Nr 5 (183–238) MAJ 2022 Tom LXVII

POLIMERY

Biopolymers as renewable polymeric materials for sustainable development – an overview

Abhinav Srivastava[1] (ORCID ID: 0000-0001-8483-6697), **Atul Kumar Srivastava**[2] (0000-0002-4092-8706), **Ashutosh Singh**[3] (0000-0002-3601-2607), **Priti Singh**[3] (0000-0002-8989-7285), **Sangeeta Verma**[4] (0000-0001-5758-1879), **Monika Vats**[5] (0000-0002-3660-7192), **Suresh Sagadevan**[6), *)] (0000-0003-0393-7344)

DOI: dx.doi.org/10.14314/polimery.2022.5.1

Abstract: Based on the review of 115 literature items, the article presents biopolymers as renewable polymer materials for sustainable development. The types of biopolymers and their applications are discussed, including biopolymers based on starch, cellulose, bacteria, soy and natural polyester. It also describes the issues of biocompatibility, the principles of sustainable chemistry and sustainable development, as well as market trends and future application directions.

Keywords: biopolymers, biocompatibility, biodegradability.

Biopolimery jako odnawialne materiały polimerowe dla zrównoważonego rozwoju – przegląd literatury

Streszczenie: Na podstawie przeglądu 115 pozycji literaturowych w artykule przedstawiono biopolimery jako odnawialne materiały polimerowe dla zrównoważonego rozwoju. Omówiono rodzaje biopolimerów i ich zastosowanie, w tym biopolimery na bazie skrobi, celulozy, bakterii, soi i naturalnego poliestru. Opisano również zagadnienia dotyczące biokompatybilności, zasad zrównoważonej chemii i zrównoważonego rozwoju oraz trendy rynkowe i perspektywiczne kierunki zastosowań.

Słowa kluczowe: biopolimery, biokompatybilność, biodegradowalność.

Polymers have become ubiquitous in a diverse range of companies, from wrapping to toy manufacturing, grocery bags to plastic cutlery, and straws to 3D printed rocket nozzles [1–6]. High-molecular-weight polymers have a chemical structure of one thousand to ten thousand monomeric repeating units [7, 8]. The initial step in the production of conventional petroleum-based synthetic polymers is the distillation of crude oil at an oil refinery. In this process, the heavy crude lubricant is separated and fractionated into groupings of lighter compo-

---

[1] Department of Chemistry, Lucknow Christian Degree College, Lucknow, U.P, India.

[2] Department of Chemistry, Magadh University, Bodh Gaya, Bihar, India.

[3] Department of Chemistry, K.S. Saket P.G. College, Ayodhya, U.P, India.

[4] Department of Chemistry, Sri. J.N.P.G.College, Lucknow, U.P, India.

[5] Department of Chemistry, Biochemistry and Forensic Science, Amity University of Applied Sciences, Amity University Haryana, India.

[6] Nanotechnology and Catalysis Research Centre, University of Malaya, Kuala Lumpur 50603, Malaysia.

[*] Author for correspondence: drsureshnano@gmail.com

nents, known as segments. Each segment is made up of different sizes and structures of polymeric hydrocarbon chains. Naphtha is an important ingredient in the manufacture of monomers such as ethylene, propylene, and styrene, which are used to make plastics. These monomers are polymerized through polyaddition and/or polycondensation, which is facilitated by particular catalysts [9, 10]. On the other hand, this conversion produces pollutants and greenhouse gases like carbon dioxide (CO_2), resulting in pollution and global warming. Furthermore, several petroleum-based plastics are non-biodegradable, resulting in their persistence at the disposal site and a detrimental impact on environment [11]. Polymers are in high demand in these applications due to their low production costs and advantageous properties such as high mechanical strength while remaining lightweight, high resistance to water, chemicals, sunlight, and bacteria, and their ability to provide adequate electrical and thermal insulation [12–14]. On the other hand, conventional polymers are mostly made from non-renewable petrochemicals that are resistant to daylight and bacteria [15, 16]. Several studies published in the previous two decades have explored alternatives to petroleum-based polymers. Biopolymers are a type of polymeric substances that behave similarly to synthetic polymers while also being mostly environmentally friendly. The environmental damage caused by discarded synthetic polymers has prompted the search for alternatives. Biopolymers are appreciated as promising new materials to solve these problems because they are functionally and environmentally similar to synthetic plastics. Biopolymers are polymers that are either (1) biodegradable, like PCL or PBS, or (2) like starch, cellulose, vegetable oil, and lipids, they may or may not be biodegradable, however, they are made from biological or renewable resource [17]. Biopolymers degradability, like that of any other polymeric material, is influenced by its composition, degree of crystallinity, and conservational variables, with degradation durations varying from a few days to many years. As a result of these considerations, biodegradable biopolymers have aroused a lot of attention in recent years [18–22]. There are two types of biodegradable biopolymers based on their degradation mechanisms: oxo-biodegradable and hydro biodegradable [23, 24]. Chief features of oxo- and hydro- biodegradable polymers are discussed in Table1. Polymers that are oxy-biodegradable are manufactured from petroleum-based polymers plus a pro-degradant element that aids in the decomposition of the plastic [25]. A metal salt, such as manganese or iron salts, is added to speed up the abiotic disintegration of the oxo-biodegradable polymer in the presence of oxygen [26, 27]. At the moment, oxo-biodegradable polymers are primarily made from naphtha, an oil or natural gas by-product. [28]. The time needed for biodegradable oxo products to disintegrate can be

Table 1. Classification of biopolymers

	Oxo-biodegradable	Hydro-biodegradable
Source	Petroleum (oil) based	Plant (starch) based
Uptake	Oxygen	Water
End products	Carbon dioxide, water, cell biomass	Carbon dioxide, water, cell biomass
Strength	Thin and light weight	Thick and heavier
Degradation (Breakdown)	Breakdown faster. Process accelerated by UV and heat	Degradation initiated by hydrolysis process
Recycling	Recyclable	Non-recyclable
CO_2 emission	Slow emission while degrading produces biomass	Rapid emission while degrading
Calorific value	Incinerated with high calorific value	Incinerated with low calorific value
Cost effective	Less expensive	Costly

