Contractor's Report to the Board

Performance Evaluation of Environmentally Degradable Plastic Packaging and Disposable Food Service Ware - Final Report

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Executive Summary

As a way to conserve resources, reduce waste, and eliminate litter that harms marine life, the people of California, green businesses, environmental organizations, and local governments are increasingly interested in alternatives to the use of plastic bags and disposable food service ware. In response, a growing number of manufacturers are offering plastic products and packaging which they claim will decompose naturally in the environment or through composting. The growing presence of these new plastics raises a number of important questions for consumers and policymakers.

In response, the California Integrated Waste Management Board (CIWMB) contracted with California State University (CSU), Chico to study and report on the following:

- The designed-use performance and compostability of commercially available products and packaging that claim to be “compostable” and “degradable.”
- The degradability of several commercially available compostable plastics under laboratory conditions.
- How well degradable plastic products decompose in actual composting facilities and in a simulated marine environment.
- The potential for degradable plastics to contaminate conventional recycled plastics.

Test Products and Facilities

The researchers tested several commercially available degradable plastic products in six different composting environments and a simulated marine environment. The composting environments included a laboratory and actual facilities composting greenwaste, cow manure and straw, food waste, municipal solid waste, and an enclosed “in-vessel” facility in the absence of oxygen. The possible effects of contamination were examined by chemically and mechanically testing molded blends of degradable plastics and recycled plastics.

Research Results

The following results are based on the experimental conditions described in this report:

1. All of the products tested, except those that degrade in sunlight or oxygen, disintegrated satisfactorily in commercial composting operations within 180 days. Specifically, a minimum of 60 percent of the organic carbon converted to carbon dioxide by the end of the test period. See Table 1.
2. For all products, the measured amounts of lead and cadmium in finished compost were less than one percent of maximum allowable levels.
3. The polylactic acid (PLA) straws, polyhydroxy alkanoate (PHA) bags, Ecoflex bags, sugar cane plates and corn starch based trash bags released no toxic materials into the compost and successfully supported the growth of tomato seedlings after ten days.
4. The PLA lids, PHA bags, Ecoflex bags, Husky bags and corn starch based trash bags degraded completely in the enclosed “in-vessel” composting facility. However, oxodegradable and uv-degradable bags, low-density polyethylene (LDPE) plastic bags, sugar cane lids, and Kraft paper did not degrade.
5. The PHA bags experienced some disintegration in ocean water; all the other products did not disintegrate at all.
6. Biodegradable plastics and plastics that degrade in oxygen or sunlight reduce the quality and impair the mechanical properties of finished products manufactured with recycled content.

Recommendations

1. Perform additional research to:
    - Better understand the fate of degradable plastics in land and marine environments and to understand the effect that degradation residues may have on wildlife, plants, and marine life.
    - Assess the life cycle costs incurred during the manufacturing, collection, and reprocessing of compostable bags compared to the costs incurred managing conventional plastics through processing, recycling, and disposal. Local governments need this information to make informed decisions about uses for compostable bags.
2. Propose a law requiring the development of an identification code for compostable bags and containers to help identify and separate compostable plastics from recyclable plastics. The presence of degradable plastic material in regulated rigid plastic packaging containers and trash bags would make compliance with present law very difficult and, as indicated above, would reduce plastic recycling opportunities.

Table 1 summarizes the result of the testing in the six different composting environments:

Table 1. Test results in six different composting environments.

PRODUCT TESTED	**Testing Environment**						**Biodegradable Products Institute (BPI) CERTIFIED**	**PASS PLANT TEST**	**PASS METAL TEST**
	1	**2**	**3**	**4**	**5**	**6**			
Sugar Cane Plate or lid	●	●	●	●	●	●		●	●
PLA container	●	NT	●	NT	NT	NT	●	●	●
PLA cup	●	NT	NT	NT	NT	NT	●	●	●
PLA lid or straw	●	●	●	●	●	●	●	●	●
Corn-based BioBag trash bag	●	●	●	●	●	●	●	●	●
PHA bag	●	●	NT	●	●	●	●	●	●
Ecoflex bag	●	NT	NT	●	●	●	●	●	●
Oxodegradable bag	X	X	NT	X	X	X		●	●

Note: X *denotes no biodegradation*
Note: ● *denotes biodegradation consistent with ASTM standards*
Note: NT *denotes not tested*

***1**: Laboratory* *__2__: Greenwaste* ***3**: Cow Manure and Straw*

***4**: Food Waste* ***5**: Municipal Solid Waste (MSW)* ***6**: In-vessel*

Introduction

The California Integrated Waste Management Board (CIWMB) initiated a research program to evaluate performance, degradation rates, and the environmental impact of degradable plastic packaging and food service ware products in commercially operated compost facilities and in simulated marine environments. The term “degradable” encompasses products that are marketed as biodegradable, compostable, photodegradable, oxodegradable, or degradable through other physical or chemical processes.

The Department of Mechanical Engineering, Mechatronic Engineering and Manufacturing Technology at California State University, Chico, performed the research in the polymer technology laboratory. The objectives of the research project were:

1. To evaluate the effectiveness of commercially available degradable plastic products on the basis of intended use, degradability, toxicity, and cost.
2. Generate environmental safety assessments.
3. Assess the impact of degradable plastics on the plastics recycling stream.
4. Identify future research needs.

The project is broken down into four areas, including: a detailed work plan and budget, literature review, testing for performance evaluation in full-scale composting and anaerobic digestion, and evaluation report.

This research is the continuation of a previous research study that presented the results of biodegradation testing on several compostable plastics that are commercially available in California. The research found that the compostable materials degrade under laboratory compostable conditions as specified in ASTM D6400. The past research project was an initial study of several common compostable plastic materials. The research did not address other degradable products nor accelerated in-vessel composting methods.

Background Information

Conventional Plastics

Plastics can be produced from natural or synthetic materials. Traditional plastics, with an annual world production of approximately 140 million tons [1], are typically made from petroleum-based products. Alternatively, biobased polymers are produced from natural materials, e.g., starch from corn, potato, tapioca, rice, wheat, etc.; oils from palm seed, linseed, soy bean, etc.; or fermentation products, like polylactic acid (PLA), polyhydroxyalkanoate (PHA), and polyhydroxybutyrate (PHB).

Some petroleum-based products are considered biodegradable polymers since they are consumed by microbes in the soil and biodegrade in compost environments. For example, aliphatic-aromatic co-polyester polymers from BASF™ and ε-caprolactam are made from petroleum materials and are consumed by microorganisms.

Most petroleum-based polymers are not biodegradable. However, additives can be blended that cause them to behave similar to a biodegradable plastic by fragmenting in soil.

Petroleum-based plastics that have starch or degradable additives as a component are not biodegradable since only the starch portion of the plastic is consumed by microbes in the soil. Prodegradant additives are combined with polyethylene to produce an oxodegradable synthetic polymer that causes the plastic to disintegrate into small fragments when exposed to oxygen. Similarly, photodegradable plastics have additives that cause the plastic to disintegrate in sunlight.

The fragmented plastic leaves small pieces in the soil and may take many decades to fully disappear. Additionally, since they are not consumed by microorganisms, they may cause considerable environmental harm to animals if ingested.

