year throughout the world and 93% of them are disposed of in landfills and oceans [3]. Unfortunately, the global recycling rate is rather low, with only 9 % of used plastic. Although, the EU attempts to come up against the disposal of plastic wastes and improve reusing and recycling applications, developing countries are still dependent on the conventional landfilling. Incineration of plastic wastes were also primarily applied in European countries such as Denmark which had the highest rate of incineration (76%). Except for the generation a significant amount of CO_2, also, a huge amount of ash and slag who contain hazardous and toxic compounds which are required to be disposed, can cause other serious environmental problems [4].
Particularly, plastics used in everyday activities such as bags, packaging, and bottles undergo continuous degradation into smaller particles - microplastics (MPs <5 mm) or nanoplastics (NPs <100 nm), due to various external factors such as sunlight, pressure, wind, moisture, oxygen, heat, bacterial activity, and ionizing radiation. Microplastics are globally spread throughout the environment, and their negative impact is enhanced by their ability to adsorb organic pollutants and heavy metals [5]. Given these concerns, substitution of conventional plastics with sustainable material is necessary. In the last decades, bioplastics have garnered great interest in the research community.
The main objectives of this paper are to analyze the biodegradation of bioplastics and to investigate their ability to biodegrade under different conditions. In addition, this mini review is intended to highlight the potential of these materials, and their application in Republic of Serbia.

Bioplastics

Bioplastics were first manufactured in the 1950s and re-emerged in the 1980s, but in the 2000s received the necessary attention when their industrial-scale production began [6]**.** As an alternative to conventional petrochemical plastics, bioplastics have been proposed as an environmentally friendly alternative. The main advantages of bioplastics are the fact that biogenic raw materials are used to manufactured them, needed less fossil fuel consumption, less toxic and sustainable, biodegradable, and environmentally friendly. Despite their many environmental advantages, bioplastics have disadvantages like higher prices and a lack of regulations [7].

Bioplastics are produced from edible feedstocks such as vegetable oil and starch as well as algae, wood, and agricultural wastes, e.g., sugarcane bagasse, corn stover, rice husk, and wheat straw [8]. The European Commission defined bioplastics as materials that are either a) produced from renewable resources; b) biodegradable; c) made through biological means; or d) a combination of the aforementioned requirements [9]. On the other hand, IUPAC provided recommended terminology for bioplastic, such as it could be a) bio-derived; b) industrially/home compostable; c) non-compostable or d) chemically equivalent to traditional plastics [10]. Most bioplastics are biobased and biodegradable (e.g., PLA, PHA); although there are biobased materials that are not biodegradable (e.g., bio-PET, bio-PE) [11]. In the Table 1 is given classification of the most produced bioplastic materials.

Bioplastics can be divided into three groups. The first group includes those that are bio-based and non-biodegradable (Bio-PE, Bio-PET, Bio-PVC, Bio-PU). In the second group is bioplastics that are bio-based and biodegradable (PHA, PHB, PLA) and the third groups, includes those that are synthesized by petrochemical feedstock but are still biodegradable (PBS, PCL, PBAT) [12]. The term bio-based means the product derived from biomass (plant materials). The group of mixed sources (bio/petro) includes biopolymers based on blends of Polyhydroxy alkanoates (PHA), Polylactic acid (PLA) produced by fermentation, biobased epoxy, biobased polyesters such as polytrimethylene terephthalate which are obtained from sugarcane biomethanol [13]. In fact, the production of bioplastics, as biopolimers, is mostly from agro-waste, plant residues, woodchips, starch, or microbes. The isolated monomers are converted to plastics thorough innovative fermentation or through polymer technology by using techniques such as casting, internal mixing, extrusion and injection molding.

Briefly, PLA is a biodegradable and bio-based polymer derived from renewable resources such as corn starch or sugarcane. It is the most commonly used bioplastics, with applications in various industries, such as packaging, textiles, 3D printing, biomedical implants, and disposable tableware. PHAs are a family of thermoplastic polyesters synthesized by microbial fermentation of renewable carbon sources like sugars or lipids. PBS is a biodegradable polyester produced from succinic acid and 1,4-butanediol, and had a similar property to PE and PP. PCL is a biodegradable polyester synthesized through the ring-opening polymerization of ε-caprolactone. Cellulose-based plastics are derived from the modification of cellulose.

Table 1. *Classification of the most produced bioplastics [14].*

	Source	Name	Abbreviation
Bioplastics	Petroleum based	Polybutylene succinate	PBS
		Polylcaprolactone	PCL
		Polyethylene succinate	PES
		Polybutyrate adipate terephthalate	PBAT
		Polyamide	PA
		Polyethylene	PE
		Poly(ethylene terephtalate)	PET
		Polypropylene	PP
	Bio-based	Poly(lactic acid)	PLA
		Polyhydroxyalkanoate	PHA
		Starch plastics	–
		Cellulose esters	–

		Bio-polyethylene	Bio-PE
		Bio-poly(ethylene terephtalate)	Bio-PET
		Bio-polyamide	Bio-PA

Approximately 2.47 million tons of bioplastic was produced in 2024 (Fig. 1), with degradable and non-degradable materials amounting for 1.55 and 0.86 million tons, respectively.

