Chapter 9

Plastics Versus Bioplastics

Faizan Muneer¹, Sabir Hussain², Sidra-tul-Muntaha¹, Muhammad Riaz³, Habibullah Nadeem*¹

¹Department of Bioinformatics and Biotechnology, Government College University Faisalabad, Pakistan

²Department of Environmental Sciences and Engineering, Government College University Faisalabad, Pakistan

³Department of Food Sciences, University College of Agriculture, Bahauddin Zakariya University, Multan, Pakistan

*habibullah@gcuf.edu.pk

Abstract

Plastics are polymers of long chain hydrocarbons based on petrochemicals. Due to their physiochemical properties these are almost non-degradable and their complete recycling is impossible. High production rate and less disposal capacities have made plastic environmental pollutant resulting in severe impacts on the health of organisms and destruction of habitats thus effecting the biosphere in different ways. Biodegradation, thermal and catalytic degradation of plastics is widely studied to ensure a sustainable disposal of plastic waste with limited results until the present however, a new field where ecofriendly polymers obtained from natural biomass are used to make materials is flourishing. Bioplastics are polymers derived from biomass such as cellulose, starch, chitin and microbial polyhydroxyalkanoates that have the ability to produce products of daily use that can replace their counter parts made from the synthetic plastics. Bioplastics degrade easily in natural environment and replace the petrochemical based plastic polymers, thus saving the natural environment from plastic pollution and ensuring a sustainable environment.

Keywords

Polyhydroxyalkanoates, Biopolymers, Biodegradation, Polyethylene, Plastic Pollution

Contents

Plastics Versus Bioplastics193

1.	Introduction to plastics	195
1.1	Types of plastics	196
1.1.1	Polyethylene terephthalate (PETE or PET).....	197
1.1.2	High-density polyethylene (HDPE).....	197
1.1.3	Polyvinyl chloride (PVC)	197
1.1.4	Low-density polyethylene (LDPE).....	197
1.1.5	Polypropylene (PP).....	197
1.1.6	Polystyrene or Styrofoam (PS).....	198
1.1.7	Miscellaneous plastics	198
2.	Recycling codes for plastics	198
2.1	SPI codes.....	198
3.	Global industry and production rates of synthetic plastics.....	200
4.	Plastics: From a marvelous synthetic material to a nightmare	201
4.1	Destruction of water reservoirs due to plastics.....	202
4.2	Effects of plastics on marine life and human health	203
4.3	Economic losses due to plastic pollution.....	204
5.	Possible solutions for plastic pollution.....	204
5.1	Recycling and conversion to other useful and efficient products.....	204
5.2	Ban on the single use of plastics.....	205
5.3	Biodegradation of synthetic plastics.....	205
6.	The future of plastics	206
6.1	What is poly diketoenamine or PDK?	206
7.	Bioplastics	207
7.1	Bio-based or partly bio-based non-biodegradable bioplastics	207
7.2	Bio-based biodegradable plastics	208
7.3	Biodegradable, fossil-based plastics.....	208
7.4	Bioplastic: Plastic from biomass and its effectiveness to counter plastic problems	208
8.	Sources of bioplastic production	209

9. Polysaccharides for the production of bioplastic materials	215
9.1 Starch	215
9.2 Cellulose	215
9.3 Pectin and chitin	216
9.4 Animal & plant derived proteins as bioplastic sources	216
10. Polyhydroxyalkanoates (PHAs): Biopolyesters from microbial sources used as bioplastics	217
10.1 Structural classification of PHAs	217
11. Polylactic acid (PLA): A bioderived monomer used for bioplastic production.....	219
12. Applications of bioplastics	220
12.1 Antimicrobial films for food wrapping (fruits & vegetables)	222
12.2 Agricultural mulching.....	222
12.3 Removal of heavy metals	222
13. Comparison of plastics & bioplastics.....	222
Summary and conclusion	223
References	224

1. Introduction to plastics

Plastics are large variety of materials or products that are synthetic or semisynthetic organic compounds and are basically the petrochemical derivatives [1]. The term plastic came from the Greek word “plastikos”, means ‘ability to change into different shapes [2]. Plastics consist of various elements such as carbon, oxygen, nitrogen, hydrogen, chlorine, and sulfur. In 1907, Leo Baekeland invented the world’s first fully synthetic plastic-bakelite ($C_6H_6O.CH_2OH$)_n in New York [3]. Since the discovery of bakelite, plastic industry got a sharp jump in its production and different types of plastics were discovered that are available today in different forms. Some most common examples include polyvinyl chloride (PVC), polyethylene (PE), polyethylene terephthalate (PET), polyurethane (PU) and a lot more. The invention of the first synthetic plastic at the very beginning of 20th century was seen as a great development, which opened the road for a variety of new plastic developments and established a completely new industry. Unfortunately, plastic in 21st century is the biggest environmental concern which has taken up the planet earth as an

invading pollutant [4]. The use of plastic in almost all of the consumer products has produced piles of plastic waste which stands high above the ground like a mountain peak and floats in oceans and rivers like living creatures [5].

The use of plastic in the US is approximately 109 Kg/person/year, Europeans use 65 Kg of plastic per person/year, and every Indian uses at least 9.7 kg of plastic annually [6]. A long term study in the North Atlantic has shown that some of the water sample collected had 5,80,000 pieces of plastic per square kilometer of the ocean [7]. This is a huge environmental concern not only for the marine life and eco system but also for the human beings who hold the highest rank in the food chain of biosphere. It is found that more than 5 million tons of plastic either microplastic or macroplastic, is lost to the environment every year [8]. The main reason behind plastics turning from a marvelous product (which is used in almost all of the aspects of modern life) to an alarming concern for the environment is its slow degradation. The synthetic plastic may take more than 1000 years to degrade, not completely but partially and this again depends upon the type, environmental conditions and molecular mass of the polymer used for its synthesis [9]. The global production of plastic is currently ~320 billion tons per annum [10]. The current global production of plastics is estimated to triple by 2050 [11]. The global plastic industry was worth 1,722 billion Euros in 2015 showing its mightiness as a giant global industry [8]. The synthetic plastics like PVC, PE and PET cannot be recycled at the rate at which these are being produced. There is no method that can effectively remove these plastic wastes from the environment without negative effects on the environment and disturbing the human health. Burning plastic waste will lead to the production of toxic gases which will directly result in a number of health problems and will deplete ozone layer causing more ultra violet (UV) radiations to reach the ground which will increase the global warming and other health related issues (skin cancer) [11]. If production of synthetic plastic will rise, plastic pollution will follow suit. There is a dire need to concentrate and focus research on some natural and sustainable ways to produce plastics from renewable organic sources like biomass from plants, agricultural waste residues and microorganisms that produce natural polymers (biopolymers) that can be used for the production of plastic, i.e. bioplastic.

1.1 Types of plastics

Plastic to be straightforward is the most abundantly used material used in our daily life commodities, goods and other articles. Depending upon their physiochemical behaviour and recyclability plastics can be of seven different types as discussed below.

1.1.1 Polyethylene terephthalate (PETE or PET)

PET was introduced in 1940 by J. Rex Whinefield and James T. Dickson. It is the most widely used plastic on the planet, however, it took almost three decades to produce crystal-clear beverage bottles from it. In United States up to 96% of all plastic bottles are PET based and only 25% of them are recycled [12].

1.1.2 High-density polyethylene (HDPE)

High-density polyethylene was first introduced by Karl Ziegler and Erhard Holzkamp in 1953. They used a number of catalysts and low pressure to create high-density polyethylene. Primarily it was used for pipes in drains and culverts. In modern world high-density polyethylene is used for the production of a wide variety of products [13]. HDPE is recyclable, Environmental protection agency (EPA) suggests that almost 12% of all high-density products are recycled each year however, it still a very small dent in the world's carbon footprint [14].

1.1.3 Polyvinyl chloride (PVC)

If we call polyvinyl chloride an accidental discovery it will be true. In 1838 French physicist Henri Victor and in 1872 German Chemist Eugen Baumann discovered Polyvinyl chloride inside the vinyl chloride flasks that were somehow exposed to sunlight. The major use of the polyvinyl chloride is in the production of pipes and related goods [15]. It is the least recyclable plastic type. Less than 1% of PVC plastic is recycled per year. Due to its toxic nature and harmful impacts on health and the environment, it is known as “Poison Plastic”.

1.1.4 Low-density polyethylene (LDPE)

Low-density polyethylene has less molecular mass as compared to high-density polyethylene, hence, these are considered as separate recycling type of plastics. LDPE was the first polyethylene to be ever produced [14]. Almost 56% of the plastic waste on planet earth is due to the packaging material produced from low-density polyethylene.

1.1.5 Polypropylene (PP)

Polypropylene was discovered in 1951 at Phillips Petroleum Company by J. Paul Hogan and Robert L. Banks when they were trying to convert propylene into gasoline. A very small fraction of this plastic is recycled [16]. In United States only about 3% of the products made from polypropylene are recycled each year.

1.1.6 Polystyrene or Styrofoam (PS)

Polystyrene too like polyvinyl chloride was discovered accidentally. A German scientist Eduard Simon while working on a medication in 1839 accidentally came across polystyrene. Another German Chemist Hermann Staudinger studied this polymer and expanded its uses. Due to its lightweight it is used as a multipurpose plastic however, as it breaks apart easily it contributes very badly polluting our water resources and endangering marine life. In United states almost 35% of plastic materials in landfills are made up of styrofoam [17].

1.1.7 Miscellaneous plastics

All other plastic materials that do not fit in the above mentioned categories due to their diverse properties and varying conditions of recycling and degradability in the environment such as polycarbonate, polylactide, acrylic, styrene and nylon are placed in this group.

2. Recycling codes for plastics

In order to have more information about the plastics and make the consumer aware of the type and its possible impacts on the health and environment recycling codes for plastics are used [18]. Resin identification numbers that are more commonly known as SPI (society of the plastic industry) codes are used to sort plastics more effectively for the purpose of recycling.

2.1 SPI codes

In order to properly manage, organize, recycle and dispose of plastics they must be labeled with information pertaining to their use and properties. The Society of the Plastic Industry (SPI) established a classification system in 1988, which we now call as SPI code. Codes are given to different classes of plastics which explains the recyclability of the plastic material and its specific type [19]. Manufacturers around the world follow this coding system and label their specific plastic products with it so that the consumer or the recycler can have the basic knowledge of the type and properties of the plastic material they are dealing with. Different plastic types with SPI code, their symbols, and uses are summarized in Table 1 [6-14].

Table 1 Classification of different plastics based on the SPI codes [6-14]

SPI Code	Symbolic Representation	Polymeric Name (Abbreviation)	Melting temperature range (°C)	Major Use(s)	Recycled to make
1.		Polyethylene terephthalate (PET or PETE)	163-200	Beverage bottles, Medicine jars, Rope, Fiberfill in winter clothing	Storage containers, Carpets, Auto parts, Life jackets
2.		High density polyethylene (HDPE)	65-140	Grocery bags, Detergent containers, Toys	Lumber, fencing
3.		Polyvinyl chloride (PVC)	215	Pipes for plumbing purposes, Ducts, Window frames	Flooring
4.		Low density polyethylene (LDPE)	65-135	Squeezable bottles, Frozen food bags,	Lumbers and Garbage canes
5.		Polypropylene (PP)	65-170	Disposable utensils like cups and plates, Bottle caps, Kitchenware	Battery cables
6.		Polystyrene or Styrofoam (PS)	65-240	Plastic cutlery, Packing foam	Insulations
7.		Miscellaneous Plastics (polycarbonate, styrene, nylon etc.)	85-225	Multipurpose uses depending upon type	Plastic lumber often used in outdoor decks and park benches

3. Global industry and production rates of synthetic plastics

With the population surge, in recent years the demand for plastics is increasing on daily basis. All sectors use plastic based products directly or indirectly to manufacture different products. Approximately 395 million metric tons of plastics is being manufactured each year with an approximate net worth of 1900 billion Euros [10]. Polyethylene (PE), polyvinyl chloride (PVC), styrofoam, polyethylene terephthalate (PET) constitutes the major plastic polymers used [20]. Data used from different sources and international forums such as United Nations Environmental Programme, World Economic Forum 2019 suggest that the seven major types of plastics are being produced on different scales according to their demands and use in the industry. Fig. 1 [8-11] shows a graph exhibiting the average production rates of different types of plastic for past five years from 2014-2019.