Biodegradable Plastics

Biodegradability is defined as a process where all material fragments are consumed by microorganisms as a food and energy source. Biodegradable polymers cannot have any residuals or by-products remaining.

The time period required for biodegradation is dependent upon the disposal system environment, which can be landfill soil, aerobic compost, anaerobic digestion, or marine. Many types of biodegradable polymers are available that degrade in a variety of environments, including landfill, sunlight, marine, or compost. The three essential components of biodegradability are:

1. That the material is used as a food or energy source for microbes.
2. That a certain time period is necessary for the complete biodegradation.
3. That the material is completely consumed in the environment.

Most biobased materials are biodegradable, though some are not. For example, polyesters can be made from soybean oil, but they are not biodegradable since the polymer is not consumed by microorganisms. Polyurethane can be made by reacting organic alcohol with isocyanate, but it is not biodegradable since it also is not consumed by microorganisms.

Definitions of biodegradable plastics are of utmost importance today. All plastic materials are degradable, though the mechanism of degradation can vary. Most plastics will degrade through the breakage of polymer chains when exposed to ultra violet (UV) light, oxygen, or high heat. Stabilizers are added to polymers to prevent their breakdown in the sun, heat, and oxygen.

Biodegradation occurs when microorganisms break down the polymer chains by consuming the polymer as a food source. Many plastics claim to be biodegradable yet are not completely consumed by microorganisms, nor are they completely mineralized. Also, biodegradation does not specify a length of time for the plastic to completely disappear. To be considered biodegradable should also mean that degradation occurs in a reasonable time frame. Traditional petroleum-based plastic might degrade completely in approximately 100 years. Thus, traditional plastics are not biodegradable. To be considered biodegradable, a practical time span is usually one growing season or 180 days.

Biodegradable plastics can degrade in composting facilities and break down into water, methane, carbon dioxide and biomass. Microorganisms in the soil or compost degrade the polymer in ways that can be measured by standard tests over specified time-frames. Biodegradable plastic is defined according to the American Society for Testing and Materials (ASTM) D6400 standard as a degradable plastic in which the degradation results from the action of naturally occurring microorganisms such as bacteria, fungi, and algae.

The key to understanding true biodegradability is to ensure that the plastic will behave like other organic materials in the soil, i.e., like leaves and sticks. Organic materials completely disappear because they are a food source for the organisms in the soil. With a good soil environment such as compost, which is about 60°C and moist, organic materials will disappear within 180 days and not leave any small fragments or residue. True biodegradable plastics should behave the same way and not leave any small pieces or residue that might harm the soil.

The general effects degradable materials have on physical and chemical soil properties as well as on the soil ecology were evaluated.[2] The degradation of several biopolymers improved the soil quality, resulted in no residue, and had a positive environmental effect. The biopolymers included starch-based, PHB, PLA, polyester, and polyester copolymers. [3] The ecotoxic effects of biodegradable polymers after composting or degradation in soil or marine environments are rarely studied. Additional research is needed in the future to study the environmental fate of degradable materials.

Compostable Plastics

"Compostable" is an even more accurate term than biodegradable. Compostable specifies that, in a proper compost environment, the plastic not only completely biodegrades, but is also completely consumed in 180 days or less.

The ASTM D6400 standard defines compostable plastics as materials that undergo degradation by biological processes during composting to yield carbon dioxide, water, inorganic compounds, and biomass at a rate consistent with other known compostable materials and that leave no visible distinguishable or toxic residue. If a degradable plastic does not meet these requirements, then it cannot be labeled as "compostable" in California. [4]

Compostable plastics can then be collected along with non-plastic compostable materials and sent to composting facilities rather than landfills. Unfortunately, not all products marked as biodegradable are also compostable. This compostable requirement can lead to confusing product labeling and a misunderstanding of acceptable biodegradability.

Two independent organizations, the US Composting Council (USCC) and the Biodegradable Products Institute (BPI), jointly established procedures to verify the compostability claims of biodegradable products and created a "compostable" logo to verify the compliance with ASTM D6400 compostability standards.[5]

BPI, in conjunction with the USCC, performs product evaluations on every product awarded the compostable logo. BPI provides important criteria for valid full-scale testing of compostable plastics. [6] The BPI Logo Program is designed to certify plastic products that will biodegrade and compost satisfactorily in actively managed compost facilities. To help consumers, BPI provides a list of certified compostable products. The products include compostable bags and film, food service items, and resins.

Degradable Plastic Products

Many communities are interested in using biodegradable products to reduce the pollution caused by lightweight plastic bags. For example, San Francisco is requiring the use of compostable or recyclable bags in supermarkets, drugstores, and other retail stores. [7]

Similarly, the compost facility of the City of Hutchinson, MN, will collect greenwaste only in biodegradable plastic bags. [8] Biodegradable bags are delivered every four months to those who participate in the curbside organics program. All types of organic materials can be placed in the biodegradable bags, especially if the material is smelly, drippy, or might blow around in the wind. The EcoGuard compost bag that Hutchinson distributes converts into carbon dioxide and water within a few weeks after disposal.

In Europe, compostable plastic bags are available for use as supermarket carrier bags, "knot" bags for fruits and vegetables, kitchen waste bags, and garden waste sacks.[9] Eastman Chemical opened an Eastar Bio plant in the United Kingdom in 2002 with a production capacity of 33 million pounds per year. [10]

In 1999, the total polymer consumption for plastic bags and sacks in the European Union was on the order of 2 to 2.5 million tons per year. The total consumption of all biodegradable polymer products in the European Union was estimated to be 20,000 to 25,000 tons per year. [11] Approximately 8,000 tons per year of Novamont's Master-Bi™ corn starch plastic bags are used. [12]

In Australia, biodegradable polymer materials are being used in grocery, retail, and compost industries as bags for fruit, bait, bread, and ice.[13] Australia uses the European standards for compostable and biodegradable plastics certification. Biodegradable plastic bags are available in the local bottle-shop and liquor stores. The environmentally friendly bags are made from Mater-Bi™ biodegradable plastic. In Australia and Europe, Cadbury Chocolates of Australia has selected Plantic™, a biodegradable polymer from Plantic Technologies of Australia, for thermoformed trays that hold individual chocolates in their box of chocolates. The compostable plastic material is made from starch.

Table 2 lists the product applications, supplier information and production capacity of several commercially available degradable plastics. The plastic products include biodegradable, compostable, oxodegradable, and UV-degradable polymers.

Compostable products are produced in higher volumes every year. Many suppliers are expanding production facilities to meet the increasing worldwide demand for true biodegradable or compostable plastics. With several production plants in the world, the most common biodegradable plastic is PLA. It has found success in rigid containers and cutlery. Mater-Bi™ starch based plastics are also used in many applications worldwide and are expanding production capacities. Mater-Bi™ is most commonly used in bag and film applications. Ecoflex® also is very successfully used for bag and film applications.

Unfortunately, several plastic products with prodegradant additives are sold throughout the world and claim to be biodegradable when they clearly are not degraded by microorganisms. Likewise, polyethylene plastics blended with starch are also produced worldwide and claim to be biodegradable, even though only the starch portions of the plastic will biodegrade and disappear. The rest of the plastic will remain in the soil for decades.

