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ADVANCES IN BIO-BASED FOOD PACKAGING MATERIALS - A REVIEW

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Abstract

In the recent years there has been a constant need for the development of novel packaging materials, which can be defined as made from materials derived from renewable sources, that can provide alternative and sustainable routes for the food packaging industry in order to replace the petroleum-based polymers with bio-based materials. A constant concern for the environment wellbeing has been the agricultural waste which is not valorised in a sustainable matter but rather incinerated or disposed of in landfills. A novel way to promote a circular bio economy would be to utilise these agri-food waste and by-products for the development of novel and sustainable packaging materials. This article aims to review the development of bio-based packaging materials and production technologies considering by-products and waste minimization, recyclability, biodegradability, and their impact on the circular bio economy and sustainability.

***Key words**: agricultural waste, circular bioeconomy, sustainable packaging materials.*

INTRODUCTION

One of the main problems that the industry in general, and the food packaging industry in particular, will have to solve in the next few years is that of the resources it uses. Currently, the raw materials used to meet most of the needs of human society are based on fossil fuels (Yi et al., 2023). Most of the researchers believe that the reduction of the fossil resources stock is inevitable and even their exhaustion in the course of a few decades (Azni et al., 2023).

Plastic materials have become more and more important during the last century, finding applications in the most diverse fields of industry and the life of the common human beings. Plastic materials are a convenient solution for many technical fields, due to their good physical-mechanical characteristics, their low weight and reasonable price. The main disadvantage is given by the long-term pollution effect they produce after their lifespan (Gustavsson et al., 2017; Solarin, 2020). In recent years, in the food packaging polymer industry, there is a tendency to replace conventional plastic materials with ones that show improved biodegradability or, even better, with ones that come from renewable resources and are susceptible to biodegradation (Rai et al., 2021). The main issue for the food packaging industry is the elimination of harmful substances that could be in the packaging materials, recyclability, safety and easy separation of materials in order to be recycled, use of recycled resources and handling precautions (Mangaraj et al., 2019; Tajeddin & Arabkhedri, 2020; Motelica et al., 2020).

The newest economic interest is the use of resources of renewable plastic materials as a respect for the environment, and as an ecological management for exhaustible fossil materials. From this perspective, plant raw materials and biopolymers of this origin possess properties of great interest in the plastics industry such as: biodegradability, biocompatibility, selective permeability and modifiable physical-mechanical properties (Asgher et al., 2020).

Bioremediation - an emerging approach towards environment restoration

Environmental bioremediation represents a new field within biotechnologies. Bioremediation is a method of eliminating pollutants from the environment with the help of microorganisms, by transforming them from toxic compounds into non-toxic compounds, without affecting the environment (Mehrotra et al., 2021). In other words, bioremediation is a technology that aims to remove pollutants from the environment, restoring the original natural environment and preventing future contamination (Gu, 2021). These microorganisms can be isolated from contaminated areas or from other sources and transferred to polluted regions. Starting from the degradative activities of microorganisms, numerous depollution technologies have been researched and developed, which are included generically in the term bioremediation (Pande et al., 2020). The control and optimization of bioremediation processes is a complex system that involves several factors including: the existence of a microbial population with a high capacity to degrade polluting compounds; the availability of some contaminants in the populations of microorganisms; environmental factors (soil type, temperature, pH, presence of oxygen and other acceptors, nutrients) (Ayilara & Babalola, 2023; Kapur et al., 2023). Microorganisms can be isolated from almost all environmental conditions such as from regions with low temperature below zero degrees, from regions with very high temperatures, desert conditions, from water, etc. (Hlihor & Cozma, 2023). The most important factor for these microorganisms to survive is the carbon source and the energy source.

MATERIALS AND METHODS

The information and data presented in the review article is composed of novel researches made in the past decade regarding the advances in bio-based food packaging materials. The analysis focused in the importance of developing bio-based materials for the food packaging industry in order to replace the fossil fuel ones, the methods of bioremediation and biodegradation and the impact on the environment. Another critical point of the research was to gather the latest applications of the bio-based packaging materials and give a clear example on what food products were they used on. Web of Science, Elsevier, PubMed, ScienceDirect, JSTOR and Springer databases were electronically searched for articles published in the last decade. The literature search included document types such as research articles and reviews, on the following topics: „bio-based materials", „bioremedation", „food packaging sustainability", "food packaging biopolymers". Research articles published in the last decade were gathered and synthetized from publisher databases in order to give an in-depth view of the discussed subject.

