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Biodegradation of Plastic Waste

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ABSTRACT

Plastic waste has greatly contributed to water and land pollution worldwide and marine plastic waste has caused havoc on numerous biological species. Most plastics are fossil-based and cannot be fully degraded by microorganisms. Bio-based plastics derived from biomass, such as starch or cellulose, can be generally degraded into CO_2 and microbial biomass. Recent scientific studies have shown that several pro-degradant additives did not perform, as claimed by plastic processors, under standard biodegradation conditions. Life cycle assessment studies in the United States and Canada confirm that the standard polyethylene grocery bag has significantly lower environmental impacts than a 30% recycled content paper bag. Major factors that differentiate cradle-to-grave impacts of plastics and alternative packaging materials include: (a) less weight of plastic material required to perform same packaging function, (b) lower water consumption per kg of plastics compared to alternatives, (d) no methane releases for land-filled plastics and (e) higher energy credits for plastics disposed via waste-to-energy combustion. A Dutch study showed that substitution of fossil-based plastics by bio-based polymers generally leads to lower non-renewable energy use and reduced greenhouse gas emission. Research at the University of the Philippines (UP) deals with the utilization of agricultural by-products, such as chitin and cellulose, to make bioplastic film for packaging. Nanoclay was also incorporated to produce a nano-composite polymer. Plastic degrading microorganisms have been isolated by UP researchers from local sources including plant root nodules, alkaline spring and soil samples. The following policies regarding plastic products are being recommended under Philippine conditions: (a) government incentives for processors/manufacturers of biodegradable plastic products, (b) restricted importation and sale of non-biodegradable, esp. single-use, plastic products, and (c) funding and logistical support for R & D on commercial additives for plastic biodegradation, local production of bioplastics and isolation of plastic-degrading microorganisms.

Keywords:
plastic waste, biodegradation, bioplastics, microplastics, plastic pollution

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Definitions (van den Oever et al. 2017)

Bio-based – means that the material or product is, wholly or partly, derived from biomass (esp. plants).

Biodegradable materials – can be broken down by microorganisms (bacteria or fungi) into water, CO_2, methane (CH_4) and microbial biomass. Biodegradability depends on temperature, presence of microorganisms, oxygen and water. Both extent and rate of biodegradability vary with soil and climate, properties of the water medium and composting conditions.

Biodegradation – a biochemical process through which microorganisms that are available in the environment convert (via enzymatic reactions) materials into water, carbon dioxide and, in the absence of oxygen, methane.

Biomass – matter derived from recently-photosynthesized plant materials, i.e. within the human timescale, in contrast with fossil-based matter which took millions of years to be formed.

Bioplastics – plastic materials that are either (a) bio-based or (b) biodegradable. Bio-based and biodegradable are not synonymous. Figure 1 (Tokiwa et al. 2009) illustrates the meaning of the labels.

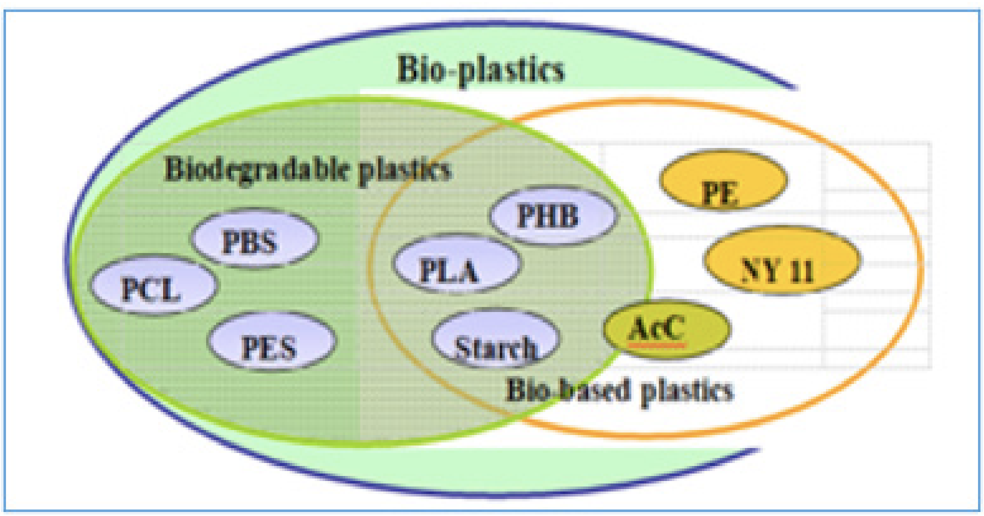

Figure 1. Bioplastics consist of biodegradable and bio-based plastics (Tokiwa et al. 2009)

Closed-Loop Recycling – transformation of a recovered material into an equivalent form (e.g. recycled product is equivalent to product in previous life, no loss in inherent material properties), and/or use of post-consumer recycled material as an input to the same type of product system from which the material was recovered.

