# A Review of Plant-Based Alternatives to Plastics

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**Abstract**

It is undeniable that plastics play a major part in daily life and permeate all industries because they are lightweight, durable, and cost relatively little to produce. Despite the benefits that plastics provide, plastic pollution has become a major environmental concern globally that needs to be addressed urgently. Therefore, the development of sustainable alternatives to plastic products, such as plant-based plastics, are still needed. The goal of this review is to summarize the development of such alternatives, current state of research, and an assessment of whether these alternatives are preferable to the products that they may potentially replace.

## Introduction

Plastics are so ubiquitous in every industry that it is nearly impossible to get through the day without interacting with some product that either contains or is entirely made up of the material. Plastics are found in makeup, soaps, toothpaste, food and drink packaging, appliances, cars, medical devices, computers, etc. (Auta, Emenike, & Fauziah, 2017). The list is absolutely endless and, seemingly, growing exponentially along with the total production of plastics. Due to their durability, light weight, and low cost of production, demand for plastics is unlikely to change anytime soon. Other notable features of plastics that continue to drive demand include reduced shipping and transit costs due to lighter packaging and longer-lasting perishable products to the airtight and water-resistant properties of plastic packaging (Ellen MacArthur Foundation, 2016).

The same qualities that make plastics a preferred production material – low cost, durability, light weight – are the same reasons why they are so environmentally problematic. Plastics are also a large drain on fossil fuels as manufacturing plastic takes up approximately 8% of the world's oil production (Thompson et al., 2009). The low production costs have resulted in increased production of single-use plastics (SUPs), particularly packaging, which make up over a third of plastic production and half of which are disposed after just one use (Geyer, Jambeck, & Law, 2017; Thompson, Moore, Saal, & Swan, 2009). More importantly, most plastics do not degrade; rather they break down into smaller and smaller pieces that do not truly go away but rather accumulate in the environment (Tokiwa, Calabia, Ugwu, & Aiba, 2009). Plastic particles pollute every part of the environment including air, water, land and the extent of this pollution is deemed irreversible and, therefore, a planetary boundary threat (Villarrubia-Gómez, Cornell, & Fabres, 2018).

Since the introduction of plastics in the 1950s through 2015, the compound annual production growth rate is estimated at 8.4% and a cumulative total of over 7,800 million metric tons (Mt) of plastic has been produced over the same time period (Geyer et al., 2017). Between 2010 and 2015, annual production exceeded 300 Mt and continued to grow every year. Production rates of packaging materials alone, the largest segment of plastic production today, are expected to grow significantly from 78 Mt in 2013 to over 300 Mt by 2050 (Ellen MacArthur Foundation, 2016). Just over 80% of all plastics produced have been disposed of and, of that amount, approximately 77% (4,900 Mt) is in landfills, water, and other parts of the environment (Geyer et al., 2017).

The buoyancy and durability of plastics have resulted in the accumulation of floating garbage patches found in ocean gyres and even smaller bodies of water like the Mediterranean and North Seas (National Geographic Society, 2012). The Great Pacific Garbage Patch (GPGP), which is the largest of the world's garbage patches, is conservatively estimated to have a mass of 79,000 tons and 99.9% of samples pulled from it were plastic and microplastic (particles measuring less than 5 millimeters) (Lebreton et al., 2018). Samples gathered and analyzed from the water reveal that plastics constitute the largest proportion of all marine litter (Lebreton et al., 2018). Nearly all (92%) marine animal encounters with marine litter involve entanglements in or ingestion of plastics (Gall, & Thompson, 2015). Similarly, over 260 species of wildlife including terrestrial animals have been observed to ingest or become entangled in plastics (Thompson et al., 2009)

Plastics have even been found in consumable products that include zooplankton (on which many marine species feed), seafood, and sea salt all of which raise concerns about human health (Auta et al., 2017). A recent study also found that 94% of US tap water and 83% of the world's tap water is contaminated with microplastics (Kosuth, Mason, & Wattenberg, 2018). There are many toxic chemicals involved in the production of plastics that can leach into their surroundings such as BPA which can bioaccumulate and has been shown to affect reproduction in all studied animal groups including fish, amphibians, and crustaceans (Thompson et al., 2009). Alternatively, plastics can also absorb contaminants from their environment and even provide ideal conditions for microorganisms like bacteria to colonize and spread (Auta et al., 2017). The collection of microbial communities that form on plastics are cause for concern to human health because they can lead to the development and spread of antibiotic resistance along with other harmful bacteria like E.coli (Arias-Andres, Klümper, Rojas-Jimenez, & Grossart, 2018).

Plastic waste continues to accumulate in the environment, food chain, and even humans at an alarming rate. The negative and extensive environmental effects of plastic pollution may soon outweigh the benefits they bring; therefore, there is an urgent need to not only reduce plastics production but to find novel ways to replace this material. This review will cover the efforts that have been undertaken to reduce plastic waste, the types of plant-based alternatives to plastics developed to date, and an assessment of whether these alternatives are better for the environment than plastics.

