Chapter 10

Versatile Applications of Degradable Plastic

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Abstract

In the last 50 years, plastics has become a favorite industry for packaging materials for their ease of manufacture and excellent performance. The advancement of food, electronics, automobile, medical and agricultural industries has increased the demand for packaging and casing materials made of large hydrocarbon polymers. Since plastics show resistance to biodegradation, they pose considerable threats to the environment. Degradable plastics and biopolymers offer promising solutions to this problem. Degradable plastics can be easily absorbed in the environment while exhibiting the properties of conventional plastics. There are three types of biopolymers according to their source: biomass extracted polymers, synthesized from microorganisms and produced from bio-derived monomers. Biodegradable plastics are commonly used in one-off packaging such as crockery, food service containers and cutlery. Although biodegradable plastics can replace conventional plastics in a lot of applications, their performance and cost are sometimes problematic. This chapter analyses the growth of the degradable plastic industry and explores their potential applications.

Keywords

Degradable Plastic, Plastic Waste, Industrial, Agricultural, Consumer, Energy, Waste Management

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1. Introduction

Public and government awareness of using sustainable products has increased considerably over the last decade. This provided an impetus for researchers to develop sustainable technologies and eco-friendly materials. A combination of climate change and environmental destruction threats pressed governments to apply for strict industry regulations to limit their plastic pollution [1]. This encouraged the research and development of degradable plastics that dissolve in the environment at the end of their life cycle without any negative impact. Understanding the application aspects and sprouting trends of this promising technology will aid investors, policymakers, and researchers in investing further advance the research on degradable plastic.

In 1907, Bakelite - the first synthetic plastic was produced, which paved the way for the plastic industrial revolution in the 1950s. However, within a span of only 65 years, the production of plastic has increased 200 folds and reached an annual production rate of 381 million tons in 2015. Disposing of this enormous amount of plastic waste is near impossible; therefore, it is essentials that the produced plastic can decay naturally or be disposed using inexpensive physio-chemical treatments. The production of plastics by industrial sectors is shown in Fig. 1 [2].

Fig. 1 Production of plastics by industrial sectors, 2015[2].

From Fig. 1, it is evident that a considerable amount of plastic is produced for packaging, which is essentially single-use disposable plastic. Research has shown that photodegradable and thermally degradable plastics have the ideal properties for being potential packaging material [3,4]. After their useful life cycle, these plastics degrade naturally in the presence of light and heat.

This study provides a bibliographic analysis of the potential application of degradable plastic in various industrial sectors. Additionally, the chapter highlights existing research landscape and predicts the future developing trends focusing on the contexts of degradable plastics such as polylactic acid (PLA), polycaprolactone (PCL), polyhydroxy alkenoates (PHAs), polybutylene adipate-co-terephthalate (PBAT) and polybutylene succinate (PBS). More specifically, PLA is at the top preference for both industry and academy, and PHAs are in almost all international biodegradable polymer patents. However, in technological terms, PLA is the fastest expanding technology in terms of both technology strength and maturity whereas PBS, PCL and PHAs are uncertain in the matter of technology and PBAT has less developmental potential.

The chapter discusses possible industrial applications based on the physio-chemical properties of each type of degradable plastics. Section 2 highlights the negative impact of plastic waste, providing a detailed view of the plastic waste scenario. Various applications of degradable plastics are discussed in section 3. In section 4, the growth of the degradable plastic industry is studied to assess its potential market share. Section 5 summarizes the findings.

2. Plastic waste and its adverse effects

2.1 Plastic waste scenario

Different aerospace and automobile parts, health and medical industry, clothing, pipes and fittings in buildings, engineering parts, plastic home appliances, and food packaging, etc. sectors widely use plastic. Due to this immense dependence on plastics, their overall production has reached almost 8 billion tons [5], and the production rate is increasing exponentially. Due to the absence of proper waste management, almost all plastics are accumulated on land or in the ocean. Some of the most common ways of plastic disposal are landfilling, open dumping and burning or littering [6]. These conventional ways of plastic disposal cause severe damage to the environment [5]. The plastic products are also washed into water bodies causing significant harm to marine lives.

