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Challenges and opportunities of biodegradable plastics: A mini review

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Abstract

The concept of materials coming from nature with environmental advantages of being biodegradable and/or biobased (often referred to as bioplastics) is very attractive to the industry and to the consumers. Bioplastics already play an important role in the fields of packaging, agriculture, gastronomy, consumer electronics and automotive, but still they have a very low share in the total production of plastics (currently about 1% of the about 300 million tonnes of plastic produced annually). Biodegradable plastics are often perceived as the possible solution for the waste problem, but biodegradability is just an additional feature of the material to be exploited at the end of its life in specific terms, in the specific disposal environment and in a specific time, which is often forgotten. They should be used as a favoured choice for the applications that demand a cheap way to dispose of the item after it has fulfilled its job (e.g. for food packaging, agriculture or medical products). The mini-review presents the opportunities and future challenges of biodegradable plastics, regarding processing, properties and waste management options.

Keywords

Bioplastics, biodegradable plastics, biobased plastics, biodegradation, composting

Introduction

In recent years, bioplastics have attracted considerable attention because of their environmental advantages. One might assume that biobased plastics are a new development, but some were used in man's earliest times. The latex ball used by Mayan pelote players, for example. Throughout history, man has looked to biomass to meet his needs and to innovate. Biomass is the whole of living matter: Plant and animal. About 172 billion tonnes of organic matter is produced a year, of which we currently use only 3.5%, mainly for food (Plastics the Mag, 2012).

As the industrial era dawned, chemists looked to biomass for the first artificial polymers, like celluloid – the first plastic created in 1856 from cellulose nitrate and camphor or galalithe, a biodegradable polymer derived from a mixture of formalin and casein, the milk protein. The work of pioneers in chemurgy (the chemical and industrial use of organic raw materials) enabled Henry Ford to make plastics car parts derived from soybeans (Plastics the Mag, 2012). The history of plastics changed dramatically in the early 1900s, as petroleum emerged as a source of fuel and of chemicals. The early bioplastics, such as polylactic acid (PLA), which was discovered around 1890, were simply displaced by plastics made from synthetic polymers. World War II brought on a large increase in plastics production, a growth that continues to this day. One well established bioplastic that has survived the growth of the synthetic plastics industry is cellophane, a sheet material derived from cellulose. Although production peaked in the 1960s, it is still used in packaging for candy, cigarettes and other articles (Stevens, 2001).

Almost 300 million tonnes of plastics consumed each year require only about 4% of the fossil resources extracted in the world to manufacture. But if the current strong growth of plastics usage continues as expected, the plastics sector will account for 20% of total oil consumption by 2050 (World Ecomomic Forum, 2016). Growing scarcity and the rising cost of raw materials has put the manufacture of plastics, based on renewable raw materials, firmly back centre stage (Plastics the Mag, 2012).

In the pursuit of objectives of sustainable development and the reduction of environmental impacts, biodegradable plastics from renewable resources logically represent the best possibility. Among renewable resources are those that are of natural origin, but their quantity is not decreasing owing to human use, as they are fairly quickly restored through natural processes. These include wind-, solar-, geothermal-, wave- and tidal energy, biomass. Even fossil fuels are in essence a natural resource – created from dead organisms. The problem is that fossil resources are generated over millions of years, while human beings consume them at the level of centuries. From the perspective of human

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life, oil and natural gas are therefore non-renewable resources; while we cannot claim this if we look at the situation through the prism of the geological age of the Earth. Fossil fuels are exploited much quicker than they are formed, i.e. carbon, which has been forming over millions of years, is released in accelerated fashion (over decades and centuries) back into the cycle, not to be bound again for a long time (Šprajcar et al., 2012).

Expedience of the use of bioplastics is simplistically presented in the Figure 1.

In a green economy, it is imperative to reduce the demand for resources and energy, minimise wastes, prevent environmental pollution and hazards, reduce greenhouse gas emissions, optimise manufacturing processes and establish effective recycling of wastes. These elements are an integral part of sustainable (green) chemistry and many existing polymers and polymerisation processes meet its demands. Prominent examples of successful sustainable materials are polyolefins, such as polyethylene and polypropylene. An integral part of the green economy concept is fostering the use of renewable resources and biobased products, but there is a growing recognition that 'bio' does not automatically imply 'green'. Prospects and problems concerning the use of biofuels and biofeedstocks are listed in Table 1 (Mülhaupt, 2013).