Fig. 1 Production rates for different types of plastics [8-11].

The plastics find different applications in our daily life; it follows us like a shadow, from a motorbike to a jumbo jet all have plastic components of some types employed [21]. It will be very difficult to discuss the percentage of use of different plastic materials, however; we can easily summarize the facts in a graph, which will give us a sharp estimation of the facts that which particular sector is using more plastic.

Depending upon the physiochemical properties and suitability for manufacturing and use of plastic consider, Fig. 2 [12-18] which shows estimated use of plastics in different sectors [5]. It can be seen from the graph that the largest use of plastic materials is packaging. Plastic packaging constitutes 36% of the total use of plastics. Polyethylene either high-density polyethylene or low-density polypropylene is used most commonly for this purpose. Thus the demand for polyethylene and its consumption rates are higher than the other types of plastic materials [22].

Fig. 2 Chart showing the percentage use of plastics in different sectors of daily life [12-18].

4. Plastics: From a marvelous synthetic material to a nightmare

With the industrial revolution, the plastic polymers have got prominence in our daily life. It is almost impossible to create a new product without incorporation of some sort of plastic material in it. The world stands indebted to the greatness of plastics and its support in creating a developed and modern world hence no one can underestimate its importance in anyway [23]. Although they have countless uses in our modern world but due to some of their characteristics they are now turning invaders of the biosphere and are close to destroying the normal functioning of the food chain. Plastic pollution has got more prominence in recent years due to the drastic effects we are experiencing now. Plastics are turning into a nightmare as they are destroying our habitat and natural environment [24]. The non-degradability, recycling limitations, more production and less disposal of plastics have turned them environmental pollutants. High temperature requirements for molding or

melting them is another environmental problem in addition to energy. The temperatures required for molding and melting different types of plastics are shown in Fig. 3 [25-29]. Plastic debris in oceans and on land is visible without any minute speculation and its impacts are harsh both for the environment and life. Some of the major environmental problems caused by plastics are discussed to get an idea about its destructive effects on environment.

Fig. 3 Maximum temperature for molding and melting different plastics [25-29]

4.1 Destruction of water reservoirs due to plastics

Aquatic reservoirs such as ponds, lakes, and oceans are worst affected by plastic pollution as more and more land based plastic enters them. Marine organisms such as different species of fish, and turtles are facing alarming situations and awful scenarios due to the water pollution caused by plastics. Plastic products that enter these water bodies changes to smaller and smaller fragments of plastic upon mechanical disruption of water currents and other factors with the passage of time [24]. These smaller plastic fragments depending upon their varying size are nano, micro and macroplastics. Water polluted with these plastic particles generates different health issues and are a direct threat to the destruction of natural habitat to marine and fresh water flora and fauna. Plastics that end up in ocean and fresh water bodies usually flows from the land based sites. Marine environment is currently acting as a plastic sink. A number of different studies suggest that approximately over 250,000 tons afloat at sea [25]. It has been well estimated that 2/3rd of the surface of planet earth is covered by water while the remaining is land. Oceans make up 98% of the total water of the globe which cannot be used for drinking purposes without treatments such as

filtration at water filtration facilities which no doubt cost a lot to fulfil the growing demand of population. Today, as much as 40% of our seas are intensely affected by human activities, fresh water constitutes about 2% of the total water available on earth. This water however, is still limited to only 0.4% in freely usable form as the rest 1.6% is locked as glaciers and polar ice caps, which are beyond our access to use which indicates us for a dark future if we don't save these water resources. Today, human activities such as plastic pollution has intensely affected as much as 40% of our seas and oceans [26].

4.2 Effects of plastics on marine life and human health

United Nations department for the environment estimated that approximately 800 species are affected by ocean debris globally and nearly 75-80% of which is plastic or products derived from plastics. It is measured and evaluated that almost 67% of marine plastic comes from land-based sources while the remaining come from ocean-based sources [23]. It is calculated that nearly 13 million metric tons of plastics enter the ocean every year. Seabirds, fishes, sea turtles and mammals can ingest plastic debris, which ultimately results in suffocation, starvation, and drowning of these marine creatures. Scientists have estimated that nearly 60% of all the seabird species have ingested fragments of plastics at some point in their lives: the point of concern here is a study that foresees this figure to increase to 99% by 2050 [27]. A number of long term scientific studies in oceanic environment has shown that the plastic particles can get ingested by a number of different marine organisms including fish and tortoises which can pass from the intestines reaching into the animal's circulatory system eventually generating an immune response [18,19]. Bioaccumulation as a result of ingesting these nano size particles is possible. As a result of bioaccumulation of plastic particles in different organisms inhabiting a wide range of water bodies the food web can get disturbed. Bioaccumulation usually starts from simpler microorganisms and reaches higher animals in the food web for example algae to zooplankton and then to fish [28]. It has been studied that the nano size plastic particles that are accumulated inside the bodies of different organisms can get access to the brain and incite behavioral disorders [29-31]. In nature, however, many animals throughout their lifetime are rarely exposed to nanoparticles. Most commonly used plastic types are enlisted in Table 1 [6-14]. Egg hatching and algal feeding was shown to diminish in copepods due to polystyrene ingestion with negative consequences for its survival. Polyvinyl chloride microplastics have effected soil-dwelling worms by reducing their energy reserves and normal physiology and functions [20, 21]. It has been evaluated through studies that 8.7 % of the turtles that died due to plastic pollution had a plastic or polyethylene bag blocking the esophagus and preventing the food passage to stomach which eventually resulted in the death [32]. Almost 19% of the global population depends on sea food in order to meet their animal protein intake [21]. Human beings hold the highest level in food web and trophic

levels hence, they consume plastics indirectly for example by consuming seafood more commonly shellfish and small fish which are eaten as a whole including their gut on the other hand larger fish has more flesh hence human consume only their meat and are therefore, less effected by them. It has been estimated and evaluated through experiments that nano plastics have more mobility rates in the tissues of living organisms as compared to other types hence their larger surface to volume ratio increases their concentration in the tissues causing mass concerns of health and reproduction. If such sea food is taken it may have unknown and uncharacterized effects on humans [33].

4.3 Economic losses due to plastic pollution

Pollution creates challenges on different frontiers including health, environment and common day life. A bad environmental condition can result in the shutdown of business and health problems, need more medical treatments and accurate tests to diagnose the disease which means that more money from the budget and savings will be spent on such issues which otherwise could have been used in a more promising way such as education or personal development. Plastic pollution in sea and oceans can render the quality as well as quantity of seafood low effecting the fish market and seafood market. Plastic results in a loss of 13 billion dollars to marine ecosystem each year [34] suggesting huge economic losses due to plastic pollution alone.

5. Possible solutions for plastic pollution

Researchers, innovators, environmentalists, and other stakeholders have put forward different solutions to counter plastic pollution. These solutions are important to be met with immediate effect as the plastics are continuously damaging the planet. Some of the major proposed solutions are discussed here.

5.1 Recycling and conversion to other useful and efficient products

Waste plastic or plastic debris can be recycled depending upon its type and conditions that are needed for its recycling. However, apart from recycling difficulties and expenses, only 12-20% of the plastic is recycled every year [35]. Plastic can be converted into fuels by catalytic and thermal cracking. Plastic is degraded into fractions like gas, crude oil, and solid residue upon thermal degradation. Parameters such as the catalyst, design of the reactor, and pyrolysis temperature plays an important role in the generation of gasoline and diesel grade fuel. Despite all these results this is not usually cost effective apart from reasons that the process generates toxic byproducts in gaseous and solid residual forms [13].

5.2 Ban on the single use of plastics

It has been proposed on different forums that a ban on single use of plastics such as polyethylene shopping bags that are used once and thrown away results in plastic pollution on a faster rate hence ban on single use can effectively control plastic pollution. If a plastic is used for multi times it will not become debris until thrown away as a used one.

5.3 Biodegradation of synthetic plastics

Palm et al. [36] 2019 has recently shown that polyethylene terephthalate debris that has been known as an environmental pollutant because of its extreme durability can now be degraded using a microbial strain *Ideonella sakaiensis* 201-F6 [37,38]. The polyethylene terephthalate degradation is a two-step simple process; during the first step, the bacterial enzyme PETase converts polyethylene terephthalate to mono-(2-hydroxyethyl) terephthalate. In the second step another enzyme known as MHETase hydrolyzes mono-(2-hydroxyethyl) terephthalate to the ethylene glycol and terephthalic acid both of which are nontoxic and can be used for other useful purposes.

The conversion of polyethylene terephthalate to its simple residual form which are non-toxic to the environment using *Ideonella sakaiensis* is of great importance in plastic waste management [36]. From this simple example of plastic degradation by the microorganisms, we can now say that there are a lot of opportunities out there in environment to degrade plastics using different microbes or enzymes isolated from them for this purpose. Some important bacterial strains that are shown to degrade plastics (without concerning the fact that how efficient these strains are in the process of degradation). The microbial strains mentioned in Table 2 [39-45] are a few examples where microbes are used to degrade plastics. One important thing to bear in mind is that these microbial strains that have been studied until now are not available on commercial scale to degrade large garbage dump sites in land, or to degrade plastic liter in oceans. These studies are just a hope that in near future we might discover some strains or modify the existing strains using biotechnology, recombinant DNA technology or our knowledge of protein and enzyme engineering. Scientists are working to enhance the speed of catalytic activity of enzymes that degrade plastics so that these modified enzymes can break the strong bonds between the synthetic polymer chains of the plastics and convert them into simpler residues that might be less toxic or can be used in making a diverse range of other useful products [46]. Hence, there is a hope that in near future it is possible to come up with new versions of plastic degrading enzyme that will help to counter plastic pollution not only in land but also in ocean and other water bodies like rivers, lakes and ponds [47].

Table 2 Microbial degradation of synthetic plastics [39-45].

Microbial strain	Type of plastic degraded	References
<i>Pseudomonas</i> sp.	Polyethylene, Polypropylene, Polyvinyl chloride.	[39]
<i>Aspergillus flavus</i> , <i>Mucor circinilloides</i> ,	Low density polythene, Polyvinyl chloride films	[40]
<i>Alcaligenes faecalis</i> <i>Clostridium botulinum</i>	Polycaprolactone	[41]
<i>Micrococcus</i> sp.	Polyvinyl chloride	[42]
<i>Ideonella sakaiensis</i> <i>Flavobacterium</i> sp.	Polyethylene terephthalate, Nylon	[43]
<i>Thermophilic Bacillus</i>	Low-density polyethylene, High density polyethylene	[44]
<i>Bacillus magaterium</i> strain B1	Polyvinyl chloride	[45]

6. The future of plastics

Due to revolution in information technology and recent developments of scientific research, people are becoming more and more aware of the negative impacts of the plastics. We have a society that is more conscious of its activities on the globe than ever before. Researchers, innovators and international forums are in continuous struggle to find solutions and better alternatives to plastics. Scientists at Berkeley Lab have found a brand new plastic material that may become efficient without becoming a pollutant for the environment as it can be made over and over again without losing its characteristic properties. They have called this plastic as poly diketoenamine (PDK) plastic.