The production of plastic is gradually increasing as only a meagre amount isadequately recycled [5]. In developed countries, about 98% of plastic waste is collected, whereas in

developing countries, the share falls to 41%, and the rest is littered or burned. In the USA, the recycling rate for plastics is about 9%, and in Europe, the amount is up to 30%. As packaging is a primary application of plastic, about 24-42% of packaging plastic is recycled in developed countries [5].

2.2 Effects of plastic waste

2.2.1 Landfills

In the whole world, about 22-43% of plastics are disposed in landfills, which is one of the cheapest methods of disposal [7]. Such landfilling practices reduce the capacity of potential land that can be used for other productive purposes. Although landfilling is not a recommended practice but is common among many countries, for example, in the USA most unrecycled plastics (about 90%) are landfilled, and in the EU, this landfill rate is about 31%[8]. In developing countries, open landfills and dumps is a common scenario [9]. This causes severe damage to the environment [10]. Plastic production will increase with urbanization and that will bring upon even more wastes in the future [10, 11].

2.2.2 In ocean

According to Jambeek et al. [12] about 50% of the plastic waste that enters the ocean, comes from five south Asian countries. Plastic waste of at least 100 million tons is predicted to enter the ocean in the period 2010- 2025 [5]. It is predicted that by 2050, the ocean will contain more plastic than fish by weight [13]. Cellulose acetate, polyethylene (PE), polypropylene (PP) are some of the common plastic wastes found in the ocean [14]. The used plastic enters the ocean body through wastewater discharge points, coastal areas and rivers etc. Due to pollution caused in the ocean, the following problems occur:

- The tourism industry is negatively affected
- Marine life is damaged and threatened by extinction
- Coastal species numbers are severely depleted
- Interference with boats cause accidents
- Organic pollution

Fig. 2 shows the impact of several waste materials on marine animals [14].

Plastic waste entanglement and ingestion leads to choking and starvation of marine animals such as sea birds, whales, fish, dolphins etc. The global environmental impact of plastic waste causes an estimated economic loss of about 40 billion USD per annum.

Fig. 2 Comparative effects of several waste materials on marine animals [14]

3. Application of degradable plastic

3.1 Packaging

Plastics are used widely as packaging materials over the last 50 years. With the expansion of the food processing industry, the demand for plastics is also increasing. This caused an alarming ecological issue as conventional plastics resist biodegradation.

Some of the conventional packaging materials, i.e. polyamide (PA), polyvinyl chloride (PVC), polystyrene (PS), polyethylene terephthalate (PET), polypropylene (PP) exhibit specific properties for which they are used including low cost, tensile strength, and O₂ and CO₂ transmission properties [15–17]. These properties increase shelf life and attractiveness of the food to the consumers [18,19]. But these synthetic materials are non-degradable [20,21]. Biopolymers can be divided into three categories [22–26]. The first type is biopolymers derived from biomass, the second type is derived from renewable bio-based monomers and the third type is derived from microorganisms.

The first group of biopolymers extracted from biomass are hydrophilic and crystalline and are unsuitable for moist food products packaging; however, they play significant role in the food packaging industry due to their gas barrier property [23–26]. Conversely, some protein-based biopolymer (e.g., milk, gelatin, whey, egg white, wheat gluten, zein,

corn, soy protein) of this group can be used to make edible films to be consumed with the food. Such protein-based films are already used as edible packaging materials [27].