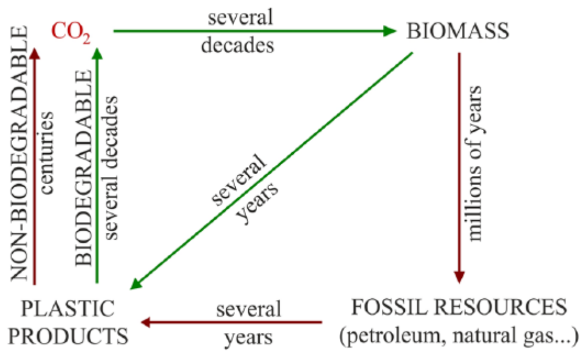

Figure 1. Global carbon cycle (Šprajcar et al., 2012).

Types of bioplastics

There is still much confusion about the word 'bioplastics'. There is a common (incorrect) belief that if something is derived from biomass then it must also be biodegradable. However, the use of biofeedstocks does not necessarily mean that the finished product will be biodegradable. It is important to understand that biobased plastics are not always biodegradable and that biodegradable plastics are not always biobased.

The term bioplastics was coined by European Bioplastics, a European umbrella organisation for bioplastics. Bioplastics are biodegradable, biobased or both (European Bioplastics, 2016).

Biodegradable plastics and biobased plastics are often confused with each other as eco-friendly plastics, although they are not identical in terms of the original concept. Biodegradable plastics have been developed from the view point of biodegradability, whereas for biobased plastics, biomass is used as the raw material instead of oil (Iwata, 2015). Biodegradable plastics are made with polymers (i.e. macromolecules), which are recognised by enzymes present in nature (Razza and Innocenti, 2012).

The biodegradability of plastics depends on the raw materials and the chemical composition and structure of the final product, as well as on the environment under which the product is expected to biodegrade. Not just on the raw materials used for its production. While some biobased plastics may be biodegradable, others are not, as a result of their specific polymer structure. In addition, some polymers degrade in only a few weeks, while others take several months to degrade under the same environment (Briassoulis and Dejean, 2010). To illustrate this

Table 1. Prospects and problems of biobased feedstocks (Mülhaupt, 2013).

Pro biobased feedstocks	Contra biobased feedstocks
Renewable resources conserve non-renewable fossil raw materials	Competition with food production
Lowering of carbon dioxide greenhouse gas emissions by switching from fossil fuels to biofuels	Intensified farming, extensive use of fertilisers, deforestation and grassland conversion causes drastic increases of greenhouse gas emissions
Domestic energy supply and less dependence on oil imports	Energy crop monocultures threaten biodiversity
Plant cells and bacteria serve as solar microreactors for producing chemicals	Use of transgenic plants and genetically modified bacteria
Energy crops as non-food incentives for farmers in industrialised countries with surplus food production	Rising costs of food because farmers abandon food production in developing countries that are unable to feed their rapidly increasing population
Use of agricultural and forestry wastes	A portion of the biomass must remain on agricultural land to secure soil quality and natural habitats for animals emissions
Biodegradation	No biodegradation in the absence of water and oxygen
No toxicity and no health hazards	Disintegration may cause nanoparticle
	Spongy degrading biopolymer particles are food sources and breeding grounds for bacteria and spores, which could be inhaled

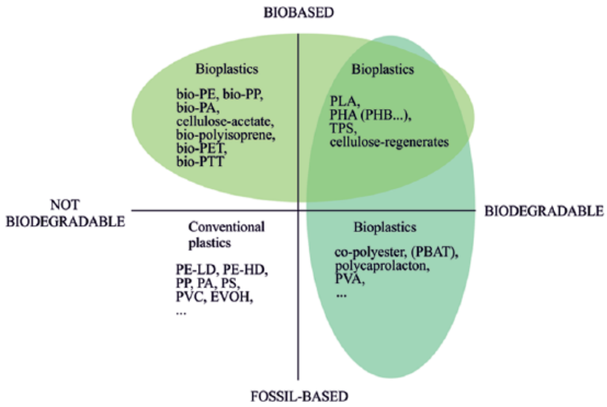

Figure 2. Material coordinate system of bioplastics (European Bioplastics, 2011; UK National Info Point, 2014).
EVOH: ethylene vinyl alcohol; PA: polyamide; PBAT: polybuthylene adipate terephthalate; PE: polyethylene; PE-HD: high density polyethylene; PE-LD: low density polyethylene; PET: poly(ethylene terephthalate); PHA: polyhydroxyalkanoate; PHB: polyhydroxybutyrate; PLA: polylactic acid; PP: polypropylene; PS: polystyrene; PTT: polytrimethylene terephthalate; PVA: polyvinyl alcohol; PVC: polyvinyl chloride; TPS: thermoplastic starch.

distinction, European Bioplastics has provided a simple two-axis model that encompasses all plastic types and possible combinations (Figure 2).

