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BIOPOLYMERS: TYPES AND THEIR POTENTIAL FOR USE IN VARIOUS FIELDS OF BIOMEDICAL AND COSMETIC ENGINEERING

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Abstract

In recent years, biopolymers have attracted the attention of specialists and researchers in various fields, including biotechnology, materials science, engineering, and medicine. The main driver is the possibility of combining scientific and technological progress with sustainability. This is a vast research topic because there are several classes and varieties of biopolymers. Polyhydroxyalkanoates (PHAs), a specific type of polyesters, are biodegradable polymers with various thermoplastic characteristics formed by microorganisms under adverse growth conditions. In recent years, PHAs have been increasingly employed in biomedical applications owing to their adaptive mechanical features, cytocompatibility, capacity for cell adhesion, and controlled biodegradability. The increasing potential is also indicated by the benefits of 3D-printing technology for fabricating intricate structures, fast prototyping, and personalization. This study aims to detail the types of biopolymers, as well as their areas of use, after a thorough description of the synthesis and manufacture of PHAs. The most recent and significant medical applications of PHAs in tissue engineering, medication delivery, and vascular stenting are listed below.

***Key words**: Polyhydroxyalkanoates, biomedical uses, medical devices, biodegradability.*

INTRODUCTION

Polyhydroxyalkanoates (PHAs), a specific class of polyesters, are biodegradable polymers with various thermoplastic characteristics formed by microorganisms under adverse growth conditions (Rodriguez-Perez et al., 2018; Angra et al., 2023). In recent years, PHAs have been increasingly employed in biomedical applications owing to their adaptive mechanical characteristics, cytocompatibility, capacity for cell adhesion, and controlled biodegradability. The benefits of 3D-printing technology also show increasing potential for fabricating intricate structures, fast prototyping, and personalization (Kovalcik, 2021; Cecen, 2023).
In this study, we list the most recent and important medical applications of PHAs in tissue engineering, drug delivery, and vascular stenting. Recently, biopolymers have attracted the attention of specialists and researchers in various fields, such as biotechnology, material science, engineering, and medicine (Rehakova et al., 2023; Kourmentza et al., 2017). The main reason is the possibility of combining scientific and technological progress with sustainability (Koller et al., 2017). Biopolymers can be divided into many classes and variations, making them a broad field of research.
Biofuels are recommended, special mainly because they are environmentally beneficial, renewable, easy to use, and less dependent on petroleum (Dilkes-Hoffman et al., 2018). However, the production costs of biofuels are higher compared to fossil fuels. For this reason it is important to find alternative fuels with lower production costs (Angra et al., 2023). Therefore, the development of suitable production processes is necessary.

1. BIOPOLYMERS

Biopolymers can be obtained in different ways: through bacterial biosynthesis, or through different processes, such as syntheses chemicals from renewable natural materials (polyesters from lactic acid - obtained by fermentation starting from starch).

They can be obtained from microbial systems, extracted from plants (e.g., corn, soybeans, and various trees), or chemically synthesized from basic biological systems. They have attracted particular interest from the scientific community owing to their wide range of properties and potential uses (Subash et al., 2023). Biopolymers are chain molecules composed of repetitive monomer-building units. They are being materials with specific properties, such as biocompatibility, biodegradability, low antigenicity, high bioactivity, processability to complicated forms with adequate porosity, capacity to support cell growth and proliferation, and adequate mechanical properties (Chai & Isa, 2013). Biopolymers can be used for biomedical applications such as wound healing acceleration or drug carrier.

These characteristics have stimulated research on their potential applications in the production of biosensors, absorbents, packaging, cosmetics, food, electronics, medical devices, and biofuels (Bugnicourt et al., 2014; Keskin et al., 2017; Koller & Mukherjee, 2022). They might be polynucleotides, polypeptides (short-chain monomer polymers), or polysaccharides (linear polymeric carbohydrate structures), depending on the monomer unit in the biopolymer structure.

Biopolymers (Table 1) are abundant in nature and come from various sources.

Table 1. Types of biopolymers and areas of use.