RESULTS AND DISCUSSIONS

The biodegradability of polymers is influenced by numerous structural parameters and by the use of statistical data interpretation methods which. Through these methods it can be established which of them correlates best with biodegradability (Idrees et al., 2020; Van der Zee, 2020). Most natural polymers such as starch, cellulose and proteins are easily biodegraded by hydrolysis followed by oxidation with the help of enzymes (Bahl et al., 2021). In order to evaluate the biodegradation process, it must be taken into account that the molecular properties of the polymer, such as the distribution of molecular masses, crystallinity and morphology, will dictate the physical properties of the packaging products obtained from these polymers (Glaser, 2019; Mangaraj et al., 2019).

Characteristics and types of biodegradable plastics

In the recent decades, plastic has conquered the world and penetrated all spheres of our life from industry to everyday life: plastic windows, tableware, furniture, packaging, almost everything we use is made of plastic or contains the material plastic. The production of biodegradable plastics and food packaging reached its peak in 2010, when several major companies producing bioplastics manufactured products from a large set of raw materials (Haider et al., 2018). In the last decades, synthetic polymers are used on a large scale in many fields of activity. These macromolecular substances are usually of petroleum-based origin and are not biodegradable (Gowthaman et al., 2021). However, oil resources are limited and the use of non-biodegradable polymers causes serious environmental problems.

Many solutions have been proposed for waste management such as recycling, incineration and degradation of food packaging materials. Quality products are not obtained through recycling due to the heterogeneous nature of plastic materials and the incineration of plastic materials with the release of toxic gases and vapours can be a serious health hazard, thus the most appropriate solution is represented by using biodegradable food packaging materials (Shaikh et al., 2021; Panou & Karabagias, 2023).

Technologies for obtaining new polymer materials are very promising from the point of view of applications, such as: agriculture (films, products with herbicidal action), consumer goods (packaging) with a determined life span, products based on polymer matrices with controlled release of active substance (medicines), recovery and recycling of polymer waste, medicine and implants (To'ychiyev & Soliyev, 2022; García-Collado et al., 2022). Current trends in the science of polymer processing are oriented towards the creation of new types of materials with biodegradability properties (Figure 1), biocompatibility, corrosion resistance, flexibility, optical and electrical properties, to replace the materials traditionally used in agriculture, electronics, industry, medicine and the possibility of recovery and recycling of these materials to protect the ecosystem (Terzopoulou et al., 2022; Gnanasekar et al., 2023).

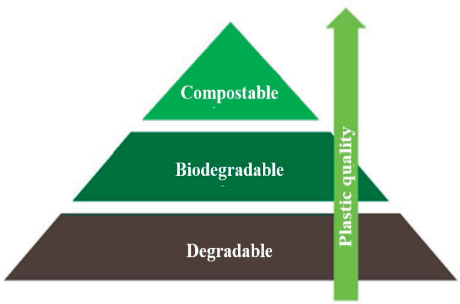

Figure 1. Novel types of biodegradable materials

On a worldwide level, the idea is accepted that the prolonged use of polymers for applications that require a short lifetime (packaging, food industry, surgery, hygiene) is not entirely adequate. This is not recommended when there are concerns about preserving ecological systems (Nanda et al., 2022). Most synthetic polymers are obtained from petroleum resources and are not biodegradable.

Their introduction in the manufacture of landmarks for industrial purposes is not negligible. Obtaining biodegradable polymer mixtures constitutes a priority and multidisciplinary research direction, closely connected with fundamental research in the field of thermodynamics and polymer compatibility, environmental engineering, biotechnologies (Rajeshkumar, 2022).

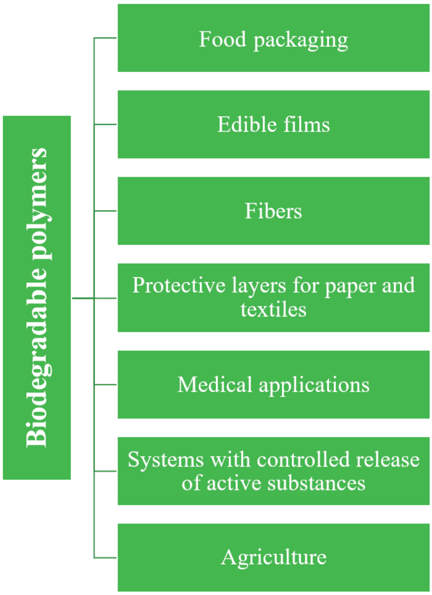

Figure 2. Uses of biodegradable polymers in the industry

Plastic waste is resistant to microbial attack and thus accumulates in large quantities in the soil, thus this resulting waste does not help to fertilize the soil. The best alternative for plastic waste is to use degradable plastic materials. Natural polymers such as starch, wood flour are biodegradable, while most synthetic polymers are not. Additives of high molecular weight plastics, such as plasticizers and reinforcing agents, are susceptible to microbial attack (Maitlo et al., 2022).