6.1 What is poly diketoenamine or PDK?

Plastics create problems due to non-degradable behaviour and harsh requirements to partially degrade and even then, releasing harmful and toxic gases and byproducts. Plastic is also known for being tricky to recycle. PDK or poly(diketoenamine) is an up-and-coming plastic that can be recycled again and again without creating any waste ever having to go into landfills. As of 2019, research is still under progress with the goal to produce new

polymeric material, which can be used effectively for the production of like textile materials, foams, and 3D printing.

7. Bioplastics

Bioplastics are ecofriendly, naturally derived polymers or monomers that can be used to synthesis materials that have properties and uses almost similar to synthetic plastics but differ in the sense that these are the derivatives of biomass and are renewable while plastics are the derivatives of petroleum compounds [38]. Bioplastic is not a single material or substance rather it is a family of materials that are either bio-based, biodegradable or both [39]. We can divide bioplastic family in to three main groups namely:

- a) Bio-based or partly bio-based non-biodegradable bioplastics
- b) Bio-based and biodegradable bioplastics
- c) Fossil based biodegradable bioplastics [40]

Bioplastics, depending upon their direct or indirect biomass source are divided as first-generation bioplastics and second generation bioplastics. The first generation bioplastics are manufactured directly from natural polymers such as starch or cellulose while those which are obtained as monomers like lactic acid or extracted as polyesters from renewable sources such as polyhydroxyalkanoates (PHAs) from microbes are second generation bioplastics [41]. Each of the above group of bioplastic family is discussed here comprehensively.

7.1 Bio-based or partly bio-based non-biodegradable bioplastics

Some most commonly used plastics such as polyethylene (PE), polyvinyl chloride (PVC) and polypropylene (PP) are known as commodity plastics which are usually made from petrochemical derivatives but these can be made from renewable resources too, for example from bioethanol. Approximately 200000 tons per annum (p.a) of Bio-PE (Bio-based polyethylene) is being produced by some industries like Braskem, Brazil. Similarly, Bio-PP (Bio-based polypropylene) and Bio-PVC (Bio-based polyvinyl chloride) are in the pipeline for production [42]. The world renowned beverage industry icon Coca-Cola uses partially bio-based polyesters polyethylene terephthalate (Bio-PET) for beverage bottles. These bio-based or partially bio-based variants of the synthetic commodity plastics are bioplastics by definition but these retain most of the properties of their parent types i.e. these are non-biodegradable like their fossil based parent types but are called bioplastics due to their bio-material composition [43].

7.2 Bio-based biodegradable plastics

Bioplastics in this group includes biopolymers like starch or thermos-plastically modified starch polymers as well as polyesters like polyhydroxyalkonates (PHAs) or polylactic acid (PLA). These are not only derived from biomass (e.g. starch from plants, vegetables and PHAs like polyhydroxybutyrate from microorganisms) but are also biodegradable [44]. Bio-based biodegradable plastics are in real sense the ecofriendly bioplastics that are desired in real sense however, they have been available on commercial scale only for a few years [45]. Until now their use have been limited to short-lived packaging but still this dynamic and flourishing and even the future of plastic industry continues to grow smoothly due to the recent introductions of some new bio-based monomers like fatty acid derivatives, propane diol, succinic acid etc. Their renewable basis for production, biodegradability to reduce the concern of becoming a pollutant and environmental safety has made them a sustainable group of bioplastic family. Hence, these are at the prime focus of research to create ecofriendly plastics for daily use.

7.3 Biodegradable, fossil-based plastics

These constitute a comparatively small bioplastic group because these are used in combinations with other biomass polymers such as starch. These improve and enhance the performance of the plastic in respect to its biodegradability and mechanical properties. Most of the biodegradable fossil based plastics are usually produced in petrochemical production processes [46]. Partially biobased versions of theses plastics will be available for commercial use in the near future.

7.4 Bioplastic: Plastic from biomass and its effectiveness to counter plastic problems

Bioplastics or biopolymers can be derived from sources like plants and microorganisms i.e. bacteria and algae [47]. Some macroalgae like seaweeds has also been studied for the production of bioplastics [48]. There are monomers like carbon dioxide (CO₂), terpenes, vegetable oils and carbohydrates, which can be effectively used and employed as feedstock for the manufacture of a variety of sustainable materials and products, including elastomers and plastics. The global bioplastic industry is growing at more than 20 to 25% each year. In 2007 the bioplastic industry worth 7 billion US\$ which is estimated to reach more than 10 billion US\$ by 2020 [7]. The early developing history of some biomaterials that lead to the modern research and industry of bioplastic is given in Table 3 [48-51].

Table 3 A brief history of biobased and biodegradable plastic materials [48-51].

Year	Biomaterial	Characteristics	References
1862	Parkesine: Derived from cellulose.	Biobased	[48]
1897	Galalith: derived from casein (milk)	Biobased and biodegradable	[49]
1912	Cellophane: derived from cellulose	Biodegradable	[50]
1926	Polyhydroxybutyrate (PHB): polyester derived from bacteria	Biobased and biodegradable	[51]
1947	Rilsan or Nylon 11: Produced by the polymerization of 11-aminoundecanoic acid from castor beans.	Biobased and biodegradable	

8. Sources of bioplastic production

Bioplastics, as discussed earlier are either bio-based, biodegradable or both hence any monomer, polymer or polyester that is either obtained from biomass (organic source) like plant and microbes or which might be degraded by them will be considered as a bioplastics [49]. Plants such as switch grass (*Panicum virgatum* L.) and *Arabidopsis thaliana* [50] and microorganisms like *Bacillus megaterium* NCIM 2475, *Bacillus cereus* SPV, *Bacillus flexus*, *Sinorhizobium meliloti* [9,51] are widely studied for this purpose. Table 4 [52-61] shows some important microbial strains that have been studied and used for the purpose of production of different biopolymers.

Table 4 Microbial sources of bioplastic polymers [52-61]

Microbial source(s)	Bioplastic Polymer(s)	References
<i>Alcaligenes latus</i>	PHB	[52]
<i>Bacillus</i> sp.	PHB	[53]
<i>Bacillus megaterium</i>	P3HB	[54]
<i>Pseudomonas oleovorans</i>	P3HB, P3HV	[55]
<i>Burkholderia sacchari</i>	P3HB	[56]
<i>Cupriavidus necator</i>	PHB, PHA	[57,58]
<i>Hydrogenophilus thermoluteolus</i> TH-1	PHB	[59]
<i>Hydrogenophaga</i> sp.	P3HB	[60]
<i>Pseudomonas putida</i> KT2440	mcl-PHA	[61]

It is evident from the Table 4 [52-61] that the most commonly produced biopolymer from the microbial strains is polyhydroxyalkanoates, especially the short chain length polymer known as polyhydroxybutyrate or (PHB). Plants on the other hand are a good source of lignocellulosic biomass which includes starch, cellulose and lignin which can be used to produce biopolymers for the production of bioplastics. Some important plant sources that have been previously studied for this purpose are enlisted in Table 5 [62-69].

There is an enormous amount of biomass available in different forms and from different sources, which can be somehow used directly or indirectly to produce bioplastics, which can help us to replace the synthetic plastics with these naturally produced and environmental friendly bioplastics. In order to have a quick look at the different polymers, proteins and polyesters that have been used and are still being extensively studied for the production of bioplastics consider Fig. 4 [23-32] and Table 6 [69-81].

Table 5 Important plant sources that have been studied for the production of bioplastic materials [62-69].

Plant sources	References
Switch grass	[62]
Wheat	[63]
Maize and Potato	[64]
Kenaf (<i>Hibiscus cannabinus L.</i>)	[65]
Flax (<i>Linum usitatissimum</i>)	[66]
Water hyacinth(<i>Eichhornia crassipes</i>)	[67]
Banana	[68]
Rice straw	[69]

Fig. 4 A wide variety of sources of biopolymers that can be used to produce bioplastics [23-32].

Table 6 Natural polymers and proteins from different sources like plants, animals and microbes that can be used for the production of bioplastic products [69-81].

Natural polymers & proteins	Structure	Summary of the properties	Uses	References
Polysaccharides				
Starch		Used for the production of biocompatible, rigid & elastic plastic. It yields a thermoplastic and can act as a gas barrier. Degradable in soil and water.	Packaging & trash bags	[69]
Cellulose		Cellulose triacetate & cellulose acetate are two biopolymers derived from cellulose. These molecules yield thermostable and rigid bioplastic which is degradable in soil and water.	Air filters, Wound dressing and textiles	
Chitin		It is the second most abundant polysaccharide in nature, which is used to form ultrathin & labile nanostructured films.	Construction of bioplastic for bone repair.	[70]
Chitosan		It is derived from chitin and is structurally similar to it.	It is used as bioplastic film for enhancing structural characteristic of other polymers.	[71,72]

Plant proteins				
Gluten		It is plasticized with glycerol yielding bioplastic film. This wheat gluten derived bioplastic is elastic and resistant to oxygen and water but is completely biodegradable in nature.	Biopolymers formed from wheat gluten are used as nanofibers in many medical applications such as drug delivery.	[73]
Animal Proteins				
Whey		Whey protein is used with the polyethylene glycol or PEG, glycerol and water to form bioplastic films that have good mechanical properties	Food packaging and development of other biomaterials	[74]
Keratin		Keratin protein is present in abundant quantities in hair and nails. It is non-burning and hydrophilic in nature.	Used for the development of bioplastic films with a wide range of properties	[75]
Gelatin		It is derived from collagen from different parts of an animal. It is odourless and translucent.	Used as a biomaterial to produce edible biocomposite films.	[76]

Lactic acid and Lactides				
PLA		<p>Poly(lactic acid) is an aliphatic polyester that can be derived from a wide range of petrochemicals but the most common and obvious sources of its production are starch or sugar rich plants and crops. High transparency and surface gloss that make it a replacement for synthetic plastics like PET and PVC.</p>	Used in food packaging.	[77]
PHAs (Polyhydroxyalkanoates) or Polyesters				
P(3HB)		<p>Poly 3 hydroxybutyrate is a polyester produced in microbial strains under limited nutrient conditions as granules in the cytoplasm.</p>	Is widely used in biopolymer studies for the production of bioplastics.	[78]
P(4HB)		<p>Poly-4-hydroxybutyrate is a short chain length PHA (Polyhydroxyalkanoates) that is produced by different microbes as intracellular granules.</p>	Approved by the FDA for use in medical devices.	[79]
PHV		<p>Polyhydroxyvalerate is a biopolyester that has been produced by bacteria. It has special characteristics that enable it to be used in bioplastic production.</p>	PHV is used as blends and copolymers along with other PHAs	[80]
PHBV		<p>Poly(hydroxybutyrate-co-hydroxyvalerate) is a copolymer of PHB and PHV. This copolymer is formed to get a better version of polyester material with dual characteristics of both the individual molecules.</p>	It enhances the mechanical performance of the bioplastic products.	[81]

9. Polysaccharides for the production of bioplastic materials

9.1 Starch

Starch is widely associated with plant based biomass and is most common among polysaccharides found in nature [82]. The monomer that forms this polysaccharide is a simple monosaccharide- glucose. The glucose monomers are joined by 1,4-linkage. There are two forms of starch available in nature, a linear polymer known as amylose and a branched polymer called as amylopectin [83]. Starch has been used for centuries for different purposes with paper manufacturing being the most common. Large quantities of starch are also used in textile industry where it is used to impart strength to the thread during weaving process. Starch has been investigated for the development of bioplastics as a natural derivative of plant based biomass. Maulida et al. [84] (2016) investigated the potential of starch based bioplastic production using cassava peel [85]. They used sorbitol as plasticizer during their experiments and found that the starch from cassava peel reinforced with microcrystalline cellulose and sorbitol as plasticizer increased the tensile strength of the bioplastic that was formed. Their study confirms that starch, as a biopolymer is a potential candidate for the synthesis of bioplastics. Starch based bioplastic films are not only degradable in water and soil but are also used to form plastic films that are biocompatible, rigid and elastic. These bioplastic films can act as gas barriers and can be used in food packaging with some slight modifications in their tensile strength properties by preparing their composites with some other biobased materials [86].