Table 2. Production information for commercially available degradable plastics

Trade Name	Product Application	Supplier-location	Production Capacity
Biomax™	Plates, bowls, containers	Dupont	10 million lbs. per year
Miral™ PHA	Film, sheet, cups, trays, containers	Metabolix Inc-USA	100 million lbs. per year[14]
EASTAR Bio	Bags, films, liners, fiber and nonwovens applications	Novamont NA-Italy	33 million lbs. per year[15]
Ecovio plastic PLA-Ecoflex	Bags, sheets, film	BASF- USA	20 to 50 million lbs. per year
Cereplast resins	Nat-UR cold drink cups, foodservice containers, cutlery	Cereplast Corporation-Hawthorne CA	40 million lbs. per year[16]
EcoFlex	Bags, liners, film	BASF-Denmark	60 million lbs. per year[17]
NatureWorks PLA	Cold drink cups, foodservice containers and cutlery	Nature Works LLC, Cargil-Dow- USA	300 million lbs. per year[18]
Stalk Market Sugar Cane	Foodservice containers and cutlery	Asean Corporation, China	30 million lbs. per year
Mater-Bi Resins	Bags, liners, film products	Novamont Corporation-Italy	40 million lbs. per year[19]
EPI additives for polyethylene	Bags, sheets, film, trays. Additive is available for many plastic products.	Biocorp, Inc. Becker, MN, USA	20 million lbs. per year
Oxo-UV-degradable additives for polyethylene	Bags, sheets, film, trays. Additive is available for many plastic products.	EPI Environmental Technologies, Nevada, USA	20 million lbs. per year
Polystarch master batch for polyethylene	Bags, sheets, film, trays, containers. Starch additive is available for many plastic products.	Willow Ridge Plastics, Inc. Erlanger, KY, USA	10 million lbs. per year

Table 3 lists polymer type, degradation extent and rate, shelf life, and certification of several degradable plastics. The degradable polymers can degrade aerobically in compost, landfill, and marine environments. The rate of decomposition depends upon the temperature, moisture content, and population of microorganisms in the particular environment. All of the compostable plastics are certified by BPI and therefore completely mineralize and biodegrade in six months under composting conditions. They also have a reasonable shelf life of 12 to 18 months. The UV-degradable plastics and oxodegradable plastics are not certified as compostable and will not fully degrade in compost environments within six months.

Table 3. Certification information of commercially available degradable plastics

Trade Name	Polymer Source/Type	Rate and Extent of Degradation (Environment)	Shelf Life	BPI Certified	ISO Certified
Biomax™	Mixed aliphatic and aromatic polyester	Compostable in six months (compost)	12 to 18 months	Yes	Yes
Biopol™ PHA	Poly-hydroxyalkanoate via bacteria	Compostable in six months (compost)	12 to 18 months	No	No
EASTAR Bio	Modified polyethylene terephthalate (PET) polyester	Compostable in six months (compost)	12 to 18 months	Yes	Yes
Ecovio plastic	PLA-Ecoflex	New product	TBD	No	No
Cereplast resins	Plant organic sources	Compostable in six months (compost)	12 to 18 months	Yes	Yes
EcoFlex	Mixed aliphatic and aromatic polyester	Compostable in six months (compost)	12 to 18 months	Yes	Yes
NatureWorks PLA	Polyester	Compostable in six months (compost)	12 to 18 months	Yes	Yes
Stalk Market Sugar Cane	Sugar cane	Biodegradable (compost)	12 to 18 months	No	No
Mater-Bi™ Resins	Family of bioplastics that use vegetable components, such as corn starch, that have been modified (or complexed) with biodegradable polyesters.	Compostable in six months (compost)	12 to 18 months	Yes	Yes
EPI additives for polyethylene	Oxodegradable additive for HDPE and LDPE	Disintegrates but not compostable	2 to 3 years	No	No
Oxo- UV-degradable additives for polyethylene	Oxodegradable additive for HDPE and LDPE	Disintegrates but not compostable	2 to 3 years	No	No
Polystarch master batch	Starch and LDPE or HDPE, and Polypropylene (PP)	Disintegrates but not compostable	2 to 3 years	No	No

Biodegradable plastics that are certified by BPI are fully biodegradable in compost environments. The bacteria in soil and compost will consume the organic components of the biodegradable plastics. See Table 4 for a list of biodegradable and compostable plastics that degrade safely leaving no harmful residue.

The majority of compostable plastics belong to the polyester family, including poly-lactic acid (PLA), which is manufactured and supplied by NatureWorks, LLC. PLA is produced from the polymerization of lactic acid. It is also referred to as poly lactide. PLA is a very common biodegradable polymer that has high clarity for packaging applications. It can be used for thermoformed cups and containers, forks, spoons, knives, candy wraps, coatings for paper cups, optically enhanced films, and shrink labels. PLA plastics are the biodegradable plastics most commonly used by customers around the world. PLA has applications in the United Sates, Europe, Japan, Australia, and other countries.

In 1999, Dow Chemical and Cargill created a joint venture, named Cargill Dow, LLC, to become the largest biodegradable polylactic acid producer in the world with annual capacity of 140,000 tons per year.[20] In 2005, Dow and Cargill ended the partnership when Cargill purchased all of Dow Chemical's interests in Cargill Dow, LLC.

Some degradable products are made from synthetic polymers that have additives that will, over time, cause disintegration in outside environments. EPI Environmental Technologies Incorporated provides TDPA® (Totally Degradable Plastic Additive) for polyethylene and polypropylene manufacturers to produce plastic bags, films, and products that degrade over time.[21] This non-starch based additive uses ultraviolet light and oxidation to break the polymer chains, resulting in a reduction of the plastic's molecular weight. The additive is for use in food contact applications. [22] TDPA® additive technology has been used in plastic products in North America, Europe, Asia, Australia, and New Zealand.

Oxodegradable plastics can leave small plastic fragments as residue after oxidation. When starch is added to polyethylene and then degrades, a similar residue is left. Microorganisms in the soil digest the starch that causes the plastic to break down into smaller pieces.

Starch-based polyethylene plastics are available at Willow Ridge Plastics Incorporated. The starch master-batch products have been developed for use in blown film, injection molding and other applications with polyethylene, polypropylene, and polystyrene plastics.[23]

In 1989, Mobil Company produced Hefty bags from polyethylene with a cornstarch additive. When exposed to sunlight, the bags broke down into smaller plastic particles but did not degrade in landfills.[24] The starch-polyethylene bags are not BPI certified and can cause serious environmental consequences as fragments of polyethylene will be left in the soil after the starch biodegrades.

