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Recycling and the Environment: a Comparative Review Between Mineral-Based Plastics and Bioplastics

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Since their conception in the 1950s, mineral-based plastics have completely revolutionised our society with production reaching record highs year upon year. This cheap, and durable material has seen usage across a plethora of diverse industries and products, replacing traditional materials such as metals and wood. However, our reliance on mineral-based plastics has led to their improper disposal across the global, affecting our environments and ecosystems. As a response, different methods have been developed to help dispose of the large amounts of plastic waste produced, such as incineration or dumping in landfill sites, but these methods are not without their drawbacks including release of toxic substances into the air and leachate into the soil and waters respectively. Consequently, much interest is generated and channelled in recent years to the introduction of several types of biopolymers. These include plastics based on cellulosic esters, starch derivatives, polyhydroxybutyrate and polylactic acid. These biopolymers have been viewed as a suitable replacement for mineral-based plastics, and their production a good strategy towards sustainable development as they are mainly composed of biocompounds such as starch, cellulose and sugars. This short review article provides an overview as to whether biopolymers can rival mineral-based plastics considering properties such as mechanical strength, Young's modulus and crystallinity and could they be regarded as a suitable material to reduce our reliance on mineral-based plastics, whilst simultaneously reducing non-renewable energy consumption and carbon dioxide emissions.

1. Introduction

Plastics are a group of materials that are synthesised through the process of polymerisation using a range of synthetic or semi-synthetic compounds. They are composed of a network of molecular monomers bound together to form macromolecules, of which most are commonly derived from petrochemicals (North and Halden, 2013). Their cost-effective price to produce in comparison to other material such as glass or metals, coupled with desirable properties (e.g. high durability and plasticity) has led to them to being used extensively in many different industries. Worldwide in 2015, the use of plastics was mostly dominated by packaging (36%) followed by building and construction (16%), textiles (12%), consumer and institutional products (10%), transportation (7%), electronics (4%), industrial machinery (1%) and other industries (14%) such as medical and leisure (Geyer, Jambeck and Law, 2017). Plastics have completely revolutionised human society and brought benefits in terms of economic activity, jobs and quality of life. For example: (1) Plastic packaging protects food and goods from getting wasted and/or becoming contaminated; hence saving resources. (2) They can also be used for various medical applications, which contribute to improving our health (e.g. disposable gloves, syringes and blood pouches as well as sutures and implants). (3) Their lightweight properties in comparison to other materials aid in saving fuel and helps to reduce emission during transportation.

In just ~70 years the global demand for plastics has grown exponentially, considering large-scale production of plastics only began shortly after the Second World War in the 1950s, when global plastic production was only 2 million tonnes (MT) per year. Since then, annual production of plastics has increase almost 200-fold reaching a record high of 381 MT in 2015 (Geyer, Jambeck and Law, 2017). However, with as many benefits plastics provide, they are not without their faults. With such a tremendous increase in demand coupled with diverse usage across many different industries has led to the accumulation and mismanagement of plastic

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waste, specifically within our environment. Large amounts of plastic waste can accumulate quickly due to the short life span of many plastics products, which has been estimated to be less than a month for approximately 40% of all plastic products (Hahladakis *et al.*, 2018). This type of waste has caused economic and ecological concerns around the globe and the need for a suitable, alternative material has never been greater.

Fossil-fuel derived plastics (polymers) such as polyvinyl chloride (PVC), polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET) account for ~80% of the total global usage of plastics (Table 1), and it is these particular types of plastics that has been the greatest cause for concern. These plastics have been derived from fossil fuels such as crude oil, a finite resource consisting of a mix of different length hydrocarbon chains. The major issue with these plastics is the negative externalities they are able to impose on the environment such as their ability to persist within the environment for many years once they have been discarded. By design fossil-fuel derived plastics are intended to be non-biodegradable, as they are unable to be decomposed and assimilated by microorganisms (biotic factors) through the process of biodegradation. Although, these plastics are affected by temperature, UV radiation and physical stress (abiotic factors), which can begin to fragment when exposed to physical factors over long periods of time (Gewert, Plassmann and MacLeod, 2015).