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Compostable materials – able to break down under composting conditions. Industrial composting requires elevated temperature (55-60°C) combined with high humidity and the presence of oxygen. These are optimal conditions compared to non-industrial biodegradation in soil, surface water or marine water. According to the EN13432 standard, plastic packaging can only be called compostable if it is demonstrated that the plastic material and its relevant organic components (>1 wt.%) are naturally biodegradable and disintegration of the packaging material takes place in a composting process for organic waste within a certain specified time.

Compostable plastics – a subgroup of biodegradable plastics and are biologically decomposed under composting conditions and within the relatively short period of a composting cycle. Compostable always means biodegradable. Biodegradable does not necessarily mean compostable.

End-of-Life – refers to the life cycle stage of a product following disposal.

Fossil-Based Plastics – utilize fossil feedstocks like petroleum. About 7% of all petroleum is converted into plastics; examples are PE, PP, PET and PS. They could also be produced from biomass which would describe them as bio-based. For example, PE is made from ethylene which could be derived from petroleum (fossil-based PE) or from ethanol produced by fermentation of sugar (bio-PE).

Hydro-biodegradable plastics – made from plant sources such as starch and can be industrially composted.

Life Cycle Assessment (LCA) – assessment or evaluation aimed at understanding the magnitude and significance of potential environmental impacts for a product system throughout the life cycle of the product.

Macroplastics – plastic particles that are 5 mm in size or greater.

Microplastics – very small pieces of plastic that pollute the environment. Microplastics are not a specific kind of plastic, but rather any type of plastic fragment that is less than 5 mm in length according to the U.S. National Oceanic and Atmospheric Administration.

Nanoplastics – nanoparticles (whose average size is one-thousand of a micron) formed by the degradation of a plastic.

Open-Loop Recycling – recycling in which the inherent properties of the recycled material changes with recycling and/or when the recycled material is used as an input to a product different from its previous use.

Oxo-degradable plastics – non-biodegradable fossil-based plastics that are supplemented with a pro-degradant catalyst (e.g., salt of transition metals). The catalyst is claimed to promote abiotic degradation process so that oxo-biodegradable plastics degrade in the presence of oxygen much more quickly than ordinary plastics.

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Photodegradable bioplastics - have light sensitive groups connected to the backbone of the polymer. Exposure to UV radiation for a long time can disintegrate its polymeric structure, allowing further bacterial degradation. Absence of sunlight in landfills, however, keeps this plastic virtually non-degraded.

Photodegradable plastics – polymers that undergo chemical degradation when expose to light, especially ultraviolet radiation.

Plastics (short for thermoplastics) – polymers that do not change their chemical composition when heated and can undergo molding multiple times. These include the common plastics (PE, PP, PS, PVC and PTFE), whose chemical names and structures are shown in Figure 2.

Polymer – a large molecule consisting of many replicated single units (monomers) of the basic molecular structure. For example, polyethylene (PE) consists of many ethylene monomers (typically more than 500) and has the chemical structure $(–CH_2\text{-}CH_2\text{-})n$ where n is the number of subunits or monomers (degree of polymerization). Polymers can either be organic, where the backbone is based on carbon (e.g. PE, cellulose, etc.) or inorganic, where the backbone does not contain carbon atoms (e.g. silicone rubber). Most commercial plastics are organic polymers.

Recycling – reprocessing of a used material, by physical or chemical methods, into the original or a new product.

a) **Material recycling** - reprocessing of a used product material, after collection, sorting and reprocessing, into a new product. This type of recycling is called mechanical recycling.

b) **Chemical recycling** – involves breaking down a polymer into monomers (depolymerization) followed by chemical re-synthesis of the original polymer. An example is the Loopla process developed for polylactic acid (PLA). Within the EU Directive 94/62/EC of 20 December 1994, composting and anaerobic digestion (biogasification) are considered a specific form of material recycling, which is sometimes referred to as 'organic recycling'.

Renewable material – comes from resources which are naturally replenished on a human timescale, in contrast to fossil materials which take millions of years to be formed.

Sustainability – a requirement to manage the resource base such that the average quality of life of the present generation can potentially be shared by all future generations. Development is sustainable if it involves a non-decreasing average quality of life over time.

Thermoset plastics – polymers that remain solid when heated and cannot be melted nor reformed (unlike thermoplastics). The chemical change involved is irreversible; hence these plastics are not recyclable because they have a highly cross-linked structure unlike linear thermoplastics. Examples are phenol–formaldehyde and polyurethanes.

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1. INTRODUCTION

Plastic waste, whose weight has been estimated to be 275 million metric tons (MT) and about half of which comes from Asia, was generated by 192 coastal countries in 2010, with about 5–13 million MT entering the ocean. Without improvements in waste management infrastructure, the total quantity of plastic waste which could enter the ocean from land is predicted to increase by an order of magnitude by 2025 (Jambeck et al. 2015). With this grim prospect of massive marine pollution of the earth with man-made polymers, especially macroplastics, it is now imperative to look at effective means of facing this crisis using everything at our disposal, especially science and technology, government policies, international cooperation and socio-economic measures.