As can be seen in Figure 2, plastics have been divided into four characteristics groups. The horizontal axis shows the biodegradability of plastic, whereas the vertical axis shows whether the material is derived from petrochemical raw materials or renewable materials. This gives possibility for four groups (European Bioplastics, 2011; UK National Info Point, 2014).

1. Plastics that are not biodegradable and are made from petrochemical resources: This category encompasses what is known as classical or traditional plastics, like polyethylene, polystyrene, polyvinyl chloride, etc.
2. Biodegradable plastics from renewable resources: Plastics that are made from biomass feedstock material and show the property of biodegradation. The examples in this group include starch blends made from thermo-plastically modified starch and other biodegradable polymers, and polyesters such as PLA or polyhydroxyalkanoate (PHA).
3. Biodegradable plastics from fossil resources: Plastics that can biodegrade but are produced from fossil resources. This comparatively small group is mainly used in combination with starch or other bioplastics. Their biodegradability and mechanical properties improve the application-specific performance of the starch and other bioplastics. Examples of such plastics are polycaprolactone (PCL), polybutylene succinate (PBS) and polybuthylene adipate terephthalate (PBAT).
4. Non-biodegradable plastics from renewable resources: Plastics produced from biomass but without the biodegradation property. Often they are made from bioethanol biofuel, like polyethylene (bio-PE) that is being produced on a large scale in Brazil, where bioethanol is produced from sugar cane by a fermentation process. Bioethanol is then used for production of ethylene and hence biopolyethylene. Some other commodity plastics are produced as well, like polyvinyl chloride (bio-PVC), polyethylene terephthalate (bio-PET) or polypropylene (bio-PVC, bio-PET, bio-PP).

However, in spite of the effort spent by the associations, the term 'bioplastics' is still prone to misunderstandings. Basically, the problem arises because 'traditional' plastics made of renewable raw materials (e.g. bio-PE or bio-PET) are indistinguishable from the fossil-based plastics and labelling them as bioplastics could cause a lot of confusion in the market. Innovation in this case lies in the production process rather than in the product. Therefore, the term 'biobased' plastics seems more suitable to describe traditional plastics that are made from renewable resources. On the other hand, the term 'bioplastics' seems more suitable to describe those innovative materials that are biobased and biodegradable (Razza and Innocenti, 2012).

In the further text, the use of the term 'bioplastics' is avoided and a distinction is made between 'biobased' and 'biodegradable'" plastics.

Processing of biodegradable plastics

Processing of biobased non-biodegradable plastics and fossil-based biodegradable plastics is similar to processing of conventional plastics and can be done on the same processing equipment. This can also be said for the processing of biobased biodegradable plastics, but there are some potential aspects that have to be taken into account owing to their renewable origin. These aspects include moisture, flow anomalies (wall slipping), thermal degradation and batch-to-batch variations. Biobased biodegradable plastics tend to be hygroscopic, so moisture can cause various problems, for example uncontrolled reduction of viscosity, undesired foaming and acceleration of thermal degradation or hydrolysis. Therefore, pre-drying is mainly required, at a required drying temperature and time, and no water separating additives (e.g. chemical blowing agents) should be used. Material that is too dry may also cause problems (e.g. flowability of thermoplastic starch). Polymers reinforced with natural fibres may especially show flow anomalies because natural fibres may have very heterogeneous geometries and properties, and use of such fibres may result in wall slipping (Laske, 2015).

Biobased biodegradable plastics are prone to thermal degradation, so special precautions have to be made in processing. They need to be subjected to elevated temperatures as little as possible, therefore plasticising units with short residence time are essential for their processing. Also, regions with extremely high shear rates should be avoided, and flow hesitations in dies and runners kept at a minimum. Because of the different crystallisation kinetics, a change in process design is needed. One of the problems during processing include the formation of adhesive pellets when drying, in which case an additional crystallisation step may be needed. In some processes part can become very

Figure 3. Cutlery at the London Olympic Games made of compostable plastics (BioCycle, 2012).

sticky. Because of their natural origin, biobased biodegradable plastics possess higher variability in processing relevant properties. Possible solutions include adding additives that enhance properties (mainly fossil-based) and optimising part design and processing machines for robust processes in order to get larger processing windows (Laske, 2015; Lemstra, 2012).

Application of biodegradable plastics

Biodegradable plastics have found use in many short service life applications where biodegradability is a key advantageous feature (European Bioplastic, 2008).