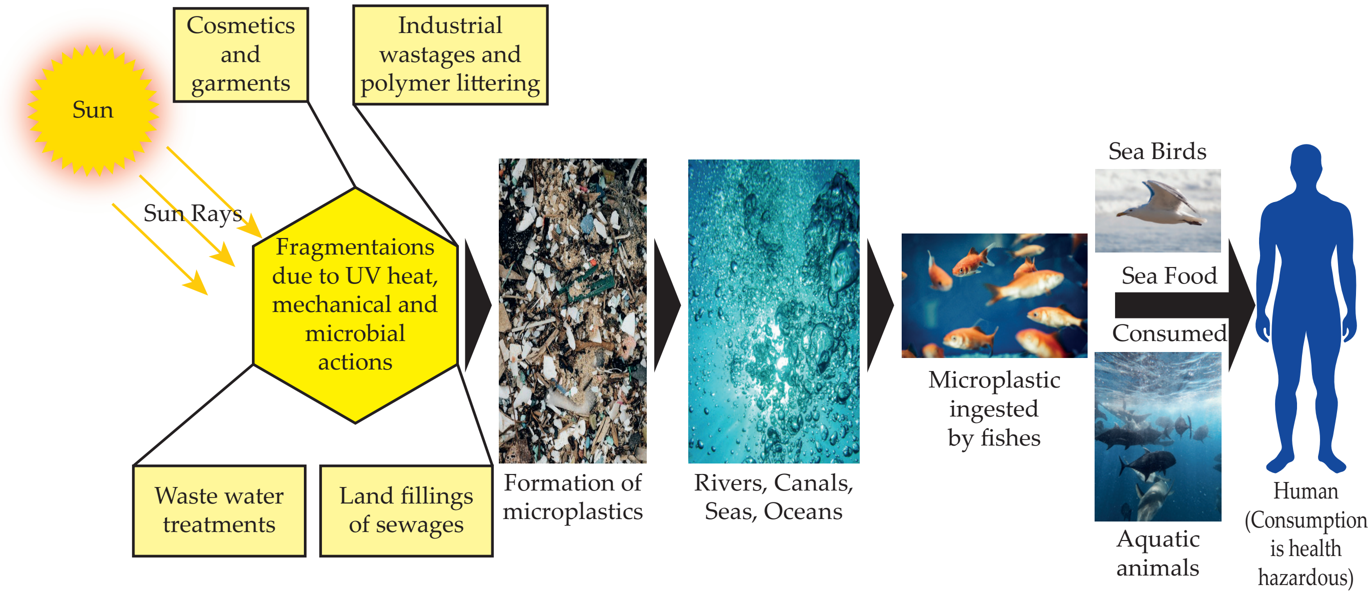

Fig. 1. Schematic of microplastic food chain affecting animal and human health

'programmed' during production, similar to methane or nitrous oxide industrial operations [29]. Polymers that are oxo-biodegradable take months to years to degrade [30]. On the other hand, plant-based produced polymers are hydro-biodegradable polymers. They are heavier and thicker when compared to the same strength oxy-biodegradable polymer. The hydrolytic degradation is faster than in the case of oxo-degradable polymers. These polymers can be used to make synthetic fertilizers. Polylactic acid (PLA) and biopolymers derived from plant sources (such as starch) are two examples [31].

As a result of the polymer use, the amount of pollutants in the environment is increasing. Microplastic (5 mm) and other plastic-based pollutants have been detected in our food supply and the environment, posing a health risk. Fig.1. Represents the formation of microplastic, its contamination in the food chain of living beings. Bio-based polymer research will now focus on making a world that is more sustainable, greener, and has a lower environmental pollution. Biopolymers are polymers that come from biological origins, such as renewable feedstocks or microorganisms of various types, and have the potential to lessen the impact on the environment. Fig. 2. shows the bio-polymer cycle system. In medical, packaging, structural, and automotive engineering, to name a few sectors, research and development in the field of bio-renewable resources could seriously lead to the adoption of a low-carbon economy [32]. On the other hand, crosslinking, crystallinity, molecular weight, and the microbe species used affect the biodegradability of polymers. According to studies, crosslinked polymers disintegrate the slowest, followed by crystalline and finally amorphous polymers. [33, 34].

Polymers manufactured from biomass such as corn and sugarcane are known as biopolymers. These compounds have become increasingly popular as a means of conserving fossil fuels, lowering CO_2 emissions, and minimizing polymer waste [35]. Biopolymers' biodegradability has been actively promoted, and the demand for packaging is continuously expanding among traders and the food industry. Population increase has resulted in a large build-up of non-biodegradable waste materials all over the world. In terms of the environment, the accumulation of polymer garbage has become a big worry. [36]. Traditional polymers not only take decades to disintegrate, but they also produce poisons in the process. As a result, polymers must be created from materials that can be easily removed from our biosphere in an "environmentally friendly" manner [37]. Biopolymers are naturally occurring biopolymers that are generated and catabolized by a variety of species. Under stressful situations, they build up as storage resources in microbial cells [38, 39]. On the other hand, biopolymers have long been disregarded due to their high manufacturing costs and the widespread availability of low-cost petrochemical-derived polymers. As a result, now we live in the era of polymer, in which polymer and polymeric goods have become vital in our everyday lives. Massive amounts of non-biodegradable polymer waste products have accumulated around the world as a result of the exponential growth of the human population. Traditional synthetic polymers and polymeric materials, such as polyethylene and polypropylene, stay in the environment for many years after disposal and represent a significant portion of total municipal solid waste in many countries [40]. Since the previous few decades, effective management of daily generated polymer waste and adequate treatment solutions have been a major environmental problem. The existence of such non-biodegradable residues and their toxic leachates has a negative impact on the biosphere's

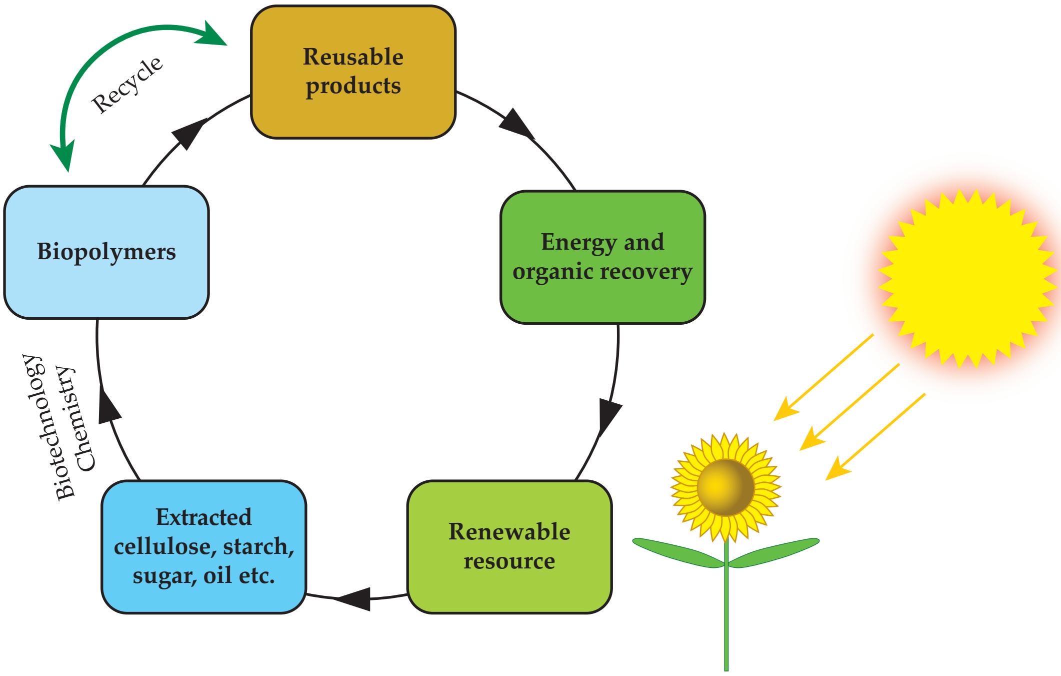

Fig. 2. Biopolymer cycle system

quality. Garbage including polymer waste necessitates huge landfill areas for effective disposal, and burning polymer waste can release harmful gases such as dioxin, furans, carbon monoxide, and others [41].

Innovative trash handling and management approaches may be used to limit the negative consequences of polymer waste in a society, built on reducing, recovering, regenerating, recycling, and reusing (5 R's) factors for environmental sustainability. As a result, various studies have been conducted to develop environmentally friendly and biodegradable polymeric materials that can be easily removed from the biosphere, as well as unique methodologies directed toward custom applications [42]. Biopolymers, such as starch, cellulose, natural rubber, gelatin, lignin, alginate, collagen, chitosan, and chitin, are derived from living creatures and form a diverse class of natural renewable polymers [43]. Biopolymers, which are found in or made by living organisms, are used to make biopolymer materials. Among them there are biodegradable polymers derived from renewable sources that can be polymerized to make biopolymers [44]. Bacteria, fungi, and algae degrade biodegradable polymers that have been placed in bioactive environments [45]. Chemical hydrolysis and other non-enzymatic processes can also break down their polymer chains. During biodegradation, they are transformed into CO_2, CH_4, water, biomass, humic matter, and other natural chemicals. Biopolymers have been found to decompose 10 to 20 times faster than standard polymers while producing no hazardous waste. [46]. They are biocompatible, eco-friendly materials, with low carbon footprint, and may be tailored to specific needs. Studies revealed that several biopolymers exhibited compatible physiochemical, thermal and mechanical durability as synthetic polymers. Such characteristics enable their suitability for the production of biopolymers [47]. The present manuscript reviews the chemical composition of some well-known biopolymer materials and their applicability, biocompatibility, advantages over conventional synthetic polymer as well as sustainability.

DIFFERENT TYPES OF BIOPOLYMERS AND THEIR UTILITY

Biopolymers are a form of biomaterial made up of a wide range of biodegradable polymers derived from various sources and materials [48]. Biopolymer polymers are classified into the following categories based on their origin, renewable sources, and key properties. Fig. 3. shows different types of biopolymers.