9.2 Cellulose

Cellulose is the most common polysaccharide associated with the cell wall of plant cells [55]. Being a polymer made from simple repeating monomer units of glucose it is widely used in paper production and as cotton in manufacturing clothing. Cellulose triacetate and cellulose acetate are two biopolymers derived from cellulose. These molecules yield thermostable and rigid bioplastic, which is degradable in soil and water. Lignocellulosic biomass sources like wood and rice straw can be effectively used as non-food mass for the sustainable development of bioplastics however, the conversion of this biomass to simple residues to be used sustainably in biopolymeric research needs cost effective routes for developing bioplastics [56]. Bioplastic production from cellulose of oil palm empty fruit bunch has been investigated by Isroi et al. [57] (2017), nearly 40% cellulose is present in the empty fruit bunch of the oil palm, although cellulose has no direct properties to become a potential bioplastic however, its composites with plasticizers is a key success in the development of bioplastics [87]. Bioplastic composite of cellulose-starch was prepared by solution casting and evaporation process using cassava starch as the polymers matrix and glycerol as plasticizer. Cellulose side chain was oxidized to reduce hydroxyl group and

increase the carboxyl group. Their research successfully produced bioplastic sheet. It is believed that further research can make bioplastic from EFB cellulose which can be used to develop plastic bags and can be used in food packaging [57].

9.3 Pectin and chitin

Pectin is a hetero polysaccharide that is found primarily in the cell walls of the terrestrial plants. On chimerical scale it is produced as a white to light brown powder most commonly from citrus fruits [58]. Pectin is the main agent behind the thickening properties of jams and jellies. The pectin bioplastics film can be produced by adding 5-gram pectin obtained from banana peel extract in distilled water and heating the mixture at 60 °C. The film obtained will have a thickness of 0.00387 cm, water resistance of 63.63%, the tensile strength value of 10.562 MPa, and the elongation value of 58.33% [59,86]. Chitin is the second most abundant polysaccharide in nature. It is the main structural component of the exoskeleton of arthropods like insects and crustaceans. Crab, shrimps and fish scale are the ideal biomass for the production of chitin. Pandharipande and Bhagat [60] (2016) used chitin extracted from the crab shell to develop bioplastic film with properties that help us to conclude that chitin obtained from natural sources can be used sustainably to develop biomaterials like bioplastics [60,87]. It is also used to form ultrathin and labile nanostructured films [60]. He et al. [61] (2017) constructed a biocompatible bioplastic from chitin that was used to aid bone repair. It is completely evident that chitin derived biodegradable and biocompatible products can be used for the sustainable development of different eco-friendly biobased products [61].

9.4 Animal and plant derived proteins as bioplastic sources

With more understanding of the sustainable use of biological materials scientists have now developed new methods to use proteins as an excellent source for the manufacturing of bioplastic materials and products as a replacement to conventional plastics [62]. Proteins are complex heteropolymers, which offer a number of different functional side groups capable of forming strong intermolecular bonds. The most important aspects of protein processing include denaturing, cross-linking and plasticization. All these properties give proteins a unique characteristic to be used as a biomass resource in the development of sustainable products such as bioplastics [62]. Proteins such as casein, whey, gelatin, zein, soya and gluten can be used as precursors for the development of biomaterials such as bioplastics [63-66]. Chalermthai et al. [67] (2019) has shown the synthesis of protein-based thermoset elastomers using whey protein isolates through free radical polymerization. The whey protein based copolymers produced in their study have shown the potential to bear a high tensile strength, which make a future possibility to use them as packaging material and thus diminishing the role of conventional plastics. Whey protein is also used with the

polyethylene glycol or PEG, glycerol and water to form bioplastic films that have good mechanical properties[67]. Bioplastic containers for planting have been produced by Helgeson et al. [68] 2009 using zein protein extracted from corn as a bio-renewable component [68]. Gluten is a protein obtained from cereals. Wheat gluten derived bioplastic is elastic and is resistant to oxygen and water but is completely biodegradable in nature [69]. Aziz et al. [69] (2019) has shown that wheat gluten can be used efficiently for the manufacturing of electrospun nanofibers based on wheat gluten containing azathioprine for biomedical applications [88]. In nutshell there are a lots of possibilities available or can be derived further to employ plant and animal based protein biomass for the sustainable and ecofriendly development of biobased materials. A large part of which can be used as bioplastics that will not only counter the pollution caused by the synthetic or conventional plastics that are non-degradable but will also ensure the sustainable development of the ecosystem and the global environment effected very badly by the plastic wastes.

10. Polyhydroxyalkanoates (PHAs): Biopolyesters from microbial sources used as bioplastics

Prokaryotes such as bacteria produce polyesters from renewable resources like lipids, carbohydrates, organic acids and alcohols under insufficient or limited supply of nutrients, one such type of polyester is polyhydroxyalkanoates (PHA) [70]. PHA is actually a diverse class of polymers which have at least 100 different types of monomers which are either obtained from plant sources such as wheat, corn, sugar beet, potatoes and vegetable oils or from different microbial sources [89]. More than 300 species of microorganism have been reported to produce PHA [72]. The diversity and versatility in PHA is due to the difference in molecular structure and chain lengths of its members.

10.1 Structural classification of PHAs

Polyhydroxyalkanoates are classified into three different types depending upon the carbon chain length which include short chain length PHAs (scl-PHAs), medium chain length PHAs (mcl-PHAs) and long chain length PHAs (lcl-PHAs) [61]. The general structure of PHAs is shown in Fig. 5 [38].

Scl-PHAs have 3-4 carbon atoms such as poly(3-hydroxybutyrate) or P(3HB) and poly(4-hydroxybutyrate) or P(4HB). Scl-PHAs can be used in food packaging and disposable products [90-92]. Polyhydroxyalkanoates with 6-14 carbon atoms are termed as mcl-PHAs these can either be homopolymers like poly(3-hydroxyhexanoate), simplified as P(3HHx) and poly(3-hydroxyoctanoate) or P(3HO). The scl-PHAs homopolymers or mcl-PHAs homopolymers have quite different properties [74]. Fig. 6 [33,36, 45-49] provides a

comparison between the different properties of the two main types of PHAs i.e. scl-PHAs and mcl-PHAs.

Fig. 5 General structure of polyhydroxyalkanoates [38].

HP= homopolymers

Fig. 6 Comparison between the properties of two main types of PHAs i.e. scl-PHAs and mcl-PHAs [33,36, 45-49]

The heteropolymers include P(3HHx-co-3HO). These can be used to manufacture high value added products such as drug delivery systems, medical implants and stitching [93-95]. Lcl-PHAs are less frequent and are therefore, rarely studied [61].

PHAs, depending upon these differences can be polyhydroxybutyrate (PHB), polyhydroxyvalerate (PHV) or the copolymer of the PHB and PHV i.e. PHBV [76]. PHAs have been studied for their application in the development of bioplastics, medicines, fine chemicals and implantable biomaterials [96]. Different microbial strains accumulate PHAs in the presence of abundant carbon sources. The simple hydroxyalkanoates (HAs) monomers are polymerized in to long chain polyesters with the help of PHA synthase – a key enzyme in the biochemical conversion of hydroxyalkanoates into PHAs. The PHA accumulation in the cytoplasm is due to its insolubility in water. Hence, several bacteria can therefore, store 80% of PHAs of their cell dry mass [97]. PHA has been in the focus of research for bioplastic development due to its near identical properties to that of conventional plastics that are nonrenewable and non-biodegradable and possess serious environmental threats [77]. PHAs are not only environmental friendly but can be applied in different fields where its conventional counterparts can't be applied [78]. The commercial production of bioplastics from PHAs has grown in recent years but their market share is still marginal due to higher manufacturing costs, which make them an economic challenge. Despite using all expertise in creating good microbial strains using biotechnology, high production facilities, and better fermentation technologies, only reduction of the cost of PHAs production up to US\$ 5 per Kg has been possible in 2009, which is still three times the rate of its closest synthetic version of plastic-polypropylene (PP) [98].

11. Polylactic acid (PLA): A bioderived monomer used for bioplastic production

Poly lactide most commonly termed as polylactic acid is one of the most promising polymer that has the ability to become a focused biomolecule for the bioplastic production [80]. Polylactic acid is an aliphatic polyester that can be derived from a wide range of petrochemicals but the most common and obvious sources of its production are starch or sugar rich plants and crops [81]. PLA has characteristics like high transparency and surface gloss that make it a replacement for synthetic plastics like PET and PVC [82].

Polylactic acid can be produced from lactide or lactic acid through the reaction as shown in Fig. 7 [34-36]. Dehydrative condensation of the lactic acid will yield polylactic acid while polylactic acid and lactide are interconvertible through a reverse reaction i.e. the ring opening polymerization of lactide will yield polylactic acid whereas the depolymerisation of the PLA will yield lactide molecule [40]. PLA has more recently got more attention due

to its ability to be used in food packaging where it is blended with other biopolymers to enhance its required characteristics [83].

Fig. 7 Conversion of lactic acid to polylactic acid through Dehydrative condensation and interconversion of PLA and Lactide through ring opening polymerization [34-36].

12. Applications of bioplastics

Bioplastics are actually meant to replace the synthetic versions of conventional plastics that are accumulated in environment causing pollution and effecting thousands of species living in aquatic and terrestrial environments [84]. Synthetic plastics such as polyethylene (PE), polypropylene (PP), Polyvinyl chloride (PVC), polyethylene tetrphalate (PET) are used in daily life. Their multipurpose uses have increased their consumer demand, hence industry is producing millions of metrics of tones of plastic each year which ultimately results to environmental pollution and is also associated with health effects [85]. Bioplastics are primarily meant to replace conventional plastics therefore, they are desired to replace the applications as are provided by the petrochemically derived plastics. However due to their ecofriendly behaviour, biocompatibility bioplastics have found a wide range of application ranging from home appliance to food packaging material and from industrial products to pharmaceuticals see Table 7 [99-108] and Fig.8 [46,48,55-64].

Apart from the applications mentioned in the Table 7, protein based bioplastics which are derived from casein, gelatin and keratin impart special characteristics to the bioplastic product which include flexibility, strength and toughness [109]. Protein based biopolymers that can be used as bioplastic materials, have the potential applications in formation of food packaging, and as biomaterial for the reconstructive surgery and tissue engineering [110].

Fig. 8 Three main application sectors of bioplastic i.e. Health, Industry and Agriculture [46,48,55-64].

Table 7 Some important applications of bioplastics derived from different derivatives [99-108].