- Compostable waste bags to collect organic waste and carrier bags, which can also be used as organic waste bags. They can increase the volume of collected organic waste, therefore reduce landfill, and improve the composting process and compost quality. Such bags – most of them are biobased too – are often regarded to be a key market for biodegradable plastics with regard to the sizeable market volume and valid arguments in favour of their use.
- Biodegradable mulch film, which can be ploughed into the field once it has been used, offering the opportunity to reduce labour and disposal cost.
- Catering products for large events or service packaging for snack food sales. They can simply be composted after use, along with any remaining food scraps. The available compostable product portfolio includes trays, cups, plates, cutlery and bags among others (Figure 3).
- Film packaging for foods with a short shelf life that require attractive presentation, or to extend shelf life. These include compostable pouches, netting and (foam) trays for (organically produced) fruit and vegetables, and recently also fresh meat. The simple disposal and the fact that the sale period could in part be extended are beneficial to retailers. Spoiled foodstuffs can be recovered via composting with no need for separation of packaging and contents at point of sale.
- Rigid packaging, such as containers and bottles. Bottles made from PLA are used for non-sparkling beverages and dairy products.
- Many other products make use of their specific functionalities, such as tyres with starch materials incorporated to reduce hysteresis and fuel consumption, diapers with silky soft-touch back sheet, urns, etc.

In the field of medical technology, special biodegradable plastics have been in use for some time as stitching materials and for decades for screws or implants (niche products with extremely high prices) (European Bioplastics, 2008).

Waste management options of biodegradable plastics

The biodegradation rate of biodegradable material depends on the end-of-life options and the physico-chemical conditions (e.g. the presence of oxygen, temperature, presence of light, presence of specific microorganisms). The main end-of-life options for biodegradable plastics include (Mudgal et al., 2012; Song et al. 2009):

- recycling (and reprocessing);
- incineration (and the other recovery options);
- biological waste treatments: composting and anaerobic digestion;
- landfill.

In most cases, the nature of the biodegradable material would determine suitable end-of-life management practice. The most favourable final disposition, from an environmental point of view, for biodegradable plastics is represented by the composting process, taking into account that the process conditions in terms of humidity, oxygen, etc., must be strictly controlled in order to achieve appreciable results in terms of final products (Gironi and Piemonte, 2011). Also, plastics suitable for composting should be collected through a separate collection scheme and brought to an industrial composting facility, neither of which is still present in many countries.

Recycling and reprocessing

Biodegradable materials in the recycling waste stream may bring new treatment and quality issues to recycling. Stakeholders from the recycling industry have raised the concern that the proportion of reprocessed materials will contain biodegradable parts and thereby the technical characteristics (e.g. strength, durability, etc.) of the final product would be compromised. Thus, the sorting and separation steps have an important role to enable the production of quality end-products. The issue is particularly relevant for plastics as biodegradable, and conventional plastics cannot be distinguished by the optical systems used for waste separation. In addition, both types of products have similar weights and densities, which prevent any easy mechanical separation. New technologies are being introduced that better allow plastics waste to be automatically sorted, such as near infrared spectroscopy, but these systems currently face considerable technical and economic challenges (Mudgal et al., 2012).

Biodegradable plastics that enter the municipal waste stream may result in some complications for existing plastic recycling systems (La Mantia et al., 2013). For example, the addition of starch or natural fibres to traditional polymers can complicate recycling processes. Although it is feasible to mechanically recycle some bioplastic polymers, such as PLA, a few times without significant reduction in properties, the lack of a continuous and reliable supply of bioplastic polymer waste in a large quantity presently makes recycling less economically attractive than for conventional plastics. Finally, for certain applications, such as food packaging (e.g. in modified atmosphere packaging of meat products), multilayer lamination of different biopolymers may be necessary to enhance barrier properties, just as in conventional plastics, and this will compromise recyclability of the scrap during packaging manufacture and of post-consumer waste (Song et al., 2009).

Incineration with energy recovery

Most commodity plastics have gross calorific values (GCVs) comparable with or higher than that of coal. Incineration with energy recovery is thus a potentially good option after all recyclable elements have been removed. It is argued that petrochemical carbon, which has already had one high-value use, when used again as a fuel in incineration represents a more eco-efficient option than burning the oil directly (Song et al., 2009).

Energy recovery by incineration is regarded as a suitable option for all bioplastic polymers and renewable (bio)resources in bioplastic polymer products are considered to contribute renewable energy when incinerated. Natural cellulose fibre and starch have a relatively lower GCV than coal, but are similar to wood and thus still have considerable value for incineration. In addition, the production of fibre and starch materials consumes significantly less energy in the first place, and thus contributes positively to the overall energy balance in the life cycle (Song et al., 2009).