Starch-based biopolymers

Corn, wheat, potatoes, rice, and other plants provide a cost-effective, easy available, and annually renewable source of starch. The amylase and amylopectin ratios in starch differ depending on the starch source. The change

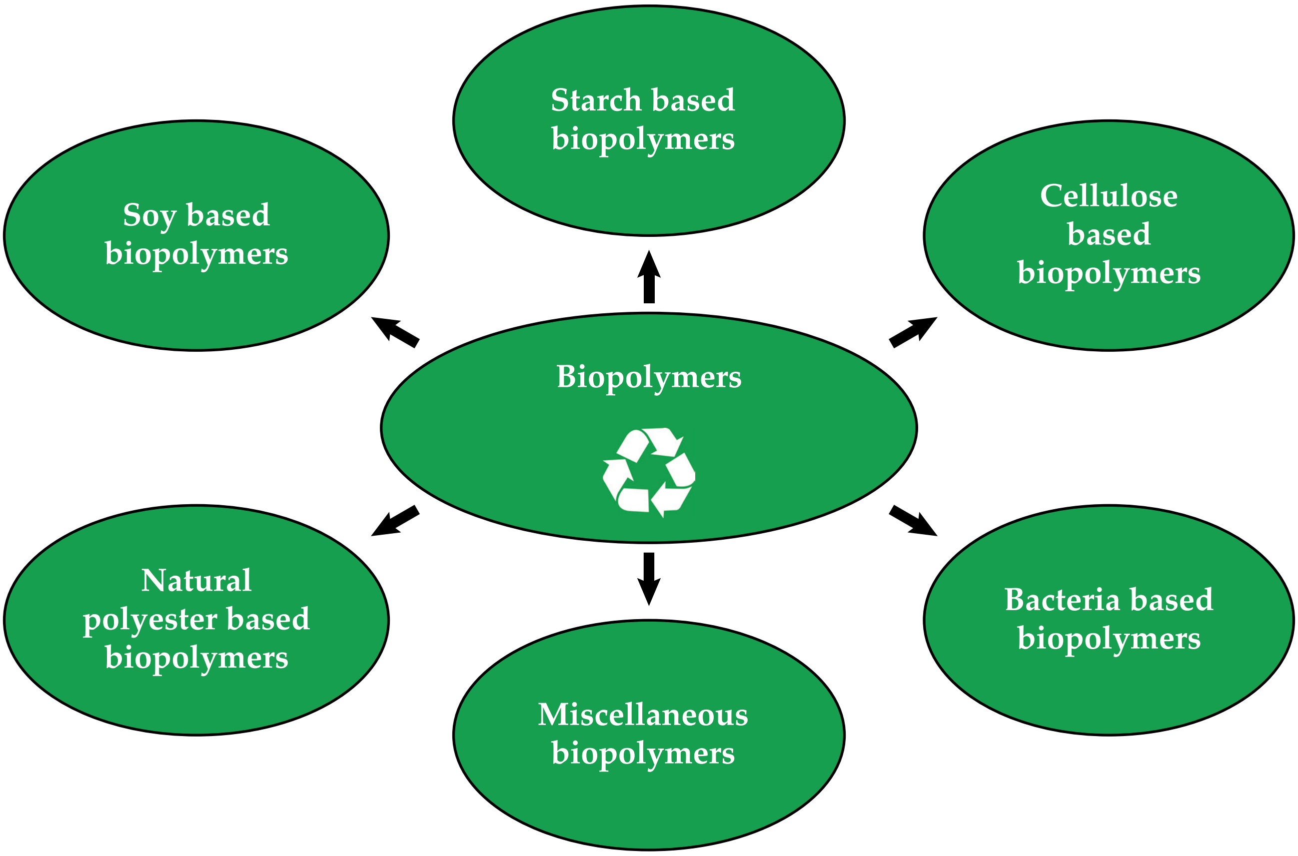

Fig. 3. Different types of biopolymers

in polymer units acts as a natural regulator of starch material characteristics [49]. Biodegradable starches can be processed by injection moulding, blow moulding, film blowing, foaming, thermoforming, and extrusion [50]. The method converts starch from a monomer of lactic acid to a polymer chain known as polylacitide (PLA) or polyglycolic acid (PGA). PLA and PGA are both crystalline polymers that can be used to make biopolymer [51]. About half of the whole biopolymer market is made up of starch-based polymers. Starch-based polymers have already been used to make eating utensils, plates, cups, and other items. Because starch-based polymers can absorb moisture, they are commonly used in the manufacturing of medicine capsules [52].

Starch is a biopolymer obtained from renewable plant resources that are biodegradable, low-cost, renewable, and easily changed. The two main component polymers are amylose and amylopectin. Amylopectin is a polysaccharide made up of -D-glucose monomers connected together by 1,4-glycosidic bonds. Amylopectin is a linear polysaccharide made of -D-glucose monomers linked by -1,4-glycosidic linkages, whereas amylose is a linear polymer composed of -D-glucose monomers linked by -1,4-glycosidic links [53–55]. Strong hydrogen bonds hold starch chains together, resulting in a rigid structure with well-organized crystalline areas [56–57]. Starch may be made into a thermoplastic substance that can be easily transformed into useful shapes. Starch undergoes thermal processing, which alters its microstructure, phase transitions, and rheology. Starch can be chemically altered and combined with other biopolymers to make it less brittle. Starch-based biopolymers are used to make packaging materials and culinary utensils such as cups, bowls, bottles, cutlery, egg cartons, and straws [58]. Polysaccharides, the most common macromolecules in both flora and fauna, are one of the most promising raw materials for biopolymers in the form of starch, which is not only renewable and sustainable but also abundant and cheap. Starch is biodegradable and has excellent thermoplastic properties [59–61]. Amylose and amylopectin, two forms of glucose macromolecules, make up the majority of starch [62], but there are functional and structural differences between them [63], As a result, starch's efficacy as biopolymers raw material is determined by its structure and content [64–66].

Cellulose based biopolymers

Biopolymers manufactured from cellulose or cellulose derivatives are known as cellulose polymers. In the manufacturing of cellulose polymers, softwood trees are the principal raw material. The bark of the tree is removed and used as a source of energy in the manufacturing process. To remove the cellulose fiber from the timber, it is cooked or heated in a digester. According to Transparency Market Research, the digester produces resins and lignin's as a byproduct. The byproducts can be used as a source of energy or as a starting material for other chemical processes. Hemicelluloses and alpha-cellulose make up the pulp that is generated. The pulp is next bleached to remove any remaining resins and lignin's, as well as to minimize the amount of hemicelluloses in the pulp. Before being processed into pulp with a high alpha cellulose content, water is removed from the processed pulp. Cellulose esters, which are used to manufacture cellulose polymers, are made from the pulp. Cellulose esters are created by reacting of processed pulp with a variety of acids and anhydrides at varying temperatures and concentrations, depending on the end-user needs. The properties and chemical composition of cellulose esters are determined by the acids and anhydrides used in the manufacturing process.

Among the most common cellulose esters are butyrate, acetate, and propionate. The most popular cellulose esters product is cellulose acetate, and this trend is expected to continue during the forecast period. Among the most typical applications are thermoplastics, extruded films, eyeglass frames, electronics, sheets, rods, and other cellulose polymers. The most common application category for cellulose polymers is molding materials, and this movement is expected to stay for the predictable future. Polymer is primarily made from nonrenewable resources such as crude oil and its various by-products, resulting in a large carbon footprint during the manufacturing process. Furthermore, other concerns with traditional polymers, such as biodegradability and other environmental threats, have resulted in a rise in the figure of regulations governing their usage. Regulations on polymers have resulted in a boom in demand for bio-based polymers, which has increased the request for cellulose polymers.