As defined earlier in this paper, plastic is a polymer or large molecule consisting of many replicated single units (monomers) of the basic molecular structure. The chemical structures and names, as well as abbreviations, of some common plastics are shown in Figure 2.

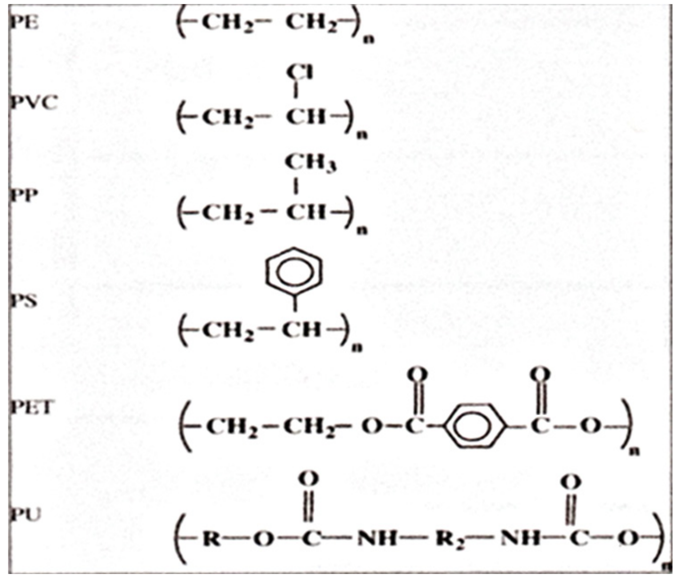

Figure 2. Chemical structures of polyethylene (PE), polyvinyl chloride (PVC), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET) and polyurethane (PU) (Shah et al. 2008).

Plastics represent one of the most widely used materials, and are usually designed to have long lifetimes. Unfortunately, many desirable properties of plastics such as their chemical, physical and biological inertness and durability present challenges and problems when plastics are released into the environment. Common fossil-based plastics such as PE, PP, PS and PET are extremely persistent in the environment because they undergo very slow fragmentation, which can take centuries, into small particles through photochemical and physico-biological degradation processes. Unfortunately, this fragmentation of plastic materials into increasingly smaller pieces (microplastics and nanoplastics) is a necessary step in the degradation process and presents potential serious harm to marine organisms and human beings.

Although specific plastic materials can be considered biodegradable according to test methods designed to assess biodegradability under optimized industrial composting conditions, there is limited control or regulation on how the resulting data are utilized. Recently, the term "biodegradable" has become a popular, albeit misleading, marketing term; in many cases, biodegradability is tested under very specific conditions and does not represent an inherent property of the material. When plastic materials are promoted as biodegradable or "compostable" consumers and processors get the impression that these materials biodegrade in the same way under different end-of-life situations. Actually, however, these same materials take much longer times to fully biodegrade (even several decades or centuries); furthermore, the degradation process generates large quantities of microplastics and nanoplastics. For example, in the early years of 2000 use of oxo-degradable plastics for grocery carrier bags became popular as they were considered more environmentally friendly compared to conventional fossil-based PE carrier bags, since the large plastic fragments would persist in the environment for a shorter period of time. However, new technical findings caused a shift away from oxo-degradable plastics, which are designed to rapidly fragment into small particles, toward truly biodegradable plastics and so-called multiple use

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'bags for life' made from conventional, recyclable materials. (Kubowicz and Booth 2017).

2. PLASTIC DEGRADATION PROCESSES

2.1. Microbial Degradation of Plastics

The general pathway for biodegradation of a biodegradable polymer is given in Figure 3 (Alshehrei 2017). The initial depolymerization step (breakdown of the polymer into short oligomers or simple monomers) is catalyzed by a depolymerase enzyme, which is specific for the polymeric substrate. Depolymerases are named based on the substrates. For example, polyesters are depolymerized by polyesterases while cellulose is broken down into shorter chains, as well as cellobiose and dextrose, by cellulases and cellobiase. The resulting products of depolymerization, namely oligomers, dimers and monomers, in turn are metabolized by the degrading microorganism completely into carbon dioxide and water in the presence of O_2. In the absence of oxygen (anaerobic condition), methane and hydrogen sulfide are also formed.