Biodegradable biopolymers represent a current field of scientific research of great ecological, scientific and economic importance (Figure 2) (Baranwal et al., 2022). However, the concern for the environmental consequences of products made of such materials, when they end up in landfills after having fulfilled their role, is continuously increasing. In particular, it raises material, disposable problems, such as food packaging. Macromolecules with high molecular mass, containing covalent bonds, are not easily decomposed naturally, under the conditions provided by waste management infrastructures. Polymeric materials manufactured starting from natural biopolymers, such as polysaccharides (such as starch and cellulose), proteins, triglycerides (vegetable oils), generally agricultural products, can be biodegradable and can play a considerable role in solving the environmental problems raised by the use of polymeric food packaging materials (Berradi et al., 2023). Biodegradable polymers can also be obtained by bacterial biosynthesis from natural materials (polysaccharide polyesters), or by chemical synthesis from renewable natural materials (lactic acid polyesters - obtained by fermentation starting from starch). Small products based on synthetic polymers and biopolymers can present a greater or lesser degree of biodegradability (Garrison et al., 2016). Biodegradable materials undergo a decomposition process, resulting in carbon dioxide, methane, water and other organic products, under the enzymatic action of some microorganisms (Figure 3).

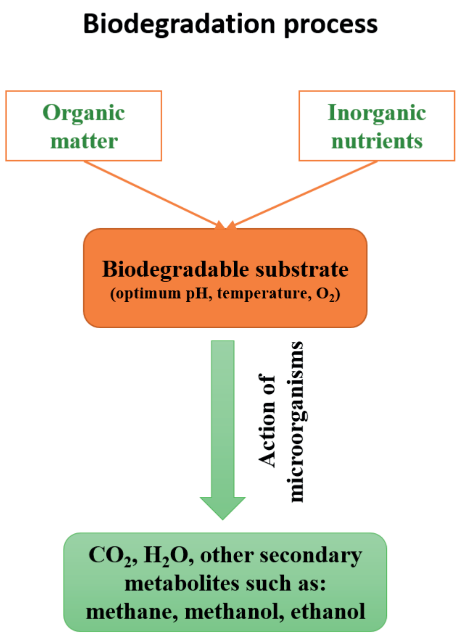

Figure 3. Biodegradation process (own source)

Biodegradable polymers of petrochemical origin

The first researches for their realization were undertaken in the 1970s, consisting in the association of polyethylene with starch or cellulose (Čolnik et al., 2020). By introducing a quantity of 10% starch into a polyethylene matrix, to which 1% catalysts are added to cause the breaking of chemical chains and the consumption of starch by microorganisms, the biological degradation of the plastic material is achieved (Wani et al., 2018). The process was used in the manufacture of polyethylene films for the protection of agricultural seedlings or for bags and packaging, today being abandoned. Recently, a new family of biodegradable polymers containing iron carbamates, nickel and manganese or nickel stearate, as oxidizing agents, were developed (George et al., 2018). Environmentalists were very circumspect about these oxidants, since they actually fragment and not biodegrade the polymers, and the metals that come from the mentioned salts will themselves pollute the environment. The latest research aims to obtain biodegradable materials, through various processes, starting from polymers of petrochemical origin: aliphatic polymers (polycaprolactam, polytetramethylene), polyesters and vinyl polymers. The materials obtained correspond to the norms of environmental protection, but they are expensive (Singh et al., 2014).

Biodegradable polymers of natural origin

They are substances synthesized through biological or chemical processes, starting from natural monomers. This category includes biopolymers, polymers of bacterial origin and synthetic polymers. Biopolymers (natural polymers) are of vegetable and animal origin or are produced by microorganisms (Luckachan & Pillai, 2011). The most important family of natural polymers is that of polysaccharides, which includes starch (derived from potatoes, wheat and corn), cellulose and lignin. Another family of natural polymers is composed up of proteins from oleaginous plants (rapeseed, sunflower, soybean, pea and bean), from cereal bran (wheat gluten), from animal tissues (collagen, gelatine) or from cow's milk (casein) (Gandini et al., 2016).

Polymers of bacterial origin are produced by certain bacteria that accumulate them in the cytoplasm, through fermentation (Rehm, 2010). Examples of polymers of bacterial origin are polyhydroxybutyrate and polyhydroxyvalerate. These polymers are considered semi-biosynthetic and they can also be obtained from some genetically modified plants, in which case they are called biosynthetic (McAdam et al., 2020).