Compared to fossil-fuel derived plastics, bioplastics are similar in the sense that they are formed of singular monomeric units that are covalently bonded together to form larger macromolecules. However, fundamentally there are two main difference between these types of polymers; their chemical structure and sustainability (Mohan *et al.*, 2016). Biopolymers are naturally occurring polymers that are formed during the growth the cycles of all organisms. They have well defined structures in comparison to their fossil-fuel derived counterparts, which have much simpler, stochastic structures. The structure of bioplastics is an important characteristic, as they serve vital cellular functions within microorganisms that they are produced within.

Bioplastics are seen as a viable substitute to fossil-fuel derived plastics owing to their sustainability, but also carbon neutrality and biodegradability. These properties address the inherent flaws associated with mineral-based polymers, given the problems faced with their disposal and the environmental consequence they impose. In many cases biopolymers such as polyhydroxyalkanoate (PHA) can be synthesised from renewable sources (e.g. vegetable oils and orange peels), which can be produced indefinitely as they are derived from plant-based materials. Thus, biopolymers can be classed as being a sustainable product. They can also be considered to have a smaller carbon footprint or even be carbon neutral and biodegradable as they able to sequester atmospheric carbon dioxide during the growth of the raw materials and once disposed of can be broken down via biotic factors allowing for the raw materials to be absorbed back into the environment and used for the next generation of biopolymers. The advantages of bioplastics (although more expensive than traditional plastics) can be further attributed to their reliance on plant-based materials over fossil fuels, which suffer from price and supply instability (Mohan *et al.*, 2016).

While the term bioplastics is often used in scientific literature interchangeably with biopolymers, it encompasses a large array of different polymers that may not pertain to biopolymers. The term bioplastic can be misleading to an extent as the prefix “bio” invokes thoughts of biodegradability (the process in which a material whose physical and chemical property completely disintegrate when exposed to microorganisms), but this is not necessarily the case with all bioplastics. Bioplastics can be defined as a polymer that is created from renewable raw materials or can be biodegrade, but this does not necessarily mean that they are mutually exclusive and can be both produced from renewable raw materials and biodegradable. This definition can be considered to be broad or a sweeping generalisation as it only excludes polymers derived from fossil fuels or polymers that are not biodegradable. Bioplastics, (which can also encompass biopolymers by its definition) are created from renewable biological material, but are then often put through a process of chemical polymerisation to create the final polymer. Though, this polymer produced may not be biodegradable and as a result could mean they are able to persist within the environment causing the same economic and ecological issues as fossil fuel derived plastics. There are bioplastics such as polylactic acid (PLA) that are able to be created from renewable sources such as corn starch and can be broken down into its constituent monomers through biotic factors.

Table 1: Uses of mineral-based plastics and bioplastics (adapted from Shah et al., 2008)

Mineral-Based Plastics	Use(s)
Polyethylene (PE)	Plastic bags, milk and water bottles, food packaging film, toys, irrigation and drainage pipes, motor oil bottles
Polyethylene terephthalate (PET)	Used for carbonated soft drink bottles, processed meat packages peanut butter jars pillow and sleeping bag filling, textile fibers
Polyurethane (PUR)	Tires, gaskets, bumpers, in refrigerator insulation, sponges, furniture cushioning, and life jackets
Polystyrene (PS)	Disposable cups, packaging materials, laboratory ware, certain electronic uses
Bioplastics	Use(s)
Polylactic acid (PLA)	Packaging and paper coatings; other possible markets include sustained release systems for pesticides and fertilizers, mulch films, and compost bags
Polyhydroxyalkanoates (PHA)	Products like bottles, bags, wrapping film and disposable nappies, as a material for tissue engineering scaffolds and for controlled drug release carriers
Polyglycolic acid (PGA)	Specialized applications; controlled drug releases; implantable composites; bone fixation parts
Polyvinyl alcohol (PVOH)	Packaging and bagging applications which dissolve in water to release Products such as laundry detergent, pesticides, and hospital washables

2. Disposal of mineral-based plastics

With fossil-fuel derived plastics having such a resistance to biodegradation, alternative methods are employed to deal with plastic waste. Currently, there are three main different methods for handing plastic waste; using landfill sites, incineration of waste and recycling. However, each of these methods have their own limitations.

