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Evolution and Impact of Plastics and its Application

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ABSTRACT

This review comprehensively evaluates the development, applications, and impact of both conventional and bio-based plastics. Conventional plastics have been essential and commonly used in industries and humans' daily lives since World War II but are accompanied by long-term environmental challenges. The review investigates the development of bio-based plastics, derived from renewable resources, and their potential field of application as sustainable alternatives. The environmental impact of both conventional plastics and bioplastics is also investigated. To acquire technological advancements, understanding and implementing a successful strategy for environmental management are needed. Besides that, consumers and industries need to change their mindset and highlight the importance of responsible material usage. Based on the review done, despite being necessary for daily life, conventional plastics have negative environmental effects that require immediate attention. The development and application of bio-based polymers point to a more sustainable future.

1. Introduction

Plastics have become an essential material that shapes our modern world, transforming industries, improving everyday conveniences, and stimulating economic growth. Plastics are extremely versatile due to their resilience and flexibility, which makes them necessary for manufacturing, packaging, and countless other applications [1]. However, this rapid surge in popularity comes at a cost. The environmental damage caused by traditional plastics, due to their inability to break down and the pollution they produce, has driven a critical re-evaluation of the materials used [2].

Along with technological developments, one solution to overcome this problem is by creating environmentally friendly alternatives such as bioplastics. The era of bioplastics represents the dreams and hopes for a more sustainable future. They are made from renewable resources such as plant starches or microbiological sources. As the world now discusses overcoming plastic pollution and seeking innovative solutions, the search for bioplastics has turned into a focus point on responsible material consumption [3].

This review helps to let readers understand the concept of conventional plastics and bio-based plastics by examining their history, applications, and impact on the environment. This review aims to deduce the differences between plastics and bioplastics to identify the importance of the

opportunities and challenges in the choices made regarding the reliance on plastics or the adoption of bioplastics. By the end of this review, it becomes increasingly clear that potential changes to sustain the environment depend not only solely on the advances in green technology but also on the attitudes and behaviors of humans toward environmental conservation and consumerism.

2. Conventional Plastics

2.1 History of Plastics and its Application

The formation of plastics can be categorized into two major categories which are natural plastics and man-made plastics. Since a long time ago, natural plastics have been used by humans for a variety of applications. For example, Egyptians soaked burial wrappings in natural resins to help in the long-term preservation of their deceased. However, many natural plastics were hard to form and had limited supply. This matter had scientists started to find more efficient ways and reliable plastic source materials than what they had [4], [5].

The first plastics were introduced before World War II in 1939 when the first man-made plastic called Parkesine was invented by a British scientist named Alexander Parkes in 1862 [5]. Back in 1869, John Wesley Hyatt invented the first synthetic polymer, inspired by a $10,000 reward from a New York company to anyone who could come up with a replacement for ivory. This material makes up the majority of animals that need to be slaughtered before obtaining their tusks. that needs to be slaughtered before obtaining their tusks [6]. The increasing population in conjunction with the increasing use of plastics has limited the supply of ivory. With that, Hyatt experimented by applying camphor to cellulose obtained from cotton fiber and successfully obtained a plastic that could be formed into a variety of shapes that can mimic natural materials such as tortoiseshell, horn, linen, and ivory This discovery has made a remark where humans can create new materials without depending on nature and being constrained by the limits of nature since nature can only supply wood, metal, stone, bone, tusk, and horn. The use of cellulose has protected animals from slaughtering for their tusks, horns, or shells.

Besides that, the development of new materials also contributed to freeing humans from social and economic limitations due to the restricted supply of natural resources. The low cost of cellulosic materials has made it possible for more usage of plastics worldwide and can be obtained easily. In 1907, the first fully synthetic plastic called Bakelite was invented by an American scientist named Leo Baekeland [7]. After World War II in 1939, the usage of plastics evolved to other industries, besides military use. This is because the industry discovered that preserving limited natural resources is needed by using synthetic products, which are plastics, as an alternative. With this, the production of new plastics expanded to other countries due to their adaptability to many situations of different conditions along with their low cost, safe, and abundant characteristics [5].