While energy recovery by incineration may be a technically viable option for biodegradable packaging, it negates many of the potential benefits from the material's biodegradability potential (Mudgal et al., 2012).

Landfill

Landfill of waste plastics is the least favoured option in the waste hierarchy. The European Union (EU) sent 30.8% of the total recoverable plastics in household waste (8 million tonnes annually) to landfill in 2015 (PlasticsEurope, 2015). However, suitable sites for landfill across Europe are running out and public concerns are increasing about the impact of landfill on the environment and health from the amount of toxic materials in landfilled municipal waste and their potential leaching out of landfill sites (Song et al., 2009).

The landfill of biodegradable materials, including biodegradable polymers, garden and kitchen waste, presents a particular problem in that methane, a greenhouse gas with 25 times the effect of CO_2, may be produced under anaerobic conditions. Landfill gas is mostly captured (this is mandatory in the EU under the Landfill Directive) (Landfill Directive, 1999) and used as an energy source. However, many landfills do not have any gas collection system in practice, and this is also the case for several thousand illegal dumps. The presence of biodegradable packaging may then increase the greenhouse emissions from these sites that operate outside of the requirements of the Landfill Directive (Mudgal et al., 2012; Song et al., 2009).

Biological waste treatments: Composting or anaerobic digestion

Composting has a potential to transfer biodegradable waste, including biodegradable plastics that is biodegradable under composting conditions, into useful soil amendment products. Composting is the accelerated degradation of heterogeneous organic matter by a mixed microbial population in a moist, aerobic environment under controlled conditions. Aerobic waste management systems, such as composting facilities, generate carbon- and nutrient-rich compost for addition to soil. However, the available capacity of composting facilities in the EU is limited. Many of composting facilities address only garden waste, and are not adapted to processing compostable packaging and would have to undergo numerous technical modifications, particularly at the level of pre-processing, to ensure an efficient packaging compostable process. Separating biodegradable and compostable plastics from conventional plastics using near infrared detection technology is possible, as stated before, but costly to put into operation. Certain biodegradable plastics are suitable for anaerobic digesters whereby biowastes can be converted to methane, which can be used to drive generators for energy production (Mudgal et al., 2012; Song et al., 2009).

Biodegradability

One-fifth by volume of solid urban waste, in the modern economy, is disposable materials manufactured from synthetic polymers that are barely degradable, such as polyethylene, polypropylene or polystyrene. Often, these materials are collected in landfill sites or subjected to incineration in municipal plants. Only a few thermoplastic materials are subject to differential collection and industrial recycling (mostly polyethylene and polyethylene terephthalate). Furthermore, some of these materials come directly into environment. Consequently, contamination by plastic materials has become a serious problem and has stimulated the increased interest in biodegradable plastics (Tucker and Johnson, 2004).

Biodegradability is an end-of-life option that allows one to harness the power of microorganisms present in the selected environment to completely remove plastic products designed for biodegradability from the environmental compartment via the microbial food time chain in a timely, safe and efficacious manner (Narayan, 2009).

Because it is an end-of-life option, and harnesses microorganisms present in the selected disposal environment, one must clearly identify the 'disposal environment' when discussing or reporting on the biodegradability under composting conditions (compostable plastic), under soil conditions, under anaerobic conditions (anaerobic digesters, landfills) or under marine conditions (Narayan, 2009).

The biodegradation of these materials is a process that involves chemo-organotrophic prokaryotic (bacteria) and eukaryotic (fungi and protozoa) microorganisms, capable of excreting enzymes (depolymerases) that degrade the polymeric matrix and/or utilise water-precursors and energy-storing materials. Conceptually, the biodegradation of plastic materials must be distinguished from the ageing process that normally takes place in the environment by photochemical degradation and non-specific biological attacks, in that this kind of degradation can be accompanied, or not, by a complete bio-assimilation of the compounds released. Furthermore, this type of degradation could give rise to a 'stealth' form of pollution by releasing into the environment crytotoxic or phototoxic substances, as demonstrated for some kind of polyesters (Tucker and Johnson, 2004).

Compostability – a subset of biodegradability

The majority of biodegradable plastics are compostable, a definition that has been laid down in several standards and norms from which in Europe EN 13432 (EN 13432:2000) can be considered as the most important norm owing to its harmonised and binding character (Deconinck and de Wilde, 2013). The counterparts of EN 13432 are ASTM D 6400 (and ASTM D 6868 (US), AS 4736 (Australia) and ISO 17088 and ISO 18606 (worldwide) (ASTM D 6400-12; ASTM D 6868-11; AS 4736-2006; ISO 17088-2012; ISO 18606-2013).