Table 4. Commercially available biodegradable and compostable polymers*

Material	Type	Supplier/ Distributor	Products	Degradation Products	Extent of Degradation	Standard Met
Biomax™	aliphatic copolyesters, modified PET	Dupont/ www.allcompost.com	Coating and film for food packaging, sandwich bags, utensils, fibers	Carbon dioxide, water, biomass	Two to four months in compost depending upon temperature	ASTM D6400
Biopol™	PHB/V polybuty-rate and valeric acid	Metabolix Inc.	Consumer disposables, containers, trash bags, packaging	Carbon dioxide, water	20 days in sludge, to one month in compost	ASTM D6400, EN13432
Eastar Bio™	Biodegradable copolyester	Eastman Chemical Company/ Farnell Packaging Biodegradable Products	Trash bags, film, liners	Carbon dioxide, water, biomass	Two to four months in compost depending upon temperature	ASTM D6400, EN13432
Ecoflex™	Aliphatic-aromatic Polyester	BASF/ www.allcompost.com	Compost bags, trash bags, carrier bags, fruit and vegetable bags	Carbon dioxide, water, biomass	Two to six months in compost depending upon temperature	ASTM D6400, EN13432
Mater-Bi™	Modified corn starch with biodegradeable polyesters	Novamont/ BioBag Corporation	Trash bags, lawn and garden bags	Carbon dioxide, water, biomass	Three to six months in compost depending upon temperature	ASTM D6400, EN13432, BPI
Nature-Works™	Polylactic acid (PLA)	Cargill Dow/ Biodegradable Food Service, Eco-Products, Inc.	Clear cups, clamshells, salad bowls	Carbon dioxide, water	One to three months in compost depending upon temperature	ASTM D6400, EN13432

**Note: The polymers are available in bag, Gaylord, or truckload quantities.*

Life Cycle Assessment of Biodegradable and Conventional Plastics

Environmental Life Cycle Assessment (LCA) is a method developed to evaluate the overall environmental costs of using a particular material. LCA includes the inventory and measurement of system inputs and outputs and then organizes and converts these into environmental themes or categories relative to resource use, human health, and ecological areas.[[25] LCA consists of three stages:

1. Life cycle inventory
2. Life cycle impact assessment
3. Life cycle improvement [26]

The first stage inventory includes setting the goal and scope of the analysis, which determines the extent of the work to be done and the procedures to be used. Additionally, the first stage includes measurement of the inputs and outputs of a system, including all emissions on a volume or mass basis (e.g., kg of CO_2, kg of cadmium, cubic meter of solid waste).

The impact assessment, or interpretation stage, links the results from the inventory to potential environmental problems.

And the third stage, life cycle improvement, suggests changes to reduce or eliminate any negative impacts on the environment.

In the case of plastics, LCA reports all the inputs and outputs necessary to produce 1 kg of material (polymer resin).

In *Handbook of Biodegradable Polymers*, the life cycle analyses of PLA, Mater-Bi™, PHA, and other biodegradable plastics from thirteen publications are compared.[27] Table 5 is a summary of LCA key indicators for several biodegradable polymers and conventional plastics. The results assume a functional unit of 1 kg of plastic.

Table 5. Summary of key indicators from LCA studies [28]

Type of plastic	Cradle to grave non-renewable energy use (MJ per Kg)	Type of waste treatment	Green House Gas emissions (kg CO_2 per kg)
LDPE	80.6	Incineration	5.04
PET (bottle)	77	Incineration	4.93
Polycaprolactone (PCL)	83	Incineration	3.1
Mater-Bi™ starch film grade	53.5	Incineration	1.21
PLA	57	Incineration	3.84
PHA	81	Incineration	Not available

However, this summary is subject to uncertainties, as it does not represent uniform approaches to the LCA. For one thing, the research studies used different functional units. Incineration is a common method in Europe for disposing of materials. Composting is more common in the U.S. and would require much less energy and is a more sustainable alternative.

Very little LCA research is available for composting solutions. The number of LCAs for biodegradable polymers is limited. No comprehensive LCAs have been published for PLA (plant based), cellulose polymers (plant based), or for petroleum-based biodegradable polymers such as Ecoflex.

A life cycle analysis of bags made of Mater-Bi™ showed that they can have a better environmental impact than paper bags, and are comparable with bags made of polyethylene that are separated from the waste and incinerated alone.[29]

NatureWorks® polylactide (PLA) is a versatile polymer produced by Nature Works, LLC. [30] NatureWorks® polymer requires fewer fossil resources to manufacture and emits significantly less greenhouse gases than most of the traditional plastics. The cradle-to-factory gate production process of NatureWorks® polymer currently uses 62-68 percent less fossil fuel resources than the traditional plastic materials such as polyethylene terephthalate (PET), polystyrene (PS), polypropylene (PP), high density polyethylene (HDPE), and low density polyethylene (LDPE).[31]

Current Standards for Biodegradable Plastics

Several worldwide organizations are involved in setting standards for biodegradable and compostable plastics, including: American Society for Testing and Materials (ASTM), European Committee for Standardization (CEN), International Standards Organization (ISO), German Institute for Standardization (DIN), Japanese Institute for Standardization (JIS), and British Plastics Federation. The standards set by these organizations have helped the industry create biodegradable and compostable products that meet the increasing worldwide demand for more environmentally friendly plastics. [32]

Germany, the United States, and Japan are cooperating in developing certification schemes to enable international cross-certification of products, so that a product certified in one of these countries would automatically be eligible for certification in another.

United States

In the US, ASTM D6400 is the accepted standard for evaluating compostable plastics. The ASTM D6400 standard specifies the procedures for certifying that compostable plastics will degrade in municipal and industrial aerobic composting facilities over a 180-day time period.[33] The standard establishes the requirements for materials and product labeling, including packaging made from plastics, to be designated as "compostable in municipal and industrial composting facilities." The standard determines if plastics and products made from plastics will compost satisfactorily, including biodegrading at a rate comparable to known compostable materials. The standards assure that the degradation of the materials will not contaminate the compost site nor diminish the quality of the finished compost.

ASTM D6400 utilizes ASTM D6002 as a guide for assessing the compostability of environmentally degradable plastics, in conjunction with ASTM D5338 to determine aerobic biodegradation under controlled composting conditions. ASTM D6400 specifies that a satisfactory rate of biodegradation is the conversion of 60 percent of the organic carbon in the plastic into carbon dioxide over a time period not greater than 180 days. If a biodegradable polymer does not meet the requirements listed in ASTM D6400 or EN13433, then it is not considered compostable. It must degrade in the specified time frame without leaving any residuals in the compost. [34]

In this research, ASTM D6400 was followed when testing the compostability of several rigid packaging containers, bags, and cutlery that are made from biodegradable and compostable plastics.

Compostable plastics are being used safely in the United States with the help of a certification program and the establishment of ASTM D6400 standards. BPI and the US Composting Council (USCC) established the Compostable Logo program in the United States.[35] The BPI certification demonstrates that biodegradable plastic materials meet the specifications in ASTM D6400 and will biodegrade swiftly and safely during municipal and commercial composting. Several degradable plastics, which are available for composting, were certified "compostable" in 2002. [36] The "compostable" logo helps consumers to identify which products meet the ASTM D6400 standard. [37] To ensure objectivity, verification of the ASTM standard is accomplished through an independent third-party consultant selected by the manufacturer.

Biodegradation of biodegradable plastics in marine environment is based upon ASTM D6691 and ASTM D7081. ASTM D6691 is a test method for determining aerobic biodegradation of plastic materials by a defined microbial consortium in the marine environment. ASTM D7081 is a standard specification for non-floating biodegradable plastics in marine environments. Both standards also require measuring the amount of CO_2 generated during the degradation process. A test sample demonstrates satisfactory biodegradation if after 180 days, 30 percent or more of the sample is converted to carbon dioxide.

As shown in Table 8, the heavy metal limits in the European standard are more stringent that those listed in the US standards.