Furthermore, one of the key development causes for the cellulose polymers market has been increased demand for electronics devices such as transparent dialers, screen shields, and other similar items. The most prevalent raw material used to create cellulose polymers is softwood, and an increasing number of deforestation regulations is a major market limitation. The easy availability and low cost of traditional polymers are one of the key impediments to the growth of the cellulose polymers sector. Furthermore, cellulose polymers' market expansion has been stifled by the great efficiency and cost advantage of traditional polymers over cellulose polymers. In the cellulose ester industry, increasing research and development to produce high-efficiency and low-cost cellulose polymers is likely to be a huge opportunity [67–68]. Non-food residues from agricultural waste or wood waste are often high in lignocellulose and hemicellulose, which serve as a renewable feedstock for making desirable biopolymers. Chemically, they are cellulose esters or derivatives that can be made thermopolymer under the right conditions. Carboxymethyl cellulose (CMC) and hydroxyethyl cellulose are two water-soluble biopolymers (HEC). Because of their excellent tensile strength and biodegradability, coir-based biopolymers are widely used as packaging and thermopolymer materials [69].

Bacteria based biopolymers

Using the polymer chain polyhydroxyalkanoate (PHA), which is produced inside bacteria cells, bacteria are employed to naturally generate a different type of biodegradable polymer. After the bacteria have developed in the culture, they are harvested and turned into biodegradable polymers. PHA materials were developed in nonwoven biodegradable polyesters for disposable items like drapes, gloves, and surgical gowns that could be thrown away after one usage. PHA can be degraded both aerobically and anaerobically in nature, but total digestion requires an alkaline media [70, 71]. Scientists have created genetically modified bacteria that can use organic resources to produce polymers ("PHAs"). PHAs are significant because they are biodegradable that does not require petroleum and is renewable, as scientists can synthesize the polymers in the lab using the appropriate components and bacterial strains. PHA polymers can be extracted using a variety of enzymes and solvents before being processed into polymers (Reemmer). Bacteria make polyhydroxyalkonoates (PHAs) when there are low concentrations of key nutrients (mostly nitrogen, but sometimes oxygen) and high concentrations of carbon sources. Because of the extra carbon, bacteria create carbon reserves (PHAs) to conserve for a time when nutrients are more available and they need the energy to carry out routine tasks (growing, reproducing, other biosynthesis, etc.). PHAs are stored in granules by bacteria for subsequent use. Humans can use these PHAs to make biopolymers since the polymers made by bacteria are similar to the chemical structure of petroleum-based polymers (Gilmore). New methods for synthesizing biopolymers that are biodegradable, eco-friendly, and manufactured from plant biomass/renewable resources as polymer alternatives have been tested by researchers [72–73]. Polyesters, polyhydroxyalkanoates (PHAs), and polylactic acid (PLA) are examples of biopolymers with properties similar to conventional polymers in terms of physicochemical, mechanical, and thermal properties [74–76]. Under unbalanced development conditions, bacteria store PHAs as intracellular carbon and energy stores [77–80].

Soy based biopolymers

Another renewable biopolymer for biopolymers is soy protein. Soybeans have a protein content of 40–55 percent, with very little fat and oil. For proper molding into polymer products and films, such a large amount of protein demands the use of a suitable plasticizer. Plasticizers in soy-based biopolymers are typically sorbitol, glycerol, or ethylene glycol. Food coatings, freestanding polymers (used for bottles), vehicle parts, and other items are made with biopolymer films. [81] Because polymer goods do not degrade in the environment, they constitute a huge hazard to the ecosystem. To combat this issue, soybean polymers were developed. These polymers differ from traditional polymers in several ways, some of which are useful and others are not. Soy's availability and accessibility, as well as its potential for utilization, thermoplastic properties, low rate, and biodegradability, are the factors that have contributed to its popularity in the polymers sector. Because the physical and chemical properties of the raw material used to make them are strongly linked to the functional characteristics of the end product, a full understanding of soy-based materials are required for changing them for a variety of purposes. Additionally, sustainable soybean production emits fewer greenhouse gases, and biodegradable soybean polymers can be used to replace petroleum-based products for a "greener" product lifecycle. The two most common types of soy-based polymers are polyurethane and polyester thermoset products. Soy polyols, which are generated from soybean oil, are used in adhesives, coatings, sealants, inks, vehicle panels, and urethane foam, including rigid foam insulation. When made with the correct ingredients, soy polyols can compete with petroleum-based counterparts in terms of stability, durability, and price. Because they contain non-biodegradable polymer components that contribute resilience and strength to the final product, some soy-based polymers are not biodegradable. However, many soybean polymers are biodegradable, and the biodegradation of soy-based polymers is comparable to that of paper. The final products of soy polymer decomposition are carbon, oxygen, water, and bio-products, also known as "biomass." These polymers can be decomposed by bacteria, fungi, and other microbes to be thrown away [82–84].

Natural polyester based biopolymer

PLA is a thermoplastic polyester made from lactic acid. It's a clear biopolymer that is used for non-medical purposes including packing (film, thermoformed ampules, and short-shelf-life decanters). PLA is mostly degraded by hydrolysis and can be composted in municipal composting facilities [85]. PCL, or poly(-caprolactone), is a thermoplastic biodegradable polyester made by chemically converting crude oil followed by ring-opening polymerization. PCL has a low melting point and viscosity and is resistant to water, oil, solvents, and chlorine, making it easy to process thermally. Blended PCL is used to make scrub suits, incontinence products, backpacks, and bandage carriers. The rate of hydrolysis and biodegradation of PCL is determined by its molecular weight and degree of crystallinity. On the other hand, many bacteria in nature produce enzymes that can completely degrade PCL [86]. Poly-3-hydroxybutyrate is polyester manufactured from renewable raw materials (PHB). It has properties that are similar to petrochemical polymers. It is biodegradable and creates a translucent layer with a melting point of over 1300 degrees Fahrenheit [87]. Polylactic acid is an aliphatic thermoplastic with a wide variety of mechanical properties that is potentially biodegradable and biocompatible. PLA is created from lactic acid (LA), a naturally occurring organic acid obtained from renewable sources such as corn sugar, cane sugar, and beet sugar by microbial fermentation. PLA may be made and used as an environmentally friendly material because it creates LA when hydrolyzed PLA is a flexible, high-strength, high-modulus polymer that can be used to manufacture industrial packaging materials or biocompatible medical equipment. PLA is really easy to work with, and it may be made in a variety of ways, including molded parts, films, and fibers, using typical plastic equipment. L and D are the two isomers of LA, a chiral molecule possessing two isomers. These monomers can be polymerized into crystalline or amorphous high-molecular-weight polymers such as pure poly-L-LA (PLLA), pure poly-D-LA (PDLA), or poly-D-LLA [88].

Miscellaneous biopolymeric materials

Polyamide-11 (PA 11) is a biopolymer made from non-biodegradable vegetable oil. Applications of PA 11 are highly specific, including packaging, automotive fuel/oil/gas pipeline, pneumatic airbrake tubing, anti-termite electrical cable sheathing, sports shoes, bio-medical catheters, etc. [89]. Water-soluble biopolymers poly (aspartic acid) and poly (glutamic acid) have been used as detergent builders, scale inhibitors, flocculants, thickeners, emulsifiers, and paper-sizing agents. Poly (vinyl alcohol) is the only water-soluble polymer that is considered biodegradable, and it is currently used as paper coatings, adhesives, and films in the textile, paper, and packaging sectors [90]. In addition, microalgae have also been used for the production of biopolymer [91]. Several agro-wastes, as well as renewable biomass, have been effectively applied for the formation of biopolymer [92]. In a pioneer study, biopolymer from rice straw was obtained having similar mechanical properties to cellulose and polymers [93]. In another study, S. Sharma et al fabricated binary biopolymers from whey, natural rubber latex, and egg white albumin [94].