Biopolymers	Resources	Uses	References
Polylactide (PLA)	Renewable resources	Implant devices, stents, vascular prostheses	Da Silva et al., 2018; Amnieh et al., 2021; Blume et al., 2022
Poly-lactic-co-glycolic acid (PLGA / PLG)	Fossil resources	Regenerate bone tissues Tissue/organ deficiencies	Alsaab et al., 2022; Yoo & Won, 2020; Huo et al., 2019
Polycaprolactone (PCL)	Fossil resources	Drug-controlled applications Implants	Dash & Konkimalla, 2022; Baghersad et al., 2022
Poly(3-hydroxybutyrate-co-3-hydroxyvalerate) – PHBV	Renewable resources (microbial polymer)	Packaging Agriculture Medical industries Medical implants	Ponjavic et al., 2023; Kaniuk & Stachewicz, 2021

For example, there are biopolymers obtained from natural sources that are classified in: 1) polysaccharides (starch, cellulose, pectin, chitosan) and 2) proteins and lipids (gluten, soy, casein, gelatin, collagen). Another type of biopolymers are obtained from renewable sources: 1) microbial polymers (polyesters, polyhydroxyalkanoates, pullulan, curdulan) and 2) natural polymers (polylactic acid). The third type of biopolymers are obtained from fossil resources, such as polyvinyl alcohol or aliphatic and aromatic polymers (PGA, PCL, PVA etc.).

1.1. Biodegradable synthetic polymers

- ***Polylactide (PLA)***

Polylactic acid (PLA) is obtained by converting carbohydrates into lactic acid. This process is often used in the food industry (e.g., milk industry, wine production, meat industry, obtaining fermented plant products) (Da Silva et al., 2018). Due to the increased interest the need to replace conventional plastic materials, the development of PLA production bioprocesses has increased significantly. In 2020, approximately 1 million tons of PLA were produced $2 / kg (Rajendran & Han, 2023). Lactic bacteria (LAB) are bacteria that ferment, and are used to produce PLA. *LAB* are gram-positive *Bifidobacterium*, *Enterococcus*, *Lactobacillus*, *Aerococcus*, *Streptococcus*, etc. (Wang et al., 2021).

Polylactic acid (PLA) is an aliphatic polyester with thermoplastic properties. To obtain it you can use various natural raw materials such as rice, corn starch, potatoes, sugar cane, etc. Compared to other biopolymers, PLA has the benefit of relatively low manufacturing costs and is biodegradable (Amnieh et al., 2021). It also exhibits mechanical qualities equivalent to synthetic polypropylene polymers (DeStefano et al., 2020). Furthermore, PLA is a bioabsorbent that may provide advantages over implanted devices (Da Silva et al., 2018).

For instance, in the case of stents, the biopolymer can biodegrade into body fluids after being utilized as an intravascular dilator, preventing the need for a second surgery to remove the stent. Studies show encouraging results after testing biodegradable stents in human models (Soares et al., 2010). Positive findings were also obtained in a study that examined the biodegradation of PLA stents in the rabbit aorta (Yang et al., 2023). Polyglycolic acid-based PLA-PGA copolymer-based devices have been used in orthopedic applications. Copolymers compressed into plates or screws have been used to repair fractures and fill in bone deformities (Castañeda-Rodríguez et al., 2023). A technique for making woven wavy vascular prostheses made of PLA and polyethylene terephthalate (PET) that restores blood flow in damaged blood artery segments was patented by Rebelo et al. (2017). These prostheses are particularly useful for vascular surgery. To create a system in which the human body may absorb PLA while the other offers mechanical support, these two biocompatible wires have been employed.

PLA has been employed extensively in tissue engineering applications, including bone support (Zhang et al., 2017), cartilage, tendons, and neurons (Schedin-Weiss et al., 2017), and vascular regeneration. Because PLA resorbs (in roughly 4-6 years) and resembles the bone structure in appearance, it has significant potential for bioactivity in mending bone fractures (Zhang & King, 2020).