Table 6. Heavy metal limits in European and US Standards [38]

	Lead	Cadmium	Chrome	Copper	Nickel	Zinc	Mercury
Europe	30 mg/kg	0.3 mg/kg	30 mg/kg	22.5 mg/kg	15 mg/kg	100 mg/kg	0.3 mg/kg
USA	150 mg/kg	17 mg/kg	*	750 mg/kg	210 mg/kg	1400 mg/kg	8.5 mg/kg

** Not specified*

The EN13432 standard allows a limited amount of heavy metal concentration. Acceptable levels of heavy metals in sewer sludge are provided per US EPA Subpart 503-13. Testing of five biodegradable garbage bags found the heavy metal content lower than allowable standards. Green and blue colored pigments cause the amount of copper to increase in soil. [39] Heavy yellow pigments can cause the amount of lead to increase in soil.

Europe

In Europe, compostable plastics are used in several applications. Compostable plastics must comply with the European Norm, EN13432. EN13432 requires 90 percent of a compostable plastic material to break down to H_2O, CO_2, and biomass within a six month period.

DIN-Certco is a well known and commonly utilized certification system in Europe.[40] Sample materials are tested for regulated metals, organic contaminants, complete biodegradation, disintegration under compost conditions, and phytotoxicity.[41] The regulated metals and organic chemical tests ensure that neither organic contaminants nor heavy metals such as lead, mercury and cadmium can enter the soil via the biodegradable materials. The procedures for testing complete biodegradation in the laboratory and disintegration under compost conditions ensure that materials are completely degraded during one process cycle of a standard composting plant. The DIN compostability certification is very similar to BPI certification.

ISO

The International Standards Organization (ISO) is a network of the national standards institutes of 157 countries who agree on specifications and criteria to be applied consistently in the classification of materials, in the manufacture and supply of products, in testing and analysis, in terminology, and in the provision of services.[42] ISO 14855 stipulates the percentage conversion of carbon to evolved carbon dioxide as well as the rate of conversion, and the degree of plastic disintegration at the end of testing. ISO 14852 determines the ultimate aerobic biodegradability of plastic materials in an aqueous medium. The test method measures the evolved carbon dioxide and is similar to ASTM standards.

Australia

The Australian standard for degradable plastics includes test methods for validating the biodegradation of degradable plastics. It certifies degradable polymers that conform to the European standard, EN 13432. [43] The standard covers the range of potential application areas and disposal environments in Australia. The standard does not exclude Kraft paper, as do some European standards. Kraft paper is excluded as a positive control due to the potential presence of sulfonated pollutants. A more effective positive control can be either cellulose filter paper or microcellulose AVICEL PH101.

The Australian standard was developed with reference to existing international standards. The standard differentiates between biodegradable and other degradable plastics, as does ASTM D6400. It clearly distinguishes between biodegradation and abiotic disintegration; even though both demonstrate that the plastic has degraded sufficiently within the specified testing time. The standard is modeled after ASTM D5152 and addresses environmental fate and toxicity issues. Lastly, the Australian standard is more restrictive than ASTM D6400 as it states that total mineralization is required in 180 days; i.e., all of the plastic is converted to carbon dioxide, water, inorganic compounds and biomass under aerobic conditions, rather than disintegration into finely indistinguishable fragments and partial mineralization.[44]

Standards Australia Incorporated is developing two separate standards for compostable and oxodegradable materials. The draft standards are based upon established international standards. The DR 04425CP standard is based on ISO 14855-99 for determining the ultimate aerobic biodegradability and disintegration of plastic materials under controlled composting conditions. The DR 04424CP standard will determine the ultimate aerobic biodegradability and disintegration of plastic materials in an aqueous medium. The standards committee has established two subgroups to develop the standards: one for biodegradable plastics and the second for other types of degradable plastics, including oxodegradable and photodegradable plastics. [45]

Japan

The Japanese JIS standards are met with a GreenPLA certification system. The GreenPLA system has very similar testing requirements as the US and European certification methods. In particular, the GreenPLA certification assures biodegradability by measuring:

1. Carbon dioxide evolution after microbial biodegradation.
2. Mineralization (the ability to disintegrate and not leave visible fragments after composting).
3. Organic compatibility (the ability of the compost to support plant growth).

The JIS standard requires the same amount of carbon dioxide evolution as ASTM D6400 for certification: 60 percent in 45 days. The same 11 regulated metals are monitored in GreenPLA as in EN 13432. However, several aspects of the certification are different from the US BPI and European Din-Certco certifications. GreenPLA certification requires toxicological safety data on the biodegradable plastic material from either oral acute toxicity tests with rats or environmental safety test with algae, Daphnia, or fish. [46]

Biodegradable and Compostable Plastic Costs

Compostable plastic products are more expensive than conventional plastic products due in part to their low volume of production. If more products are purchased and the production rate rises, the price should be reduced. Biodegradable plastic products currently on the market are from two to ten times more expensive than traditional plastic products. The cost for biodegradable polyesters varies from $1.50 to $2.00 per pound. The high cost of the compostable plastic is a disadvantage when compared to paper, LDPE, PP, PS, and PET. One Australian company is trying to produce affordable biodegradable plastics by incorporating low-cost materials and processing methods. [47]

Nat-UR Cutlery Food Service provides biodegradable spoons, knives, and forks at a price of $15.50 for 240 pieces. They also sell compostable trash bags for San Francisco residents. The cost of 40 bags of 20-gallon size is $19. They also offer plates and a trash bag at a cost of $24 for 100 plates and $24 for 40 bags of 40-gallon size, respectively. Plastic cups are also available at a cost of $26 for 100, 10-oz cups. All of the products claim to meet ASTM D6400-99 standards.

Several companies provide compostable, rigid plastic packaging containers (RPPC), cutlery, and bags. [48] NatureWorks® PLA is made into many different types of containers, including cups, lids, plates, and storage containers. The cost for 1000 pieces can range from $25 to $145. [49]

Other environmentally friendly and biodegradable bags and cups are available at BioBag USA Corporation. [50] The bags are produced from Mater-Bi materials. All of the BioBag products meet the ASTM D6400 standard for degradation and safe residues, are certified by the US Composting Council, and comply with California state law regarding biodegradation. BioBag products are available for bags and liners, shopping bags, pet products, composting systems, Agro Film, and toilet systems. Retail biobags are available for kitchen bags, garden film, toilet systems, and Nature Waste Bags. Biodegradable plastic cups are also available. The costs range from $0.08 to $0.20 per bag and $0.07 to $0.14 per cup. The cost of biodegradable plastic bags is expensive when compared to the cost of typical polyethylene bags at $0.01 to $0.02 per bag.

Some environmental organizations argue that the cheaper price of traditional plastics does not reflect their true cost when you consider the expenses of disposal and environmental impact. The true costs of compostable plastics can be offset by the cost of disposal. California's cost for cleaning up and diverting plastic waste to landfills is conservatively estimated at more than $750 million annually.[51] Plastic represents 50 to 80 percent of the litter volume collected from roads, parks and beaches, and 90 percent of floating litter in the marine environment. In 2005, the California Department of Transportation spent $16 million cleaning up litter on California highways. [52]

Case Study of Costs at CSU Chico

The costs of disposal at CSU, Chico were studied in the research project. For one week, compostable plastic products replaced the standard plastic products at the university campus cafeteria. The compostable products were collected and sorted to remove non-compostable items and then sent to the university farm for composting. The disposal costs were monitored and compared to typical weekly costs.