Microorganisms utilize biodegradable plastics as sources of carbon and energy. The biodegradation reaction (Chinaglia et al. 2018) under aerobic conditions is written as Equation (1):

$$C_{polymer} + O_2 \rightarrow CO_2 + H_2O + C_{biomass} \quad (1)$$

The polymeric carbon ($C_{polymer}$) is microbially assimilated (as $C_{biomass}$) and is either mineralized into CO_2 and H_2O or used for growth and reproduction (more $C_{biomass}$). Microbial biomass is ultimately mineralized as a result of subsequent turnover of the soil microbial community after exhaustion of the carbon substrate. This indicates a biphasic biochemical process where a rapid phase of CO_2 formation is followed by a slower CO_2 evolution phase. Therefore, biodegradation of the plastic polymer can be represented more accurately as a two-step biochemical process:

$$C_{polymer} + O_2 \underset{(a)}{\rightarrow} C_{biomass} \underset{(b)}{\rightarrow} CO_2 + H_2O \quad (2)$$

In step (a) $C_{polymer}$ is first converted into $C_{biomass}$ followed by step (b) where biomass carbon ($C_{biomass}$) is then converted into CO_2 with different kinetics. Thus, reaction (a) is biodegradation and reaction (b) is mineralization. Note that Equations (1) and (2) above are not balanced chemically and only emphasize the fate of carbon.

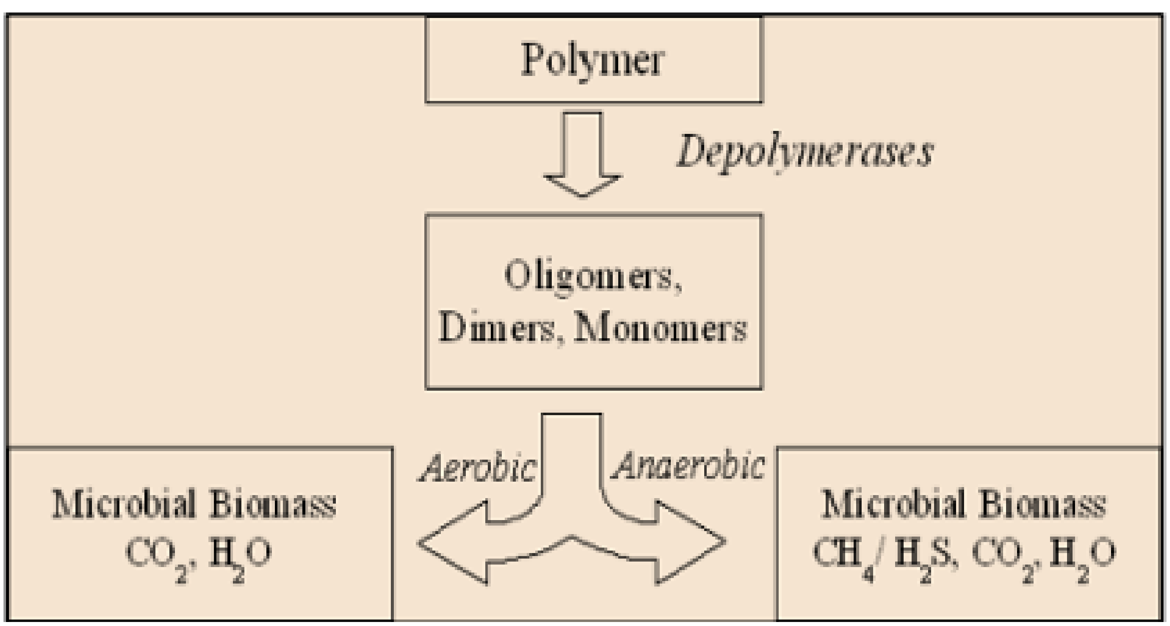

Figure 3. Biochemical reaction pathways during polymer/plastic biodegradation (Alshehrei 2017).

As for any chemical reaction, biodegradation may be monitored either by following the consumption of reagents or appearance of products. The most logical way to monitor and quantify biodegradation is to measure the reactant (O_2) and end product (CO_2) of Equation (2). This can be expressed as biodegradation percentage, which is the ratio of evolved CO_2 to the theoretical CO_2 , i.e. the amount of CO_2 expected for total oxidation of the carbon present in the plastic polymer ($C_{polymer}$) inside the reactor (Chinaglia et al. 2018); this is given in Equation (3).

$$\%\text{Biodegradation} = 100(C_{\text{evolved as } CO2})/(C_{polymer}) \quad (3)$$

Experimental methods for measuring polymer biodegradation are commonly based on measurements of gas evolution (CO_2 and/or CH_4), as well as visual and physical tests (reduction in mechanical strength and mass). The basis for these tests can be seen in Figure 4 in terms of the three phases of the biodegradation process, part of which is shown in Equation (2). Gas evolution is negligible during the early stage of biodeterioration (lag phase) and subsequently exhibits a substantial increase (biodegradation phase), followed by a plateau phase when biodegradation is close to completion. These phases roughly correspond to distinct steps involved in the degradation process. The biodeterioration stage is dominated by depolymerization of the material by either enzymatic hydrolysis (e.g. ester and amide bonds) or peroxidation of carbon chain polymers. The biofragmentation stage results in disintegration and fragmentation of the material without significant gas evolution. Finally, the microbial assimilation stage corresponds to digestion of the low-molecular-weight species produced during earlier stages, resulting in significant gas evolution and mineralization (Harrison et al. 2018).