- ***Poly-lactic-co-glycolic acid (PLGA / PLG)***

Polylactic-co-glycolic acid polyester consists of poly-lactic acid (PLA) and poly-glycolic acid (PGA). Owing to its biocompatibility, biodegradation rate, and capacity to alter surface characteristics to ensure better interaction with biological materials, polylactic-co-glycolic acid (PLGA) is frequently utilized as a primary material for biomedical applications. An examination of the state of the art in this area indicates the existence of novel techniques for fabricating PLGA-based biomimetic supports that can alter cell interactions for better replacement, repair, or enhancement of bone tissue function (Alsaab et al., 2022). PLGA is primarily utilized to regenerate bone tissues and exists in several forms, including microspheres, hydrogels, and porous supports. However, poor osteoconductivity prevents the therapeutic use of pure PLGA in bone repair.

To make PLGA more biomimetic, it is frequently combined with other materials, such as ceramics or bioactive glass, or suitably changed. From a structural standpoint, lactic acid and glycolic acid, the two monomers constituting PLGA, can be combined in various ratios to create a linear copolymer. PLGA supports are now employed to heal tissue/organ deficiencies in the skin (Pathan & Shende, 2021), blood vessels (Han et al., 2011), liver (Ayhan & Ayhan, 2017), and bones (Sharma et al., 2016). Over time, the biopolymer structure was also altered. To considerably enhance tissue regeneration, medications or proteins, in particular growth factors or genes that express growth factors, have been incorporated into porous PLGA supports (Wang et al., 2023).

- ***Polycaprolactone (PCL)***

Polycaprolactone (PCL), an aliphatic polyester prepared using petrochemical processes, is a biocompatible synthetic polymer. It is appropriate as an implantable biomaterial despite its poor mechanical stiffness because its breakdown products do not induce inflammation in the human body (Nejati-Koshki et al., 2017). PCL is frequently employed in drug-controlled applications and long-term implants (which scarcely deteriorate) (Irani et al., 2017). The Food and Drug Administration (FDA) has provided a green light for using PCL-based media in human applications, which are primarily employed in cell therapy (Kamath et al., 2014). The PCL biopolymer increases the production of collagen, making it possible to treat early signs of aging, such as loss of skin elasticity (Dash & Konkimalla, 2022).

Polyacrolactone is used as a composite material in dental medicine to fill root canals and PCL and PLA stents for the treatment of cardiovascular diseases (Guerra et al., 2018). PCL ensures the proliferation of endothelial vessel cells in the outer wall of the stent, while the internal PLA wall prevents the accumulation of cells that cause restenosis.

1.2. Biodegradable natural polymers

- ***Polyhydroxyalkanoates (PHAs)***

Biopolymers of bacterial origin are an exciting area of research with numerous potential applications. These biopolymers are produced by bacteria and are composed of natural macromolecules such as polysaccharides, proteins, and polyesters. One of the most well-known biopolymers of bacterial origin is polyhydroxyalkanoates (PHAs), which are biodegradable and biocompatible polyesters that are synthesized by bacteria as a form of carbon and energy storage (Silva et al., 2012; Krumnow et al., 2009; Kaur & Sharma, 2023).

Polyhydroxyalkanoates (PHA) are a group of biodegradable polymers that have gained considerable attention recently due to their potential use as an alternative to conventional, petroleum-based plastics. A wide range of microorganisms produces PHA polymers and are fully biodegradable under various environmental conditions (Kourmentza et al., 2017; Sabapathy et al., 2020). One of the main advantages of PHA is their ability to biodegrade in water and soil (Koller & Mukherjee, 2022). Microorganisms biodegrade PHA that break down the polymer chains into simpler compounds that can be used as a food source. In water, PHA is degraded more slowly than in soil due to lower microbial activity and other organic matter, such as dissolved organic carbon (Koller, 2018).

However, the biodegradability of PHA in water and soil can be affected by various factors, such as temperature, pH, nutrient availability, and oxygen levels. For example, PHA biodegrades more rapidly in warm, moist environments with high microbial activity and nutrient availability, whereas colder and drier conditions may slow the process (Roy & Visakh, 2014).