In the early 20th century, the petroleum and chemical sectors started forming alliances as seen in companies like Dow Chemicals, ExxonMobil, DuPont, and BASF. These companies are still among the top producers of resins used as raw materials in the plastic industry. [7] This alliance was formed due to the need to repurpose the byproducts from processing crude oil and natural gas. The most abundant waste was found to be ethylene gas, a by-product that the British company Imperial Chemical Industries outperformed its rivals in Germany and the US to turn into a plastic form, where it achieved its first big success with Perspex in 1932. In 1957, the development of plastics or polymers rose when Giulio Natta discovered polypropylene (PP), and in 1957, the commercial production of the resin began. It was the single most widely used thermoplastic globally. Developmental work continued through the nineteenth century on natural/synthetic polymers producing such notables

as celluloid for billiard balls, polyvinyl chloride (PVC), which is used in many applications, and viscose (rayon) for clothing [5], [8].

In the 20th century, the increase in making new plastics expanded for 50 years with at least 15 new classes of polymers being produced. Plastics have been a very successful material due to their usefulness in a wide range of ways and forms such as natural polymers, modified natural polymers, thermosetting plastics, thermoplastics, and biodegradable plastics which have recently developed [8]. Plastics are an essential resource for humans because they frequently offer functionality that other materials cannot affordably or quickly replace. Most plastics are durable and can last up to hundreds of years. Since plastics have taken the place of metals in many of the manufactured goods, items such as computers, car parts, and refrigerators are frequently stronger, lighter, safer, and easier to recycle [9]. Paper, glass, and cardboard have been replaced by plastics in packaging, which helps reduce costs and carbon emissions [10].

2.2 Impact of Plastics on the Environment

The post-war era shows the wide usage of plastics in consumer goods, leading to an area of mass production and convenience. Single-use plastics proliferated and new plastic materials like polyethylene terephthalate (PET) and PP grew in the 1950s and 1960s. However, the convenience of plastics also comes with rising concerns about the effects on the environment. Awareness of environmental pollution and "throwaway culture" opened the door for discussions on waste management and sustainable plastic use. Conventional polymers made from petroleum have many disadvantages that affect the environment despite their diverse applications and advantageous qualities. The amount of plastics degraded is lower than the amount of plastics generated. With this, the number of landfills needed to bury these plastics is increasing, causing the need to deforest to have more space for the landfills.

While plastics are essential in many cultures for everyday needs, if they are not properly managed, their after-use can alter many aspects of the globe. A few of these effects may be harmful to both the environment and people. Before managing plastic waste, it is critical to go into further detail about some of the negative consequences that improper plastic management might have after use. Poor waste management and non-biodegradability can lead to several environmental risks, including choking of the drains in cities and other production areas [11]. These physicochemical characteristics of plastics promote their durability advantage, which underpins both their utility and waste after use. These features also help to make plastics useful. They lose their edge in durability, which helps them survive under many environmental circumstances [12]. Less than 10% to 12% of the plastic residue is burned in municipal solid garbage. The gases that are discharged into the atmosphere during burning increase air pollution and greenhouse effects. The compounds that were discharged into the atmosphere include dioxins, furans, mercury, and polychlorinated biphenyls. To appropriately handle and manage them and safeguard the environment, prompt actions and implementations are required. Since many of these pollutants are hydrophobic, plastic in the aquatic environment may act as a sink for pollutants, making them less accessible to wildlife, especially if they are buried on the seafloor. This is also applied in aqueous for aquatic and aquaculture protection [13]. The consequences of improper disposal and misuse of plastic trash fall into three main classes, including the effects of plastic waste on animals, public health, and the environment [14].

Consequently, the very qualities that lend plastics to human versatility have also given rise to a growing environmental risk [15]. Globally, only 18% of plastic waste is recycled, while 24% are incinerated. The remaining 58% are either dumped in landfills or sent into the environment, where plastics accumulate and linger for a very long time [16]. These polymers currently make up a

significant fraction of 19% of total municipal solid trash in the United States, where the disposal rate for discarded plastics surpasses 75% [17]. By 2050, it is predicted that the amount of plastic garbage that accumulates in landfills and/or the environment will reach up to 12,000 MT worldwide at present growth rates [16], [18].