BIOCOMPATIBILITY

Biopolymer has also been proven to be useful in the biomedical field. It has been discovered to be effective for intracellular transport and long-term release of therapeutic drugs into the acidic environments of cancers,

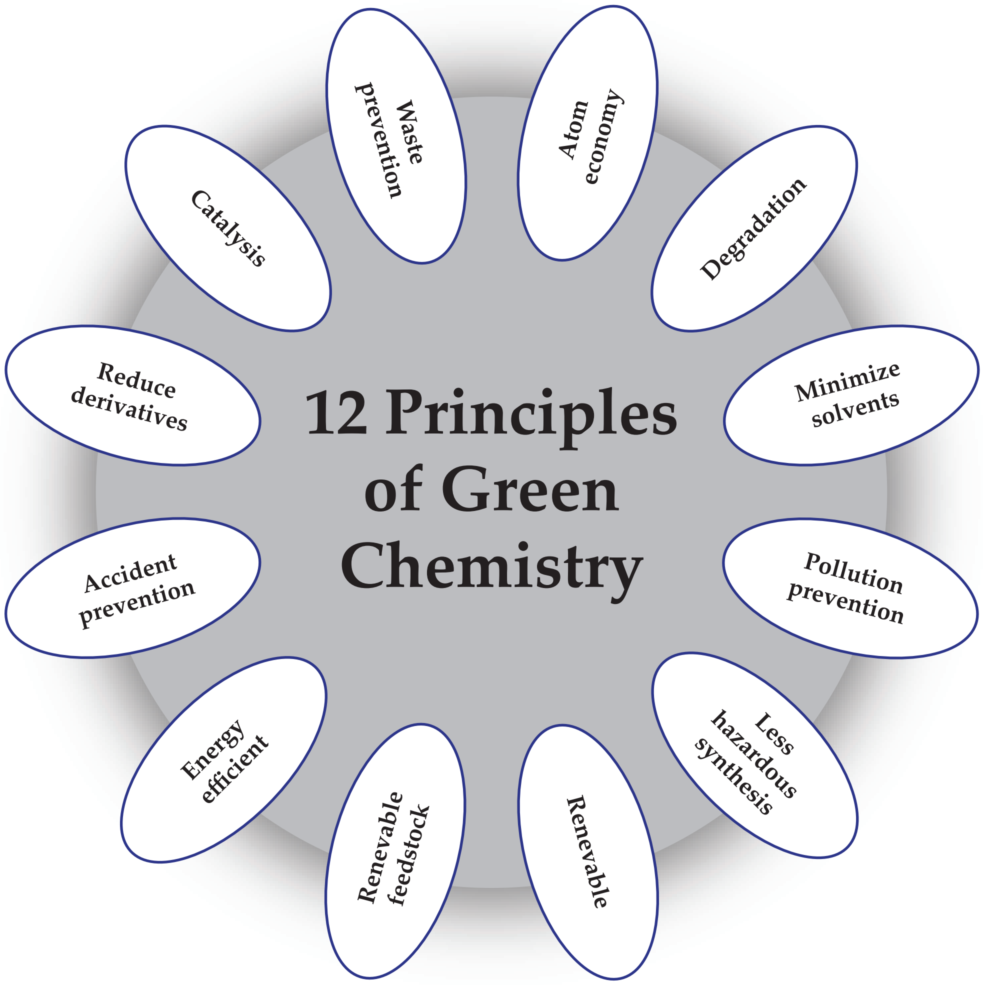

Fig.4. Principles of green chemistry

inflammatory tissues, and intracellular vesicles that hold foreign materials, among other applications [95, 96]. It has also been found to be effective for bone healing and implant placement [97]. Degradation of the biopolymer in a living system does not create an inflammatory acid, but rather membrane-permeable compounds that allow all of the polymer's components to diffuse outside the cell. This means that byproducts should not accumulate in a patient's tissue and cause inflammation. Furthermore, there is no need for post-treatment surgery to remove the frame, screws, or supporting rod [98]. Degradable biomedical waste is produced after usage, which may be safely degraded. Biopolymers are now used to make biodegradable implant devices, target-specific medications, tissue engineering aids, fake breasts, polymer surgery materials, and catheters, among other things.

SUITABILITY OF BIOPOLYMER IN ACCORDANCE WITH SUSTAINABLE CHEMISTRY PRINCIPLES

Biopolymer finished products are also made, used, and disposed according to sustainable or green chemistry principles [99]. There are twelve principles of sustainable green chemistry depicted in Fig.4. Biopolymers are made of biopolymers derived from renewable biomass (agricultural waste, animal biomass, microorganisms, and so on), therefore there are no hazardous emissions or environmental depletion during the manufacturing process. The process of producing biopolymers from renewable biomass is also an energy-efficient and low-carbon process. Biopolymers are biodegradable and environmentally friendly materials. Their decay is similar. During the biodegradation of biopolymer acid, carbon dioxide is released, which can be easily absorbed by green plants during photosynthesis. Biopolymer recycling is also an environmentally friendly and cost-effective method of acquiring high-quality recycled material [100]. The strategic use of biopolymers may result in a reduction in pollutant load, which is a requirement of a sustainable society and a clean environment. As a result, biopolymer is seen as a sustainable option for the long run. It is completely natural and does not cause dangerous chemicals to be released into the environment.

ENVIRONMENTAL FATE AND SUSTAINABILITY

Biopolymer is created to degrade when exposed to the action of live organisms. Practical methods and products derived from polymers such as starch, cellulose, and lactic acid have advanced significantly. Microorganisms such as bacteria, fungus, and algae use enzymes to decompose biodegradable polymers that have been deposited in bioactive environments [101]. Environmental sustainability is the crucial aspect of biopolymer shown in Fig. 5.

Polymer chains can also be broken down by non-enzymatic processes such as chemical hydrolysis. During biodegradation, they are transformed into carbon dioxide, methane, water, biomass, humic matter, and other natural compounds. Because the world creates so much waste, research into making biopolymers consisting of biodegradable materials has sparked a lot of interest. The creation of biodegradable polymers has numerous advantages. Starch-based polymers are more environmentally friendly than standard polymers, degrading 10 to 20 times faster. It has been proven that biodegradable polymers increase soil quality. This process occurs when microbes and bacteria in the soil digest the debris, resulting in more fertile ground. When non-biodegradable or compostable biopolymers are dumped carelessly, they have no negative impact on the environment. Biopolymer development can also be viewed in the context of green chemistry's renewable alternative. The biopolymers manufacturing method aids in the efficient use of renewable feedstocks and biomass, which reduces the usage

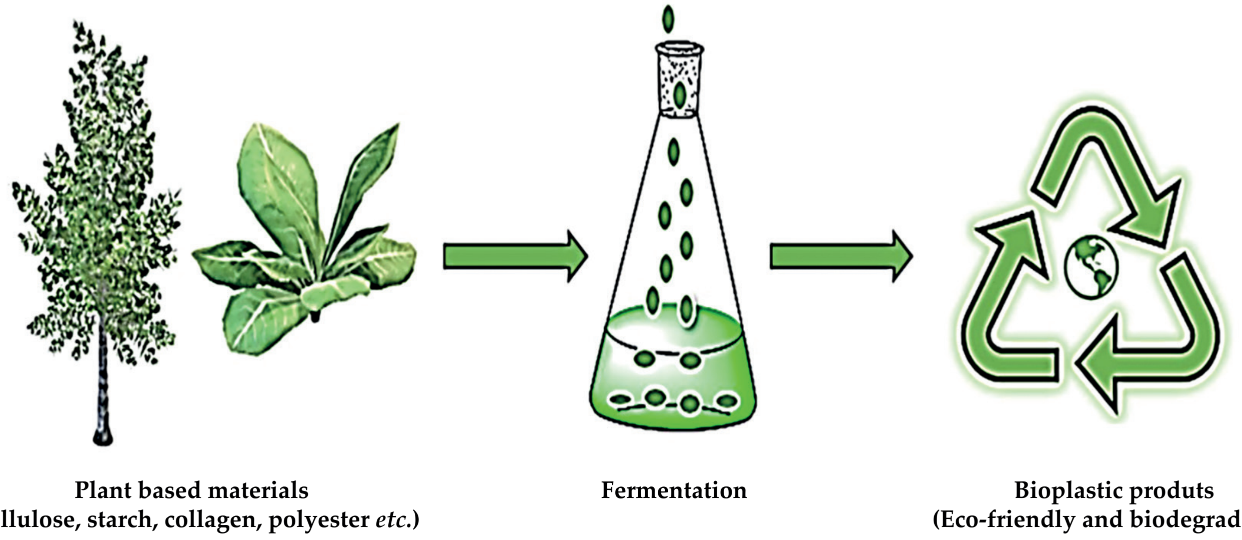

Fig. 5. Environmental sustainability of biopolymers

of petroleum byproducts and the emission of CO_2 originating from fossil fuels. Furthermore, biopolymer waste treatment uses less energy and emits less greenhouse gases [102]. Microbial mechanisms allow biodegradable biopolymers to decompose into natural components and integrate harmlessly into the soil [103, 104]. Water and/or oxygen contribute to the decomposition process. When a biopolymer made from cornstarch is composted, for example when buried, the cornstarch molecules slowly absorb water and swell up. This allows the starch biopolymer to decompose into small pieces that bacteria may easily eat [105–106].