PHA biopolymers occur naturally and are produced from renewable carbon sources. They are made as intracellular granules that serve as energy and carbon reserves absorb electrons, protect against stress, and provide cells with a means of survival under stressful conditions (Somleva et al., 2013). A variety of microbial species produces them. PHAs are made as a precaution against nutrient limitation and extreme conditions) (Koller, 2018). PHA accumulates when the culture medium contains too much carbon, but cell development is limited by nitrogen, phosphorus, oxygen, or magnesium.

About 150 different hydroxyalkanoic acids have been identified as PHA constituents, leading to the production of many polyesters of bacterial origin. These polymers can be used in pure form or as additives in petrochemical plastics, such as polyethylene, and have a wide range of applications (packaging materials, including films, boxes, coatings, fibers, and foams); however, they are handy for medical applications because they are fully biodegradable thermoplastic biomaterials that are environmentally friendly and biocompatible (Morgan-Sagastume, 2016). PHA can be used as a material for implanted devices because it degrades slowly and does not cause an immune response in humans (Vicente et al., 2023).

- ***Poly(3-hydroxybutyrate-co-3-hydroxyvalerate) – PHBV***

Polyhydroxybutyrate-valerate (PHBV) is a biopolymer that has attracted attention due to its potential use as a biodegradable plastic. PHBV comprises two monomers, 3-hydroxybutyrate (3HB) and 3-hydroxyvalerate (3HV). It is biodegradable, compostable, and has similar mechanical properties to conventional plastics. PHBV has potential applications in packaging, agriculture, and medical industries, which can be used in medical implants (Ponjavic et al., 2023). The creation of medical devices implanted for dental, orthopedic, thermoplastic, and skin surgeries is one area where PHBV has various uses (Bolbasov et al., 2017). This biopolymer has created numerous medical devices, including PHBV-coated surgical meshes for thermoplastic surgery and wound coatings. Other potential medical devices include bioresorbable surgical sutures, screws, plates for fixing cartilage and bone, biodegradable membranes for periodontal treatment (Chen et al., 2020), and biodegradable membranes.

1.2.1. PHA producing microorganisms

The standard strain described as producing PHA is Bacillus sp. It is the first strain in which Maurice Lemoigne observed PHA accumulation (Gilmore et al., 1990). The carbon source used for microbial growth influences the formation of homopolymers and copolymers of acids [R] - hydroxyalkanoic.

To date, Gram-positive and Gram-negative bacteria from approximately 300 species have been found to produce polyhydroxyalkanoates (Awasthi et al., 2022; Westlie et al., 2022). The most common are Alcaligenes latus, Bacillus megaterium, Cupriavidus necator, and Pseudomonas oleovorans, which can use a variety of carbon sources, such as plant oils or wastes, to do so (Meereboer et al., 2020). PHAs are thus produced from a wide range of substrates, including organic acids, methane, cellulose, and by-products such as molasses and whey, as well as renewable resources such as starch and glycerol (Kiselev et al., 2020; Hafis et al., 2023; Koller & Obruča, 2022).

Many PHA-producing strains are easy to isolate because they come from natural sources, e.g., soil, sea, plants, estuaries, salt rock from mountains, etc. The bioprocess development must occur under certain optimal conditions that meet the needs of the bacterial strain used (Madkour et al., 2013). These conditions include temperature, pH, salinity, carbon substrates, and concentrations of organic or inorganic matter. Recent studies have reported that mesophilic and extremophilic microorganisms can accumulate PHA (Koller, 2017; Kourilova et al., 2021). Halomonas sp. is a strain isolated from marine waters that produce PHA, as mentioned in the Abd El-malek et al. (2020) study. A novelty is the isolation of PHA-producing strains from polluted environments such as oil fields - Aneurinibacillus thermoaerophilus (Musilova et al., 2022; Xiao et al., 2015).

For the industrial production of PHA, species have been sought out that can grow to a final high cell density from basic and inexpensive substrates in a relatively short amount of time and with a high PHA content. As a result, the research focused on Pseudomonas species that fit the requirements above (Khanna & Srivastava, 2005). PHAs develop up as inclusions or granules that are typically above 100 monomers in number and range in size from 0.2 to 0.5 m. These granules are produced and preserved without endangering the bacteria that produce them (Arumugam et al., 2020). Because this form of polymer slows down the autolysis of cells and, ultimately their mortality, it has been demonstrated that bacteria using PHA as spare materials may survive longer during food-limited availability than bacteria without PHA. Additionally, PHA-producing bacteria have shown enhanced resistance to brief environmental stresses such as ultraviolet (UV) light (Slaninova et al., 2018), heat (Sun et al., 2018), and osmotic shock (Sedlacek et al., 2019).