Compostable plastics are degradable owing to a biological process occurring during composting and are converted into carbon dioxide, water, mineral salts and biomass. There are no toxic side effects, like toxic residue for water, soil, plants or living organisms. Products fully complying with the requirements of these standards are capable of undergoing a complete biological decomposition solely owing to the action of naturally occurring microorganisms under industrial composting conditions. It should be noted that not all biodegradable materials meet composting criteria. Materials that do not fulfil these criteria may still be biodegradable under specific environmental conditions (PlasticEurope, 2012).

Product claims pertaining to compostability or the content of renewable resources are generally difficult for consumers to verify. Certification links standards and independent third party labels such as the compostability label 'Seedling' logo (European Bioplastics, 2016). Certification ensures that the product can be industrially composted and that not only the plastic but also all other components of the product are compostable, for example colours, labels, glues and – in case of packaging products – residues of the content (European Bioplastics, 2016).

In order for a plastic to be categorised as compostable, four criteria must be fulfilled (Deconinck and de Wilde, 2013).

1. Chemical characteristics: The product must contain at least 50% organic matter and may not exceed several heavy metal limits.
2. Biodegradation: The products should biodegrade by at least 90% within 6 months under controlled composting conditions. Biodegradation, or mineralisation, is defined as the conversion of the organic carbon to CO_2.
3. Disintegration: The product, under the form that enters the market, should, within a timeframe of 12 weeks, fragment sufficiently to visually undetectable components (<2 mm) under controlled composting conditions.
4. Ecotoxicity: The compost obtained at the end of the composting trial, eventually containing undegraded residuals from the product, should not pose any negative effects to the germination and growth of plants (and also earthworms in the case of AS 4736, 2006).

EN 13432, and its counterparts, are, however, only applicable for industrial composting, leaving an open space with regard to standardisation for home compostability and biodegradation in other environments, like soil, fresh water, marine water and anaerobic digestion (Deconinck and de Wilde, 2013). For example, no European standard is available today concerning the testing of biodegradable plastics for biodegradation in soil (Briassoulis and Dejean, 2010).

For biodegradable plastic materials to be accepted in composting plants, both biodegradability and disintegration are important. Disintegration is the physical falling apart of the biodegradable plastic material, or more precisely the product that has been made from it, into fine visually indistinguishable fragments at the end of a typical composting cycle (Briassoulis et al., 2010).

Need for complete biodegradability

Objective proof of (bio)degradation (and compostability) of biodegradable plastics is available in different forms. The most robust evidence are the many certificates. Certified materials have been tested according to well defined and recognised test methods and fulfil the requirements of internationally accepted standards and norms like EN 13432. In general, it can be concluded that all biodegradable plastics biodegrade completely under industrial composting conditions, a smaller group also biodegrades under home composting conditions and in soil, and an even smaller group also in fresh and marine water or even under anaerobic conditions (Deconinck and de Wilde, 2013). Plastic bags and other products, for example agricultural mulching films, made with polyethylene are appearing on the market with the claim of being 'degradable', 'oxo-degradable' or 'oxo-fragmentable', 'oxo-biodegradable' and sometimes even 'compostable'. This claim, however, does not comprise the same features as biodegradability. The underlying technology of oxo-degradability or oxo-fragmentation is based on special additives, which, if incorporated into standard resins, are purported to accelerate the degradation of the film products. These additives are inorganic metal salts that should cause the plastic to