One of the main concerns now is the quantity of plastic garbage that ends up in the oceans. Both the Eastern Pacific Ocean gyre and the South Pacific subtropical gyre exhibit large-scale, concentrated plastic accumulations [19]–[21]. It is expected that there will be 150 million tons of plastic waste in the ocean by 2023 which is an increase from 50 million tons in 2015, even in the case of a medium waste-to-debris conversion rate [22]. There is a strong correlation between the origins of this material and the lack of efficient waste management infrastructure. Roughly, 90% of the plastic waste that ends up in the ocean is thought to originate from 10 rivers, all of which are in Asia or Africa [23]. Ocean plastic debris is mixed with persistent organic pollutants (POPs), including polychlorinated biphenyls (PCB), pesticides, and polycyclic aromatic hydrocarbons (PAHs), due to the presence of higher affinity of these hydrophobic molecules for plastics compared to their affinities for sediments or water [24], [25]. Lastly, it was observed that around 700 marine species directly interacted with plastic marine debris through smothering, ingestion, and/or entanglement [26].

The rates of plastic degradation reported in the popular press and those described in the peer-reviewed literature are frequently different significantly. A few media reports admit the lack of understanding regarding the rates at which plastic deteriorates, however, they frequently report degradation rates as known even without having strong scientific support. Many of the media estimated the period plastic bags take to degrade which is around 10 to 20 years or 500 to 1000 years, while plastic bottles were estimated to degrade around 70 to 450 years. Some media however reported that plastics do not degrade at all [27]. In these claims, however, the kinds of plastics and the environmental conditions are frequently undefined. Furthermore, the extrapolation technique is unclear. These factors all have a significant influence on degradation times, which are always changing. New evidence can cause expected lives to drastically alter. For instance, a recent study discovered that polystyrene exposed to sunlight deteriorates far more quickly than the previous estimation of thousands of years [28].

The majority of the monomers such as ethylene and PP that are used to produce plastics come from fossil hydrocarbons. Most plastics are not biodegradable which causes build-up in landfills and other natural environments since they are not able to decompose [29]. The only method to eliminate plastic garbage is through destructive thermal treatment such as pyrolysis or combustion. Thus, there is growing worried over the near-permanent contamination of the environment with plastic waste. It was found that there was plastic waste of around 4 to 12 million MT generated on land entering the marine environment in every major ocean basin in 201 [22], [29]. There are also more reports of synthetic fiber pollution in the environment, as well as contamination of freshwater systems and terrestrial habitats [30], [31]. Since plastic debris is now widespread in the environment, it has been hypothesized that it serves as a geological marker for the Anthropocene [32].

3. Bio-Based Plastics

3.1 Development of Bioplastics

Petrochemicals, which are mostly used to make conventional plastics, have a lot of disadvantages including pollution, exhaustibility, and non-biodegradability [33]. Compared to conventional plastics that are mostly derived from petroleum, which is a non-renewable resource, bioplastics have a clear advantage because they can be made from a wide range of renewable chemicals and sources. Some of the sources of bioplastics include food waste, plants and animals, and microorganisms [34].

Innovative bio-based plastic polymers including polylactic acid (PLA), polyhydroxyalkanoates (PHA), polyhydroxybutyrate (PHB), starch blends, and microbial polymers are referred to as bioplastics. Currently available bioplastics are mostly made from first-generation feedstocks, which include potatoes, wheat, corn, sugarcane, and castor oil plants [35]. The second generation of feedstocks consists of those that are unsuitable for human consumption such as animal feed. These can be byproducts of first-generation feedstocks like corn stover or sugarcane bagasse, or they can be non-food crops like cellulose. The commercialization of second-generation feedstocks is still in its early phases. This is a result of the unusually high cost of these feedstocks. The third generation contains the most advanced feedstocks available today, many of which are still in the early phases of development. It is composed of both industrial or municipal waste and biomass from algae [36].

While biodegradability results from biological processes during composting, it also produces no other visible hazardous residue and produces carbon dioxide, water, inorganic compounds, and biomass at a rate comparable to that of other known compostable materials [36]. Comparably, compostable plastic has to comply with strict guidelines for it to biodegrade in industrial composting facilities [37]. Bio-based materials are mostly made of renewable resources and are considered bioplastics. Plastics derived from petroleum are recognized as non-bioplastics. Since bioplastic materials can come from a variety of renewable and non-renewable sources and have a wide range of biodegradability percentages, multiple classifying methods based on various criteria have been established to differentiate them [38].

