*Mini Review*

# Environmental Impact of Biodegradable Packaging Waste Utilization

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**Abstract**

Packaging waste is a significant portion of municipal solid waste. It is made mainly of polymers of petroleum, which are usually non-biodegradable and are in many cases difficult to be recycled or reused. In recent years, the development of biodegradable packaging materials from renewable natural resources has gained more attention, especially in the EU. The use of biodegradable materials is expected to have a lower environmental impact than traditional materials based on non-renewable raw materials. The LCA environmental impact analysis of biodegradable plastic used in the packaging industry and comparison to other materials as well as the results of physicochemical analyzes are presented here, in addition to a discussion on the effects of replacing petroleum materials with biodegradable materials.

**Keywords:** LCA, environmental impact, biodegradable plastics, packaging waste

## Introduction

Synthetic polymers are widely used in modern society. The majority is used for packaging and distribution of food and other goods. Polyethylene is a synthetic polymer made of long-chain monomers of ethylene. It is a thermoplastic material widely used for packaging. About 140 million tons of synthetic polymers are produced worldwide annually with their utility rising at a rate of 12% per annum [1].

Polyethylene is regarded as probably the most resistant to microbial attack. A long-term study of the biodegradation of 14C-labeled polyethylene found that polyethylene subjected to 26 days of artificial UV irradiation before being buried in soil evolved less than 0.5% carbon (as $CO_2$) by weight after 10 years [2]. The durability, light weight, and process ability of these polymers causes them to linger in nature for centuries and end up in landfills and natural water resources, creating a severe threat to the environment and its ecosystems [3-5].

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Similarly, a polyethylene sheet that had been kept in contact with moist soil for a period of 12 years showed no evidence of biodeterioration [6]. Only partial degradation was observed in a film of polyethylene that had been buried in soil for as long 32 years [7].

Standard polymer bags consist of polyethylene (PE) or polypropylene (PP), the most commonly used plastics. The material can be differentiated into different categories based on density or molecular branching. Two types are important to produce plastic bags: low-density (LDPE) and high-density polyethylene (HDPE). Polypropylene consists of polymerized propene ($C_3H_6$) molecules. Both these plastics are not biodegradable, and it may take centuries until the material effectively decays, mainly by UV-triggered photocatalytic disintegration.

Incinerating plastic waste is no longer an environmentally friendly option due to the possibility of toxic emissions, for instance dioxins. The calorific value of polyethylene is similar to that of fuel oil. However, it should be noted that hydrocarbon polymers can produce only carbon dioxide and water on incineration and are consequently clean fuels [8]. On the other hand, it should be underlined that plastic is not an efficient source of energy. The amount of energy consumed during the whole manufacturing process of polyethylene is higher than the energy produced during its incineration. The ration of energy utilized during manufacture to Energy produced by incineration of the product is 43:57 [9].

Mechanical recycling of individual polymers results in the reformation of similar but generally downgraded products [10]. The re-processing operations are energy consuming and the energy used is usually of non-renewable origin. Materials recycling of household waste plastics is particularly difficult when they are contaminated with biological residues or, as is usually the case, when they are a mixture of different kinds of plastics [11].

Due to problems with traditional methods of plastic utilization, degradable polymers are becoming gradually more popular. Biodegradable polymer bags are either made of plant-based materials such as starch or bio-synthesized (bacteria) materials. These polymers have been produced since 1990.

Natural biodegradation of plastics could be treated as a road sign pointing to proper development of technologies of plastics production. Biodegradable polyethylene should have good utilitarian properties but should demonstrate their degradability more rapidly than conventional ones [12].

Biodegradable polyesters that have been developed commercially and are in commercial development are as follows: PHA, PHB, PHH, PHV, PLA, PCL, PBS, PBSA, AAC, PET, PBAT, and PTMAT [13]. The most popular biodegradable plastic is PLA (polylactic acid or polylactide). It is a thermoplastic aliphatic polyester derived from renewable resources, such as corn starch.

The appropriate environmental impact analysis is essential in order to reach the highest levels of optimization of all processes during the entire life cycle [14, 15].

The environmental degradation of polyethylene proceeds by synergistic action of photo- and thermo-oxidative degradation and biological activity. Enhanced environmentally degradable polyethylene is prepared by blending with biodegradable additives or photo-initiators or by copolymerization [16].

Some studies deal with the isolation of polyethylene degrading micro organisms from the municipal landfill soil [17]. Experiments with low density polyethylene films were carried out. The microorganisms with the ability to degrade LDPE were isolated in synthetic medium supplemented with LDPE powder and these organisms were used for degradation study. As a result, it was shown that for instance fungal isolates are able to grow on minimal medium with LDPE as a sole carbon source. The hydrophobic nature of LDPE film acts as a substratum for microorganisms that colonize the surface of the LDPE films. Production of $CO_2$ during the Sturm test indicates positive degradability for the polyethylene [17].