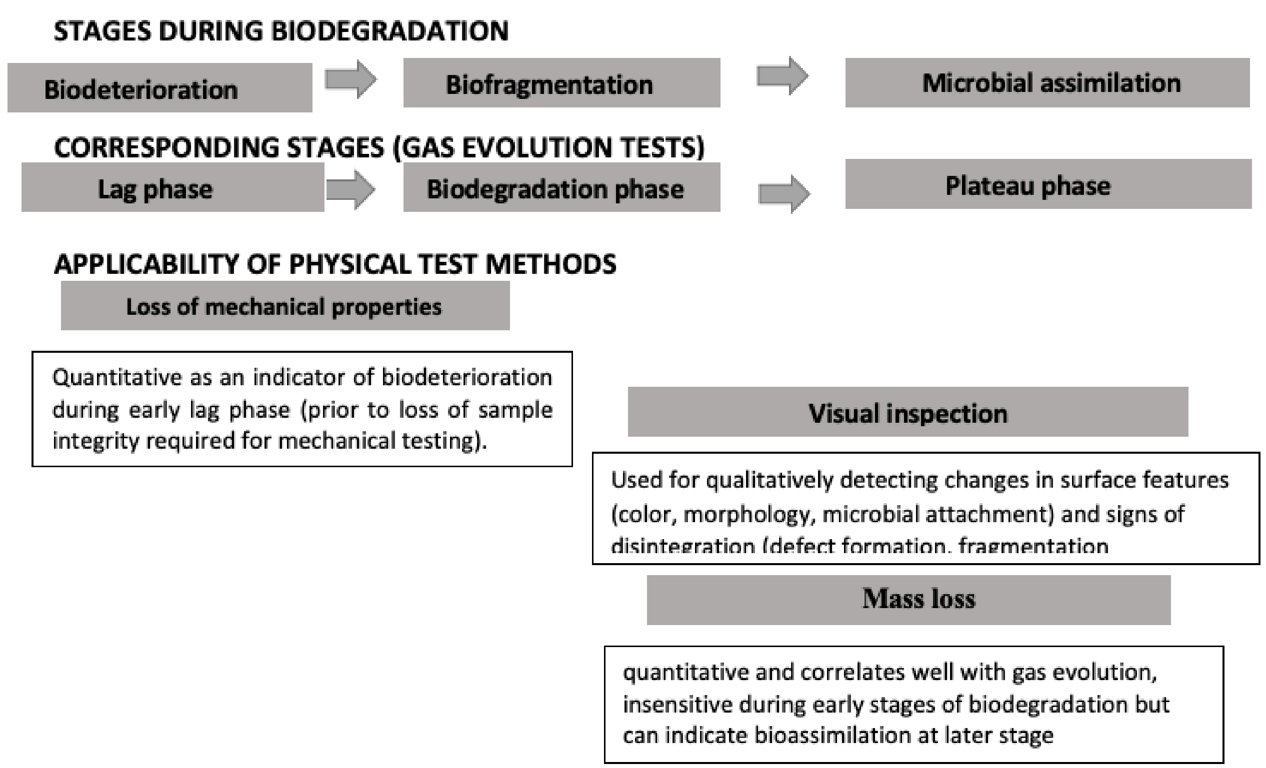

Figure 4. Plastic biodegradation — stages during polymer breakdown and corresponding tests: visual, physical and gas evolution of CO_2 and CH_4 (Harrison et al. 2018).

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Many microorganisms, e.g. over 90 genera of bacteria, fungi and actinomycetes, have the ability to degrade plastics (Mahdiyah and Mukti 2013; Singh and Gupta 2014; Alshehrei 2017). A review article (Raziyafathima et al. 2016) discussed several plastics and their applications, as well as plastic degrading efficiencies of microbes. Some examples of plastic-degrading microorganisms are presented in Table 1, as well as the enzymes responsible for the microbial plastic-degrading capabilities (Shah et al. 2008; Wei and Zimmermann 2017).

2.2. Pretreatment Effects on Biodegradability of Plastics

In the early years of 2000, use of oxo-degradable plastics for supermarket carrier bags became popular as they were considered environmentally safer compared to the conventional fossil-based PE carrier bags, since the large plastic fragments would persist in the environment for a shorter period of time. However, new technical findings caused a shift away from oxo-degradable plastics, which are designed to rapidly fragment into small particles, toward truly biodegradable plastics and so-called multiple use 'bags for life' made from conventional, recyclable materials (Kubowicz and Booth 2017).