3.2 Properties of Bioplastics

Bioplastics come in a variety of forms and are made from various source ingredients. The characteristics of each form of bioplastic vary from one another, including strength, transparency, biodegradability, and the raw material from which it is made [5].

Starch can be found everywhere naturally, especially in many parts of most plants. It is made up of chains of carbon, hydrogen, and oxygen atoms that make up glucose molecules. [39]. Since starch is readily available, it can be extracted easily, and is inexpensive where many of its qualities are necessary for its usage as coating or packaging [40]. Other characteristics of starch as a molecule with its potential use in packaging applications are its tastelessness, odorlessness, and overall nontoxicity. Depending on the use of the bioplastic, color, and transparency are additional crucial characteristics of starch-based bioplastics or any other polymer. These characteristics are connected to marketing and consumer acceptability of a particular product. However, starch-based bioplastics are known to have a low mechanical property, which is one of the disadvantages. Starch-based biofilms tear easily and have hydrophilic properties which is not a good property, especially in the food packaging application [40], [41]. Besides that, these bioplastics also have low water vapor barrier properties and low freeze stability during bioplastic formation. Many techniques, including physical, genetic, chemical, and enzymatic techniques, are used to change the molecular structure of starch and hence enhance the characteristics of starch-based bioplastics to solve this issue [40].

Proteins can be found in both animals and plants which are constructed from long chains of amino acids, composed of carbon, hydrogen, oxygen, nitrogen, and sulfur [42]. The use of conventional plastics has raised environmental concerns due to the chemicals released when disposing of the plastics in landfills. With this, protein-based bioplastics are gaining attention to reduce the impact petroleum-based plastics have on the environment [42]. However, limitations also exist in protein-based bioplastics which include poor mechanical and surface hydrophobicity properties [42]. Besides that, various protein sequences and functional characteristics found in various sources urge suitable research for the production of bioplastics. To prepare packaging materials, this means that

appropriate designing of parameters is put into practice, including processing conditions, the choice of physical, chemical, enzymatic, or cross-linking treatment, the use of plasticizers, and the mixing of other sources.

Cellulose is an organic compound, containing the carbon, hydrogen, and oxygen elements that form units of glucose, and is usually found in cell walls of various plants, algae, and other biological materials [43]. Cellulose is the sturdiest and most structural component in a plant which contains long chain polymers made up of monosaccharides which are linked together by glycosidic linkage to produce a polysaccharide. The polymer contained in cellulose can be applied in various sections such as wood and paper, cosmetic and pharmaceutical, and fiber and clothes due to the characteristics present to produce the desired product [44]. Cellulose is currently being used as a reinforcement filler in a matrix around the world due to its advantages in increasing the strength and stiffness of a composite material. In a composite material, cellulose from biomass materials is used as fibers, which is much more environmentally friendly compared to glass and carbon fibers which are made from non-renewable materials.

Aliphatic polyester is a type of biodegradable implantable polymer that is frequently utilized in pharmaceutical and biomedical engineering. Polyesters are made up of repeating ester groups, whereas polymers are big molecules with repeating subunits. Instead of being in a ring, aliphatic molecules are found in long straight chains. As a result, long-chain molecules with repeated ester groups are aliphatic polyesters. A carbon atom can be single-bound to another carbon atom, double-bound to an oxygen atom, or single-bound to an oxygen atom that is also single-bound to another carbon atom to form an ester group. Aliphatic polyesters are commonly used by scientists due to their adjustable, sturdy, and environmentally friendly characteristics. Besides that, they are low-cost and easy to work with [45]. There are various types of aliphatic polyesters namely PLA, polyvinyl alcohol (PVA), PHA, bio-derived polyethylene, and lipid-derived polymers.