The second group of biopolymers is dominated by polylactic acid (PLA). It is economically viable during processing, and that is why becoming a popular choice for different types of applications [28,29]. PLAs performance was significantly better than synthetic plastics [30]. So, day by day, it is becoming a good alternative as a food packaging material. Resistance to water solubility, large molecular weight, ease of processing through biodegradability and thermoforming established PLA as a food packaging material [22,31,32]. Moreover, PLA exhibits similarities with some conventional plastics like polyethylene, PET, PVC, polystyrene etc. that makes it an ideal alternative of conventional plastics. It can be processed in several ways, which makes the processing pathway more flexible. Additionally, it can be processed into different forms and shapes. It can also be recycled and re-polymerized. Fig. 3 [29] illustrates some of the positive traits and limitations of PLAs.

Fig. 3 Some positive and negative traits of PLA [29]

Some limitations of PLA include the tendency to degrade rapidly in elevated temperatures and its brittleness can be an issue, but these limitations are likely to be eliminated in the near future.

The third group consists of polyhydroxyalkanoates (PHAs), which is a type of bacterial polyester. The PHA has a small share of the overall biopolymer market as only 453.59 tons of PHAs are produced annually. Fig. 4 [33–40] illustrates the favourable properties of PHAs. Some of these properties are unique while others are similar to conventional plastics.

Fig. 4 Some favorable properties of PHA and some of its derivatives[33–40].

PHAs are practical for biodegradable bottles, sheets, containers, coatings, films, fibres, and laminates. Furthermore, “Metabolix PHA” is a blend of poly (3-hydroxyoctanoate) and polyhydroxybutyrate (PHB) which is approved by Food and Drug Administration (FDA) for food packages that match the characteristics and performance of non-degradable plastics.

Several companies from the USA, Japan, Denmark, Canada, Germany, Thailand, France, etc. have been producing biodegradable plastic films. Table 1 [27] shows some of the companies and the type of biodegradable film they manufacture and Fig. 5 [6] shows the different applications of those films.

Table 1 *Manufacturers of bio-based films[27]*

Country	Company name, Film name		
	Starch-based films	PLA based films	PLA/Starch-based films
USA	Plantic technologies, Plantic	Nature works, Ingeo	Nature works, Ecovio
	Biotec, Bioplast		Plantic Co, Plantic
	Novamont, Mater Bi		
Japan	Rodenburg biopolymers, Solanyl	Teijin, BIOFRONT	Japan corn starch, Compole
Germany	Biop, Biopar		BASF, Bioflex
Canada		Revoda, HiSun	
France			Limagrain, Biolice

Biopolymers have a wide variety of commercial use. The major types of biopolymers discussed above can be used as an alternative for PP, PET, PES, and PE. They can be shaped like cups, trays, cutlery, shrink and stretch films, etc. Figure 5 shows a detailed overview of the plastics that biopolymers can alternate [6]. It also shows the form in which they are available for use in the food packaging industry.

Fig. 5 *Alternating potential of biopolymers with conventional plastics [6].*

To increase the shelf life of food materials, a special type of packaging is used that decreases the O₂ level inside the package and increases the CO₂ level. This slows down the overall metabolism rate and hence increases the shelf life. This type of packaging is called modified atmosphere packaging (MAP). Some biodegradable polymers such as chitosan-based films, biofex, PLA, PVC films etc. are used for MAP of some fruits and vegetables, and they are described in Fig. 6 [6].

Fig. 6 Application of MAP in different fruits and vegetables [6].

Undoubtedly, biopolymers reduce the adverse environmental effect of plastic production and processing, creating a pathway towards a green economy. But surprisingly, only 1% of the total plastics are replaced by the biodegradable polymers. Limitations such as complex processing operation, lack of durability and stability, production cost etc. have prevented biopolymers from offering a competitive alternative to plastics. More research is needed to improve their thermal and physiochemical properties, to reduce cost by simplifying the production process. A comprehensive study about the interaction between biopolymers and the food components should be performed prior to recommending a biopolymer for food packaging. The utilization of agricultural waste, solid waste management, health hazards issues, and greenhouse gas emission can be at least partially addressed by the use of biodegradable polymers contributing to sustainable environment society and economy.