Some commercial additives, which are presently used by many plastic processors, have been claimed to be effective in enhancing biodegradability of non-biodegradable plastics. However, recent scientific studies in the U.S.A. and Europe have shown that several of these additives did not perform as claimed by the processors under standard biodegradation conditions, such as composting. There is need to test such additives, as claimed for biodegradability enhancement, using standard physical tests for evolution of gases (CO_2 and CH_4), quantitative loss of mass and sample integrity, as well as visual inspection of surface features and disintegration.

Evaluation of pro-degradant additives for plastics was done in Michigan (U.S.A.) in 2015. The 3-year study with PE plastic treated with additives, which were labeled by their producers as 100% degradable, did not show any visual signs of degradation. The effect of biodegradation additives for PE and PET was evaluated in the study using compost, anaerobic digestion and soil burial. None of five different additives significantly increased biodegradation. Thus, no evidence was found that these additives enhance biodegradation of PE or PET (Selke et al. 2015). Degradation behavior of plastics containing pro-degradant additives during composting had also been studied in the Czech Republic (Adamcova

Table 1. Some examples of microorganisms and enzymes involved in biodegradation of plastics.

Microorganism	Enzyme	Plastic/Polymer	Reference
Aureobasidium pullulans	Extracellular esterase	Dioctyl adipate (DOA)	Webb et al. 2000
Cryptococcus sp.	Cutinase/lipase	Polylactic acid (PLA)	Masaki et al. 2005
Pestalotiopsis microspora	Serine esterase	Polyurethane (PU)	Russel et al. 2011
Comomonas acidivorans	Esterase	Polydiethylene adipate (PDA)	Russel et al. 2011
Brevundimonas sp	PCL depolymerase	Polycaprolactone (PCL)	Nawaz et al. 2015
Aspergillus tubingensis	Esterase and lipase	Polyurethane (PU)	Khan et al. 2017
Ideonella sakaiensis	Aromatic polyesterase	Polyethylene terephthalate (PET)	Austin et al. 2018

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and others 2016). Commercial bioplastics and a PE plastic with additives (claimed to be degradable) were used in the study. The samples certified as compostable degraded in real composting conditions. PE plastic with additives, which were labeled by their producers as 100% degradable, did not show any visual signs of degradation.

Oxo-degradable plastics, are fragmented into microplastics and partially degrade chemically in the ocean, especially under sunlight, and could further fragment into nanoplastics but apparently do not biodegrade. These have been banned in 12 countries where oxo-biodegradable technology for making these products is now mandatory. An EC report of October 2018 states that microplastics need to be restricted, including oxo-degradable plastics. Publications in support of oxo-degradable plastics have claimed about 60% biodegradation in two years, leaving to speculation the fate of the remaining 40%. It is assumed that oxo-degradable materials only disintegrate and finally visibly disappear under the influence of UV radiation and oxygen. However, if there is no real biodegradation, the process of disintegration results in the formation of invisible plastic fragments contributing to the ubiquitous environmental and health hazard of micro- and nano-plastics in the environment.

Another group of plastic materials supplemented with additives, that are supposed to support biodegradation, are so-called enzyme-mediated plastics. Naturally occurring biodegradation relies on enzymatic reactions initiated by naturally present organisms. The producers of enzyme-supplemented plastics intend to emulate the process of biodegradation by adding enzymes to conventional polyolefins. So far, no independent study nor publication shows any positive results for such materials with regard to biodegradation, even though most of the producing companies claim that their plastics are 100% biodegradable or even compliant with accepted composting standards. These claims are often made not on the basis of conversion to carbon dioxide, but instead on the basis of mass loss, which is not a scientific proof of biodegradation.

2.3. Local Research and Development (R&D) on Bioplastics

Some bioplastic-related researches in the University of the Philippines Diliman (under the supervision of L.J.L. Diaz) deal with the utilization of locally available agricultural by-products for bioplastic production. Extraction processes were developed for chitin and cellulose obtained from local manufacturers of crab meat and banana chips, respectively. These polymers were then blended to obtain more pliable polymer films for packaging applications. In order to improve strength and minimize permeability of water through the polymer film, nanoclay was also incorporated to produce a nanocomposite polymer. Despite these modifications the polymers retained their biodegradability. Some shape-memory effect was also observed for the materials (Poblete et al. 2014; Fernando et al. 2016; Lao et al. 2019).

Local microbiological research with relevance to plastic pollution has focused on isolating microorganisms as potential plastic degraders from a variety of local sources, including plant root nodules, soil and leachate, alkaline spring, forest soil and soil contaminated with copper-containing mine tailings. Thirteen local bacterial isolates, as well as a fungus, were found to be potential biodegraders of PE based on dry weight reduction of plastic films, scanning electron microscopy of the plastic film surface and FT-IR spectra (Bolo et al. 2015; Baculi et al. 2017; De la Torre et al. 2018). Four fungal isolates were able to degrade polyurethane (PU) based on microbial biomass production when PU was used as sole source of C and N and by transparency changes in the medium (Urzo et al. 2017). Identification of most of the isolates was done used molecular methods.