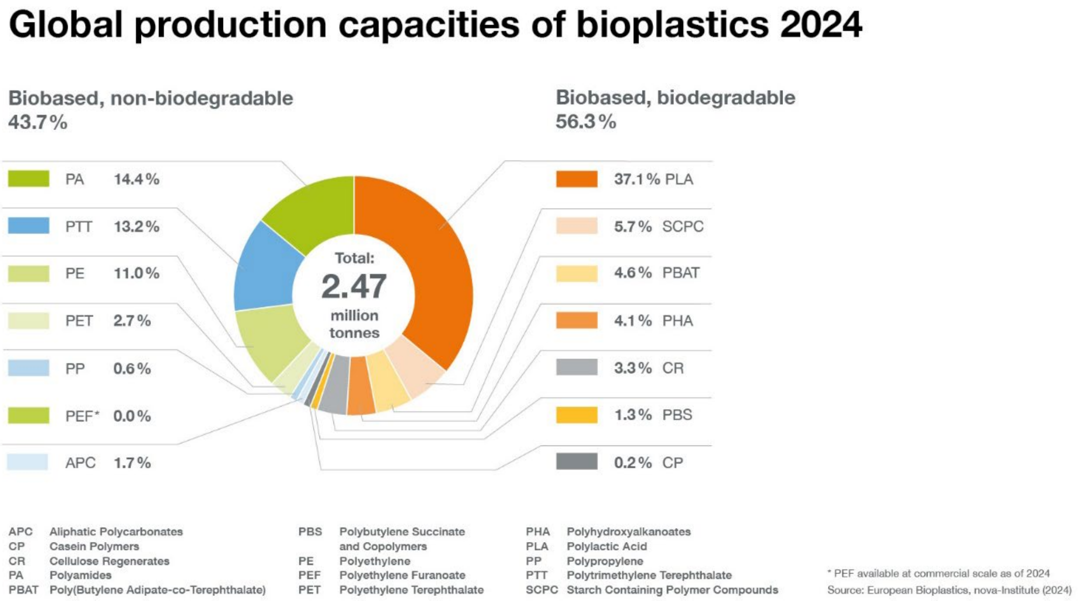

Fig. 1. *Global production of bioplastics 2024 (by material type) [14].*

The main advantage of these bioplastics is their capacity to biodegrade. The biodegradation of polymers consists of three important steps:

1. Biodeterioration, which is the modification of mechanical, chemical, and physical properties of the polymer due to the growth of microorganisms on or inside the surface of the polymers,
2. Biofragmentation, which is the conversion of polymers to monomers and oligomers by the action of microorganisms and
3. Assimilation where microorganisms are supplied by necessary nutrient sources, carbon, and energy from the fragmentation of polymers and convert carbon of plastic to CO_2, water and biomass.

Biodegradation can be further classified into aerobic and anaerobic according to the presence or absence of oxygen.

Aerobic biodegradation is the mineralization of organic compounds by the action of aerobic microorganisms in the presence of oxygen:

$$\text{Polymer} + O_2 \rightarrow CO_2 + H_2O + NO_2 + SO_2 + \text{biomass} + \text{heat} \quad (1)$$

Anaerobic biodegradation is the same process but in the absence of oxygen, resulting in the production of methane and carbon dioxide:

$$\text{Polymer} \rightarrow CO_2 + CH_4 + NH_3 + H_2O + H_2S + \text{biomass} + \text{heat} \quad (2)$$

In anaerobic degradation, energy is mainly released as methane, and less as a heat.

Polymer biodegradation is influenced by the combination of environmental factors (humidity, light, temperature, pH, nutrient supply, etc.) and the physio-chemical characteristics of the polymer (molecular weight, hydrophobicity, morphology, crystallinity, porosity, etc.). The biological degradation occurs by surface erosion, where extracellular enzymes operate only on the polymer surface, which prevents them from penetrating deeply into the polymer matrix. The process cross through three steps: first were microorganism interaction with the polymer surface, the second step is microorganisms' growth multiplying itself and breaking down the polymers and lowering their molecular weight. And finale step is mineralization of the polymer, where production of CO_2, H_2O, or CH_4 occurs. It should be noted, the process of biodegradation is influenced, excepting the material's physico-chemical structure, by the polymer's chain configuration. The longer the polymer's chain is, the more difficult it is to degrade. However, the polymer's crystallinity is also an important parameter of biodegradation, as the amorphous parts of the polymer are, easier to degrade, compared to the crystalline parts.
Biodegradable polymers are decomposed by microbial attack. More than 90 types of microorganisms are responsible for biodegradation in different environments. Besides microbes, bacteria and fungi are involved in bio-polymers' biodegradation. Various microorganisms isolated from soil environments utilized bioplastics as the carbon source. Actinobacteria species suchas *Amycolatopsis*, *Thermomactimyces*, *Actinomadura*, *Nonomuraea*, *Laceyella* and *Streptomyce*s species were obtained from soil among which *Amycolatopsis* and *Streptomyces* were the most common species. *Paenibacillus*, *Pseudomonas*, *Bacillus* and *Bulkholderia* species were mainly isolated from different soil environments and they were capable of degrading the bioplastics. Among the soil isolated fungi species responsible for bioplastics biodegradation, *Aspergillus*, *Fusarium* and *Penicillium* were the main species. In the Table 2 is given the microbes used in biodegradation different types of bioplastics.