3.2 Industrial Application

3.2.1 Paper covers

PHA latex is used to make paper or cardboard coverings. This cover is water-resistant and is much cost-efficient than the cardboard-aluminium mixture that is used at present. It is also used to make diaphragms, foils and films [41,42].

3.2.2 Day to day accessories

A German company “Biomer” makes P(3HB) from the bacteria “*Alcaligenes latus*”. It degrades within two months, and accessories like comb, pen etc. are made with this material [43].

3.2.3 Piezoelectric objects

As PHAs have piezoelectric nature; therefore, they can be used to produce acceleration measuring instruments, stretch sensors, lighters, shockwave detectors, keyboard pressure sensors, etc. [42].

3.2.4 Acoustics

Microphones, sounds pressure sensors, ultrasonic sensors, etc. can also be made by PHAs. This can be done by virtue of their acoustic properties [42].

3.2.5 Oscillators

PHA is used for making headphones, atomizing liquids, ultrasonic therapy, and loudspeakers. Oscillatory properties of PHAs can be useful in this regard [42].

3.2.6 Others

The combined effort of some companies from China, USA, and Korea, allowed P(3HB-3HHx) to be industrially produced from “*Aeromonas hydrophila*” and to make flexible packaging, synthetic papers, nonwovens, medical devices, thermoformed articles etc. [44].

3.3 Aerospace & automobile

Nearly 27 million tons of plastic are being used in the automotive industry each year. Hence, there is a significant concern for their proper recyclability. To comply with the environmental regulations, various automobile companies are using bio-based degradable plastics such as bio-based polyamides and polyesters to produce the various components. Research has shown that high-performance bio-based polypropylene and polyesters have

similar properties to the polybutylene terephthalate. These plastics have high durability, which makes them ideal for designing dashboard components.

Toyota is using degradable plastic polytrimethylene terephthalate (PTT) for manufacturing the interior vent louvre vanes of their latest Toyota Prius vehicle. PTT allows for thinner and stronger vent design. Moreover, Toyota is producing 60% of the interior fabrics of their cars from bio-based polyesters, which makes them a front-runner in adopting degradable plastic in the automobile industry. In their newest hybrid-electric compact vehicle model Lexus CT 200h and Lexus HS 250h, Toyota uses bio-based polypropylene/polylactic acid (PP/PLA) for interior design. Similarly, Röchling automotive are using high heat PLA compounds to design their interior trim parts and air filter box. A selection of applications is in Table 2 below [45].

Table 2 Use of biopolymers in the automobile industry[45]

Name	Use
Bio based polyamides	
PA 11	Mono and multi-line fuel lines, flexible tubing, fluid transfer lines, pneumatic brakes, friction parts and quick connectors, oil and fuel filters, steering shafts and coil springs etc
PA 6,10	Air filter, fuel contacting line, special cables etc.
PA 10,10	Turbo air duct, air coolers, oil pans, engine mounts, transmission parts etc.
PA 5,10	Housing of air filter, steer angle sensor cogwheel, cooling fan etc.
Bio based glass reinforced polyamides	
PA 6, 10 30% GF	Technical automotive parts
PA 10, 10 50% GF	
PA 10, 10 65% GF	
PLA based materials	
Standard commercial PLAs	Protective vehicle management wrappings
PLA fabrics and fibers	Roof, floor and carpet mats
Bio-based polyurethane foams	
Raw material: Soybean oil	Seats, door and body panel, head rests, head liners, impact absorbing foams, bumper fascia, etc.
Raw material: Castor oil	Head and arm rests, seats
Raw material: Sunflower oil	Seats

3.4 Medical application

Biodegradable plastics have versatile uses in medical applications being used as biomaterials in tissue engineering, surgical and pharmaceutical practice.