Several companies provide compostable Rigid Plastic Packaging Containers (RPPCs), cutlery, and bags, which are sold through retailers and distributors.[53] Three of them are Eco-Products of Colorado, Biodegradable Food Service of Oregon, and NAT-UR Store of California. The products include: trash bags, storage bags, pet products, lawn and leaf bags, and typical food services items, e.g., cups, plates, and utensils. Eco-Products provided a quote for one week's worth of products for use at the CSU, Chico cafeteria.

Table 6 lists the costs for the compostable products. The costs of conventional plastic items are available from **www.foodservicedirect.com** and are listed in Table 7. The cost penalty for using compostable products is the difference between the two costs, or $1,561 per week. The extra costs can be offset by the reduced costs for disposal, since the waste products will be composted in an aerobic in-vessel compost facility at the university farm and not sent to a landfill.

Table 7. Costs for compostable food service items for CSU, Chico cafeteria

	Product	Volume, weekly	Price per unit	Cost
1	Plate: 9" Plate. Unbleached BioCane	5000	$0.11	$550
2	Oval plate: 10". Unbleached BioCane	5000	$0.10	$500
3	Plate: three item plate. Unbleached BioCane	5000	$0.11	$550
4	Cup: 16 oz PLA	10000	$0.09	$900
5	Cup: 24 oz PLA	10000	$0.07	$700
6	Salad container- 6" x 6" with lid: PLA	5000	$0.14	$700
7	To go Container: PLA	5000	$0.22	$1,100
8	Fork: PLA	5000	$0.04	$200
9	Lid: PLA	10000	$0.04	$400
10	Straw:PLA	10000	$0.01	$80
11	Trash bag: 55 gallon: Corn starch	500	$1.00	$500
12	Office trash bag - ten Gallon: Corn starch	100	$0.12	$12
	Total			$6,192

Table 8. Costs for conventional plastic food service items for CSU, Chico cafeteria

	Product	Volume, weekly	Price per unit	Cost
1	Plate: 9" Plate	5000	$0.03	$166
2	Oval plate: 10"	5000	$0.14	$677
3	Plate: 3 item plate	5000	$0.15	$737
4	Cup: 16 oz	10000	$0.06	$584
5	Cup: 24 oz	10000	$0.06	$584
6	Salad container- 6" x 6" with lid	5000	$0.12	$611
7	To go container	5000	$0.09	$450
8	Fork	5000	$0.03	$141
9	Lid	10000	$0.04	$384
10	Straw	10000	$0.01	$80
11	Trash bag: 55 gallon	500	$0.42	$209
12	Office trash bag: ten gallon	100	$0.09	$9
	Total			$4,631

Compostable plastics are more expensive than petroleum-based plastics. Compostable plastic performance is limited primarily by low temperature requirements and high cost. PLA compostable plastic has a maximum use temperature of 60°C. The temperature performance can be improved with the addition of natural reinforcements or nanocomposites.

The cost of the compostable plastics can be reduced if larger volumes are produced in expanding production facilities. The cost of compostable plastics should be reduced in the next several years and the performance to cost ratio will become similar to traditional petroleum-based plastics.

Degradation, Residuals, Toxicity, and Safety of Degradable Plastic

The by-products of the biodegradation of compostable polymers have minimal environmental effect. The by-products of compostable plastics are water, CO_2, and a biomass similar to plant biomass. The biomass residue provides carbon and nitrogen amendments as it is absorbed by the soil.

Degradable plastics can break down into smaller particles if blended with an additive to facilitate degradation. However, oxodegradable plastic bags in compost environments can take several years to biodegrade, depending on the amount of sunlight and oxygen exposure.[54] Polyethylene plastic bags produced with starch additives also partially degrade over time as microorganisms digest the starch, but leave the polyethylene intact.

Degradable plastics break down in one of two ways: [55]

- **Disintegration** occurs when the plastic materials break up and are no longer visible, but the polymer still maintains a finite chain length.
- **Mineralization** occurs after the initial oxidation process and the polymer chains are metabolized by microorganisms into carbon dioxide, water, and biomass.

Oxodegradable polymers break down into small fragments over time but are not considered biodegradable, since they do not meet the degradation rate or the residual-free content specified in the ASTM D6400 standard. The plastics do disintegrate but leave small plastic fragments in the compost, which violates the ASTM D6400 standard.

Results From Similar Biodegradable Plastics Studies

Mater-Bi™ is a wholly compostable polymer based on a blend of at least 50 percent starch and a

synthetic hydrophilic degradable polyester. The polymer was evaluated for suitability in disposal by composting. [56],[57],[58] The results indicate that Mater-Bi is readily degradable in standard laboratory biodegradation tests, including a semi-continuous activated sludge (SCAS) test for simulating breakdown in municipal wastewater treatment plants and pilot composting systems. The degradation rate of Mater-Bi™ bags depends on the exact formulation used and the physical properties of the product. Toxicity tests undertaken with the Mater-Bi™ bags and composted products have shown that they are nontoxic in standard animal and plant tests.

Biological degradation of the aliphatic-aromatic copolyester, Ecoflex®, was investigated by evaluating the degree of degradation and the intermediates that are formed during the degradation process. [59] No significant toxicological effects were observed, either for the monomeric intermediates or the oligomeric intermediates. The risk for Ecoflex in a composting process was assessed as minimal and indicates no environmental risk. More research is needed to assess the environmental risks and fate of intermediated products of other biodegradable plastics in composting environments.

Biodegradation

The research documented in this report is a continuation of a previous research study on the biodegradation of several compostable plastics that are commercially available in California. That research found that the selected compostable materials degrade under laboratory compostable conditions as specified in ASTM D6400. [60]

The degradation and disintegration results at the university farm demonstrated that the compostable materials degrade in moist, manure-based compost in 90 days. The potato starch based tray, cornstarch based trash bag, PLA plate, PLA straw, and PLA container degraded at rates similar to the cellulose control.

The degradation and disintegration results at the municipal compost facility demonstrated that the compostable materials degrade in moist greenwaste compost. The PLA container, PLA cup, and PLA knife degraded at a rate similar to the Avicell cellulose control and degraded completely in seven weeks. The cornstarch-based trash bag and sugar cane plate degraded at a rate similar to the Kraft paper control. The three materials degraded 80-90 percent after 20 weeks.

The biodegradability of five different biodegradable garbage bags was analyzed according to the DIN-standard. [61] The tests proved that a biodegradable polymer can be degraded under controlled composting conditions. The bags were made from cornstarch, polycaprolactone (PCL) and Kraft paper. PCL is a biodegradable polyester that is often used as an additive for resins to improve their processing characteristics while lowering cost and increasing biodegradability. The results demonstrated that all five plastic products decomposed to the European standards of 60 percent within six months. The bags were considered fully biodegradable since they degraded and disintegrated by breaking down into carbon dioxide and water, and left no toxic residue in the soil. The bags are not considered compostable since they were not tested for phytotoxicity.