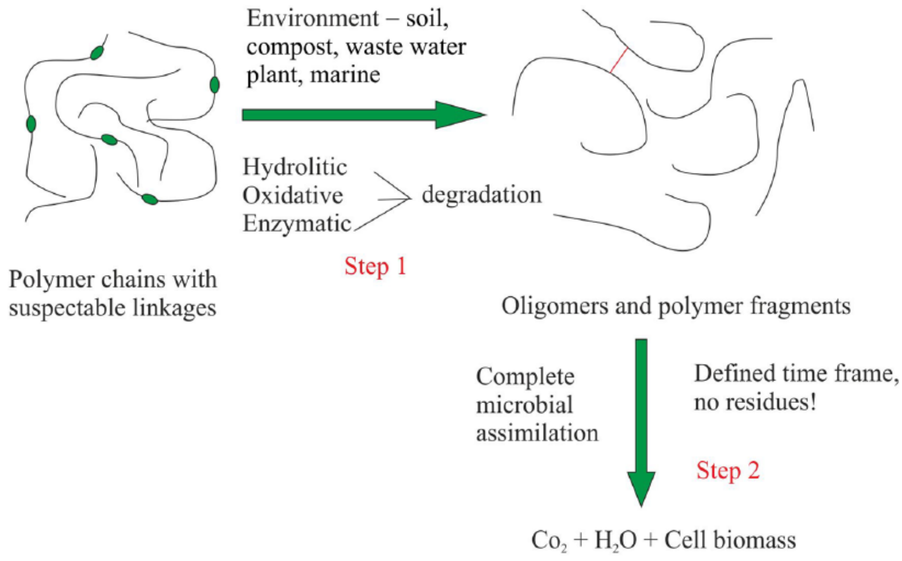

Figure 4. Complete biodegradation (Narayan, 2009).

degrade by a process initiated by oxygen and accelerated by light and/or heat. This technology and the products are not new, and many valid doubts have been expressed as to whether these products deliver what they promise (Deconinck and de Wilde, 2013; European Bioplastics, 2016).

For many years, the US guideline ASTM D6954 (ASTM D6954-04, 2013) was the only guide available for testing oxo-degradable plastics. However, since 2009, several other guides and standards were developed in Europe and the Middle East: FD T54-980 and AC T51-808 (France), UAE.S 5009 (United Arab Emirates), BS 8472 (UK), SPCR 141 (Sweden) (AC T51-808-2012; BS 8472:2011; FD T54-980-2014; SPCR 141: 2010; UAE.S.5009:2009).

The majority of these guides and standards are composed of three so called 'Tiers' (Deconinck and de Wilde, 2013).

1. Abiotic degradation (Tier 1): Using either accelerated or real-time conditions, samples are subjected to a combination of oxygen, heat and/or light to reduce the molecular weight and/or mechanical properties.
2. Biotic degradation (Tier 2): The residues from Tier 1 are retrieved for biodegradation testing using the environment in which the material is intended to end up after disposal (e.g. compost, soil, water, landfill, etc.). In most cases, the amount and rate of CO_2 production, in the case of aerobic biodegradation, and additionally CH_4 production, in the case of anaerobic biodegradation, is measured.
3. Ecotoxicity (Tier 3): By using a variety of living organisms, including plants, earthworms and aquatic organisms, the effect of the residues from Tier 2 on the growth, survival and/or immobilisation of fauna and flora can be determined.

Designing hydrophobic polyolefin plastics like polyethylene to be degradable, without ensuring that the degraded fragments are completely assimilated by the microbial populations in the disposal infrastructure in a short time period, has the potential to harm the environment more than if it was not made biodegradable. These concepts are illustrated in Figure 4, which shows that heat, moisture, sunlight and/or enzymes shorten and weaken polymer chains, resulting in fragmentation of the plastic and some cross-linking creating more intractable persistent residues. It is even possible to accelerate the breakdown of the plastics in a controlled fashion to generate these fragments, some of which could be microscopic and invisible to the naked eye. However, this degradation/fragmentation is not biodegradation per se and these degraded, hydrophobic polymer fragments pose potential risks in the environment unless they are completely assimilated by the microbial populations present in the disposal system in a relatively short period (Narayan, 2009).

In the extensive study of biodegradable and oxo-degradable plastics (Deconinck and de Wilde, 2013) it was concluded that oxo-degradable plastics do not meet the requirements of industrial and/or home composting set out in different standards, that there were very few positive biodegradation results obtained that could not be repeated and that there was no proof of the Arrhenius' time–temperature superposition principle at a wide range of temperature, which makes extrapolation from abiotic degradation at elevated temperatures to real-life conditions scientifically incorrect.

Behaviour of biodegradable products in different environments

Biodegradation is very much dependant on the environment and it can be different from one environment to another. The standards (like EN 13432) are mainly about industrial composting and they cannot be applied to other environments, such as soil, marine, etc. The most aggressive environment is compost, followed by soil, fresh water, marine water and landfill at the end. There are two reasons for that: One is temperature, and the other is presence of microorganisms, that is fungi and bacteria. In industrial composting facilities the temperature is high (60 °C),