2. BIOMEDICAL ENGINEERING

Bioengineering is an essential field in which biopolymers are preferred. Applying engineering and design concepts and techniques to problems with medical implications is the focus of interdisciplinary scientific disciplines known as biomedical engineering (Huang et al., 2021). To prevent, diagnose, and treat a wide range of diseases and improve human care's quality of life and safety, biomedical engineering is concerned with tools and devices that can significantly improve the delivery of medical interventions from diagnosis to monitoring or treatment (Egbo, 2021).

Biomedical engineering combines the knowledge of engineering with biomedical sciences (such as biomedical electronics, biomaterials, computational biology, cell, tissue, and genetic engineering, medical imaging, orthopedic bioengineering, and bionanotechnology) and clinical practice to develop breakthrough concepts for surgical robots (Rosen et al., 2011), biocompatible prostheses (Shepherd, 2016), new therapeutic drug systems (Ghadi et al., 2014), various medical diagnostic and therapeutic devices, stem cell engineering (Kwon et al., 2018), and printing of biological organs in three dimensions (Agarwal et al., 2023). Tissue and check cell experts aim to duplicate human organs (Wu et al., 2020) and improve the lives of millions of people by perfecting transplants. New implanted devices, including pacemakers, coronary stents, orthopedic implants, prostheses, and dentures, are being developed by experts (Ward et al., 2013; Liu et al., 2023). The use of medical devices in clinical settings requires both reliability and safety. Finally, developments and progress in chemistry, materials science, and biology are linked to the future of biomedical engineering.

Several areas of specialization in biomedical engineering are presented below:

(a) Bioinformatics is the field of understanding biological data using digital technology. It combines disciplines such as engineering, mathematics, statistics, and computer science. With the help of bioinformatics, it is possible to study genes, nucleotide polymorphisms, and single nucleotide polymorphisms (SNP) and determine how genetics and genetic adaptations affect different populations (especially in agriculture). Bioinformatics can provide databases to analyze biodegradation (Bionemo). Therefore, some databases (MetaCyc and BioCyc) help researchers obtain information about the biochemistry and genetics of microbial degradation

(Arora & Bae, 2014). This branch can also be used to predict the toxicity of some chemical substances. Toxicity can negatively influence the bioprocess of polymer production (Buchholz et al., 2022).

(b) Tissue engineering is a rapidly evolving discipline that uses laboratory-assisted manufacturing of organs and tissues to shorten the waiting time for patients needing organ or tissue transplantation. To be used in tissue engineering, biopolymers must be biodegradable, allow cell proliferation, and not cause an immune response in the host organism (Liu et al., 2023). Also, only polymers with mechanical properties and a suitable surface for the place where they will be inserted are used. Some studies show the wound healing effect using PHAs (Kaniuk & Stachewicz, 2021). Researchers have developed bioartificial organs compatible with host organisms by combining synthetic and biological components (Pulingam et al., 2022; Pryadko et al., 2021).

(c) Genetic engineering is a term that characterizes the newly developed field of recombinant DNA technology. Recombinant DNA technology began with the successful cloning of tiny DNA fragments. It evolved into a broad area in which whole-genome cloning, the genome transfer from one cell to another, was possible. This was achieved using various genetic techniques, such as molecular cloning or eyelash splitting. Gene manipulation using biotechnology is led by genetic engineering, often called genetic modification or gene manipulation. The production of human insulin using genetically modified bacteria or the production of erythropoietin in hamster ovaries both have a role in research thanks to techniques and knowledge in the field (Kaparapu, 2018; Saratale et al., 2021). The PHA biosynthesis process itself is controlled by genetic engineering. Many producing microorganisms are genetically modified to use different carbon substrates or increase their PHA production. Another genetic modification that can be made is the addition or increase of the effect of some enzymes with a role in biosynthesis: β-keto thiolase (phaA), acetoacetyl-CoA reductase (phaB), and PHB-polymerase (phaC). The genome of one bacterium can be transferred to another to optimize the PHA production process (Kaparapu, 2018; Wand et al., 2023).