3.4.1 Biomaterials

A number of biomaterials are in essence disposable medical products such as catheters, syringes, and blood bags. Surgery supporting materials (adhesives, sealants, suture), temporary or permanent assisting artificial organs (vascular graft, artificial kidney or heart etc.), tissue replacements materials (dental implants, intraocular lens etc.) are also considered biomaterials. Biodegradable plastics are slowly attracting attention because of their biocompatibility [46], [47].

3.4.2 Surgical use

The most popular use of biodegradable polymers is for suturing. Polyglycolide and glycolide-L-lactide are widely used for this purpose. Hemostasis, adhesion and sealing are the second most important surgical procedures that highly require biodegradable polymers. The processed products are applied in the form of liquid that turns into gel and sticks in the defect area and later on, is absorbed by the body [48].

3.4.3 Pharmaceutical use

Biodegradable polymers are used for controlled release of drugs into the body. For this reason – discs, beads, cylinders, microspheres, nanospheres are made using biopolymers [49,50].

3.4.4 Tissue engineering

Biodegradable polymers are used in scaffolds for differentiation and proliferation of cell that causes tissue construction and regeneration. Also, at the location of regeneration, biodegradable polymers are used for sustained releasing of growth factors. Collagen, copolymers of lactide and glycolide-lactide are commonly used for scaffolds [51].

3.5 Agricultural application

3.5.1 Mulching

Degradable plastics have garnered popularity in agricultural applications as mulches. In its simplest form mulches, degradable plastic films contain plants and assist its growth. Farmers use such plastic films to raise soil temperature, prevent weed growth and

maintain adequate moisture. Plastics that undergo photodegradation are highly recommended for this application.

Light sensitive degradable plastic materials such as ethylene-carbon monoxide copolymers, vinyl ketone copolymers, aromatic ketone additives, and Ti/Zr complexes substituted with benzophenones can be used for agricultural mulching [3]. Using a mixture of ferric and nickel dibutyldithio-carbamates, the photodegradation rate can be controlled. This mixture is added in such a ratio that these degradable plastics start decaying once the growing season is over [52].

3.5.2 Planting containers

The use of plastic in various types of containers is a common practice in most agricultural farms and gardening [53]. Polycaprolactone, a type of degradable plastic, can be used for producing small plant containers. One of the fundamental advantages of using polycaprolactone is its longer life cycle. It is found that after six months of application, polycaprolactone begins to undergo considerable biodegradation. Experiments show that 48% of the weight is lost after six months, and 95% of the weight is lost in a year [3]. The most common use of polycaprolactone planting containers is in automated machine seed planting.

3.5.3 Packaging

Packing is a critical section of any industrial production process, including agriculture. Various types of agricultural products are now being transported to long-distance which requires improved packaging. Moreover, adequate packaging improves consumer perception of the end product and enhances shelf life. Photodegradable polymers such as ethylene-carbon monoxide (usually 1% carbon monoxide) copolymers are widely adopted as an alternative to conventional plastic for packaging [41].

Recently, additive approaches for preparing biodegradable packaging plastics have also gained considerable attention. Some of the most commonly used additives are ceric compounds, zirconium/titanium chelates, ferric compounds, and benzophenones that are used in various ratios to control the photodegradation rate. Additionally, biodegradable starch-filled polyethylene is also popular for producing packing plastics and container bags [52].

3.5.4 Seed film cultivation

Seed film cultivation is an innovative approach cultivate crops that are grown in water, such as rice. Experiments have shown that high rice yields can be achieved in aerobic soil biosphere in the absence of water. However, this process is susceptible to aerobic weed

growth, which ultimately dominates the field and reduces rice yield. In order to ameliorate this situation, biodegradable films can be used to protect the seed and produce rice in the absence of water. Seed film cultivation (SFC) is the direct sowing of seeds protected using biodegradable film.

Similar to the mulching, various types of photodegradable polymers such as ketone carbonyl copolymers can be used for producing cultivation films. Additionally, biodegradable plastics produced from a mixture of vinyl ketone comonomer with polystyrene (PS) and polyethylene (PE) can also be used to produce the cultivation film for SFC.