Bioplastic Derivative	Applications	References
Starch	Agriculture foils, Textiles, Food Packaging	[99-101]
Cellulose	Packaging, Medical devices, Electronic devices, Bio Films	[102-104]
Polyhydroxyalkanoates (PHAs)	Coating, Food packaging, Medical implant, Agricultural grow bags and fertilizer bags, Agriculture nets	[105-107]
Polylactic acid (PLA)	Food packaging	[108]

12.1 Antimicrobial films for food wrapping (fruits & vegetables)

One of the most important role of the non-toxicity which enables the development of bioplastic films for packaging food material is the use of antimicrobial films that can save the food such as fresh fruits and vegetables from being spoiled by bacterial or microbial attacks [111]. Chitosan based nano silver and Ag-ion incorporated bioplastic films have antimicrobial properties that enhance post processing food quality and safety [112].

Padil et al. [89] (2019) has analyzed the sustainable use of gum arabic as a potential bioplastic material by using it as a food wrapping biomaterial [89]. Gum arabic (GA)-based electrospunbioplastic fibers were fabricated using GA blended with PVA (2:1 wt. % of GA/PVA) via electrospinning process the potential of the electrospun fiber were further evaluated as a food wrapper [89].

12.2 Agricultural mulching

PHA made biofilms or plastic material can be used for agricultural mulching. Mulching is used to not only protect the crops but also increase its yield. It prevents soil structure and retain its moisture [113]. Natural and synthetic mulching are two types that are available but the expensiveness and inadequateness of natural material for the synthesis of natural mulch has increased and favored the use of synthetic mulching which are made up of high density polyethylene (HDPE) [91,114]. The increased rate of synthetic mulch has increased the rate of landfill and causes environmental pollution when buried or burnt. Bioplastics have addressed the very issue as PHA based mulch films are being developed on research level and are expected to help in reduction of use of synthetic mulch films [115].

12.3 Removal of heavy metals

Hungund et al. [93] (2018) developed and used polyhydroxyalkanoates (PHAs) composites such as PHB-Starch and PHB-PEG composites for the removal of heavy metals from the aqueous solution. These composites have very positively showed successful adsorption of Pb^{2+} ion.

13. Comparison of plastics & bioplastics

Although plastic and bioplastics are derived from completely distinct sources they can replace each other due to some of their physiochemical properties [94,116]. Replacing synthetic plastics with bioplastics in everyday life can save the planet earth from a number of environmental problems, including the continuous destruction of our water reservoirs and harm to sea life. Bioplastics are still under investigation on different levels of research and there have been studies around the world where bioplastic products have replaced the

synthetic plastic materials however, this is still on very small scale [117-119]. Experts are of the view that decades of research is needed to enable bioplastics to replace the synthetic plastics used today and even then plastics will remain due to their large scale applications and their properties that cannot be completely replaced with bioplastics [120-122]. However, the adverse effects that are imposed by the plastics on the environment by the petrochemical-based plastics must be addressed in order to save the world from growing environmental issues such as pollution. In the present scenario, bioplastics can effectively help us to reduce plastic related pollution and its impacts on the ecosystem due to their invading and non-degradable behaviour. Bioplastic films for packaging can replace their synthetic counterparts [123]. Some medical devices, auto parts, and a large number of electronic equipment and parts can be replaced with bioplastics to an extent which will lower the use of synthetic plastics for the manufacturing of such products [124]. Therefore, the petrochemically derived, non-degradable and toxic plastic materials can be replaced by ecofriendly materials derived from biomass. A brief and comprehensive comparison between the properties of plastics and bioplastics is given in Table 8 [125-134].

Summary and conclusion

Plastics being the synthetic derivatives of the petrochemicals have evolved too much in the modern world where their production rates are far greater than their disposal rates. The non-degradability of the synthetic plastics is due to their physiochemical properties that enable them to become environmental pollutants. The plastics are divided into seven large categories depending upon their recyclability and some other properties. Researchers around the world have developed and tried different methods to degrade, recycle or dispose plastics in a sustainable way but the results have not been so positive. Biodegradation, thermal and catalytic degradation of plastic materials to convert them into some useful products is the hot topic nowadays but results need to be improved. Bioplastics which are derived from a large variety of biomass such as cellulose, starch, chitin, keratin protein and microbial polyhydroxyalkanoates are a new horizon to tackle the over production of plastic materials. Plastic materials can be effectively replaced with bio-derived plastic polymers that are not just environment friendly but will help to reduce the plastic pollution as these polymers actively degrade in natural environment without leaving toxic byproducts. It is believed that eventually in the future bioplastic research may help to produce environmental friendly and sustainable products.

Table 8 Comparative properties of plastics and bioplastics [125-134]

Property	Plastic	Bioplastic
Main constituents	Hydrocarbons from Petrochemical sources	A wide range of Biomass e.g. Cellulose, Starch, Chitin, Polyhydroxyalkanoates from bacteria etc.
Major categories	7	3
Degradability in natural environment	Non-degradable	Mostly Degradable
Melting temperatures	Mostly High	Moderate
Recycled for	Fuel production (By catalytic and thermal decomposition). Other products of daily use.	Different monomers that may be used again for developing the same plastic. Can be used as fertilizers.
Toxicity	Yes	Usually non-toxic
Applications for consumer product development	Very High	Low and under developed
Life Cycle Analysis (LCA) or Cradle to grave analysis		
Energy requirements MJ/kg	77-120 (For different plastics)	25-57 (For different biobased plastics)
Global warming Kg CO ₂ eq/Kg	2.70- 7.64 (For different plastics)	1.14-3.84

References

- [1] S. Thakur, A. Verma, B. Sharma, J. Chaudhary, S. Tamulevicius, V.K. Thakur, Recent developments in recycling of polystyrene based plastics, *Curr. Opin. Green Sustain. Chem.* 13 (2018) 32–38. <https://doi.org/10.1016/j.cogsc.2018.03.011>
- [2] R. Wei, W. Zimmermann, Microbial enzymes for the recycling of recalcitrant petroleum-based plastics: how far are we?, *Microb. Biotechnol.* 10 (2017) 1308–1322. <https://doi.org/10.1111/1751-7915.12710>
- [3] R. Porta, The plastics sunset and the bio-plastics sunrise, *Coatings*. 9 (2019) 526. <https://doi.org/10.3390/coatings9080526>
- [4] A. Malizia, A.C. Monmany-Garzia, Terrestrial ecologists should stop ignoring plastic pollution in the anthropocene time, *Sci. Total Environ.* 668 (2019) 1025–1029. <https://doi.org/10.1016/j.scitotenv.2019.03.044>
- [5] A.M. Brandon, C.S. Criddle, Can biotechnology turn the tide on plastics?, *Curr. Opin. Biotechnol.* 57 (2019) 160–166. <https://doi.org/10.1016/j.copbio.2019.03.020>

- [6] S. Kumar, K. Thakur, Bioplastics - classification, production and their potential food applications, *J. Hill Agric.* 8 (2017) 118. <https://doi.org/10.5958/2230-7338.2017.00024.6>
- [7] E.B. Arikan, H.D. Ozsoy, A Review: Investigation of bioplastics, *J. Civ. Eng. Archit.* 9 (2015) 188–192. <https://doi.org/10.17265/1934-7359/2015.02.007>
- [8] M.W. Ryberg, A. Laurent, M. Hauschild, Mapping of global plastics value chain and plastics losses to the environment, *United Nations Environ. Program.* (2018) 5–99
- [9] F. Alshehrei, Biodegradation of synthetic and natural plastic by microorganisms, *J. Appl. Environ. Microbiol.* Vol. 5, 2017, Pages 8-19. 5 (2017) 8–19. <https://doi.org/10.12691/JAEM-5-1-2>
- [10] (WEF) World Economic Forum, Top 10 Emerging Technologies 2019, *World Econ. Forum Annu. Meet.* 2019. (2019) 4–15. www.weforum.org
- [11] R. Devi, V. Kannan, K. Natarajan, D. Nivas, K. Kannan, S. Chandru, A. Antony, The role of microbes in plastic degradation, 2015. <https://doi.org/10.1201/b19243-13>
- [12] X. Jia, C. Qin, T. Friedberger, Z. Guan, Z. Huang, Efficient and selective degradation of polyethylenes into liquid fuels and waxes under mild conditions, *Sci. Adv.* 2 (2016) 1–8. <https://doi.org/10.1126/sciadv.1501591>
- [13] B. Kunwar, H.N. Cheng, S.R. Chandrashekar, B.K. Sharma, Plastics to fuel: a review, *Renew. Sustain. Energy Rev.* 54 (2016) 421–428. <https://doi.org/10.1016/j.rser.2015.10.015>
- [14] S. Skariyachan, A.A. Patil, A. Shankar, M. Manjunath, N. Bachappanavar, S. Kiran, Enhanced polymer degradation of polyethylene and polypropylene by novel thermophilic consortia of *Brevibacillus* sps. and *Aneurinibacillus* sp. screened from waste management landfills and sewage treatment plants, *Polym. Degrad. Stab.* 149 (2018) 52–68. <https://doi.org/10.1016/j.polymdegradstab.2018.01.018>
- [15] L. Giacomucci, N. Raddadi, M. Soccio, N. Lotti, F. Fava, Polyvinyl chloride biodegradation by *Pseudomonas citronellolis* and *Bacillus flexus*, *N. Biotechnol.* 52 (2019) 35–41. <https://doi.org/10.1016/j.nbt.2019.04.005>
- [16] C. Andreeßen, A. Steinbüchel, Recent developments in non-biodegradable biopolymers: Precursors, production processes, and future perspectives, *Appl. Microbiol. Biotechnol.* 103 (2019) 143–157. <https://doi.org/10.1007/s00253-018-9483-6>

- [17] M.C.M. Blettler, M.A. Ulla, A.P. Rabuffetti, N. Garello, Plastic pollution in freshwater ecosystems: macro-, meso-, and microplastic debris in a floodplain lake, *Environ. Monit. Assess.* 189 (2017). <https://doi.org/10.1007/s10661-017-6305-8>
- [18] C. Wabnitz, W.J. Nichols, Editorial: Plastic pollution: An ocean emergency, *Mar. Turt. Newsl.* (2010) 1–4.
<http://search.proquest.com/docview/924334169?accountid=27795>
- [19] M. Vert, Y. Doi, K.-H. Hellwich, M. Hess, P. Hodge, P. Kubisa, M. Rinaudo, F. Schué, Terminology for biorelated polymers and applications (IUPAC Recommendations 2012), *Pure Appl. Chem.* 84 (2012) 377–410.
<https://doi.org/10.1351/pac-rec-10-12-04>
- [20] L. Godfrey, Waste plastic, the challenge facing developing countries—Ban it, change it, collect it?, *Recycling.* 4 (2019) 3. <https://doi.org/10.3390/recycling4010003>
- [21] N.J. Beaumont, M. Aanesen, M.C. Austen, T. Börger, J.R. Clark, M. Cole, T. Hooper, P.K. Lindeque, C. Pascoe, K.J. Wyles, Global ecological, social and economic impacts of marine plastic, *Mar. Pollut. Bull.* 142 (2019) 189–195.
<https://doi.org/10.1016/j.marpolbul.2019.03.022>
- [22] R. Scalenghe, Resource or waste? A perspective of plastics degradation in soil with a focus on end-of-life options, *Heliyon.* 4 (2018) e00941.
<https://doi.org/10.1016/j.heliyon.2018.e00941>
- [23] S. Karbalaei, P. Hanachi, T.R. Walker, M. Cole, Occurrence, sources, human health impacts and mitigation of microplastic pollution, *Environ. Sci. Pollut. Res.* 25 (2018) 36046–36063. <https://doi.org/10.1007/s11356-018-3508-7>
- [24] J.R. Jambeck, R. Geyer, C. Wilcox, T.R. Siegler, M. Perryman, A. Andrady, R. Narayan, K.L. Law, Plastic waste inputs from land into the ocean, *Science* 80;347 (2015) 768–771. <https://doi.org/10.1126/science.1260352>
- [25] O.S. Ogunola, O.A. Onada, A.E. Falaye, Mitigation measures to avert the impacts of plastics and microplastics in the marine environment (a review), *Environ. Sci. Pollut. Res.* 25 (2018) 9293–9310. <https://doi.org/10.1007/s11356-018-1499-z>
- [26] M. Valentukevičienė, E. Brannvall, Marine pollution: an overview *Jūros Geologija.* 50 (2008) 17–23. <https://doi.org/10.2478/v10056-008-0002-9>
- [27] S. Sharma, S. Chatterjee, Microplastic pollution, a threat to marine ecosystem and human health: a short review, *Environ. Sci. Pollut. Res.* 24 (2017) 21530–21547.
<https://doi.org/10.1007/s11356-017-9910-8>