**Current Waste Reduction Efforts and Need for Plastic Alternatives**

One approach to reducing plastic pollution is the push to recycle more; however, recycling has not been particularly successful historically and is plagued with common misconceptions. Plastic recycling does not necessarily mean that demand on virgin plastics drops rather it merely delays disposal; additionally, recycling a material multiple times may not always yield higher environmental benefits (Geyer, Kuczenski, Zink, & Henderson, 2015). According to a study by Geyer et al. (2017), just 9% of all plastics ever produced were recycled and just 10% of that total was recycled more than once. However, it should be noted that plastics are usually recycled into lower-quality products that are not recyclable again (Ellen MacArthur Foundation, 2016). More concerning, is that the recycling rate is not showing signs of improvement. Assessments of municipal solid waste in the United States by the U.S. EPA, revealed that the percentage of plastic waste that was recycled dropped between 2015 and 2017 from 9.1% to 8.4%, respectively (US EPA, 2018; US EPA, 2019).

Efforts to reduce plastic waste have also been tackled at the legislative level in the form of bans, restrictions, and pledges to sustainable products with varying degrees of success, though higher than recycling. Many countries in Asia, Africa, Europe, Oceana, and the Americas have enacted some form of legislation limiting or banning SUPs including plastic bags, straws, utensils, cups, plates, and microbeads (Schnurr et al., 2018). A review of the effectiveness of SUP bag bans by Schnurr et al.(2018), revealed that such bans were between 33% and 96% effective, depending on the policy. Similar bans and restrictions have also been adopted by companies and individuals. For instance, in October 2018, the Ellen MacArthur Foundation (2018) along with over 250 companies that account for a fifth of all plastic packaging produced worldwide, joined an initiative called the New Plastics Economy Global Commitment whose goal is to achieve a circular economy for plastics such that there is no plastic waste and to create plastics that are easily “reusable, recyclable, or compostable”.

While the aforementioned strategies are worthwhile pursuing as they do provide environmental benefits, it is clear that their effectiveness varies vastly and they alone cannot solve the plastic pollution problem. Considering that plastic production is expected to continue to grow at a rapid pace, the best approach to addressing plastic waste may be to take plastic entirely out of the equation. That is, the demand for plastics will decrease only if a viable alternative material that has similar features replaces plastics as the material of choice. Plastics made from plant-based fibers, called biopolymers, may possibly be the replacement needed.

**Defining Key "Green" Terms**

Plant-based plastics are not a new innovation through new technologies and applications are being constantly developed. Many such products carry labels like "green", "eco-friendly", "biodegradable", "bioplastic", "biopolymer", "compostable", etc. The trouble with such terms is that there is not a universal definition applied to any of them. Even the best-informed consumer can be confused by such seemingly meaningless marketing terms.

The term biopolymer refers to a plastic-like material made from natural plant fibers and is considered synonymous with bioplastic or green plastic. Furthermore, biopolymers can be combined with wood and other plant fibers to create a biocomposite that is stronger and denser than biopolymers alone (Partanen, & Carus, 2019). It is important to note that biopolymers are not necessarily biodegradable and, similarly, not all biodegradable plastics are necessarily made from biopolymers (Tokiwa et al., 2009). Biodegradable is another term without a universal definition. For the purposes of this review, biopolymers that break down completely without producing toxins in natural conditions within a reasonable amount of time are considered to be biodegradable (Haider, Völker, Kramm, Landfester, & Wurm, 2018). More specifically, the material should degrade in one year or less to prevent the remaining fragments from absorbing toxins that could then contaminate the environment and even the food chain (Narayan, 2011). Therefore, an ideal biopolymer should be fully biodegradable, have a smaller carbon footprint overall than plastic production, and should not cost more to produce than plastics.

**Types of Biopolymers and Current Applications**

As of 2017, there are 5 main types of biodegradable polymers produced on an industrial scale, in order from largest to smallest market share, are: starch blends, polylactic acid (PLA), polybutylene adipate terephthalate (PBAT), polybutylene succinate (PBS), and polyhydroxyalkonate (PHA) (Haider et al., 2018). PBATs and PBSs are unique polymers in the list because they are not biopolymers, rather they are produced from oil but are designated as degradable because they can be broken down by certain enzymes (Iwata, 2015). Since PBATs and PBSs are derived from oil rather than renewable sources, they fall outside of the scope of this review. Additionally, these polymers are designed to break down quicker over time through UV light exposure, heat, or friction but they still leave small pieces of plastic in the environments like traditional plastics do (Thompson et al., 2009).

Starch blends make up the largest portion of the biopolymer market at 43.8% (Harder et al., 2018). Starches are natural polymers that are made from carbon dioxide and water by plants during photosynthesis (Lu, Xiao, & Xu, 2009). Starches are the most abundant and cheapest polymers most often commercially produced from corn, wheat, potatoes, or rice (Rosseto, Krein, Balbé, & Dettmer, 2019). Starches alone are not polymers, rather they are usually combined with either other biopolymers or with other natural polymers like cellulose or chitosan to create a usable biopolymer (Rosetto et al, 2019). Starch-blend plastics have been used in food packaging and are extensively used in agriculture in films used in greenhouses, irrigation systems, mulch, and extended release fertilizers (Rosseto et al., 2019; Lu et al., 2009).