3. COMPARATIVE LIFE CYCLE ASSESSMENTS OF PLASTIC PACKAGING MATERIALS

An LCA commissioned study had been done to examine the overall environmental impacts of three types of grocery bags in the United States and

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Canada, namely recyclable plastic, compostable/ biodegradable plastic and recycled/recyclable paper. The resulting Boustead Report (Chaffee and Yaros 2007) confirm that the standard PE grocery bag has significantly lower environmental impacts than a 30% recycled content paper bag; this supports conclusions drawn from a number of previous similar studies. This report also shows that the typical PE grocery bag has fewer environmental impacts than a compostable plastic grocery bag made from a blend of EcoFlex (BASF), polylactic acid, and calcium carbonate, when compared on an equal- or 1.5:1-weight basis. Surprisingly, the trend is the same for most of the individual categories of environmental impacts. No one category showed environmental impacts lower for either the compostable plastic bag or the paper bag. In the case of reducing dependence on overall energy, it was observed that neither the LCA of compostable bag nor paper bag provides a reduction in overall energy use. The standard polyethylene plastic grocery bag uses between 1.8 and 3.4 times less energy than the compostable and paper bag systems, respectively.

The findings in the Boustead Report were peer reviewed by an independent third party with significant experience in LCA. The review supports the conclusion that any decision to ban traditional PE grocery bags in favor of bags made from alternative materials (e.g., compostable plastic or recycled paper) would result in a significant increase in environmental impacts in several categories from global warming to the use of potable water resources. Therefore, consumers and legislators are cautioned to re-evaluate a ban on traditional plastic grocery bags, as unintended consequences can be significant and long-lasting. PE bags provide reduction in global warming gases, acid rain emissions and solid wastes. The same trend is observed when the typical PE bag is compared to grocery bags made with compostable plastic resins.

A recent commissioned LCA study (ACC 2018) analyzed the main factors responsible for the different cradle-to-grave impacts of plastics and other packaging materials. These include the following:

(a) less weight of plastic material required to perform same packaging function,

(b) higher energy per unit weight of plastics compared to alternative materials,

(c) lower water consumption per kg of plastics compared to alternatives,

(d) no decomposition (i.e., no methane releases) for landfilled plastics,

(e) carbon sequestration credits for land-filled material are only assigned to biomass-based carbon content (e.g., in paper, paperboard, wood) and not to fossil-based carbon content in plastic packaging,

(f) higher energy credits for plastics disposed via waste-to-energy combustion.

An LCA study has also been conducted that compared bio-based and biodegradable plastics with focus on food packaging in the Netherlands (van den Oever et al. 2017). Substitution of fossil-based plastics by bio-based polymers generally leads to lower non-renewable energy use and greenhouse gas (GHG) emission. However, GHG emission reduction may be negatively influenced by land-use change; this reduction due to bio-based plastics is generally significantly larger than that due to biofuels. For agricultural categories, such as eutrophication and acidification, bio-based plastics generally have a higher impact than fossil plastics. However, no absolute rule can be given because there are large differences in impacts caused by bio-based plastic types, as well as by fossil-based plastic types.

A local LCA was done which compared environmental impacts of three types of carry bags for Metro Manila, namely non-biodegradable plastic bag, paper bag and non-woven reusable PP bag. The last-named bag was found to provide the least impact among the three bag options. Based on remediation costs, the contribution to flooding from paper bags is higher compared to

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plastic ones. However, this assessment needs confirmation due to limited availability of cost and waste data. Non-biodegradable plastic bags are more environmentally desirable compared to paper ones in all impact areas, primarily because of lower material quantities used (Manuel M. Biona, personal communication 2019).

4. COMMERCIAL PRODUCTION OF BIOPLASTICS

The major commercial bioplastics are:

(a) Starch-based plastics

(b) Polylactide-based plastics (PLA)

(c) Polyhydroxyalkanoate-based plastics (PHB, PHBV, etc.)

(d) Aliphatic/aromatic polyester-based plastics

(e) Cellulose-based plastics (cellophane, etc.)

(f) Lignin-based plastics

In 2015, the production capacities for bioplastics account for nearly 1% of total global plastics production. The markets for some bioplastics are expected to grow significantly during the coming years (Bio-PET, PBS and PLA); others are expected to consolidate (CA and Bio-PA). Overall, it is expected that by 2020 the share of bio-based and biodegradable plastics will increase to 2.5% of fossil plastics production. For most of the bioplastics there are several suppliers and most supplies are readily available. In general, bioplastics are more expensive than fossil-based plastics per unit weight basis. However, specific material properties can allow cost reductions in the use or end-of-life phase. There are several examples of bioplastic products that are already cost competitive. Furthermore, the price of fossil-based plastics depends on oil prices, while prices of bio-based plastics generally depend on biomass prices that are more stable. With more favorable economies-of-scale production and logistics it is expected that the prices of bio-based plastics will come down. Figure 5 provides a summary of global production data for various plastic types (van den Oever et al. 2017).