(d) Neural engineering is a discipline in which scientists, doctors, engineers, and neurologists work to comprehend, interfere with, and modify the neurological system. To understand the complexity of the nervous system, neural engineering has been used to study the communication of neurons while employing various quantitative approaches for recording synapses. Treatments for people with different neurological conditions, such as stroke or epilepsy, can be developed using neural engineering (Kaniuk & Stachewicz, 2021). By adding neural stem cells (NSCs) to biopolymers, neural engineering is possible (Huang & Wang, 2017). NSCs can develop into neurons, astrocytes, or oligodendrocytes and can self-renew. The ability of these cells (neural stem cells) to replace or repair damaged neural cells is crucial. Therefore, several neurological illnesses like Parkinson's, Alzheimer's, or focal ischemia can be controlled by combining some biopolymers with NSCs (Zarrintaj et al., 2023; Irioda et al., 2021; Grochowski et al., 2018).

(e) Pharmaceutical engineering. This field focuses on the planning, building, and maintaining drug-manufacturing facilities. Drug variations are created using carefully managed synthetic chemical processes, standardized labor procedures, and the proper safety gear (Koller, 2018).

2.1. Medical devices

In medical devices, PHA can be used in the production of implants and sutures and in coatings for various medical instruments. PHA's biocompatibility, biodegradability, and mechanical properties make it an ideal material for these applications (Table 2). Furthermore, depending on the desired application, PHA can be tailored to have specific properties, such as flexibility or strength (Dwivedi et al., 2020; Elmowafy et al., 2019). Instruments, equipment, implants, machines, tools, reagents, or other similar objects are considered medical devices used to identify, treat, facilitate, or cure a disease or condition. Medical devices, such as pacemakers, infusion pumps, implants, lenses, and ocular or facial prostheses, achieve their aims by physical, structural, or mechanical activity instead of chemical or metabolic action within or on the body. The Food and Drug Administration (FDA)* assesses medical technology based on patient risk, with higher-risk products and lower-risk things.

Table 2. The medical field and possible uses of biopolymers

Medical field	Uses	References
Bioinformatics	Biochemistry and genetics of microbial degradation	Boyandin et al., 2013
Tissue engineering	Bioartificial organs	Jose et al., 2022
Genetic engineering	Enzymatic modification Genome modification (genomic recombination)	Syed Mohamed et al., 2022
Neural engineering	Improvement of neurological diseases Parkinson's, Alzheimer's or focal ischemia.	Bhatia et al., 2021
Medical devices	Pacemaker, infusion pump, implants, lenses, ocular, facial prosthetics	Ward et al., 2013; Liu et al., 2023
Cosmetic industry	PHA microplastic Mild cleaning products	Gupta et al., 2022; Acharjee et al., 2023

According to the level of risk with which they are connected, the EU or US clearance authorities have regulated and divided medical devices into three classes: devices classified as Class I are low risk and do not need to send data or information to the FDA. Elastic bandages, examination gloves, hand surgical tools, and other commonly used items in this category are typically utilized as mechanical barriers. Wheelchairs, ophthalmic lasers, and hemodialysis catheters are examples of class II devices, which pose a moderate risk and often come into contact with the skin or mucous membranes. Class III devices are cutting-edge, high-risk goods. They can affect health by releasing chemicals. These gadgets were subjected to a series of highly demanding tests to ensure their efficacy and safety. Heart valves, hip or knee implants, implanted cerebellar stimulants, and endoscopic implants (intra-bone) are among the most popular class III devices (Muehlematter et al., 2021; Yaqoob et al., 2019; World Health Organization, 2017).