Some very interesting studies were made on biodegradation of natural and synthetic polyethylene by different species of *Pseudomonas*. The three *Pseudomonas* spp. were indigenous to locations: domestic waste disposal site dumped with household garbage and vegetable waste, soil from textile effluents drainage site, and soil dumped with sewage sludge. The ability of these species in degrading natural and synthetic polyethylene was investigated. Among all the treatments, *Pseudomonas* sp. from the sewage sludge dump was found to degrade polyethylene efficiently with 46.2% for natural and 29.1% for synthetic polyethylene. In contrast, *Pseudomonas* sp. from household garbage dump gave the lowest biodegradability of 31.4% and 16.3% for natural and synthetic polyethylene, respectively [5]. The studies show that the ratio of biodegradation is highly dependent on types of microorganisms as well as the environment, but fairly good results could be obtained [18]. Biodegradation depends on polymer characteristics, organism type, and nature of pre-treatment as well [13].

The issue of synthetic plastic utility and their waste ending up in the environment can be partly resolved by developing and subsequently applying biodegradable materials [19].

## Biological Recycling

Composting is based on a spontaneous phenomenon. A pile of organic waste is attractive to microorganisms that are normally present in the environment. If the water content is sufficiently high, the microorganisms start to consume the nutritional substances, that is, to degrade the organic molecules, producing carbon dioxide, water, and heat (biodegradation). At the end of the process, the initial waste is transformed into a substance called compost. In the composting plants, this phenomenon is controlled and optimized in order to achieve a high conversion speed, control of the effluent, control of the quality of the final compost, etc.

The present generation of packaging polymers are not biodegradable within a realistic time scale due to the presence of antioxidants. The aim of various technologies is to create polymeric materials that conform to user requirements but are also returned to the biological cycle after use. Polymers must remain stable during manufacture and use but break down rapidly after being discarded, with conversion to biomass in an acceptable time. In recent years many studies have been carried out on that issue [20, 21].

It is now recognized that biodegradation can occur by two different mechanisms; namely hydro-biodegradation and oxo-biodegradation [22]. Polymer degradation occurs mainly through scission of the main chains or side chains of macromolecules. In nature, polymer degradation is induced by thermal activation, hydrolysis, biological activity (i.e., enzymes), oxidation, photolysis, or radiolysis [23].

The most popular biodegradable plastic used in the packaging industry is PLA. Its degradation has been found to be dependent on a range of factors, such as molecular weight, crystallinity, purity, temperature, pH, the presence of terminal carboxyl or hydroxyl groups, water permeability, and additives acting catalytically that may include enzymes, bacteria, or inorganic fillers [24]. Biodegradable polymers react in very different ways in different media [25].

Table 1. Fertilizing properties of select waste materials.

| | Unit | Packaging waste | | | Fresh grass from lawn care [13, 19] |
|---|---|---|---|---|---|
| | | oxo-biodegradable | biodegradable | VINCOTTE | |
| Moisture content | % | 2.18 | 3.54 | 3.68 | - |
| Organic matter content | % dry matter | 94.97 | 99.93 | 99.52 | 89.4 |
| Mineral matter content | % dry matter | 5.03 | 0.07 | 0.48 | 10.6 |
| RSO content | % dry matter | 1.20 | 58.53 | 89.65 | - |
| Total nitrogen content | % dry matter | 0.33 | 0.11 | 0.36 | 1.4 |
| Total carbon content | % dry matter | 0.58 | 27.51 | 42.14 | 28.7 |
| Total phosphorus content | % dry matter | 0.65 | 2.20 | 15.28 | 1.1 |
| Orthophosphate (V)($P_2O_5$) content | % dry matter | 1.98 | 6.83 | 46.69 | - |
| C/N ratio | | 2 | 250 | 42 | |
| C/P ratio | | 1 | 12 | 3 | |

PLA decomposes into carbon dioxide and water in a "controlled composting environment" in fewer than 90 days. Composting is the accelerated degradation of heterogeneous organic matter by a mixed microbial population in a moist, warm, aerobic environment under controlled conditions [26]. PLA soft film samples degraded within 3 weeks [27]. Thus, all the PLA products rapidly degraded under composting conditions [28].

## LCA of PLA

PLA is expected to produce a lower environmental footprint than its petroleum-based counterparts such as PET, PS, and PP [29].

LCA analysis allows determining a detailed overview of all the environmental impacts related to products and processes, by a "cradle-to-grave" approach. All steps and flows are linked to their direct and indirect environmental impacts. The entire process is regulated by ISO 14040 to 14043 standards.

