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Biodegradability of conventional and bio-based plastics and natural fiber composites during composting, anaerobic digestion and long-term soil incubation

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A B S T R A C T

Plastics are a major constituent of municipal solid waste that pose a growing disposal and environmental pollution problem due to their recalcitrant nature. To reduce their environmental impacts and allow them to be transformed during organic waste recycling processes, various materials have recently been introduced to improve the biodegradability of plastics. These include conventional plastics amended with additives that are meant to enhance their biodegradability, bio-based plastics and natural fiber composites. In this study, the rate and extent of mineralization of a wide range of commercially available plastic alternative materials were determined during composting, anaerobic digestion and soil incubation. The biodegradability was assessed by measuring the amount of carbon mineralized from these materials during incubation under conditions that simulate these three environments and by examination of the materials by scanning electron micrography (SEM). The results showed that during a 660 day soil incubation, substantial mineralization was observed for polyhydroxyalkanoate plastics, starch-based plastics and for materials made from compost. However, only a polyhydroxyalkanoate-based plastic biodegraded at a rate similar to the positive control (cellulose). No significant degradation was observed for polyethylene or polypropylene plastics or the same plastics amended with commercial additives meant to confer biodegradability. During anaerobic digestion for 50 days, 20–25% of the bio-based materials but less than 2% of the additive containing plastics were converted to biogas ($CH_4 + CO_2$). After 115 days of composting, 0.6% of an additive amended polypropylene, 50% of a plastarch material and 12% of a soy wax permeated paper pulp was converted to carbon dioxide. SEM analysis showed substantial disintegration of polyhydroxyalkanoate-based plastic, some surface changes for other bio-based plastics and coconut coir materials but no evidence of degradation of polypropylene or polypropylene containing additives. Although certain bio-based plastics and natural fibers biodegraded to an appreciable extent in the three environments, only a polyhydroxyalkanoate-based resin biodegraded to significant extents during the time scale of composting and anaerobic digestion processes used for solid waste management.

1. Introduction

Plastics are synthetic and semi-synthetic polymeric compounds, derived primarily from fossil carbon sources such as crude oil and natural gas. Their mechanical properties and characteristics such as low-cost, durability and processability, have led to their widespread use for diverse applications. However most commonly used plastics are very resistant to biological degradation [1]. This has led to major challenges for waste management operations especially those that are moving toward more sustainable waste management practices such as recycling, composting and anaerobic digestion.

It is estimated that of the 31 million tons of plastic waste generated annually in the U.S. only 8% is recycled [2]. Therefore, a large percentage of plastic waste is currently landfilled, or released into the environment. Throughout the world, roadsides, parks, beaches, oceans and natural areas are inundated with plastic debris pollution [3]. Waste management systems are also affected by high volumes of plastics that are often commingled with organic wastes (food scraps, wet paper, yard trimmings, soil and liquids), making it difficult and impractical to recycle both organic fractions and/or the plastics mixed with them without expensive cleaning, separation and sanitizing procedures [4].

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The fact that plastics are made from non renewable resources and their persistence in the environment and during organic recycling has resulted in global concern and intensive efforts to develop plastic materials that not only have acceptable prices and similar performance to conventional plastics, but also are made from renewable feedstocks and/or undergo biodegradation in a reasonable amount of time without leaving toxic residues [5].

Although biodegradable bio-based plastics are meant to improve the sustainable use of resources, a complete life-cycle analysis including disposal must be conducted [6] to insure that the solution is not worse than the problem. Many factors impact the life-cycle carbon balance of plastics including the source of the feedstock used to make them, whether the material is recycled and the extent and type of biodegradation during disposal. For example, most plastics are derived largely from fossil sources such as natural gas or crude oil [7]. However the monomers used to make them can also be made from renewable resources. In Brazil, ethylene, the building block of one of the most widely used plastics, polyethylene [8] is made from ethanol derived from sugar cane. Although made from a biomass feedstock, this type of polyethylene is still essentially not biodegradable. On the other hand, petroleum can also be used to make plastics that are biodegradable. The lactic acid used to make polylactic acid (PLA) can be produced both by fermentation and synthetically from petroleum [9], and either type is biodegradable. On this basis, plastics can be classified into four types with respect to whether they are biodegradable and the source of the feedstock used to make them. These four types are conventional plastic, bio-based plastic, biodegradable plastic and biodegradable bio-based plastic (Table 1). Understanding the environmental benefits of these four classes of materials (Table 1) and the impact of their use on GHG emissions can be confusing and is not always straightforward.