MARKET TREND AND FUTURE ASPECTS

Because of the natural availability of raw materials, their tailor-made advantages, biocompatibility, and ease of valuation, biopolymer is increasingly being used in the creation of a variety of domestic, biomedical, and industrial objects. During the previous two decades, the global consumption of biopolymer finished products has surged by several orders of magnitude. The target markets for biopolymers include packaging materials (trash bags, wrappings, loose-fill foam, food containers, film wrapping, laminated paper), disposable nonwovens (engineered fabrics), hygiene products (diaper covers, cotton swabs), consumer goods (fast-food tableware, containers, egg cartons, razor handles, toys), agricultural tools (mulch films, planters), and biomedical tools. Infrastructure for the proper disposal of biopolymers in bioactive environments must be developed for future growth [107]. It is also necessary to minimize the cost of biopolymer finished products by using cheap and environmentally safe polymer additives, such as sorbitol as a plasticizer, natural color and dyes, rather than synthetic pigments that include heavy metals and toxic organic residues. Biopolymers' long-term viability is directly dependent on societal acceptance. As a result, widespread consumer understanding of biopolymer's safe and effective use, composition, environmental fate, suitable composting, and waste management solutions is necessary [108].

This could help to define the future biopolymer market while also promoting the agriculture as a source of raw materials. [109]. Following food and textiles, the "organic revolution" is now expanding to materials, with biopolymers becoming fashionable and receiving a lot of media attention, even though current production quantities are only about 1% of yearly polymers output. Biopolymers have been "revived" by rising oil prices, intensifying consumer consciousness and environmental alertness, refining feedstock and process economics, greater product worth, and scale of the process. Other variables that drive biopolymers research and development include rural development: a source of added value and employment. New assets that are interesting or a blend of interesting characteristics (degradability, haptics, weight, etc). Diversification of feedstocks (less dependence on crude oil, which is finite). [110–114]. Farmers gain from biopolymers feedstock, which is often grown in rural regions [115].

CONCLUSION

Biopolymers are natural substances produced and catabolized by a variety of organisms, and they have a wide range of biomedical and biotechnological applications. They are made of renewable biomass and are biodegradable, biocompatible, and environmentally friendly. Their biological composting and recycling technology set a new standard for waste management. In comparison to other synthetic polymer products, biopolymers have a significant benefit. Biopolymers are a form of biomaterial that can be used in a variety of ways. To become more widely used in society, cost-effective biopolymer goods with a relatively short lifespan must be commercialized. Suitability assessment of biopolymer finished products requires a comprehensive approach and cutting-edge research to increase biocompatibility, tensile strength, and degradation mechanisms. The biopolymers business has a bright future, fueled primarily by consumer demand.

REFERENCES

[1] Reicher C.L., Bugnicourt E., Coltelli M.B. *et al.*: *Polymers* **2020**, *12*, 1558. https://doi.org/10.3390/polym12071558.

[2] Brydson J.A.: "Plastics Materials", seventh ed., Elsevier, Amsterdam, 1999, p. 1–18.

[3] Gervet B.: "The Use of Crude Oil in Plastic Making Contributes to Global Warming", Lulea University of Technology, Lulea, 2007.

[4] Buis A.: "The atmosphere: getting a handle on carbon dioxide", NASA Glob. Clim. Change (2019 October 9).

[5] Akindoyo J.O., Beg M.D., Ghazali S. *et al.*: *RSC Advances* **2016**, *6*(*115*), 114453.

[6] Bashir N.H.: *Japanese Journal of Veterinary Research* **2013**, *61, S-1.* https://doi.org/10.14943/jjvr.61.suppl.s1

[7] Crawford R.J: "Engineering Plastics", third ed., Elsevier, Amsterdam, 1998, pp. 1–40.

[8] Kuhn P., Siemeril D., Matt D. *et al.*: *Dalton Transactions* **2007**, *5*, 515. https://doi.org/*10.1039/B615259G*

[9] Saleh T.A., Gupta V.K.: "Nanomaterial and Polymer Membranes: Synthesis, Characterization, and Applications", Elsevier, Amsterdam, 2016.

[10] Armand M.: The history of polymer electrolytes, *Solid State Ionics* **1994**, *69*(*3-4*), 309. https://doi.org/10.1016/0167-2738(94)90419-7

[11] Tokiwa Y., Calabia B.P., Ugwu C.U., Aiba S.: *International Journal of Molecular Sciences* **2009**, *10*(*9*), 3722.

https://doi.org/10.3390/ijms10093722

[12] Hasan M., Rahmayani R.: "Bioplastic from Chitosan and Yellow Pumpkin Starch with Castor Oil as Plasticizer". In Proceedings of the IOP Conference Series: Materials Science and Engineering, Surakarta, Indonesia, 2017, 333, 012087.

[13] Pathak S., Sneha C., Mathew B.B.: Journal of *Polymer* and *Biopolymer Physics Chemistry* **2014**, *2*, 84.

[14] Zeller M.A., Hunt R., Jones A., Sharma S.: *Journal of Applied Polymer Science* **2013**, *130*, 3263. https://doi.org/10.1002/app.39559

[15] Khalil H.A., Tehrani M., Davoudpour Y. *et al*.: *Journal of Reinforced Plastics and Composites* **2013**, *32*, 330. https://doi.org/10.1177/0731684412458553

[16] Tan S.X., Andriyana A., Ong H.C. *et al*.: *Polymers* **2022**, *14*, 664. https:// doi.org/10.3390/polym14040664

[17] Babu R.P., O'connor K., Seeram R.: *Progress in Biomaterials* **2013**, *2*(*1*), 1. https://doi.org/10.1186/2194-0517-2-8

[18] Mozaffari N., Kholdebarin A.: *Scientific and Technical Journal: Technogenic and Ecological Safety* **2019**, *5*, 47. https://zenodo.org/record/2600664

[19] *Pat. U.S.* 4 187 352 (1980).

[20] Bhandari S., Gupta P.: "Chemical Depolymerization of Polyurethane Foam via Ammonolysis and Aminolysis. Recycling of Polyurethane Foams", William Andrew Publishing, Norwich, 2018, pp. 77–87. https://doi.org/10.1016/B978-0-323-51133-9.00007-3

[21] Lu J.Z., Wu Q., Negulescu I.I.: *Journal of Applied Polymer Science* **2005**, *96*(*1*), 93.

[22] Mariya D., Usman J., Mathew E.N., Aa P.H.H.: *International Journal of Computer Science and Engineering Technology* **2020**, *8*(*2*), 65.

[23] Lambert S., Wagner M.: *Chemical Society Reviews* **2017**, *46*(*22*), 6855. https://doi.org/10.1039/C7CS00149E

[24] Iwata T.: *Angewandte Chemie International Edition* **2015**, *54*(*11*), 3210. https://doi.org/10.1002/anie.201410770

[25] Thomas N.L., Clarke J., McLauchlin A.R., Patrick S.G.: *Waste and Resource Management*, **2012**, *165*(3), 133. https://doi.org/10.1680/warm.11.00014

[26] da Luz J.M.R., Paes S.A., Bazzolli D.M.S. *et al*.: *PloS One* **2013**, *8*(*8*), e69386. https://doi.org/10.1371/journal.pone.0107438

[27] Siracusa V., Rocculi P., Romani S., Rosa M. D.: *Trends Food Science Technology* **2008**, *19*(*12*), 634. https://doi.org/10.1016/j.tifs.2008.07.003

[28] Otaigbe J., Goel H., Babcock T., Jane J-i: *Journal of Elastomers and Plastics* **1999**, *31*(*1*), 56. https://doi.org/10.1177/009524439903100104

[29] Chamas A., Moon H., Zheng J. *et al*.: *ACS Sustainable Chemistry and Engineering* **2020**, *8*(*9*), 3494. Doi: https://doi.org/10.1021/acssuschemeng.9b06635

[30] Roy P.K., Hakkarainen M., Varma I.K., Albertsson A.C.: *Environmental Science and Technology* **2011**, *45*(*10*), 4217. https://doi.org/10.1021/es104042f

[31] Meereboer K.W., Misra M., Mohanty A.K.: *Green Chemistry* **2020**, *22*, 5519. https://doi.org/10.1039/D0GC01647K

[32] Coppola G., Gaudio M.T., Lopresto C.G. *et al*.: *Earth Systems and Environment* **2021**, 5, 231. https://doi.org/10.1007/s41748-021-00208-7

[33] Goldberg D.: *Journal of Environmental Polymer Degradation* **1995**, *3*(*2*), 61.