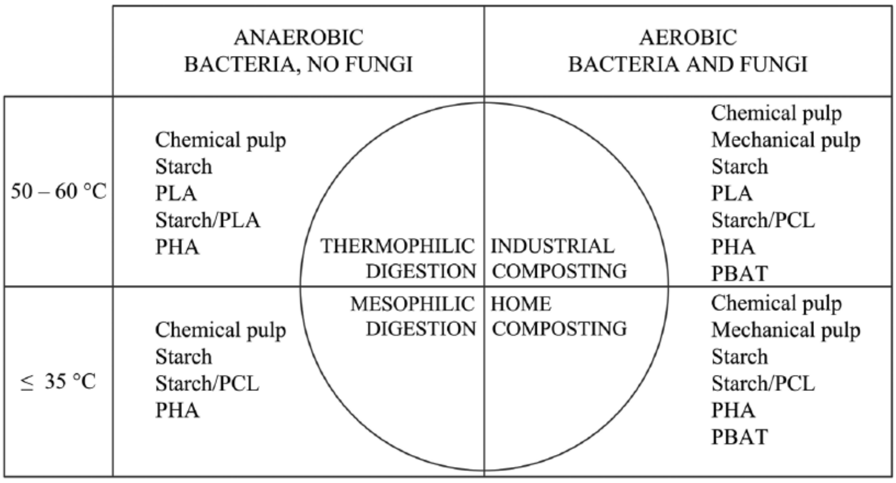

Figure 5. Classification of biodegradation processes (de Wilde, 2013).
PBAT: polybuthylene adipate terephthalate; PCL: polycaprolactone; PHA: polyhydroxyalkanoate; PLA: polylactic acid.

which is important for certain biodegradable plastics. PLA for example needs a thermal trigger in order to biodegrade – the temperature has to be above its glass transition temperature. In other environments, where the temperature is lower, PLA will not biodegrade. The second factor is the biology (microorganisms), more important the role of the fungi. Fungi are needed for biodegradation of 'difficult' biodegradable plastics, and they are active only in compost and soil. The classification of biodegradation processes is given on Figure 5 (de Wilde, 2013). It can be seen that only a few biodegradable polymers biodegrade in all conditions (PHA and chemical pulp).

Besides the way in which biodegradable products are disposed of (commercial composting facilities, home composting, etc.), the major factor influencing the rate of biodegradation of biodegradable product is its thickness. The thicker a product is, the longer it will take to degrade. This is also the reason why certifications (in Europe given by institutions DIN CERTCO or Vinçotte) can be given only to products. Materials, intermediates and additives can only be registered.

The influence of product thickness on the rate of biodegradability was tested during project MarineClean (full name of the project is Marine debris removal and preventing further litter entry). As previously mentioned, only a few biodegradable plastic materials degrade in marine waters, and one of them is Polyhydroxyalkanoate (PHA), so the material based on PHA was chosen for the MarineClean project. The material tested was used in the form of film (thickness 40 µm) and injection moulded test specimens − boxes (thickness approximately 1.5 mm).

Testing of the biodegradable material was done in a laboratory aquarium, with a bottom structured from sandstone boulders and pebbles, and populated by typical infralittoral species, such as blennies, crabs, gastropods and anemones. Besides film, thicker products were tested as well – injection-moulded plastic boxes. The boxes were left on the bottom of the aquarium and observed on a daily basis.

Results of bacterial community structure analyses and microscope observations showed a fast biofouling and a relevant importance of complex living communities of bacteria and eukaryotes (biofilm) for efficient decomposition of biodegradable plastic material. The biofilm formed on the surface of the thin PHA film after just a few days in the seawater was acting as an attractor for macrofauna, like fish and crabs, which often graze on biofilms on different surfaces. The coincident feeding with the PHA film was most probably not intentional, but accelerated the full degradation of the film. The feeding on biofilm covering thick boxes was observed as well. As opposed to the film, the boxes were not consumed by macrofauna. The reason is in the thickness of the material, which was too strong to be fragmentised (France et al., 2014).

The aquarium experiments confirmed the biodegradability of the PHA in seawater. However, the thickness of the biodegradable plastic played a major role in the degradation rate of the tested material. The degradation of the tested materials was supported also by the results of the chemical analyses (France et al., 2014).

Conclusion

Biobased plastics are not a universal solution of all the world's problems – but if we have to move someday (either by choice or by necessity) to a world without fossil resources, plastics will have to be made from some other sources, most probably agricultural. There are still some issues that have to be overcome, like its high price, lower mechanical properties compared with fossil-based plastics, agricultural land availability, etc., but the future certainly looks bright for biobased plastics. On the other hand, biodegradable plastics, once thought as a solution to landfill and littering problems, are restricted to a limited number of applications. They will not resolve the littering issue, because littering is a social problem that will not be solved by making the material biodegradable. Biodegradable plastics have a potential to be biodegraded by biological agents only under certain conditions, in a given time, but these conditions have to be met in order to fully take advantage of the biodegradability of plastic material. Undoubtedly, both biobased and biodegradable plastics will have a major role in future, but there are still some issues that have to be dealt with, particularly regarding biodegradable products.

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