A global capacity of 2.4 million tons bio-based polymers was reported in 2016, from which more than 45% of the most important bio-based plastics are produced in Asia. The worldwide capacity is expected to reach 3.6 million tons in 2021, nearly 52% of this volume is planned to be installed in Asia. This equals an increase of installed capacities of 71% in the next five years. The Asian region has a 100% share in production capacities of polybutylene succinate (PBS) and cyclic aliphatic polycarbonate (APC). Biodegradable, compostable polymers (such as PLA, PBS, PBAT and PHAs) are expected to contribute about 25% to the Asian production of bio-based polymers in 2021. However, about 75% of the total bio-based production in Asia will be in terms of non-biodegradable polymers. Leading countries in the production of bio-based plastics are China, Japan, Malaysia, South Korea, Taiwan and Thailand (Ref: Bioplastics industry in Asia 2017).

5. RECOMMENDATIONS

Based on present problems regarding limited biodegradability of most commercial plastics and dim prospects for easy solution of these problems, the following policy recommendations are made:

1. Government incentives for processors/ manufacturers of biodegradable plastic products through tax reduction/exemption, etc.
2. Restricted importation and sale of non-biodegradable, esp. single-use, plastic products
3. Funding and logistical support for R & D on:
   a. Physico-chemical and biological evaluation of the effectiveness of commercial additives for biodegradation of plastic materials
   b. Techno-economic feasibility studies on the production of biodegradable plastics from local feedstocks

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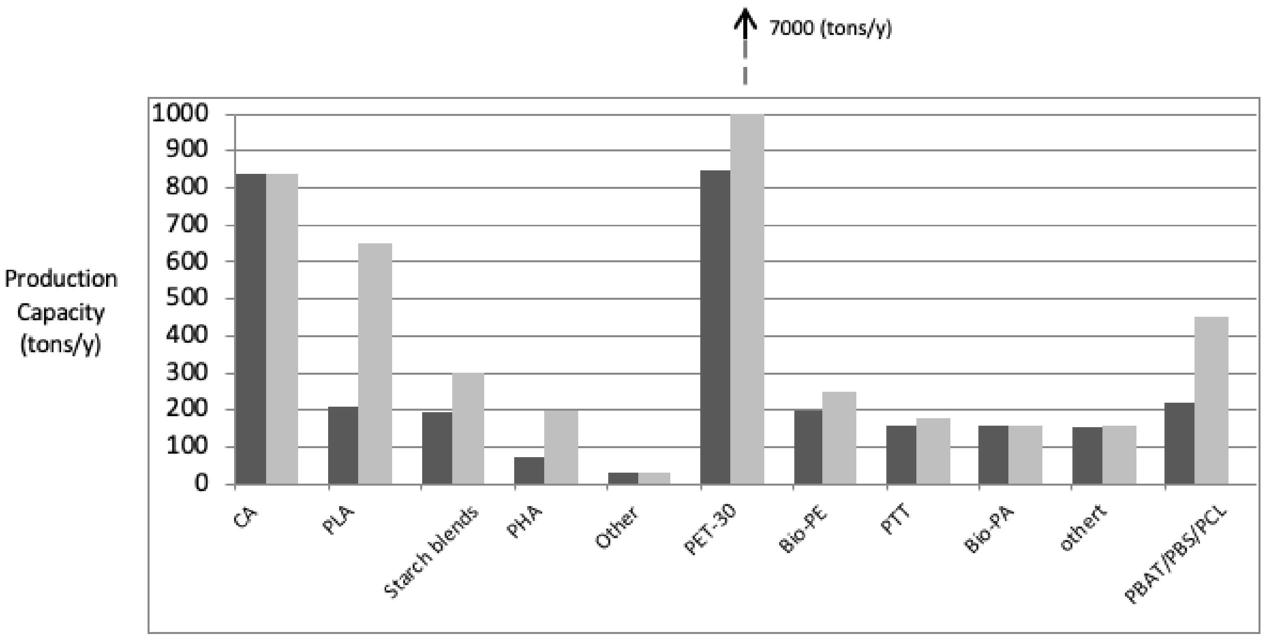

Figure 5. Global production capacity data in 2015/2016 (black bars) and announced production capacities for 2020 (gray bars) of bio-based biodegradable polymers (5 bar pairs at left), bio-based non-biodegradable polymers (5 middle bar pairs) and fossil-based biodegradable polymers (right-most bar pair) (van den Oever et al. 2017).

   c. Multi-disciplinary R&D on plastic biodegradation using local microbial isolates

4. Revision of the Procurement Law (RA 9184) in order to promote R & D in the country

6. ACKNOWLEDGMENTS

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