Plastics made from petroleum, such as polyethylene, have a well-defined life cycle. When landfilled, the carbon in the plastic will be sequestered and not contribute to global warming. Recycled polyethylene may contribute even less fossil CO_2 to the environment if less energy is used to recycle it than is used to make it in the first place. In these cases, conventional plastics may have less impact on GHG emissions that those designed to biodegrade.

For reasons presented above, efforts have been made to develop durable plastics made from renewable biomass feedstocks [5]. These are called “bio-based plastics”. On balance this type of plastic offers a great potential to reduce greenhouse gases in the atmosphere by sequestering carbon. This is because atmospheric CO_2 is fixed into the carbohydrates used as their feedstock. If the plastic is eventually landfilled, this carbon will become locked for millennia within the landfill and on balance reduce atmospheric CO_2. However these plastics also pose pollution problems [10].

Biodegradable bio-based plastics, are also made from biomass but are designed to be compostable and/or biodegradable. These types include PLA and polyhydroxyalkanoates-based resins (PHA) made from corn. This class of polymer is carbon neutral from the standpoint of the carbon in the plastic, but a substantial amount of fossil energy is used to produce the plastic and the biomass feedstocks.

Table 1
Classes of plastics.

Class	Source	Biodegradable	Example	Reference
I	Petroleum/natural gas	No	Polyethylene, polypropylene.	[7]
II	Petroleum/natural gas	Yes	PLA[a] from petroleum.	[9]
III	Biomass (Corn, sugar cane, etc)	No	Polyethylene derived from corn ethanol.	[8]
IV	Biomass (Corn, sugar cane, etc)	Yes	PHA[b], PLA derived from starch.	[14]

[a] Polylactic acid.
[b] Polyhydroxyalkanoates-based resin.

The class with perhaps the greatest potential to contribute to greenhouse gas emissions is biodegradable plastics made from petroleum. This is because not only is fossil energy used to produce them in the first place, but fossil carbon is released when the material ultimately biodegrades. If this biodegradation occurs in a landfill, then it usually will generate methane (CH_4), which is a greenhouse gas with 21 times the warming potential of CO_2. Most landfills do a poor job of capturing this gas, even those with methane recovery systems [11]. So landfilled biodegradable plastics, eventually contribute both methane and carbon dioxide to the atmosphere when they degrade.

Some novel polymers combine both biomass and fossil derived resins to decrease production prices, increase the bio-based content and improve material performance [5] (e.g. a plastarch containing a blend of a starch-based polymer and conventional plastics such as polypropylene). The biogenic renewable carbon contained in these and other biomaterials can be determined from the radioactive C_{14} signature of the product [12]. Yet these hybrid materials likely are neither recyclable nor completely biodegradable and therefore are likely worse than conventional plastics from a GHG emissions perspective.

Composting plays an important and growing role in sustainable organic waste management and recycling. However, plastics are one of the main contaminants in composts. Biodegradable plastics are meant to address this problem. Composting of these materials also reduces their environmental impact in that they will largely be converted to CO_2 and not to CH_4 as they would be in a landfill. Since this CO_2 was originally fixed from the atmosphere into renewable biomass, on balance it will not increase atmospheric CO_2.

Biodegradation is the mineralization of materials as a result of the action of naturally-occurring microorganisms such as bacteria and fungi [13]. The biodegradation of plastics is limited by their molecular weight, chemical structure [14], water solubility and the fact that most plastics are xenobiotic. That is, they were not present in the environment until very recently so that the evolution of metabolic pathways necessary for their biodegradation, a process that takes millions of years, has yet to occur.

In contrast, the biodegradation of natural polymers, such as starch or cellulose by microorganisms occurs relatively rapidly. It begins with the excretion of extracellular enzymes that depolymerize these materials. Once the polymer is reduced to a size that is water soluble and able to be transported through the cell wall, microbial metabolic pathways can then mineralize it [15]. Even though microorganisms drive the biodegradation process, other non-biotic chemical processes such as photo-oxidation and chemical degradation may also take place before or in parallel.

Biodegradable materials are used in diverse applications. Many different biodegradable plastics are used for food packaging and for waste containment. They have also been developed for medical applications, including medical devices and for drug delivery [16]. Biodegradable plastics are used widely in agriculture, as mulching films and low tunnels [17,18] as well as guide strings and plant nursery containers [19]. The physical properties and performance of biodegradable plastics made from PLA and natural fibers were found to be similar to conventional plastics for greenhouse crop production [20]. In addition, biodegradable potting containers have gained a high degree of acceptance among consumers [21].

Recently, various materials have begun to be marketed that claim to be biodegradable or compostable. Terms such as “degradable”, “oxo-biodegradable”, “biological”, “compostable” and “green” are often used to describe and promote different