Table 2. *Types of bioplastics and the microbes used in biodegradation [15].*

Type	Microbes	Use
PHB	*Rhizosphere, Alcaligenes eutrophus, Azotobacter beijierinckia, Pseudomonas oleovorans, Rhizobium sp*	Soil *Rhizosphere* of maize, wheat and trefoil eighteen PHB producers
Cellulose	*Pseudomonas strains, Neisseria sicca, Alcaligenes xylosoxidans*	Degrade cellulose acetate with DS1.8 And DS2.3. The highest degradation rates reported were 60 and 45% within 20 days.
Starch	*Pseudomonas aeruginosa*	Produces Polypropylene
protein base	*Bacillus subtilis* and *Escherichia coli*	Using cane molasses as an inexpensive substrate.
Polylactic acid	*Rhizopus delemar*	Pure lactic acid production, end product of fermentation
Polyurethane	*Pestalotiopsis microspora*	Ability to degrade the synthetic Polymer Polyester polyurethane (PUR), useful for bioremediation
Polydiethylene adipate	*Comamonas acidovorans, Pseudomonas aeruginosa, Pseudomonas stutzeri, Streptomyces badius*	Waste management, and their Consumption is increasing day by day at a rate of 12% per annum

Enzymes which can be either intracellular or extracellular, are responsible for enzymatic degradation of bioplastics. The optimal temperature range for enzyme activity is between 25ºC and 40ºC. Enzymatic degradation of polymers relies on the potential of microorganisms to produce specific enzymes such as depolymerases. These enzymes hydrolyze the polymers into water-soluble forms, so it can be dissolved in water for rapid biodegradation [16].

At the end of this short presentation on the types and ways of obtaining bioplastics, we will mention the advantages of biodegradation of bioplastics and environmental benefits. First of all is reduction in fossil fuel dependence, where plant starches, agricultural byproducts, and microbial fermentation are a few illustrations of the renewable materials used to make bioplastics. We expected lowered emissions of greenhouse gases, and at the same time cultivating plants to produce bioplastics can aid to achieve carbon neutrality by storing CO_2. The most important advantages of biodegradation of bioplastics is reduced accumulation of plastic wastes. This will lead to better end-of-life care management, by composting, anaerobic digestion, and recycling of bioplastics.

The state of bioplastics in Republic of Serbia

Although the consumption of plastic in Serbia is lower compared to the average of the European Union - about 100 kilograms per inhabitant per year, the growth trend is present. Estimates indicate that around 200,000 tons of plastic are disposed of annually in landfills in Serbia, where they remain for hundreds of years due to the slow decomposition process. However, global demand for plastic materials continues to rise despite environmental challenges, with increasing attention to recycling and the development of biodegradable plastics. In Serbia, there is currently no data on the amount of bioplastic that is produced, used and disposed of. Large quantities of (bio)plastics are also widely used for food contact, such as packaging or disposable tableware. According to the data of the Environmental Protection Agency [17], the amount of plastic placed on the market of the Republic of Serbia in 2024 is 194.3 tons. It is amount of conventional plastics. Also, general packaging waste management targets for 2023 are set at 65.8% for waste reuse and 62.5% for waste recycling.
There is no data on the use of bioplastics, so it can be concluded that they are not widely represented on the Serbian market, mainly through single-use packaging.

CONCLUSION

The production of bioplastics has received significant attention from the public in recent times, due to its contribution to the protection of the environment and the preservation of the ecosystem. The present study demonstrates the benefits of bioplastics as a potential alternative to single-use plastics and the concept of sustainable development, i.e. "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Moreover, the environmental impact caused by the large quantity of non-degradable waste materials is promoting research to develop new biodegradable materials that can be manufactured from natural resources like biomass, plants, bacteria. So, the new developments of bioplastics in the future can cause the efficiency of production will be increase, develop new applications and new opportunities of bioplastics. Nowadays, manufacture bioplastic could be significantly applying and commercialize for various industries such as agriculture, medical, pharmaceutical, veterinary, etc.
Bio-based plastics and biodegradable plastics can affect the environment and human health to different degrees, and this depends to a great extent on the type of material, the individual product and its specific life cycle. Therefore, bioplastic is not the solution for all the problems related to the current use of plastic. The application and further development of bioplastics require careful weighting and balancing between their limitations and benefits.

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