- [28] L. Ivanova, K. Sokolov, G. Kharitonova, Plastic pollution tendencies of the Barents sea and adjacent waters under the climate change, *Arct. North*. 32 (2018) 121–145. <https://doi.org/10.17238/issn2221-2698.2018.32.121>
- [29] L.G.A. Barboza, A. Dick Vethaak, B.R.B.O. Lavorante, A.K. Lundebye, L. Guilhermino, Marine microplastic debris: An emerging issue for food security, food safety and human health, *Mar. Pollut. Bull.* 133 (2018) 336–348. <https://doi.org/10.1016/j.marpolbul.2018.05.047>
- [30] Y.H. Yang, C.J. Brigham, C.F. Budde, P. Boccazzi, L.B. Willis, M.A. Hassan, Z.A.M. Yusof, C. Rha, A.J. Sinskey, Optimization of growth media components for polyhydroxyalkanoate (PHA) production from organic acids by *Ralstonia eutropha*, *Appl. Microbiol. Biotechnol.* 87 (2010) 2037–2045. <https://doi.org/10.1007/s00253-010-2699-8>
- [31] Y. Yu, D. Zhou, Z. Li, C. Zhu, Advancement and challenges of microplastic pollution in the aquatic environment: A review, *Water. air. soil Pollut.* 229 (2018) 2–18. <https://doi.org/10.1007/s11270-018-3788-z>
- [32] A.C. Vegter, M. Barletta, C. Beck, J. Borrero, H. Burton, M.L. Campbell, M.F. Costa, M. Eriksen, C. Eriksson, A. Estrades, K.V.K. Gilardi, B.D. Hardesty, J.A. Ivar do Sul, J.L. Lavers, B. Lazar, L. Lebreton, W.J. Nichols, C.A. Ribic, P.G. Ryan, Q.A. Schuyler, S.D.A. Smith, H. Takada, K.A. Townsend, C.C.C. Wabnitz, C. Wilcox, L.C. Young, M. Hamann, Global research priorities to mitigate plastic pollution impacts on marine wildlife, *Endanger. Species Res.* 25 (2014) 225–247. <https://doi.org/10.3354/esr00623>
- [33] A.L. Andrady, Microplastics in the marine environment, *Mar. Pollut. Bull.* 62 (2011) 1596–1605. <https://doi.org/10.1016/j.marpolbul.2011.05.030>
- [34] S.G. Tetu, I. Sarker, V. Schrameyer, R. Pickford, L.D.H. Elbourne, L.R. Moore, I.T. Paulsen, Plastic leachates impair growth and oxygen production in *Prochlorococcus*, the ocean's most abundant photosynthetic bacteria, *Commun. Biol.* 2 (2019) 1–9. <https://doi.org/10.1038/s42003-019-0410-x>
- [35] D. Danso, J. Chow, W.R. Streita, Plastics: Environmental and biotechnological perspectives on microbial degradation, *Appl. Environ. Microbiol.* 85 (2019) 1–14. <https://doi.org/10.1128/AEM.01095-19>
- [36] G.J. Palm, L. Reisky, D. Böttcher, H. Müller, E.A.P. Michels, M.C. Walczak, L. Berndt, M.S. Weiss, U.T. Bornscheuer, G. Weber, Structure of the plastic-degrading *Ideonella sakaiensis* MHETase bound to a substrate, *Nat. Commun.* 10 (2019) 1–10. <https://doi.org/10.1038/s41467-019-09326-3>

- [37] M. Furukawa, N. Kawakami, A. Tomizawa, K. Miyamoto, Efficient degradation of Poly(ethylene terephthalate) with *Thermobifida fuscacutinase* exhibiting improved catalytic activity generated using mutagenesis and additive-based approaches, *Sci. Rep.* 9 (2019) 1–9. <https://doi.org/10.1038/s41598-019-52379-z>
- [38] T. Volova, E. Kiselev, N. Zhila, E. Shishatskaya, Synthesis of polyhydroxyalkanoates by hydrogen-oxidizing bacteria in a pilot production process, *Biomacromolecules*. (2019). <https://doi.org/10.1021/acs.biomac.9b00295>
- [39] A. Iles, A.N. Martin, Expanding bioplastics production: Sustainable business innovation in the chemical industry, *J. Clean. Prod.* 45 (2013) 38–49. <https://doi.org/10.1016/j.jclepro.2012.05.008>
- [40] H. Karan, C. Funk, M. Grabert, M. Oey, B. Hankamer, Green bioplastics as part of a circular bioeconomy, *Trends Plant Sci.* 24 (2019) 237–249. <https://doi.org/10.1016/j.tplants.2018.11.010>
- [41] S. Beucker, F. Marscheider-Weidemann, Potentials and challenges of bioplastics – Insights from a German survey on “GreenFuture Markets”, *Borderstep Inst. Innov. Sustain.* (2007) 1–7. http://www.borderstep.de/wpcontent/uploads/2014/12/beucker_marscheider_potentials_and_challenges_of_bioplastics_2007.pdf
- [42] M.V. Reddy, Y. Mawatari, R. Onodera, Y. Nakamura, Y. Yajima, Y.-C. Chang, Bacterial conversion of waste into polyhydroxybutyrate (PHB): A new approach of bio-circular economy for treating waste and energy generation, *Bioresour. Technol. Reports*. 7 (2019) 100246. <https://doi.org/10.1016/j.biteb.2019.100246>
- [43] M.. Paridah, A. Moradbak, A. Mohamed, F. abdulwahab taiwo Owolabi, M. Asniza, S.H.. Abdul Khalid, Prospective biodegradable plastics from biomass conversion processes. *Intech*. 13 (2016) <https://doi.org/http://dx.doi.org/10.5772/57353>
- [44] R.J.K. Helmes, A.M. López-Contreras, M. Benoit, H. Abreu, J. Maguire, F. Moejes, S.W.K. van den Burg, Environmental impacts of experimental production of lactic acid for bioplastics from *Ulva spp*, *Sustain.* 10 (2018) 1–15. <https://doi.org/10.3390/su10072462>
- [45] S. Spierling, C. Röttger, V. Venkatachalam, M. Mudersbach, C. Herrmann, H.J. Endres, Bio-based Plastics - A building block for the circular economy?, *Procedia CIRP*. 69 (2018) 573–578. <https://doi.org/10.1016/j.procir.2017.11.017>
- [46] M. He, X. Wang, Z. Wang, L. Chen, Y. Lu, X. Zhang, M. Li, Z. Liu, Y. Zhang, H. Xia, L. Zhang, Biocompatible and biodegradable bioplastics constructed from chitin

via a “green” pathway for bone repair, *ACS Sustain. Chem. Eng.* 5 (2017) 9126–9135.
<https://doi.org/10.1021/acssuschemeng.7b02051>

- [47] P. Trivedi, A. Hasan, S. Akhtar, M. Haris Siddiqui, U. Sayeed, M. Kalim, A. Khan, Role of microbes in degradation of synthetic plastics and manufacture of bioplastics, *J. Chem. Pharm. Res.* 8 (2016) 211–216.
- [48] C. Rajendran, N. , Sharanya Puppala, Sneha Raj M., Ruth Angeeleena B., and Rajam, Seaweeds can be a new source for bioplastics, *J. Pharm. Res.* 5 (2012) 1476–1479
- [49] O. Valerio, J.M. Pin, M. Misra, A.K. Mohanty, Synthesis of glycerol-based biopolyesters as toughness enhancers for polylactic acid bioplastic through reactive extrusion, *ACS Omega.* 1 (2016) 1284–1295.
<https://doi.org/10.1021/acsomega.6b00325>
- [50] M.N. Somleva, K.D. Snell, J.J. Beaulieu, O.P. Peoples, B.R. Garrison, N.A. Patterson, Production of polyhydroxybutyrate in switchgrass, a value-added co-product in an important lignocellulosic biomass crop, *Plant Biotechnol. J.* 6 (2008) 663–678. <https://doi.org/10.1111/j.1467-7652.2008.00350.x>
- [51] B.T. Ho, T.K. Roberts, S. Lucas, An overview on biodegradation of polystyrene and modified polystyrene: the microbial approach, *Crit. Rev. Biotechnol.* 38 (2018) 308–320. <https://doi.org/10.1080/07388551.2017.1355293>
- [52] Maulida, M. Siagian, P. Tarigan, Production of starch based bioplastic from cassava peel reinforced with microcrystalline cellulose avicel PH101 using sorbitol as plasticizer, *J. Phys. Conf. Ser.* 710 (2016). <https://doi.org/10.1088/1742-6596/710/1/012012>
- [53] S. Mohapatra, S. Maity, H.R. Dash, S. Das, S. Pattnaik, C.C. Rath, D. Samantaray, Bacillus and biopolymer: Prospects and challenges, *Biochem. Biophys. Reports.* 12 (2017) 206–213. <https://doi.org/10.1016/j.bbrep.2017.10.001>
- [54] J. Gonzalez-Gutierrez, P. Partal, M. Garcia-Morales, C. Gallegos, Development of highly-transparent protein/starch-based bioplastics, *Bioresour. Technol.* 101 (2010) 2007–2013. <https://doi.org/10.1016/j.biortech.2009.10.025>
- [55] I. Reiniati, A.N. Hrymak, A. Margaritis, Recent developments in the production and applications of bacterial cellulose fibers and nanocrystals, *Crit. Rev. Biotechnol.* 37 (2017) 510–524. <https://doi.org/10.1080/07388551.2016.1189871>