The production (to resin stage) of PLA and reference substances PET and PS was examined on the basis of LCA. The LCI data for production of PET and PS resins was collected from the Ecoinvent database. Data for resin production included all the processes from cradle to grave, including extraction, transportation, and production of crude oil to resin manufacture. The inventory data for PLA was taken from the literature [29]. The functional unit is material required to produce units of 1000 clamshell food containers. The weights of these containers were 24.2 for PS and 29.6 g for PLA. Result are given in main impact categories [30]:

- EI in the global warming impact category (given in kg $CO_{2eq}$) is 60 kg for PLA, 65 for PET, and 70 for PS.
- EI in the aquatic acidification impact category (given in kg $SO_2$) is 1.17 for PLA, 0.36 for PET, and 0.47 for PS. In this case biodegradable material (PLA) has much more devastating environmental impact than the other two non-biodegradable materials.
- EI in the ozone layer depletion impact category (given in kg CFC-11) is 2.88E-06 for PLA, 4.10E-06 for PET, and 2.77-09 for PS. The production of PLA in this impact category is almost the same for PLA and PET.
- EI in the aquatic eutrophication impact category (given in kg $PO_4$) is 5.56E-03 for PLA, 6.83E-02 for PET, and 1.97E-04 for PS.
- EI in the respiratory in organics impact category (given in kg $PM_{2.5}$) is 0.135 for PLA, 0.0508 for PET, and 0.0683 for PS.
- EI in the respiratory organics impact category (given in kg ethylene) is 1.30E-01 for PLA, 6.52E-02 for PET, and 5.60E-02 for PS.
- EI in the aquatic ecotoxity impact category (given in kg TEG – triethylene glycol) is 2,650 for PLA, 3,888 for PET, and 9,240 for PS.
- Energy consumption is 2,010 MJ for PLA, 2,412 for PET, and 2,400 for PS.

Surprisingly the differences in climate change impact category are very small. Taking into consideration that evaluation is made on the basis of averaged and normalized data, the results should be considered as the same. In acidification impact category biodegradable material (PLA) has a much more devastating environmental impact than other two non-biodegradable materials. Generally speaking, production of biodegradable material is shown not to have undisputable advantages in comparison to non-biodegradable materials as environmental impact is concerned.

## Fertilizing Properties of Biodegradable Packaging Waste

Our study aimed to determine the fertilizing properties of three types of waste coming from large retail chains operating in the country. The used packaging waste is oxo-biodegradable packaging waste PE-LD with TDPA, biodegradable PE-LD/d2w, and bags made of PE-LD for collecting organic waste. All tests were made in accordance with standards, and each number is repeated several times [31]. Results of tests are shown in Table 1.

The moisture content of the tested packaging waste is below 4%. Chemical parameters measured in the analyzed waste confirmed the possibility of biodegradation. The content of organic matter in the waste packaging is above 94%. However, the total nitrogen content in the tested material is less than 1% of dry matter. It is four times lower than the content in fresh grass in urban areas (1.4%). Total phosphorus content for packaging waste oxy-biodegradable biodegradable is 0.65-2.20% DM and for organic waste bags (VINCOTTE) is 15.28% DM.

Organic carbon content in oxo-biodegradable packaging waste is relatively low – 0.58%, while in biodegradable packaging it is comparable to the content in fresh grass in urban areas – 28%. Much more organic carbon is present in the bags for the collection of organic waste – 42%.

The results presented in Table 1 indicate that biodegradable packaging waste is rich in fertilizing ingredients and is good material for processing by organic recycling.

The optimum ratio for the composting of organic carbon to nitrogen should remain within the range (17-30):1, and the ratio of organic carbon to phosphorus should be 100:1 [32].

The oxo-biodegradable waste has low C/N. This means that the intensity of the composing process decreases and as a result the final product is poorly mineralized compost, providing plants with only small amounts of nutrients. Generally, in all cases biodegradable packaging waste should be mixed with add-carbon-rich materials (like cardboard products, cut twigs of shrubs, dry sticks, twigs, litter, dry, autumn leaves, etc.) in order to reach highly intensive composting.

## Conclusions

The environmental impact of the production of biodegradable plastics (like PLA, currently considered one of the most widely used biodegradable plastic alternatives to traditional petroleum-based plastics) is generally on the same level as non-biodegradable ones. The EI of PLA was lower in 6 impact categories compared to PET and in only 3 compared to PS. Production of biodegradable material not shown to have undisputable advantages in comparison to non-biodegradable materials as environmental impact is concerned.

Transportation processes play an important role in the entire LC of production of goods from plastics. The total environmental impact could be easily reduced due to optimization of transportation route. It is much easier and cheaper to reach than the change of production technology.

The analysis placed in this manuscript shows that composting properties of biodegradable plastics are limited as the quality of the product is concerned. They should be processed with other material with better C/N and C/P ratios.

Biodegradable plastics disintegrate to meet compost quality requirements and, while they do not biodegrade quickly, they sequester carbon in the soil and contribute to soil structure and fertility.

Other benefits could be found in agriculture. When biodegradable plastics degrade into small pieces that can be ploughed into the soil and add structure and safely biodegrade in the same way as other organic soil components.

The results obtained from various studies [eg. 33]) make it clear that PCL, one of the biodegradable plastics, has the characteristic of being not only compostible, but also of being able to suppress $NH_3$ emissions during composting. It is expected that the use of biodegradable plastic will contribute to solving the odor problem of composting, and to promote the composting of both organic waste and the biodegradable plastic itself.

The use of polymer composites filled with natural-organic fillers, in replacement of mineral-inorganic fillers, causes reduction in the use of petroleum-based, non-renewable resources. These biodegradable plastics can find several industrial applications, although some limitations occur regarding mainly ductility, process ability, and dimensional stability [34].

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