PLAs are derived from naturally occurring lactic acid bacteria found in renewable sources such as corn, beets, and sugar cane (Mooney, 2009). Lactic acid is a monomer that is derived through the fermentation of sugars and it serves as the basic building block that gets polymerized into PLA when combined with the natural starches that were extracted during the process as well (Mekonnen, Mussone, Khalil, & Bressler, 2013). At 24% market share, PLAs are also considered among the more promising biopolymers because of their widespread applications similar to oil-based plastics including as shrink wrap, food packaging, plastic film, bottles, and even denser applications similar to styrofoam (Haider et al., 2018; Mekonnen et al., 2013). PLAs are widely used in packaging as well as in the medical industry for products like sutures because their degradation produces no toxic byproducts (Mekonnen et al., 2013).

PHAs are polyesters that are produced by several different kinds of bacteria including during fermentation of sugars that usually serve as energy stores for the bacteria (Muhammadi, Shabina, Afzal, & Hameed, 2015; Mooney, 2009). PHAs have been used to produce films, coated paper, containers and bags, food packaging, cups, disposable utensils, among others (Muhammadi et al., 2015; Mooney, 2009).

As the need for biopolymers continues to increase, researchers are looking for even more novel and innovative processes and source materials to create sustainable alternative materials that can satisfactorily replace plastics. For example, in an effort to combat e-waste, Guna, et al. (2016) use biopolymers made from banana fibers and wheat gluten as alternatives to fire resistant plastics (FRP) that are used in circuit boards. The circuit boards made from biopolymers performed very similarly to those made from FRP which are very promising results; however, the authors performed no tests on the biodegradation of the biopolymer circuit boards (Guna et al., 2016). As noted earlier, although the circuit boards were produced from sustainable and renewable materials, that does not immediately promise that the end-product is fully biodegradable.

**How Biodegradable are Biopolymers?**

As is the case with most inquiries, answering the question whether biopolymers are truly biodegradable is highly dependent on testing conditions. An in-depth analysis by Narancic et al. (2018), the authors clearly demonstrated the biodegradability of several different types of biopolymers depended not only on the environment but the biopolymer blend as well. Many of the plastics successfully broke down in managed environments including industrial composting, anaerobic digestion, and home composting but nearly all failed to degrade notably in natural environments (in water or soil) (Narancic et al., 2018). Even PLA, the most widely used biopolymer, could take upwards of 33 years to completely degrade in soil and might never degrade once in the water because it can be broken down by fewer types of microbial degraders (Narancic et al., 2018; Sintim et al., 2019).

Sintim, et al. (2019) tested whether PLA/PHA and PBAT films completely degrade under realistic composting conditions as opposed to lab-run tests of biodegradation. The study results showed that both types of film nearly completely degraded within 16 weeks (the length of the study) at the macroscopic level (99% PLA/PHA and 97% for PBAT); however, they did leave black stains made up of micro- and nano-particles, likely carbon black (Sintim et al., 2019). If the remaining material is indeed carbon black, that may because for concern because it is classified as a human carcinogen in certain concentrations though it should be noted that more research is needed into the toxicity of carbon black in soil and other environments (Sintim et al., 2019). Of the main types of biopolymers, only those made from starches are completely degradable within 20-45 days in composting environments (Lu et al. , 2009; Mooney, 2009). PHAs are also promising as they are biodegradable in just about every environment and do not need special conditions to break down (Mooney, 2009).

**Conclusion**

The problem with plastic pollution is clear and there is a rapidly growing body of academic studies looking into the magnitude of plastic pollution effects on the environment as well as human and animal health. Production of plastics continues to rise despite the known negative environmental effects because their durability and low cost to manufacture makes it hard to replace. There are many different ways that countries, companies, and individuals have worked to reduce plastic waste including, but not limited to, enacting legislation to ban or restrict SUPs, taking pledges to switch to reusable and sustainable products, increasing recycling rates, and developing biopolymers to serve as a potential replacement for plastic products.

Unlike recycling, biopolymers have the potential to actually displace plastic production *if* they provide similar features as plastics at a similar or lower cost to produce. Future biopolymers should not only have the main desired qualities of plastic but they should also be biodegradable in the environment in which they are most likely to end up. More importantly, the definition of "biodegradable" needs to be standardized and applied uniformly across industries to create clarity especially for consumers. There are several different types of biopolymers currently available including starches and PLA which make up the majority of the biopolymer market. Of the available biopolymers, only starches are completely biodegradable and even though they are cheap to produce, they are unlikely to replace plastics completely because they are weaker and less stable than other polymers. The ideal biopolymer may involve a blend of starches and other biopolymers, though more research should be done on such blends and their biodegradability.

While biopolymers may help to reduce plastic consumption, they represent only a small part of the solution. Most current biopolymers are not completely degradable in soil and marine environments and, until durable and fully biodegradable biopolymers are developed, emphasis should be placed on overall reduction of plastics use. Since plastic packaging is the fastest growing segment of the plastic industry, demand can be vastly reduced if countries, companies, and private citizens commit to permanently replace SUPs with reusable alternatives.

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