3.3 Application of Bioplastics

The common application of bioplastics is in the packaging industry. In the packaging sector, bioplastic is frequently used to make bags, films, and wraps. Non-biodegradable bioplastics are used in the beverage packaging market. For example, PepsiCo produced 100% bio-PET for their product packaging using cornhusks and pine bark while Coca-Cola created PlantBottle synthesized from bio-based ethylene glycol [46], [47]. In addition, PHA, starch, and PLA are among the other bioplastics that are frequently utilized in food packaging. However, the poor thermal stability of these bioplastics makes it more difficult to create the packaging product [47]. Reinforcing bioplastics could address the low mechanical and permeability qualities of bioplastics for use in packaging. Fresh fruit packaging uses reinforced bioplastics made from agricultural waste materials like rice straw and empty fruit bunch (EFB). Research suggests these reinforced bioplastics may extend the shelf life of fresh fruit by enhancing the permeability of the bioplastics, which in turn facilitates better airflow for fresh fruit transpiration [48]. Reinforced bioplastics are used in food packaging as takeout bags, dishes, films, bottles, and containers for dairy goods [49]. In addition, it has been stated that active food packaging uses fiber-reinforced poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV), which can extend the shelf life and provide the packaging film with an antibacterial quality, increasing the likelihood of keeping food from going bad. Furthermore, in packaging film advancements, cellulose-based films reinforced with clay also exhibit antibacterial capabilities with improved properties in gas permeability and thermal stability [49]. Furthermore, it was demonstrated that reinforced bioplastics have antibacterial qualities by the fact that poly(butylene adipate-co-terephthalate) (PBEAT)

reinforced with thermoplastic starch (TPS) bioplastic sheets may lower the number of mold and yeast while keeping food from darkening [47], [50].

In the healthcare industry, several kinds of thermoplastics have been used due to their exceptional application-specific qualities. Medical plastics are widely used in many products, including IV tubes, surgical gloves, blood bags, syringes, and medical instrument packaging, all of which help to maintain hygienic conditions. Biodegradable bioplastics are being used in healthcare applications such as therapeutic device implantation and controlled medication delivery systems. [51]. Every medical device must be sterilized before being used, and there's a good chance it may encounter bodily fluids or different chemicals. Under these circumstances, the rate of biodegradation will increase, and the molecular weight of the polymers will decrease [52]. To say it differently, materials utilized in these kinds of applications need to be highly resistant to various chemicals and sterilizing procedures while preserving the instruments' usefulness and safety [53]. Biodegradable bioplastics such as PLA and poly(ε-caprolactone) (PCL) are utilized in medical applications, including tissue engineering since they can be broken down by fungi and bacteria in human bodies [54]. For biomedical applications, bioplastics are applied to human bodies. This often requires the bioplastics to be non-toxic and biodegradable, so using them would not require any extra steps to be taken out of the body or have any negative effects on the applicants [50].

In the electrical and electronic industry, bioplastics are now widely used. These include bioplastic conductors, also known as SPEs, which are utilized in the creation of fuel cells, batteries, diodes, and electrochromic devices [55], [56]. Apart from that, bioplastics are widely used as assembly parts for high-end consumer goods, including speakers, computer mouse, vacuum cleaners, and the cases of smartphones, and computer components [57]. According to [58], bioplastics can be used as membranes for electroacoustic devices, reinforcement for electronic paper, and water treatment. When it comes to electroacoustic equipment, bioplastic diaphragms may produce deep bass with vibration intensities comparable to those of titanium and aluminum diaphragms [59]. [60] claimed that the industry's use of conductive bioplastics to replace essential metals has been restricted by their electrical and thermal qualities. In fact, thermal and electrical qualities are crucial for using bioplastics in the industrial setting. Although electrical and thermal conductivity are the primary requirements of the business, bioplastics are only used in limited applications outside of assembly parts. While bioplastics have low electrical and thermal conductivity as well as low thermal stability, which further limits their applications in the EE industry, most conventional plastics are typically electrical and thermal insulators without specific functionality incorporation or any reinforcement. Bioplastics have more applications since they can incorporate and strengthen their electrical and thermal conductivity capabilities by being reinforced with the right material [61].