Toxicity

Compostable materials must also not leave any toxic residues or chemicals that negatively affect the compost soil quality. The quality of the compost can be evaluated using analytical and biological criteria, including soil density, total dry solids, salt content, inorganic nutrients content, and eco-toxicological behavior.[62] The inorganic nutrients evaluated in the compost are total nitrogen, phosphorous, magnesium or calcium, and ammonium-nitrogen. The eco-toxicological tests include determination of growth inhibition with tomato and radish plants.

Phytotoxicity testing on the finished compost that contains degraded polymers can determine if the buildup of inorganic materials from the plastics is harmful to plants and crops and if they slow down soil productivity. [63] ASTM 6002 establishes the standards for phytotoxicity testing. The ASTM procedure determines phytotoxicity by blending the compost containing the compostable plastic material with compost soil. Plant emergence survival and growth are then evaluated. Three plant species are generally tested. The results from compost containing plastic material are compared to compost without plastic material and a soil control. [64] The plant species can be tomato, cucumber, radish, rye, barley, or grass. Plant biomass tests can reveal quality differences between composts and can indicate potential plant stress induced by the compost at the level used in the test. [65]

The PLA cup and container, sugar cane plate, and corn starch-based trash bag met the phytotoxicity requirements and supported growth of tomato seedlings after ten days. Soil samples from the compostable materials did not leave any toxic residue and had very little detectable heavy metals, i.e., lead and cadmium were 100 times lower than established limits.

Safety

A safety assessment of the biodegradable plastics is listed on each product’s materials safety data sheet (MSDS). The MSDS for the Ecoflex plastic states that the hot plastic can cause thermal burns and that frequent or prolonged skin contact can cause irritation. However, the MSDS does not provide any data on human, plant, or aquatic toxicity. The overall health hazard for Ecoflex is listed as low.

The MSDS for the Novomont Mater-Bi biodegradable plastic states that there is no evidence of harmful effects to the eyes, skin, or lungs with the product. Furthermore, the MSDS states that the Novomont product is not harmful to health if handled correctly.

The MSDS for the PLA plastic states that contact with the PLA fibers may cause skin irritation, that PLA fibers may cause discomfort for individuals who experience bronchitis or asthma, and that PLA is not hazardous to skin absorption or inhalation. The overall health hazard for PLA is listed as low.

The health risks for Mirel PHA should also be low, though an MSDS is not available.

Sugar cane powder can cause respiratory irritation. The LD-50 for sugar cane in rats is 29,700 mg/kg, which translates into a lethal dosage for 50 percent of the rats that were given 29.7g of sugar cane per kg of rat.[66]

Some aromatic aldehydes, ketones, quinones, metal complexes, and salts can activate photodegradation in plastics. However, caution should be observed since some of them might also contribute to the toxicity of the final product. Dithiocarbamates, for example, are skin irritants and responsible for long-term abnormal thyroid function. They are considered a probable carcinogen. Anthracene is a suspected endocrine disruptor, and a gastrointestinal and skin toxicant. Low molecular weight sensitizers might leach out of the plastics by diffusion and this therefore, would prevent their use in food packaging applications. Pyrene, which can be used as a sensitizer in degradable plastics, can cause health problems.

The overall health risks for UV-degradable plastics are minimal due to their LDPE basis and benign UV-additive. Oxodegradable plastics might cause some health risks due to the use of transitional metal complexes and salts. The oxodegradable additives are typically based on ionic Cobalt (II). Co (II) and its compounds may cause adverse effects to humans and the environment. It is classified as a possible human carcinogen and is very toxic to marine organisms. [67]

Biodegradation Testing Plan

Test Methods

The degradable materials were tested for biodegradation using five methods:

1. Following ASTM D6400 standards, monitor all of types of degradable plastics, including oxodegradable, biodegradable, and compostable for biodegradation by measuring the CO_2 evolution for 45 days.

   Additionally, test the compost soil for heavy metals and phytotoxicity.
2. Allow compostable and degradable plastic materials and food waste to biodegrade at the City of Chico Municipal Compost Facility.
3. Allow compostable plastic materials with BPI certification and food waste to biodegrade using aerobic in-vessel composting at a commercial compost site in Vacaville.*
4. Allow compostable plastic materials with BPI certification and manure to biodegrade using aerobic in-vessel composting at the university farm.*
5. Allow compostable plastic materials with BPI certification and municipal solid waste to biodegrade using in-vessel composting at a commercial compost site in Mariposa County, CA.*

**Note: degradable materials will not be composted with the in-vessel compost methods due to the potential contamination of the compost from residual non-degraded plastics.*

Composting is a well-accepted process of biodegrading organic materials. The compost can be produced with three techniques, namely, aerated static pile, turned windrow, or in-vessel container.

1. Windrows are long piles of compost up to two meters high. Static piles or windrows are not turned or moved until composting is completed.
2. Turned windrows are aerated by periodic mechanical mixing with a large auger.
3. In-vessel composting places the material in a tank, where the compost material is aerated and mixed by tumbling or stirring. Composting in a vessel is much faster than traditional windrow methods. [68]

The first testing environment was under controlled laboratory settings. The closely monitored environment allowed measurement of the degradation rate of the compostable materials as well as control of important laboratory conditions, such as compost temperature, moisture, and pH. The purpose of the laboratory experiment was to compare the degradation rates of several compostable materials with known compostable standard materials, as well as to assess toxicity of the degradation products from the compostable plastics. The experiment used ASTM D5338 laboratory protocols, though the successful materials will not be certified to meet the ASTM D5338 standards since the laboratory is not ASTM certified. The ASTM D6400 standard uses the experimental methods specified in ASTM D5338, but extends the test time from 45 days to 180 days and the acceptable carbon conversion percentage from 60 to 90 percent. We used ASTM D5338 standards due to limited time in the study. Future research work is needed to test the biodegradable, compostable, and degradable plastics under the longer ASTM D6400 standards.

Biodegradation can be measured at a chemical level by monitoring the conversion of starch in the plastics to carbon dioxide. The compostable plastic materials are exposed to mature compost at a constant temperature and moisture level over a 45-day period. Mature compost of 18 months is used to ensure that the degradation is due to the conversion of the compostable plastic and not from degradation of organics in the soil. The inoculums, defined as compost material that is comprised of soil and green yard waste, were screened with a sieve of less than 10 mm to remove the large pieces. The test is an optimized simulation of intensive aerobic composting where the biodegradability of the samples is determined under moist conditions.

The one-week case study at CSU, Chico disposed of the food waste and compostable products at the university farm. The materials were composted with an in-vessel aerobic method. The quality of the compost was monitored for temperature, pH, moisture, and pathogens.

Another case study was performed at the Mariposa Compost facility, which processes municipal solid waste (MSW) for Mariposa County, including Yosemite National Park. Their in-vessel system is state-of-the-art technology, using a New Zealand in-vessel process, called Hot Rot Composting Systems.[69] The in-vessel system provides sufficient oxygen for aerobic degradation, while maintaining sustained temperature in excess of 55º C for three days to achieve sanitization and odor control. The quality of the compost was monitored for temperature, pH, moisture, and pathogens.

Anaerobic digestion was studied with UC Davis and Dr. Zhang. Marine testing was studied per ASTM standards. Contamination studies will research the effects of degradable plastics on the recycling stream.