3.6 Consumer and institutional products application

Nearly 42 million tons of conventional plastics are produced to manufacture consumer and institutional products. Considering only 9% of these plastic products are recycled - this massive production rate raises grave concerns for environmental sustainability. There are thousands of types of consumer products that use plastics. Since plastic is cheap and easy to mold, finding an alternative material is challenging. However, degradable plastics can be a convenient alternative to reduce plastic pollution significantly. Based on the physio-chemical properties of various types of degradable plastic, certain products can be modelled and assembled. Table 3 [52–55,79–85] discusses the possible application of degradable plastic in consumer and institutional product applications.

3.7 Energy application

Nearly 300 million metric tons of plastics are produced globally [56]. Realizing the potential of plastic to fuel technologies, industries are investing significantly to develop effective methods for producing energy using plastics. Some of the most feasible techniques are described below.

3.7.1 Pyrolysis

Thermally treating and breaking large polymers into smaller hydrocarbons using pyrolysis is a popular method for converting plastic into fuel. In low oxygen and controlled environment with elevated temperatures, plastics can be converted into hydrocarbon-rich compounds that can be used as diesel and gasoline [57,58]. Belgiorno et al. [59] have shown that hydrocarbons with a boiling point between 35 and 185 °C are suitable for motor gasoline application. Similarly, hydrocarbons having a boiling temperature between 350 and 538 °C can be recommended as vacuum gas oil, and between 185 and 290 °C as diesel [59]. Table 4 [4,60–62,86–92] discusses various pyrolysis methods for converting plastic into fuel.

Table 3 *Application of degradable plastic for producing consumer and institutional products[52–55, 79–85].*

Type of products	Alternative Degradable Plastic	Method of Treatment	Conventional Plastic	Reference
Food containers, water bottles, soft-drinks bottles and other consumer products	Polyethylene containing pro-oxidant, Hydroxyalkanoates	Partial assimilation by microorganism, pre-aged thermally, activated sludge	PETE-polyethylene and PET	[54]
Laundry and dishwashing detergent, juice and milk bottles, grocery bags	HDPE/ starch with pro-oxidants, Polyhydroxy butyrate	Biodegradable, bioactive soil degradation, artificial weathering using UV and Xenon arc radiation	HDPE-high density polyethylene	[52,79,80]
Electrical insulation, rigid packaging sheets, food trays, irrigation pipes	Isotactic polymers (i-PP), Ethylene-propylene copolymers	Bio-assimilation and microbial attack, UV-irradiation	Polyvinyl Chloride	[81]
Wire insulation, trash bags, grocery bags, storage bags for food, bottles	LDPE comprising pro-oxidants and totally degradable plastic additives (TDPA)	Environmentally degradable, physiochemical treatment, microbial degradation	LDPE-low density polyethylene	[53,82,83]
Drinking straw, packaging of vegetable and fruit, bottle caps	PP/ starch mixed with Mater-Bi	Partially biodegradable	Polypropylene	[84]
Plastic kitchen and tableware, egg cartons, electronics, carryout containers	Polyhydroxyalkanoate (PHA), Polyolefines	Biodegradable, degradation in extremely acidic environment	Polystyrene	[85]
Baby toys, belts, book covers, household items, interior decoration, boots, shoes, slippers	Copolymers styrene-(ethylene-butylene)-styrene, Laprene, Polyolefines	Thermal degradation	Polyvinyl Chloride, polyethylene	[55]

Table 4 *Various pyrolysis methods for converting plastic into fuel [4,60–62,86–92]*