2.1 Landfill

In theory, landfill sites are carefully designed structures that are either built into or on top of the ground where waste can be stored. These sites are usually lined with a protective plastic layer, topped with many layers of clay and soil in an attempt to isolate the waste being contained within and preventing any leachate from leaking into surrounding groundwater (Yedla, 2005). Leachate can be defined as liquid that penetrates and passes through landfill and contains extracted dissolved and suspended matter from the plastics. This results from precipitation entering the landfill from the moisture that exists in the plastic waste when it is composed. However, in many developing countries open landfill sites are uncontrolled structures where designed measures are not implemented properly due to the lack of resources or the failure of Governments to prioritise the management of this waste.

A key drawback associated with this method of plastic waste disposal is the fact that the landfill sites occupy large amounts of space that could be better utilised for more productive means such as agriculture or housing developments **(**Webb *et al.*, 2012). Economically, this presents a significant opportunity cost as to either build landfill infrastructure to house plastic waste or utilise the land for economic benefits. As widely as they are used, ultimately landfill sites are ineffective in successfully decomposing plastic waste, with some waste taking over 20 years (in many cases much longer based on environmental conditions) to decompose completely and as a result, the land occupied by the landfill site remains unavailable for long periods of time and can be described often as being aesthetically unpleasing (Tansel and Yildiz, 2011). This slow rate of decomposition is associated with anaerobic conditions that are created within the landfill based on how densely packed they are with plastic waste, with any decomposition usually occurring due to the result of thermooxidative degradation **(**Webb *et al.*, 2012).

Unfortunately, another negative consequence of landfill site are the plastic fragments that are created during decomposition. They act as the source of a number of secondary environmental pollutants such as benzene, toluene, xylenes, ethyl benzenes and trimethyl benzenes, which can be contained in leachate and released as gases into the surrounding environment, of which all are potential health hazard to humans in high concentrations. Finally, the protective plastic layers that are put in place to help separate the landfill from the surrounding soil and the underlying groundwater may tear of even degrade overtime themselves (North and Halden, 2013). This represents a significant long-term risk of contamination of soil and surrounding groundwater with landfill leachate that could potentially contain toxic organic pollutants, heavy metals and ammonia nitrogen compounds.

2.2 Incineration

Alternatively, one of the simplest methods of dealing with plastic waste is via incineration. Upon first glance it could be hard to identify the possible benefits this method of plastic waste disposal holds over the alternatives, but the incineration of plastic waste could be favourable. One major disadvantage of landfill sites is that it requires large amounts of land and infrastructure to build, which incineration does not. Additionally, there is even the possibility of being able to recover energy in the form of heat given off during the burning process (North and Halden, 2013).

However, like all methods of plastic disposal incineration has its own drawbacks mainly due to the large amounts of toxic pollutants it produces, most of which are released directly into the atmosphere. Polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyl (PCBs), persistent organic pollutants (POPs) such as dioxins and bisphenol A are amongst some of the pollutants released into the atmosphere that pose a great risk to human health as a result of burning plastics (Table 2) (Verma *et al.*, 2016). Furthermore, the incineration of plastics results in the significant release of greenhouse gasses such as carbon dioxide and water vapour, which are well known to contribute to climate change (Butler, 2018). It is because of the consequences of these pollutants being released into the atmosphere that many are reluctant to adopt this method of plastic waste disposal. The significant economic and environment costs caused by incineration and even landfill far outweigh the benefits they provide, and as a result can be viewed as a driving force behind the development of many plastic recycling processes.

Table 2: Summary of toxic pollutants released during the incineration of plastics and their effects (adapted from Verma et al., 2016).