Starch is a cheap material obtained from the processing of corn and other crops. Biodegradation of starch products recycles atmospheric CO_2 produced by starch-producing plants. Starch contains amylase and amylopectin, at rates that vary depending on the starch-producing source. Biodegradable polymers obtained from starch can be produced by mixing them with synthetic polymers (Shrestha & Halley, 2014). Cellulose obtained from chemically modified plants is used in various applications, for example, cellulose acetate is used in many everyday items such as toothbrush handles as well as adhesive tape.

Synthetic polymers are obtained by polymerizing some natural monomers, the best known being polylactide (PLA) which is obtained by bacterial fermentation of lactic acid. This category also includes polyhydroxyalkanoates (PHA) which are polyesters of aliphatic hydroxy acids, polycaprolactone (PCL) and polyglycolide (PGA). The mechanical properties can be improved by combining these polymers, obtaining co-polymers (Nampoothiri et al., 2010).

Table 1. Bio-based food packaging materials – uses and advantages

Biopolymer	Treated food product	Active element	Reference
Soy protein isolate	Bluefin tuna filets	Montmorillonite and clove essential oil	Echeverría et al., 2018
Chitosan and Corn starch	Blueberries	Lemon essential oil and grapefruit seed extract	Bof et al., 2021
Corn starch	Cheese	Green synthesized AgNPs	Ortega et al., 2017
Tapioca starch	Chicken meat	Grape pomace extracts and cellulose nanocrystals	Xu et al., 2018
Polylactic acid	Cottage cheese	Commercial nanoparticles: TiO_2, nano-TiO_2 + nano-Ag	Li et al., 2017
Curdlan + PVA	Pork meat	Thyme essential oil	Zhang et al., 2020
Whey protein	Kasar cheese	Oregano and garlic essential oils	Seydim et al., 2020
Gelatin/Gellan gum	Milk and fish	Red radish anthocyanins	Zhai et al., 2018

Biocompatible polymers

Biocompatible polymers (biopolymers) are polymers present in living organisms (animals, plants, algae) or synthetic polymers of natural origin (PLA, PHA, PHB, PHV, PHBV, PCL, PGA). They are not rejected by the human body and, in general, are biodegradable. Many synthetic polymers of natural origin are obtained through a bacterial fermentation process, using renewable substrates of carbon, carbohydrates and lipids (Chen et al., 2008). There are several hundred types of bacteria that accumulate in cells natural polymers from culture media, polymers can reach 80% of the dry cell mass. They are then extracted from the dried cells by dissolution with organic solvents and then by precipitation in methanol or ethanol.

The applications of biocompatible polymers are found especially in medicine and in the pharmaceutical industry (Koller, 2018). They must have a high chemical resistance, withstand multiple sterilizations (with steam, ethylene oxide or x-rays treatment), without losing their mechanical properties and biocompatibility (Mukherjee et al., 2023). They must also possess very good mechanical properties, especially rigidity, resistance to breaking and durability in order for them to be considered for being used in the food packaging industry (Khatun et al., 2023). A field of great interest for the use of biocompatible polymers is the controlled release of some active substances in the human body or for the use in food packaging materials for the same reason (Westlake et al., 2023). This can be done multiple ways: the active substances are embedded in a core protected by a polymer membrane through which it is diffused into the food packaging system or the human body over a longer period of time or the active substance is embedded in a biodegradable polymer that disappears with the distribution of the active principle in the food packaging system or the human body (Azman et al., 2023).

CONCLUSIONS

Conventional polymers such as polyethylene and polypropylene persist for many years after their disposal in environment. These polymers are unsuitable for applications in the food packaging industry where they are used because they are complicated to recycle and they do not have the capacity to biodegrade. Moreover, plastic materials are contaminated by biological substances, making their physical recycling impractical and undesirable. Due to environmental concerns the food packaging industry is slowly changing the way it uses plastics and other non-biodegradable polymers in the production of packaging materials. Natural biopolymers, such as polysaccharides (starch and cellulose), proteins, triglycerides (vegetable oils) or other agricultural derived products are being studied and used because their biodegradable and compostable proprieties, thus playing an important role in solving the environmental problems raised by the use of polymeric materials. There are several ways biodegradable polymers can be obtained: through bacterial biosynthesis from natural materials (polysaccharide polyesters), or through chemical synthesis from renewable natural materials (lactic acid polyesters obtained by fermentation starting from starch. Bio-based food packaging materials are also very important because they can help extend the shelf=life of food products due to their capacity to be enriched with antimicrobial substances like essential oils, chitosan and many other active substances. Also, researchers have concluded that these novel packaging materials can protect the food product by preventing physical, chemical, and/or microbiological contamination, thus fulfil the function of a barrier against microorganisms, oxygen, humidity, UV and undesirable odours. The uses of these novel bio-based food packaging materials not only are sustainable and advantageous for the reduction of environmental pollution, but also can help producers keep their food products longer on the store shelfs.

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