[34] Yaradoddi J.S., Banapurmath N.R., Ganachari S.V. *et al*.: *Scientific Reports* **2020**, *10*, 21960. https://doi.org/10.1038/s41598-020-78912-z

[35] Saharan B.S., Sharma A.D.: *International Journal of Microbial Resource Technology* **2012**, *1*(*1*), 11.

[36] Barnes D.K., Galgani F., Thompson R.C., Barlaz M.: *Philosophical Transactions of the Royal Society B: Biological Sciences* **2009**, *364*(*1526*), 1985. https://doi.org/10.1098/rstb.2008.0205

[37] Gross R.A., Kalra B.: *Science* **2002**, *297*, 803. https://doi.org/10.1126/science.297.5582.803

[38] Kadouri D., Jurkevitch E., Okon Y., Castro-Sowinski S.: *Critical Reviews in Microbiology* **2005**, *31*, 55. https://doi.org/10.1080/10408410590899228

[39] Berlanga M., Montero M.T. FernandezBorrell, J., Guerrero, R.: *International Microbiology* **2006**, *9*, 95.

[40] Borrelle S.B., Ringma J., Law K.L. *et al*.: *Science* **2020**, *369*(*6510*), 1515. https://doi.org/10.1126/science.aba3656

[41] Verma R., Vinoda K.S., Papireddy M., Gowda A.N.S.: *Procedia Environmental Sciences* **2016**, *35*, 701. https://doi.org/10.1016/j.proenv.2016.07.069.

[42] He A., Li S., Ma J., Yang Z.: *International Journal of Polymer Science* **2014**, Article ID 107028. https://doi.org/10.1155/2014/107028

[43] Muneer F., Nadeem H., Arif A., Zaheer W.: *Polymer Science, Series C* **2021**, *63*(*1*), 47.

[44] Arikan E.B., Ozsoy H.D.: *Journal of Civil Engineering and Architecture* **2015**, *9*(*1*), 188. https://doi.org/10.17265/1934-7359/2015.02.007

[45] Chandra R., Rustgi R.: *Progressive Polymer Science* **1998**, *23*, 1273.

[46] Piemonte V.: *Journal of Polymers and the Environment* **2011**, *19*(*4*), 988. https://doi.org/10.1007/s10924-011-0343-z

[47] Nanda S., Patra B.R., Patel R. *et al*.: *Environmental Chemistry Letters* **2021**, *29*, 1. https://doi.org/10.1007/s10311-021-01334-4

[48] Queiroz A.U.B., Collares-Queiroz F.P.: *Polymer Reviews* **2009**, *49*(2), 65. https://doi.org/10.1080/15583720902834759

[49] Martin O., Schwach E., Averous L., Couturier Y.: *Starch* **2001**, *53*(*8*), 372. https://doi.org/10.1002/1521-379X(200108)53:8<372::AID-STAR372>3.0.CO;2-F

[50] Jopski T.: *Starch* **1993**, *83*(*10*), 17.

[51] Sagnelli D., Hebelstrup K.H., Leroy E. et al.: *Carbohydrate Polymers* **2016**, *5*(*152*), 398. https://doi.org/10.1016/j.carbpol.2016.07.039.

[52] Laycock B.G., Halley P.J.: *Starch Polymers* **2014**, *1*, 381. https://doi.org/10.1016/b978-0-444-53730-0.00026-9.

[53] Freers S.O.: "Starch-Based Delivery Systems", Rosen M.R. (Ed), in Delivery System Handbook for Personal Care and Cosmetic Products. Technology, Applications, and Formulations, a volume in Personal Care and Cosmetic Technology, William Andrew Publishing, 2005, pp. 741–760. https://doi.org/10.1016/B978-081551504-3.50040-7

[54] Huang M., Yu J., Ma X.: *Carbohydrate Polymers* **2006**, *63*, 393. https://doi.org/10.1016/j.carbpol.2005.09.006

[55] Mottiar Y., Altosaar I.: *Trends Food Science and Technology* **2011**, *22*(*6*), 335. https://doi.org/10.1016/j.tifs.2011.02.007.

[56] Zhang Y. Rempel C., Liu Q.: *Critical Reviews in Food Science and Nutrition* **2014**, *54*(*10*), 1353. https://doi.org/10.1080/10408398.2011.636156

[57] Hottle T.A., Bilec M.M., Landis A.E.: *Polymer Degradation and Stability* **2013**, *98*(*9*), 1898. https://doi.org/10.1016/j.polymdegradstab.2013.06.016

[58] Wang L., White P.: *Cereal Chemistry* **1994**, *71*, 263.

[59] Thakur V.K., Thakur M.K.: "Handbook of Sustainable Polymers", Pan Stanford Publishing, Singapore, 2016, pp. 212-245.

[60] Imre, B. Pukánszky B.: *European Polymer Journal* **2015**, *49*(*6*), 1215. https://doi.org/10.1016/j.eurpolymj.2013.01.019

[61] Jiménez A., Fabra M.J, Talens P., Chiralt A.: *Food and Bioprocess Technology* **2012**, *5*(*6*), 2058. https://doi.org/10.1007/s11947-012-0835-4

[62] Jenkins P.J., Donald A.M.: *International Journal of Biological Macromolecules* **1995**, *17*(*6*), 315. https://doi.org/10.1016/0141-8130(96)81838-1

[63] Pérez S., Bertoft E.: *Starch/Stärke* **2010**, *62*, 389. https://doi.org/10.1002/star.201000013.

[64] Carpenter M.A., Shaw M., Cooper R.D. *et al.*: *BMC Plant Biology* **2017**, *17*, 132. https://doi.org/10.1186/s12870-017-1080-9

[65] Pfister B., Sánchez-Ferrer A., Diaz A. *et al.*: *eLife* **2016**, *5*, e15552. https://doi.org/10.7554/eLife.15552

[66] Shafqat A., l-Zaqri N., Tahir A., AlsalmeA.: *Saudi Journal of Biological Sciences* **2021**, *28*, 1739. https://doi.org/10.1016/j.sjbs.2020.12.015

[67] Cellulose-based plastics address need for more sustainable raw materials from food, healthcare, coatings and construction, assed on 1 May 2022. www.plastemart.com/

[68] Isroi, Cifriadi A., Panji T. et al.: *IOP Conference Series: Earth and Environmental Science* **2016**, *65*, 012011. https://doi.org/10.1088/1755-1315/65/1/012011

[69] Avrous L., Fringant C., Moro L.: *Starch* **2001**, *53*(*8*), 368. https://doi.org/10.1002/1521-379X(200108)53:8<368::AID-STAR368>3.0.CO;2-W

[70] Brodin M., Vallejos M., Opedal M.T. *et al.*: *Journal of Cleaner Production* **2017**, *162*, 646. https://doi.org/10.1016/J.JCLEPRO.2017.05.209

[71] Urtuvia V., Villegas P., González M., Seeger M.: *International Journal of Biological Macromolecules* **2014**, *70*, 208. https://doi.org/10.1016/j.ijbiomac.2014.06.001.

[72] Narancic T., O'Connor K.E.: *Microbiology* **2019**, *165*, 129. https://doi.org/10.1099/mic.0.000749.