- [56] M. Brodin, M. Vallejos, M.T. Opedal, M.C. Area, G. Chinga-Carrasco, Lignocellulosics as sustainable resources for production of bioplastics – A review, *J. Clean. Prod.* 162 (2017) 646–664. <https://doi.org/10.1016/j.jclepro.2017.05.209>
- [57] Isroi, A. Cifriadi, T. Panji, N.A. Wibowo, K. Syamsu, Bioplastic production from cellulose of oil palm empty fruit bunch, *IOP Conf. Ser. Earth Environ. Sci.* 65 (2017). <https://doi.org/10.1088/1755-1315/65/1/012011>
- [58] R. Villa-Rojas, A. Valdez-Fragoso, H. Mújica-Paz, Manufacturing Methods and Engineering properties of pectin-based nanobiocomposite films, *Food Eng. Rev.* 10 (2018) 46–56. <https://doi.org/10.1007/s12393-017-9163-9>
- [59] S. Chodijah, A. Husaini, M. Zaman, Hilwatulisan, Extraction of pectin from banana peels (*Musa Paradisiaca Fomatypica*) for biodegradable plastic films, *J. Phys. Conf. Ser.* 1167 (2019). <https://doi.org/10.1088/1742-6596/1167/1/012061>
- [60] S.L. Pandharipande, P.H. Bhagat, Synthesis of chitin from crab shells and its utilization in preparation of nanostructured film, *Int. J. Sci. Eng. Technol. Res.* 5 (2016) 2278–7798
- [61] Z.A. Raza, S. Abid, I.M. Banat, Polyhydroxyalkanoates: Characteristics, production, recent developments and applications, *Int. Biodeterior. Biodegrad.* 126 (2018) 45–56. <https://doi.org/10.1016/j.ibiod.2017.10.001>
- [62] C.J.R. Verbeek, L.E. van den Berg, Recent developments in thermo-mechanical processing of proteinous bioplastics, recent patents *Mater. Sci.* 2 (2010) 171–189. <https://doi.org/10.2174/1874465610902030171>
- [63] M.P. Ryan, G. Walsh, The biotechnological potential of whey, *Rev. Environ. Sci. Biotechnol.* 15 (2016) 479–498. <https://doi.org/10.1007/s11157-016-9402-1>
- [64] S. Sharma, I. Luzinov, Whey based binary bioplastics, *J. Food Eng.* 119 (2013) 404–410. <https://doi.org/10.1016/j.jfoodeng.2013.06.007>
- [65] A. Jerez, P. Partal, I. Martínez, C. Gallegos, A. Guerrero, Protein-based bioplastics: Effect of thermo-mechanical processing, *Rheol. Acta.* 46 (2007) 711–720. <https://doi.org/10.1007/s00397-007-0165-z>
- [66] B. Chalermthai, W.Y. Chan, J.R. Bastidas-Oyanedel, H. Taher, B.D. Olsen, J.E. Schmidt, Preparation and characterization of whey protein-based polymers produced from residual dairy streams, *Polymers (Basel)*. 11 (2019). <https://doi.org/10.3390/polym11040722>
- [67] M. Javanmard, Biodegradable whey protein edible films as a new biomaterials for food and drug packaging, *Iran. J. Pharm. Sci.* 5 (2009) 129–134.

- [68] M. Helgeson, W. Graves, D. Grewell, G. Srinivasan, Degradation and nitrogen release of zein-based bioplastic containers, *J. Environ. Hortic.* 27 (2009) 123–127. http://www.hrresearch.org/docs/publications/JEH/JEH_2009/JEH_2009_27_2/JEH_27-2-123-127.pdf
- [69] S. Aziz, L. Hosseinzadeh, E. Arkan, A.H. Azandaryani, Preparation of electrospun nanofibers based on wheat gluten containing azathioprine for biomedical application, *Int. J. Polym. Mater. Polym. Biomater.* 68 (2019) 639–646. <https://doi.org/10.1080/00914037.2018.1482464>
- [70] M. Koller, A. Salerno, M. Dias, A. Reiterer, G. Braunegg, Modern biotechnological polymer synthesis: A review, *Food Technol. Biotechnol.* 48 (2010) 255–269
- [71] R. Jain, S. Kosta, A. Tiwari, Polyhydroxyalkanoates: A way to sustainable development of bioplastics, *Chronicles Young Sci.* 1 (2010) 10–15. <https://doi.org/10.4103/4444-4443.76448>
- [72] M.E. Grigore, R.M. Grigorescu, L. Iancu, R.M. Ion, C. Zaharia, E.R. Andrei, Methods of synthesis, properties and biomedical applications of polyhydroxyalkanoates: a review, *J. Biomater. Sci. Polym. Ed.* 30 (2019) 695–712. <https://doi.org/10.1080/09205063.2019.1605866>
- [73] B. Johnston, I. Radecka, D. Hill, E. Chiellini, V.I. Ilieva, W. Sikorska, M. Musioł, M. Zięba, A.A. Marek, D. Keddie, B. Mendrek, S. Darbar, G. Adamus, M. Kowalczyk, The microbial production of Polyhydroxyalkanoates from waste polystyrene fragments attained using oxidative degradation, *Polymers (Basel)*. 10 (2018). <https://doi.org/10.3390/polym10090957>
- [74] J. Mozejko-Ciesielska, K. Szacherska, P. Marciniak, *Pseudomonas* species as producers of eco-friendly polyhydroxyalkanoates, *J. Polym. Environ.* 27 (2019) 1151–1166. <https://doi.org/10.1007/s10924-019-01422-1>
- [75] T. Keshavarz, I. Roy, Polyhydroxyalkanoates: bioplastics with a green agenda, *Curr. Opin. Microbiol.* 13 (2010) 321–326. <https://doi.org/10.1016/j.mib.2010.02.006>
- [76] M. Kootstra, H. Elissen, S. Huurman, PHA's (Polyhydroxyalkanoates): General information on structure and raw materials for their production, 2017. <https://doi.org/http://library.wur.nl/WebQuery/wurpubs/fulltext/414011>
- [77] T.V. Ojumu, J. Yu, B.O. Solomon, Production of polyhydroxyalkanoates, a bacterial biodegradable polymer, *African J. Biotechnol.* 3 (2004) 18–24

- [78] L. Favaro, M. Basaglia, J.E.G. Rodriguez, A. Morelli, O. Ibraheem, V. Pizzocchero, S. Casella, Bacterial production of PHAs from lipid-rich by-products, *Appl. Food Biotechnol.* 6 (2019) 45–52. <https://doi.org/10.22037/AFB.V6I1.22246>
- [79] K. Dietrich, M.J. Dumont, L.F. Del Rio, V. Orsat, Producing PHAs in the bioeconomy — towards a sustainable bioplastic, *Sustain. Prod. Consum.* 9 (2017) 58–70. <https://doi.org/10.1016/j.spc.2016.09.001>
- [80] K.M. Nampoothiri, N.R. Nair, R.P. John, An overview of the recent developments in polylactide (PLA) research, *Bioresour. Technol.* 101 (2010) 8493–8501. <https://doi.org/10.1016/j.biortech.2010.05.092>
- [81] R. Coles, M. Kay, J. Song, Bioplastics, *Adv. Biochem. Eng. Biotechnol.* 166 (2010) 427–468. https://doi.org/10.1007/10_2016_75
- [82] S.M. Emadian, T.T. Onay, B. Demirel, Biodegradation of bioplastics in natural environments, *Waste Manag.* 59 (2017) 526–536. <https://doi.org/10.1016/j.wasman.2016.10.006>
- [83] P. Scarfato, L. Di Maio, L. Incarnato, Recent advances and migration issues in biodegradable polymers from renewable sources for food packaging, *J. Appl. Polym. Sci.* 132 (2015). <https://doi.org/10.1002/app.42889>
- [84] N. Benn, D. Zitomer, Pretreatment and Anaerobic Co-digestion of Selected PHB and PLA Bioplastics, *Front. Environ. Sci.* 5 (2018) 1–9. <https://doi.org/10.3389/fenvs.2017.00093>
- [85] R. Geyer, J.R. Jambeck, K.L. Law, Production, use, and fate of all plastics ever made., *Sci. Adv.* 3 (2017) e1700782. <https://doi.org/10.1126/sciadv.1700782>
- [86] S. Mangaraj, A. Yadav, L.M. Bal, S.K. Dash, N.K. Mahanti, Application of Biodegradable polymers in food packaging industry: A comprehensive review, *J. Packag. Technol. Res.* 3 (2019) 77–96. <https://doi.org/10.1007/s41783-018-0049-y>
- [87] L.A.M. Van Den Broek, R.J.I. Knoop, F.H.J. Kappen, C.G. Boeriu, Chitosan films and blends for packaging material, *Carbohydr. Polym.* 116 (2015) 237–242. <https://doi.org/10.1016/j.carbpol.2014.07.039>
- [88] J.W. Rhim, H.M. Park, C.S. Ha, Bio-nanocomposites for food packaging applications, *Prog. Polym. Sci.* 38 (2013) 1629–1652. <https://doi.org/10.1016/j.progpolymsci.2013.05.008>
- [89] V.V.T. Padil, C. Senan, S. Wacławek, M. Černík, S. Agarwal, R.S. Varma, Bioplastic fibers from gum arabic for greener food wrapping applications, *ACS*

- Sustain. Chem. Eng. 7 (2019) 5900–5911.
<https://doi.org/10.1021/acssuschemeng.8b05896>
- [90] J. Rydz, W. Sikorska, M. Kyulavska, D. Christova, Polyester-based (bio)degradable polymers as environmentally friendly materials for sustainable development, Int. J. Mol. Sci. 16 (2015) 564–596.
<https://doi.org/10.3390/ijms16010564>
- [91] H.Y. Sintim, M. Flury, Is biodegradable plastic mulch the solution to agriculture's plastic problem?, Environ. Sci. Technol. 51 (2017) 1068–1069.
<https://doi.org/10.1021/acs.est.6b06042>
- [92] T.S.M. Amelia, A.M. Sharumathiy Govindasamy, Tamothran, and K.B. Sevakumaran Vigneswari, Biotechnological applications of polyhydroxyalkanoates. Applications of PHA in Agriculture, (2019) 347–361. <https://doi.org/10.1007/978-981-13-3759-8>
- [93] B.S. Hungund, S.G. Umloti, K.P. Upadhyaya, J. Manjanna, S. Yallappa, N.H. Ayachit, Development and characterization of polyhydroxybutyrate biocomposites and their application in the removal of heavy metals, Mater. Today Proc. 5 (2018) 21023–21029. <https://doi.org/10.1016/j.matpr.2018.6.495>
- [94] F. Alshehrei, Biodegradation of synthetic and natural plastic by microorganisms, J. Appl. Environ. Microbiol. Vol. 5, 2017, Pages 8-19. 5 (2017) 8–19.
<https://doi.org/10.12691/JAEM-5-1-2>
- [95] N.A. Mostafa, A.A. Farag, H.M. Abo-dief, A.M. Tayeb, Production of biodegradable plastic from agricultural wastes, Arab. J. Chem. 11 (2018) 546–553.
<https://doi.org/10.1016/j.arabjc.2015.04.008>
- [96] T. Ahmed, M. Shahid, F. Azeem, I. Rasul, A.A. Shah, M. Noman, A. Hameed, N. Manzoor, M. Muhammad, Irfan Manzoor Sher, Biodegradation of plastics: current scenario and future prospects for environmental safety, Environ. Sci. Pollut. Res. 25 (2018) 7287–7298. <https://doi.org/10.1007/s11356-018-1234-9>
- [97] R.A. Wilkes, L. Aristilde, Degradation and metabolism of synthetic plastics and associated products by *Pseudomonas* sp.: capabilities and challenges, J. Appl. Microbiol. 123 (2017) 582–593. <https://doi.org/10.1111/jam.13472>
- [98] A.K. Urbanek, W. Rymowicz, A.M. Mironczuk, Degradation of plastics and plastic-degrading bacteria in cold marine habitats, Appl. Microbiol. Biotechnol. 102 (2018) 7669–7678. <https://doi.org/10.1007/s00253-018-9195-y>