The fundamental goal of implanted devices is to closely resemble a portion of tissue so that they can be utilized to replace an organ or other damaged component to keep the body operating normally (Gordon & Stern, 2019). They were constructed using conventional materials, including metals, ceramics, and synthetic polymers, but there are several drawbacks associated with their use, including immunological rejection. In addition, the biodegradation products of synthetic polymers may trigger an unintended immunogenic reaction in the body (Bao et al., 2022). Hydrolysis creates Carbon dioxide during the breakdown process, which lowers the local pH and results in cellular and tissue necrosis. In this approach, biopolymers play a significant role as implantable medicinal materials (Yean et al., 2017).

With applications ranging from regenerative medicine to robotics, projected tissues must reproduce the inherent structure of the tissues (Acharjee et al., 2023). Under a microscope, native tissues can be examined to reveal how they are structured and how well their inherent traits can be used to build effective biomimetic constructs. The ability of tissue engineering to solve issues ranging from vascularization to the control/determination of cellular function is becoming more widely recognized. This is because analogous structures may be included at an incredibly ordered microscopic level (Liu et al., 2023; Dhania et al, 2022).

2.2. PHAs microplastic

Conventional plastics negatively affect the environment by polluting soil and water with microplastic and nanoplastic (Ali et al., 2021). Plastic reaches a microplastic of a size of 1 nm and 5000 μm through abrasion and erosion processes. These polluting materials reach the soil and water, then the food chain from the ingested plankton. Then, from plankton to fish and birds and at the end, they reach the human food (Koelmans et al., 2022; Rodrigues et al., 2021).

Plastic recycling is done mainly using biopolymers that can replace it (polymers and biopolymers) (Cunha et al., 2020). The great advantage is that PHA particles are biodegradable and do not pollute (Koller & Mukherjee, 2022). Therefore, in 2021, the production of PHA will reach 43.6 thousand tons, compared to 25,000 tons in 2019 and is expected to increase more than ten times in the next five years. In 2022, biopolymers produced

4.5 million tons, representing only 1% of the total polymers created (Nygaard et al., 2023; Vu et al., 2022).

PHA biopolymers are used in various fields for at least partial if not total, replacement of conventional plastic and to reduce massive pollution (Koller & Mukherjee, 2022; Akinwumi et al., 2022; Elmowafy et al., 2019).

2.3. Cosmetic industry

PHA biopolymers are also used in cosmetics. The first use is biodegradable packaging (Bugnicourt et al., 2014). A second use is an insertion into creams with UV protection (solar screen), skin cleansing and moisturizing products, shower gels or washing agents. PHA microparticles can reduce the microplastic in wastewater treatment plants, lakes, rivers and the marine environment. By biodegradation, PHA releases chemicals with an increased nitrogen content (nitrates, nitrites) and nitrogen gas through the denitrification process, which helps to improve wastewater treatment (Vicente et al., 2023; Kovalcik et al., 2019; Guleria et al., 2022).

CONCLUSIONS

In conclusion, biopolymers can be obtained in different ways: through bacterial biosynthesis or through different processes, such as the synthesis of chemicals from renewable natural materials (polyesters from lactic acid, obtained by fermentation starting from starch). Biopolymers constitute an intensive subject studied by researchers because they can be used in many fields, including medical implants, stents (polylactide), regenerated bone tissues (poly lactic-co-glycolic acid), drug-controlled applications, implants (polycaprolactone), packaging, medical industries, and medical implants (polyhydrokyalkanoates).

Polyhydroxyalkanoates (PHAs) are naturally biodegradable polymers. To date, approximately 300 species of Gram-positive and Gram-negative bacteria have been found to produce polyhydroxyalkanoates. As we saw previously, this class of biopolymers is important for biomedical engineering. PHAs can be used in various fields such as tissue engineering (for the creation of artificial organs), genetic engineering (by studying enzyme changes or genome changes), and neural engineering (improvement of neurological diseases such as Parkinson's, Alzheimer's, or focal ischemia), or they can be used in medical devices such as pacemakers, infusion pumps, implants, lenses, and ocular and facial prostheses. An adjacent field is cosmetic engineering, where PHA can be used as a mild cleaning product or for the formation of microplastic PHA, which completely degrade in nature and are thus biodegradable.

Therefore, polyhydroxyalkanoates are biomaterials with high potential for use in biomedical engineering and related fields.

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