3.4 Impacts of Bioplastics on the Environment

There has been an unfounded conflict between "petrochemical-based products are all bad" and "biodegradable products are all good" [62]. Concerning how bioplastics affect the environment, opinions are becoming more and more divided. Industrial manufacturing currently requires consuming less energy and using renewable resources, especially those derived from agriculture [63]. There is an increasing interest in bioplastics since bioplastics are renewable products due to being made from agricultural raw materials rather than crude oil, or have a biodegradable nature which results in reduced landfilling [64]. Plastics produce pollutants and hazardous materials during their manufacturing, during their service life, and after their disposal, all of which have an impact on the environment and ecosystem [65]. Bioplastics as a potential substitute for petroleum-based polymers have significantly lower carbon emissions and need less energy during production [66].

For instance, two-thirds less energy is required to produce PLA than is required to produce traditional plastics [66], [67] Furthermore, it has been demonstrated by scientists that there is no net increase in carbon dioxide gas during the biodegradation of PLA bioplastics [68]. This was proven by showing that throughout their cultivation, the plants from which they were derived absorbed the same quantity of carbon dioxide that was released during their biodegradation [68]. Furthermore, when PLA breaks down in landfills, it produces 70% fewer greenhouse emissions [69]. According to other studies, using PLA bioplastics made from corn instead of regular plastic can cut greenhouse gas emissions by 25% [70]. These situations indicate that future bioplastic manufacture can be carried out with a significant reduction in greenhouse gas emissions while utilizing renewable energy sources [67].

However, although bioplastics are frequently regarded as being better substitutes for traditional plastics, there are certain drawbacks to be aware of. Although compost made by composting a biodegradable polymer can be used as soil conditioner or fertilizer, it can also pollute groundwater, water, and soil [65]. When used or wasted polymers reach the end of their service life, they are recycled with some losses due to degradation, burned to produce energy with potential environmental pollution, littered, creating environmental hazards, or landfilled, which over time releases carbon or methane emissions due to uncontrolled degradation [71]. Although biodegradable polymers are less environmentally damaging than petroleum-based polymers at this disposal cycle stage, they are typically not suited for landfilling or anaerobic digestion because of the possibility of methane production [72]. Bioplastics are integrated into disposal infrastructures through a range of processes, including recycling, anaerobic digestion, composting, and waste-to-energy generation. Bioplastics could be an alternative to petroleum-based polymers, however, more information is needed to assess the environmental effects of both petroleum-based and bio-based polymers [66].

In another study, it was stated that through microbial processes, biodegradable bioplastics can break down into natural materials and mix inertly with the soil [73]. A combination of oxygen and/or water aids in this breakdown process. For instance, when a bioplastic made of cornstarch is composted, the molecules of cornstarch gradually absorb water and swell out when buried. As a result, the starch bioplastic breaks into tiny pieces, which bacteria may readily consume [74]–[76]. However, certain bioplastics that are low-degrading or nonbiodegradable only decompose at high temperatures or when processed in municipal composters or digesters [77]. Furthermore, under certain precise and tried-and-true circumstances, certain biodegradable polymers can only break down in particular active landfill sites [103]. Furthermore, under certain precise and tried-and-true circumstances, certain biodegradable polymers can only break down in particular active landfill sites [78]. Methane gas, which is produced during decomposition during composting, is a greenhouse gas that is several times more toxic than carbon dioxide [79]. This greenhouse gas is one of the factors causing global warming [80]. Moreover, land must be repurposed for the production of plastic rather than being used to meet food needs to produce bioplastics from plants like corn and maize. According to a recent statistical analysis, the production of biofuels and bioplastics takes up about 25% of the agricultural land used to grow cereals [81]. Food prices could rise significantly as more agricultural land is used to create biofuels and bioplastics, which would hurt those on the economically disadvantaged side of society [67].

4. Conclusions

In conclusion, there is a clearer view of the difference between conventional plastics and bio-based plastics. There is also an overview of how these plastics were first invented and enhanced to meet consumer's criteria. It also shows there are and will be changes in material science in the

present and future. Conventional plastics, which are essential for humans' daily lives, come with environmental costs that demand urgent attention. A more sustainable future can be seen by the advancement and use of bio-based polymers. However, their widespread use depends on overcoming the challenges bioplastics offer.

In the future, a cooperative and broad strategy is needed. A sustainable future not only depends on the advancement of bioplastics technology but also on the way people think as consumers, or in businesses to highlight the importance of responsible material usage as part of environmental management.

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