[73] Możejko-Ciesielska J., Kiewisz R.: *Microbiology Research* **2016**, *192*, 271. https://doi.org/10.1016/j.micres.2016.07.010.

[74] Alcântara J.M.G., Distante F., Storti G. *et al.*: *Biotechnology Advances* **2020**, *42*, 107582. https://doi.org/10.1016/j.biotechadv.2020.107582.

[75] Taguchi S.: *Polymer Degradation Stability* **2010**, *95*, 1421. https://doi.org/10.1016/j.polymdegradstab.2010.01.004

[76] Nduko J.M., Matsumoto, K., Taguchi S.: "Biological lactate-polymers synthesized by one-pot microbial factory: enzyme and metabolic engineering," in "Biobased Monomers Polymers Materials", (eds P. B. Smith and R. A. Gross), American Chemical Society, New York, 2012.

[77] Kourmentza C., Plácido J., Venetsaneas N. *et al.*: *Bioengineering* **2017**, *4*, 55. https://doi.org/10.3390/bioengineering4020055

[78] Możejko-Ciesielska J., Kiewisz R: *Microbiological Research* **2016**, *192*, 271. https://doi.org/10.1016/j.micres.2016.07.010

[79] Tarrahi R., Fathi Z., Seydibeyoğlu M.Ö *et al.*: *International Journal of Biological Macromolecules* **2020**, *146*, 596. https://doi.org/10.1016/j.ijbiomac.2019.12.181

[80] Nduko J.M., Taguchi S.: *Frontiers in Bioengineering and Biotechnology* **2021**, 04 February. https://doi.org/10.3389/fbioe.2020.618077

[81] El-malek F.A., Khairy H., Farag A., Omar S.: *International Journal of Biological Macromolecules* **2020**, *157*, 319. https://doi.org/10.1016/j.jbiotec.2021.01.008

[82] Smith B.: "Do Plastics Derived from Soy Beans Exhibit Different Properties to Plastics Derived from Traditional Methods? ", December 11, 2018.

[83] Swain S.N., Biswal S.M., Nanda P.K. *et al.*: *Journal of Polymers and the Environment* **2004**, *12*, 35. https://doi.org/10.1023/B:JOOE.0000003126.14448.04.

[84] Paetau I., Chen Ch-Z., Jane J-l: *Industrial and Engineering Chemistry Research* **1994**, *33*(7), 1821. https://doi.org/10.1021/ie00031a023.

[85] Jimenez-Rosado M., Bouroudian E., Perez-Puyana V. *et al.*: *Journal of Cleaner Production* **2020**, *262*, 121517.

[86] Jimenez L., Mena M.J., Prendiz J. *et al.*: *Journal of Food Science and Nutrition* **2019**, *5*(2), 048. https://doi.org/10.24966/FSN-1076/100048

[87] Satti S.M., Shah A.A.: *Letters in Applied Microbiology* **2020**, *70*, 413. https://doi.org/10.1111/lam.13287

[88] Peelman N., Ragaert P., De Meulenaer B. *et al.*: *Trends in Food Science and Technology* **2013**, *32*(2), 128. https://doi.org/10.1016/j.tifs.2013.06.003

[89] Bharti S.N., Swetha G.: *Journal of Petroleum and Environmental Biotechnology* **2016**, *7*(2), 272. https://doi.org/10.4172/2157-7463.1000272

[90] Rahman M.H., Bhoi P.R.: *Journal of Cleaner Production* **2021**, *294*, 126218. https://doi.org/10.1016/j.jclepro.2021.126218

[91] Cinar S.O., Chong Z.K., Kucuker M.A. *et al.*: *International Journal of Environmental Research and Public Health* **2020**, *17*(*11*), 3842. https://doi.org/10.3390/ijerph17113842

[92] Coppola G., Gaudio M.T., Lopresto C.G. *et al.*: *Earth Systems and Environment* **2021**, *5*, 231. https://doi.org/10.1007/s41748-021-00208-7

[93] Bilo F., Pandini S. Sartore L. *et al.*: *Journal of Cleaner Production* **2018**, *200*, 357. https://doi.org/10.1016/j.jclepro.2018.07.252

[94] Sharma S., Luzinov I.: *Journal of Food Engineering* **2013**, *119*(*3*), 404. https://doi.org/10.1016/j.jfoodeng.2013.06.007

[95] Jain R., Tiwari A.: *Asian Journal of Pharmaceutics* **2014**, *1*, 139. https://doi.org/10.4103/0973-8398.134981

[96] Awadhiya A., Tyeb S., Rathore K., Verma V.: *Engineering in Life Sciences* **2017**, *17*(2), 204. https://doi.org/10.1002/elsc.201500116

[97] He M., Wang X., Wang Z. *et al.*: *ACS Sustainable Chemistry and Engineering* **2017**, *5*(*10*), 9126. https://doi.org/10.1021/ACSSUSCHEMENG.7B02051

[98] Saini P., Arora M., Kumar M.R.: Poly (lactic acid) blends in biomedical applications. *Advanced Drug Delivery Reviews* **2016**, *107*, 47. https://doi.org/10.1016/j.addr.2016.06.014

[99] Maheshwari R., Rani B., Sangeeta P., Sharma A.: *Research Journal of Chemical and Environmental Sciences* **2013**, *1*(*1*), 44.

[100] Soroudi A., Jakubowicz I.: *European Polymer Journal* **2013**, *49*(*10*), 2839. https://doi.org/10.1016/j.eurpolymj.2013.07.025

[101] Folino A., Karageorgiou A., Calabro P.S., Komilis D.: *Sustainability* **2020**, *12*(*15*), 6030. https://doi.org/10.3390/su12156030

[102] Ashter S.A.: "In Plastics Design Library, Introduction to Bioplastics Engineering", William Andrew Publishing, 2016, pp. 251-274. https://doi.org/10.1016/B978-0-323-39396-6.00010-5

[103] Calabro P.S., Grosso M.: *Waste Management* **2018**, *78*, 800. https://doi.org/10.1016/j.wasman.2018.06.054

[104] Kale G., Kijchavengkul T., Auras R. *et al.*: *Macromolecular Bioscience* **2007**, *7*(*3*), 255. DOI:10.11002/mabi.200600168

[105] Alshehrei F.: *Journal of Applied and Environmental Microbiology* **2017**, *5(1), 8. DOI:10.12691/jaem-5-1-2*

[106] https://www.theguardian.com/environment/2017/jun/28/a-million-a-minute-worlds-plastic-bottle-binge-as-dangerous-as-climate-change (access date 02.08.2017).

[107] https://ourworldindata.org/faq-on-plastics (access date 02.09.2019).

[108] Cabezas L., Fernandez V., Mazarro R. *et al.*: *The Journal of Supercritical Fluids* **2012**, *63*, 155. https://doi.org/10.1016/j.supflu.2011.12.002

[109] Kasirajan S., Ngouajio M.: *Agronomy for Sustainable Development* **2012**, *32*(2), 501. https://doi.org/10.1007/s13593-011-0068-3

[110] Atiwesh G., Mikhael A., Parrish C.C. *et al.*: *Heliyon* **2021**, *7*(*9*), e07918. https://doi.org/10.1016/j.heliyon.2021.e07918

[111] Venkatachalam H., Palaniswamy R.: *Journal of Advanced Scientific Research* **2020**, *11*(3), 43.

[112] Iles A., Martin A.N.: *Journal of Cleaner Production* **2013**, *45*, 38. https://doi.org/10.1016/j.jclepro.2012.05.008

[113] Thakur S., Chaudhary J., Sharma B. *et al.*: *Current Opinion Green and Sustainable Chemistry* **2018**, *13*, 68. https://doi.org/10.1016/j.cogsc.2018.04.013

[114] Maximilian L.: "Bioplastics – Biobased plastics as renewable and/or biodegradable alternatives to petroplastics", Kirk-Othmer Encyclopedia of Chemical Technology, John Wiley & Sons, 2015. https://doi.org/10.1002/0471238961.koe00006

[115] Di Bartolo A., Infurna G., Dintcheva N.T.: *Polymers* **2021**, *13*(*8*), 1229. https://doi.org/10.3390/polym13081229

Received 10 IV 2022.