- [99] G. Caruso, Plastic degrading microorganisms as a tool for bioremediation of plastic contamination in aquatic environments, *J. Pollut. Eff. Control.* 03 (2015). <https://doi.org/10.4172/2375-4397.1000e112>
- [100] R. Patil, U.S. Bagde, Isolation of polyvinyl chloride degrading bacterial strains from environmental samples using enrichment culture technique, *African J. Biotechnol.* 11 (2012) 7947–7956. <https://doi.org/10.5897/ajb11.3630>
- [101] T.C.H. Dang, D.T. Nguyen, H. Thai, T.C. Nguyen, T.T.H. Tran, V.H. Le, V.H. Nguyen, X.B. Tran, . T. P. T. Pham, T. G Nguyen, Plastic degradation by thermophilic *Bacillus* sp. BCBT21 isolated from composting agricultural residual in Vietnam, *Adv. Nat. Sci. Nanosci. Nanotechnol.* 9 (2018) 015014. <https://doi.org/10.1088/2043-6254/aaabaf>
- [102] P. Sriyapai, K. Chansiri, T. Sriyapai, Isolation and characterization of polyester-based plastics-degrading bacteria from compost soils, *Microbio.* 87 (2018) 290–300. <https://doi.org/10.1134/s0026261718020157>
- [103] S. Pathak, C.L.Rp. Sneha, B.B. Mathew, Bioplastics : Its timeline based scenario & challenges, *J. Polym. Biopolym. Chem.* 2 (2014) 84–90. <https://doi.org/10.12691/jpbpc-2-4-5>
- [104] R. Mülhaupt, Green polymer chemistry and bio-based plastics: Dreams and reality, *Macromol. Chem. Phys.* 214 (2013) 159–174. <https://doi.org/10.1002/macp.201200439>
- [105] N. Jabeen, I. Majid, G.A. Nayik, Bioplastics and food packaging: A review, *Cogent Food Agric.* 1 (2015) 1–6. <https://doi.org/10.1080/23311932.2015.1117749>
- [106] F.I. Khan, L. Aktar, T. Islam, M.L. Saha, Isolation and Identification of Indigenous poly- β -Hydroxybutyrate (PHB) producing bacteria from different waste materials, *Plant Tissue Cult. Biotechnol.* 29 (2019) 15–24. <https://doi.org/10.3329/ptcb.v29i1.41975>
- [107] S. Rohner, J. Humphry, C.M. Chaléat, L.J. Vandi, D.J. Martin, N. Amiralian, M.T. Heitzmann, Mechanical properties of polyamide 11 reinforced with cellulose nanofibres from *Triodia pungens*, *Cellulose.* 25 (2018) 2367–2380. <https://doi.org/10.1007/s10570-018-1702-x>
- [108] T.M.M.M. Amaro, D. Rosa, G. Comi, L. Iacumin, Prospects for the use of whey for polyhydroxyalkanoate (PHA) production, *Front. Microbiol.* 10 (2019) 1–12. <https://doi.org/10.3389/fmicb.2019.00992>

- [109] P. Carlozzi, A. Giovannelli, M.L. Traversi, E. Touloupakis, T. Di Lorenzo, Poly-3-hydroxybutyrate and H₂ production by *Rhodopseudomonas* sp. S16-VOGS3 grown in a new generation photobioreactor under single or combined nutrient deficiency, *Int. J. Biol. Macromol.* 135 (2019) 821–828. <https://doi.org/10.1016/j.ijbiomac.2019.05.220>
- [110] A.H.M. Fauzi, L.W. Yoon, T. Nittami, H.K. Yeohd, Enrichment of PHA-accumulators for sustainable PHA production from crude glycerol, *Process Saf. Environ. Prot.* 122 (2019) 200–208. <https://doi.org/10.1016/j.psep.2018.12.002>
- [111] H. Al-Battashi, N. Annamalai, S. Al-Kindi, A.S. Nair, S. Al-Bahry, J.P. Verma, N. Sivakumar, Production of bioplastic (poly-3-hydroxybutyrate) using waste paper as a feedstock: Optimization of enzymatic hydrolysis and fermentation employing *Burkholderia sacchari*, *J. Clean. Prod.* 214 (2019) 236–247. <https://doi.org/10.1016/j.jclepro.2018.12.239>
- [112] R.R. Dalsasso, F.A. Pavan, S.E. Bordignon, G.M.F. de Aragão, P. Poletto, Polyhydroxybutyrate (PHB) production by *Cupriavidus necator* from sugarcane vinasse and molasses as mixed substrate, *Process Biochem.* (2019) 0–1. <https://doi.org/10.1016/j.procbio.2019.07.007>
- [113] A.O. Pérez-Arauz, A.E. Aguilar-Rabiela, A. Vargas-Torres, A.I. Rodríguez-Hernández, N. Chavarria-Hernández, B. Vergara-Porras, M.R. López-Cuellar, Production and characterization of biodegradable films of a novel polyhydroxyalkanoate (PHA) synthesized from peanut oil, *Food Packag. Shelf Life.* 20 (2019) 100297. <https://doi.org/10.1016/j.fpsl.2019.01.001>
- [114] T.H. Nguyen, F. Ishizuna, Y. Sato, H. Arai, M. Ishii, Physiological characterization of poly-β-hydroxybutyrate accumulation in the moderately thermophilic hydrogen-oxidizing bacterium *Hydrogenophilus thermoluteolus* TH-1, *J. Biosci. Bioeng.* 127 (2019) 686–689. <https://doi.org/10.1016/j.jbiosc.2018.11.011>
- [115] T. Yamaguchi, J. Narsico, T. Kobayashi, A. Inoue, T. Ojima, Production of poly(3-hydroxybutyrate) by a novel alginate-degrading bacterium *Hydrogenophaga* sp. strain UMI-18 using alginate as a sole carbon source, *J. Biosci. Bioeng.* 128 (2019) 203–208. <https://doi.org/10.1016/j.jbiosc.2019.02.008>
- [116] I. Pernicova, Vojtech Enev, Ivana Marova, Stanislav Obruca, Interconnection of waste chicken feather biodegradation and keratinase and mcl-PHA production employing *Pseudomonas putida* KT2440, *Appl. Food Biotechnol.* 6 (2018) 83–90. <https://doi.org/10.22037/afb.v6i1.21429>
- [117] Z.N. Terzopoulou, G.Z. Papageorgiou, E. Papadopoulou, E. Athanassiadou, E. Alexopoulou, D.N. Bikiaris, Green composites prepared from aliphatic polyesters and

- bast fibers, *Ind. Crops Prod.* 68 (2015) 60–79.
<https://doi.org/10.1016/j.indcrop.2014.08.034>
- [118] K. Preethi, M. Umesh, Water Hyacinth : A potential substrate for bioplastic (PHA) production using *Pseudomonas aeruginosa*, *Int. J. Appl. Res.* 1 (2015) 349–354
- [119] J. Yaradoddi, V. Patil, S. Ganachari, N. Banapurmath, A. Hunashyal, A. Shettar, Biodegradable plastic production from fruit waste material and its sustainable use for green applications, *Int. J. Pharm. Res. Allied Sci.* 5 (2016) 55–66
- [120] R.G. Saratale, G.D. Saratale, S.K. Cho, D.S. Kim, G.S. Ghodake, A. Kadam, G. Kumar, R.N. Bharagava, R. Banu, H.S. Shin, Pretreatment of kenaf (*Hibiscus cannabinus L.*) biomass feedstock for polyhydroxybutyrate (PHB) production and characterization, *Bioresour. Technol.* 282 (2019) 75–80.
<https://doi.org/10.1016/j.biortech.2019.02.083>
- [121] C. Choi, J.P. Nam, J.W. Nah, Application of chitosan and chitosan derivatives as biomaterials, *J. Ind. Eng. Chem.* 33 (2016) 1–10.
<https://doi.org/10.1016/j.jiec.2015.10.028>
- [122] Y.E. Agustin, K.S. Padmawijaya, Effect of glycerol and zinc oxide addition on antibacterial activity of biodegradable bioplastics from chitosan-kepok banana peel starch, *IOP Conf. Ser. Mater. Sci. Eng.* 223 (2017). <https://doi.org/10.1088/1757-899X/223/1/012046>
- [123] S. Domenek, P. Feuilleley, J. Gratraud, M.H. Morel, S. Guilbert, Biodegradability of wheat gluten based bioplastics, *Chemosphere.* 54 (2004) 551–559.
[https://doi.org/10.1016/S0045-6535\(03\)00760-4](https://doi.org/10.1016/S0045-6535(03)00760-4)
- [124] N. Ramakrishnan, S. Sharma, A. Gupta, B.Y. Alashwal, Keratin based bioplastic film from chicken feathers and its characterization, *Int. J. Biol. Macromol.* 111 (2018) 352–358. <https://doi.org/10.1016/j.ijbiomac.2018.01.037>
- [125] S. Van Vlierberghe, E. Vanderleyden, V. Boterberg, P. Dubrue, Gelatin functionalization of biomaterial surfaces: Strategies for immobilization and visualization, *Polymers (Basel).* 3 (2011) 114–130.
<https://doi.org/10.3390/polym3010114>
- [126] S. Khalid, L. Yu, L. Meng, H. Liu, A. Ali, L. Chen, Poly(lactic acid)/starch composites: Effect of microstructure and morphology of starch granules on performance, *J. Appl. Polym. Sci.* 134 (2017) 1–12. <https://doi.org/10.1002/app.45504>

- [127] S.F. Williams, S. Rizk, D.P. Martin, Poly-4-hydroxybutyrate (P4HB): A new generation of resorbable medical devices for tissue repair and regeneration, *Biomed. Tech.* 58 (2013) 439–452. <https://doi.org/10.1515/bmt-2013-0009>
- [128] I.S. Sidek, S. Fauziah, S. Draman, S. Rozaimah, S. Abdullah, N. Anuar, Current development on bioplastics and its future: An introductory review, *I Tech Mag.* 1 (2019) 3-8. <https://doi.org/http://doi.org/10.26480/itechmag.01.2019.03.08> CURRENT
- [129] V. Mehta, M. Darshan, D. Nishith, Can a starch based plastic be an option of environmental friendly plastic?, *J. Glob. Biosci.* 3 (2014) 681–685.
- [130] W.J. Orts, J. Shey, S.H. Imam, G.M. Glenn, M.E. Guttman, J.F. Revol, Application of cellulose microfibrils in polymer nanocomposites, *J. Polym. Environ.* 13 (2005) 301–306. <https://doi.org/10.1007/s10924-005-5514-3>
- [131] V.K. Modi, Y. Shrives, C. Sharma, P.K. Sen, Review on green polymer nanocomposite and their applications, *Int. J. Innov. Res. Sci. Eng. Technol.* 2014 (2015) 17651–17656. <https://doi.org/10.15680/IJIRSET.2014.0311079>
- [132] K. Khosravi-Darani, D.Z. Bucci, Application of poly(hydroxyalkanoate) in food packaging: Improvements by nanotechnology, *Chem. Biochem. Eng. Q.* 29 (2015) 275–285. <https://doi.org/10.15255/CABEQ.2014.2260>
- [133] I.M. Shamsuddin, J.A. Jafar, A.S.A. Shawai, S. Yusuf, M. Lateefah, I. Aminu, Bioplastics as better alternative to petroplastics and their role in national sustainability: A review, *Adv. Biosci. Bioeng.* 5 (2017) 63. <https://doi.org/10.11648/j.abb.20170504.13>
- [134] F. Muneer, I. Rasul, F. Azeem, M.H. Siddique, M. Zubair, H. Nadeem, Microbial Polyhydroxyalkanoates (PHAs): Efficient Replacement of Synthetic Polymers, *J Polym Environ.* (2020)28: 2301–2323. <https://doi.org/10.1007/s10924-020-01772-1>