Type of Reactor	Plastic Feed Type	Operating Temperature	Output		Reference
			Gas (wt%)	Crude oil (wt%)	
Distillation type reactor	PETE-1	515-795	14.25	12.4	[61]
Batch Reactor with 2 litter capacity	HDPE	440	74	9	[4,86,87]
Natural State Research Inc reactor	Mixed (PE, PP, PS, PET)	370-420	90	5	[88]
Parr mini bench top	PP, PS, PET, PE	500	93	7	[89]
Fixed-bed and Fluidized bed reactor	LEPD and Mixed	330-450	15-87		[90,91]
Continuous reactor with activated carbon	PP, HDPE	520	88-96		[60,92]
Conical shaped spouted bed reactor	HDPE	500	58-70		[62]

In addition to pyrolysis, another thermal treatment method called gasification can also be used to convert plastics into combustible fuel [63]. Using gasification agents or oxidizing agent, large hydrocarbon polymers can be broken into gasoline and diesel limiting the adverse effect on the environment [64]. Moreover, hydrocracking is a potential technology where plastics can be used as feed material for energy. Scott et al. have observed that combustible gas with a hydrocarbon range of C₅₊ can be produced by hydrocracking polyethylene at 600 °C [60].

3.7.2 Cold plasma pyrolysis

Using the advanced cold plasma pyrolysis, biodegradable plastics such as polyolefines, polyesters, polyurethanes, polyvinylacetate and degradable plastics like HDPE (High-density polyethylene), polypropylene, polystyrene are converted into methane, hydrogen and ethylene. The produced gas is then combusted and used as a clean source of energy [65]. In addition to that, ethylene can be used as the raw material for biodegradable plastic production. Nearly 40% of plastic waste in the United States and 31% in the European Union is used for landfilling instead of being used as feed material for energy

generation [66]. This massive plastic waste dump causes environmental damage. Clean energy can be generated from plastic waste by utilizing cold plasma pyrolysis.

Although there are numerous advantages of cold plasma pyrolysis, it is an expensive and complicated process. Cold plasma pyrolysis operates at 500 to 600°C and maintaining the optimal reaction condition requires expert human resources and a sophisticated cooling system [67,68].

3.8 Waste management

A waste hierarchy is devised to outline the most and least preferred methods for plastic waste management (see Fig. 7 [5, 69–72]). Prevention and reuse are at the top of the hierarchy because preventing waste generation and reusing will significantly reduce the use of resources needed to manage waste. This will reduce costs and the requirement of human resources. Also, it enables the system to be a closed cycle and hence lessen further plastic production. On the other hand, landfilling and disposal are at the least as this has many side effects both to mankind and the environment. Fig. 7 [5, 69–72] shows the waste hierarchy of plastic waste management.

Fig. 7 *Waste hierarchy of plastic waste materials [5, 69–72].*

There are four conventional ways of plastic waste management; mechanical recycling, chemical recycling, incineration, and landfill. Fig. 8 [72–75] illustrates the benefits of biodegradable plastics compared to the conventional plastic in terms of recycling is represented. Some specialized recycling practices for biodegradable plastics are also represented.

Properties	Conventional plastics	Bio based degradable plastic	Comments
Landfill			
Can be landfilled	✓	✓	Production of methane gas is an issue 0-85% degradation
Degradation	✗	✓	
Incineration			
Can be incinerated	✓	✓	Nearly same energy capacity as conventional plastics
Good calorific value	✓	✓	
Release of greenhouse gases	✓	✗	Very low environmental impact
Release of toxic gases	✓	✗	
Emission control required	✓	✗	
Mechanical recycling			
Can be mechanically recycled	✓	✓	Need enough material to be recycled or else not viable
Chemical recycling			
Can be chemically recycled	✓	✓	Possible for PLA and PHA but no evidence for starch
Industrial composting			
Can be industrially composed	✗	✓	More than 90% of the material converts into CO ₂
Anaerobic digestion			
Can be anaerobically digested	✗	✓	Relatively higher capital cost

Fig. 8 Comparison of conventional plastics and bio-based polymers[72–75].

All the benefits of conventional plastics in case of recycling can also be obtained from biopolymers which are indicated by green ticks. But there are some unwanted harmful sides in some of the conventional plastic recycling processes, indicated by red ticks.