Toxic Compound	Effect(s)
Bisphenol A	Mimics and anatgonsies estrogen
Persistent organic pollutants (POPs)	Carcinogen and reproductive damage in both males and females
Dioxins	Carcinogen and interferes with testosterone
Polycyclic aromatic hydrocarbons (PAHs)	Carcinogen, cardiovascular diseases and developmental impacts (poor fetal growth)
Polychlorinated biphenyl (PCBs)	Carcinogen and interferes with thyroid hormone
Phthalates	Decreased sperm count and motility

2.3 Recycling

In theory, recycling presents itself as the superior solution to handling plastic waste when compared to alternative methods, as it allows for partial recovery of the constituent monomers and energy used to produce them (North and Halden, 2013). However, in reality there are number of considerable challenges that are associated with the recycling of plastics and as a result, not all plastics can be recycled.

The first issue that must be taken into account is the technicality of sorting plastics and the consequences of contaminating different types together (Hopewell, Dvorak and Kosior, 2009). In any given collection of waste there may be a number of different polymers as well as other materials. This has to be separated carefully, as the introduction of one type of polymer into another may lead to the reduction in the desirable properties of the recycled material being produced due to the different melting points. In turn, this contamination of different types of plastics results the production of poor-quality recycled polymers, which is another difficulty that must be overcome. For example, the blending of polypropylene (PP) in high-density polyethylene (HDPE) can lead to an increase in the brittleness of recycled HDPE. To circumvent this issue, sophisticated techniques are employed to aid in the separation of different types of plastics such as Fourier transformed infrared technique (FTIR) or magnetic density separation (Singh *et al.*, 2017). Yet, even with these systems in place it is often impossible to produced recycled plastics of the same quality as “new” (virgin) polymers as these systems are prone to error and the expectation that the materials used to produce the recycled plastics are impure or of poorer quality (Hopewell, Dvorak and Kosior, 2009). Consequently, although these recycled polymers are cheaper to produce, the quality of the end product is expected to decrease due to contamination with each recycling cycle, which ultimately limits their usage to only low-value applications (North and Halden, 2013).

The use of these separation techniques also inadvertently drives up the cost of the recycling process, which could be detrimental to the entire recycling process.

Unfortunately, not all types of plastics are able to be completely recycled. This is owing to their chemical properties and whether the polymer is either thermosetting or thermoplastic. For example, the polymer polyurethane (PUR) is widely not recycled as it is a thermosetting polymer, which means it is irreversibly hardened by curing from a liquid or soft solid pre-resin. Whereas thermoplastics are much more suitable for recycling as they can be moulded into different applications once they reach a particular temperature. As of yet, the prices of crude oil are not high enough to incentivise producers to the use of recycled materials. However, as petroleum begins to grow scarcer, and the public becomes more educated about the environmental consequences of plastic consumption, it is more than likely that the demand for products produced using recycled plastics and alternatives to fossil-fuel derived plastic becomes mainstream.

3. Mineral-based plastics and Bioplastics: Characteristics, Properties and Uses

The interest in bioplastics as an alternative material to mineral-based plastics has been gaining increasing attention due to their natural origin and minimal impact on the environment that mineral-based plastics impose. However, bioplastics have failed to gain much traction within the commercial markets of plastics. This could be owing to their glaring limitations such as high costs of production because of the high cost of the feed as well as mechanical properties- that are comparable to mineral-based plastics in some aspects- but can be brittle, less elastic and have thermal properties that are not suitable for processing them into robust products. Properties such as melting point, mechanical strength (force needed to pull a material), and Young's modulus (the ability to tolerate elongation under tension or compression) can be improved by varying polymers' composition and molecular weight, which can be achieved by modifying the types of substrates, feeding strategies, culture conditions and generic manipulation of the producing microbes.