These are not present in recycling biopolymers and are indicated by green crosses. Additionally, biopolymers can be recycled by some other methods that are not possible for conventional plastics. These methods are indicated by a red cross for conventional plastics. Anaerobic digestion and industrial composting are special types of recycling techniques only available for biopolymers. It can be seen that biopolymers are more desirable than conventional plastics in terms of flexibility of recycling and environmental issues [5,76].

4. Growth of plastic degradation industry

Plastic has entered every aspect of human life; nearly every consumable item uses plastic at some point in its supply chain. As a result, its growth has increased exponentially over the past decades and is likely to expand further. In order to evaluate the growth of plastic industries, it is helpful to look at the cumulative growth of plastic production over the years (see Fig. 9 [77, 78]). Back in 1950, the annual production of plastic was only 2 million tons per year. Over the years, plastic has entered every aspect of human life, and with that its production rate increased tremendously.

Fig. 9 Cumulative global plastic production [78].

Fig. 9 [78] depicts that by 2015 the world has produced nearly 7 billion tons of plastic, to put in context that would be more than one ton of plastic for each person on the planet. From this figure, it is evident that the plastic industry is growing faster than ever.

Therefore, it can be concluded that there is a fast-expanding market for degradable plastics.

Fig. 10 Disposal pattern of global plastic waste [78].

From Fig. 10 [78], a clear pattern can be observed, in 1950, nearly all the produced plastic was dumped, and as newer recycling technologies were introduced the percentage of discarded plastic decreased. However, despite the best effort, nearly 60% of all plastics are still dumped in the environment. This enormous amount of mass, mostly consisting of single-use disposable plastics (e.g., plastic bags, containers) can be produced from degradable plastic. Therefore, it is a clear indication that there is a potential market for degradable plastic to expand. Additionally, the decreasing use of unrecycled plastic suggests that industries and consumers are shifting more towards degradable plastics. It is estimated that with the growth of degradable plastic industries the percentage of discarded plastic would fall below 6% by the year 2050. In order to prevent climate change, the world collectively is transiting towards renewable energy usages [93–99]. Most renewable energy technologies use plastics in production. Therefore, it will create a broader market for biodegradable plastic in the future.

Conclusion

Degradable plastics and biopolymers have been proven as less harmful for the environment than traditional plastic production. Renewable food stocks and agricultural wastes are the main sources of biodegradable films; hence, researchers should devote time and effort on this topic. Unfortunately, the replacement rate of plastics by biodegradable polymers is currently only 1%. The drawbacks using biopolymers are complex downstream processing operations, durability and stability issues and economical scale of production. As future research and development will inevitably improve the quality of degradable plastics, the production of non-degradable will inevitably become obsolete in not too distal future.

Nomenclature

Symbol	Meaning	Symbol	Meaning
PLA	Poly Lactic Acid	FDA	Food and Drug Administration
PCL	Polycaprolactone	MAP	Modified Atmosphere Packaging
PHAs	Poly Hydroxy Alkenoates	PHV	Polyhydroxyvalerate
PBAT	Poly Butylene Adipate-Co-Terephthalate	PHBO	Poly (Hydroxybutyrate-Co-Hydroxyoctanoate)
PBS	Poly Butylene Succinate	PHBD	Poly(3-Hydroxybutyrate-Co-3-Hydroxydeconate)
PE	Polyethylene	PES	Polyethersulfone
PP	Polypropylene	PHB	Polyhydroxybutyrate
PA	Polyamide	PHBV	Poly(3-Hydroxybutyrate-Co-3-Hydroxyvalerate)
PS	Polystyrene	PHBH	Polyhydroxybutylhexanoate
PVC	Polyvinyl Chloride	PTT	Polytrimethylene Terephthalate
PET	Polyethylene Terephthalate	SFC	Seed Film Cultivation
TDPA	Totally Degradable Plastic Additives	HDPE	High-Density Polyethylene

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