Mineral-based plastics have been used extensively within the health and medical care industry for the production of biomedical ancillaries such as coronary stents. These types of plastics are chosen as they are flexible, possess high mechanical strength and favourable Young's modulus values, allowing for the stent to carry out its main role, which is to provide strong mechanical support to the vessel wall until it heals, which can take between 6 to 12 months. After this period has passed a permanent implant is no longer required and would usually have to be removed surgically. However, recently there has been great interest in using bioplastics as a material for the production of stents owing to their degradability, removing the need for further surgery once the implant is no longer needed. Polylactic acid (PLA) and Polyglycolic acid (PGA) are two types of bioplastics that have shown high biocompatibility and biodegradability as well as possessing high mechanical strength values (50 and 55 MPa respectively) (Table 3) (Akaraonye, Keshavarz and Roy, 2010) that rival mineral-based plastics strengths whilst also being able to completely biodegrade after 24 and 6 to 12 months respectively, improving on the function of stents produced from mineral-based plastics. Moreover, PLAs have already been used for several other medical applications, especially for devices which require great strength and toughness such as orthopedic and cardiovascular devices or sutures.

Table 3: Comparison of key properties between mineral-based plastics and bioplastics (adapted from Akaraonye, Keshavarz and Roy, 2010)

Properties	PET	PS	PP	PHA	PLA	PGA
Crystallite (%)	30-40	30	70	20-80	10	45-55
Melting point (°C)	250	110-240	130-180	30-80	150-160	225-230
Density (g/cm^3)	1.38	1.05	0.91	1.05-1.25	1.21-1.43	1.53
Mechanical strength (MPa)	35-55	50	34	20-43	50	55
Young's Modulus (GPa)	3.7-4.0	3.0-3.1	1.4-1.7	3.5-4.0	3.5	6.5-7
UV resistance	Poor	Poor	Poor	Good	Good	Poor
Solvent resistance	Good	Poor	Good	Poor	Poor	Good
Biodegradability	None	None	None	Good	Good	Good
Large scale production	Easily available	Easily available	Easily available	Partially available	Partially available	Partially available

PHAs are another example of a bioplastics that demonstrate properties that are for some applications on par or superior in comparison to mineral-based plastics (Table 3). However, there are some limitations with PHAs. The biggest concern is related to their production cost and limited availability and therefore are unable to compete with cheap mineral-based plastics that are produced on a mass scale. This is a problem faced by many bioplastics as the cost of production of mineral-based plastics often is far cheaper than the production of bioplastics, due to their ability to be used for multiple applications in comparison to niche uses. Another drawback is related to processability. PHAs have relatively low melting temperatures when compared to mineral-based plastics, which prevents them being used for applications that require high temperatures. Additionally, in some respects PHAs can be considered as materials that exhibit insufficient mechanical properties, however these properties can be improved and tailored for specific uses depending on their application. This could be achieved through the means of blending different types of PHAs together to improve their mechanical properties, whilst simultaneously reducing their costs of production.

4. Conclusions

Chapter 2 Ultimately, after evaluating the effects that the improper disposal of mineral-based plastics has had upon our environment and bodies of water, it is clear that a shift towards alternative materials such as bioplastics is much needed. This is due to the inefficient methods of disposal that are currently employed from landfill sites to incineration having negative consequences upon the environment, which has prompted attention to shift towards bioplastics touted as being materials that could replace mineral-based plastics. However, the challenge remains for bioplastics as their inability to be produced cheaply at large scale means that they are unable to step up and replace mineral-based plastics and enter the mainstream market for high volume- low cost products. They also fall short in competing with the properties of mineral-based plastics, being favoured in the use of niche appliances albeit by also improving the current materials used, such as with coronary stents as previously discussed. However, the production of bioplastic blends aids in alleviating this issue. Questions as to whether bioplastics are truly biodegradable have also been risen. Some bioplastics lack the ability to be biodegraded within the environment and can still be classified as a biopolymer due to the nature of their constituent feed to produce them. These issues remain present, but ultimately the pressures faced upon our surroundings due to our reliance on mineral-based plastics has prompted much innovation and research into suitable, environmentally friendly, alternative materials.

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