Materials

The materials were all commercially available compostable, biodegradable, UV-degradable, and oxo-degadable plastics made from polylactic acid (PLA), corn starch, copolyesters, PHA, sugar cane, and low density polyethylene (LDPE). See Table 4 for a complete description of the test materials.

Cellulose filter paper (Cellupure filter) from FilterQueen™ and Kraft paper were used as positive control materials. A polyethylene plastic sheet (Clingwrap) from Glad was used as a negative control as required in the ASTM standard. The test materials were cut up into approximately 25 mm by 25 mm pieces.

Laboratory Tests

The biodegradation of the compostable materials was tested in a controlled experimental environment. The laboratory experiment set up was based upon procedures outlined in ASTM D5338. Gases were measured with detectors allowed in the ASTM standards.

Test Procedures

The samples were prepared by adding 100g of the cut up degradable sample to 600g of mature soil compost in a 3.8-liter glass-canning jar. The sample materials occupied 1.5 liters of the vessel and left 2.3 liters of open volume for the gas to occupy. ASTM D5338 specifies that a maximum of 75 percent of the container can be filled with the test sample and compost.

The samples were placed in an oven maintained at 58° C for 45 days. The room temperature was maintained between 22° C and 27° C for the course of the experiment. The jar container tops had a rubber seal. The lids of the jars were modified to add two rubber stoppers with 5 mm tubes for moist air supply and gas withdrawal.

The mature compost, at least 18 months old, had a pH of 8.7, ash content of 35 percent, and carbon/nitrogen (C/N) ratio of ten. Carbon dioxide and ammonia measurements were taken on the compost with a Solvita test kit at the beginning of the test. These measurements were then used to calculate the C/N ratio.

Solvita is an easy-to-use test that measures both carbon-dioxide (CO_2) and ammonia (NH_3) levels in the soil and also gives a Maturity Index value.**[70]** The blank compost had a Solivita overall maturity index of seven with carbon dioxide rating of seven and ammonia rating of five. The mature compost rating indicates well matured, aged compost with few limitations for use.

The blank compost was screened with a sieve of less than 10 mm. The dry solids content was 95 percent and the volatile solids content was 63 percent. The volatile solids percentage was calculated by taking the difference between the dry weight and the ash content and dividing by the dry weight.

The experimental set-up is shown in Figure 1. Shop air was first sent to a CO_2 scrubber from Fisher Scientific to remove CO_2, H_20, and other gases from the air. It was then sent to an aluminum cylinder with water in the bottom to moisten the air. Moist air was then sent to a manifold for distribution to the 42 jars in the oven.

The moisture content of the samples was regularly monitored with a digital Sartorias moisture analyzer. Distilled water was added, as needed, to achieve an overall moisture content of 50 percent. The moisture content was found by drying the sample with infrared heat until the mass was unchanged. The temperature of the air in the laboratory was between 22° C and 27° C throughout the 45 days.

The jars were rotated and shaken weekly to maintain uniformity. Excess liquid was noted on the daily log and removed by adding air.

The jars were fed the moist air as the biogas was withdrawn with the aid of a vacuum pump. The biogases were sent to a bank of 42 gas valves. Each valve was opened to send the biogas from each jar to a gas manifold and then to a 320 ml sample jar holding either a CO_2 or O_2 Pasco gas sensor. The gas manifold and sample jars were purged with room air between each measurement. The measurement cycle took approximately 30 minutes with all 42 jars measured every 24 hours.

The gas sensors use infrared (IR) detection to measure the energy absorbed by carbon dioxide or oxygen molecules and then display the appropriate concentration. The carbon dioxide concentration is expressed in parts-per-million (ppm). The CO_2 gas sensor had a range between 0 and 300,000 ppm with an accuracy of 100 ppm or ten percent of value for a range of 0 to 10,000 ppm, whichever is greater. It had 20 percent of value accuracy for the range between 10,000 and 50,000, and qualitative only for values between 50,000 and 300,000. The CO_2 sensor was calibrated by sampling outside air at 400 ppm. The operating temperature range was 20° C to 30° C.

The oxygen sensor measured the percentage of oxygen present in the container. The detection error of the sensor was plus or minus 1 percent. The highest concentration of gas was in the composting jar in the oven. The concentration in the composting jar was out of this detector's range. The gas from the composting container was withdrawn with computer controls and diluted with room-air CO_2 concentrations in the 320 ml measurement bottle. The gas concentration readings were then converted back to the appropriate concentration from the compost container. Also, ppm concentrations in the composting vessel were converted into grams of CO_2 and then to grams of carbon, as described in Appendix A.

The sensor apparatus tested 42 jars in series and was computer controlled with a LabView data acquisition system. The CO_2 was measured with Pasco IR detectors, as previously described, and the CO_2 concentration output was saved in a computer file for each sample jar.

Figure 2 depicts the CO_2 concentration versus time for one biodegradable trash bag sample after 21 days. The figure illustrates a delay period when the biogas was initially pulled from the sample jar, followed by a steady increase of CO_2 concentration as it continued to be pulled through the detector. The slope of the ppm-time curve is the rate of carbon dioxide added to the detection jar during the experiment. The initial carbon dioxide in the sample jar was removed at the beginning of the test. The rate indicates the concentration of carbon dioxide in the sample that resulted from the biodegradation of the test samples.

The moisture content of the compost was maintained between 45 and 55 percent. Carbon dioxide was measured at daily intervals. Oxygen levels in the containers ranged between 17 and 21 percent during the experiment, which met the ASTM requirements of greater than six percent. Three replicates (experimental repetitions) of each sample were taken for the experiment.

Figure 1. Laboratory experimental setup

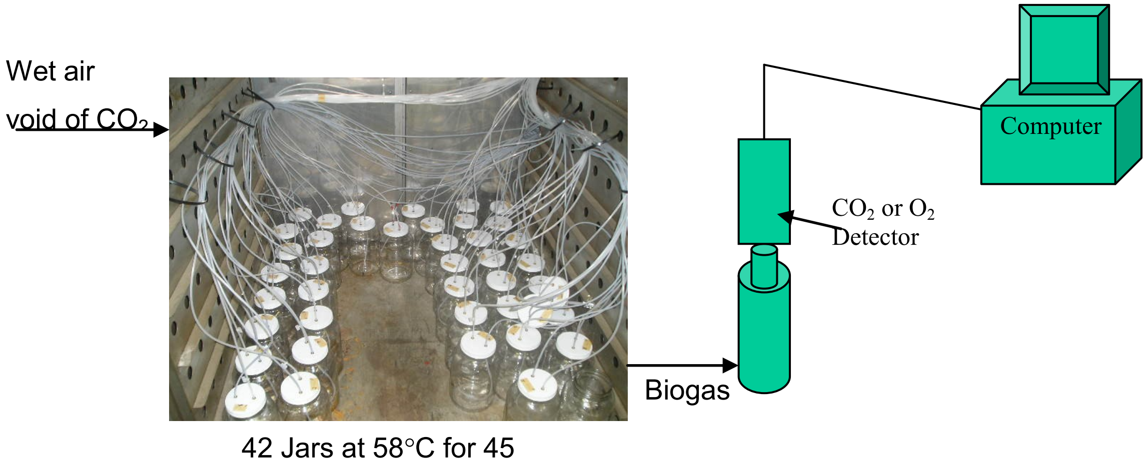
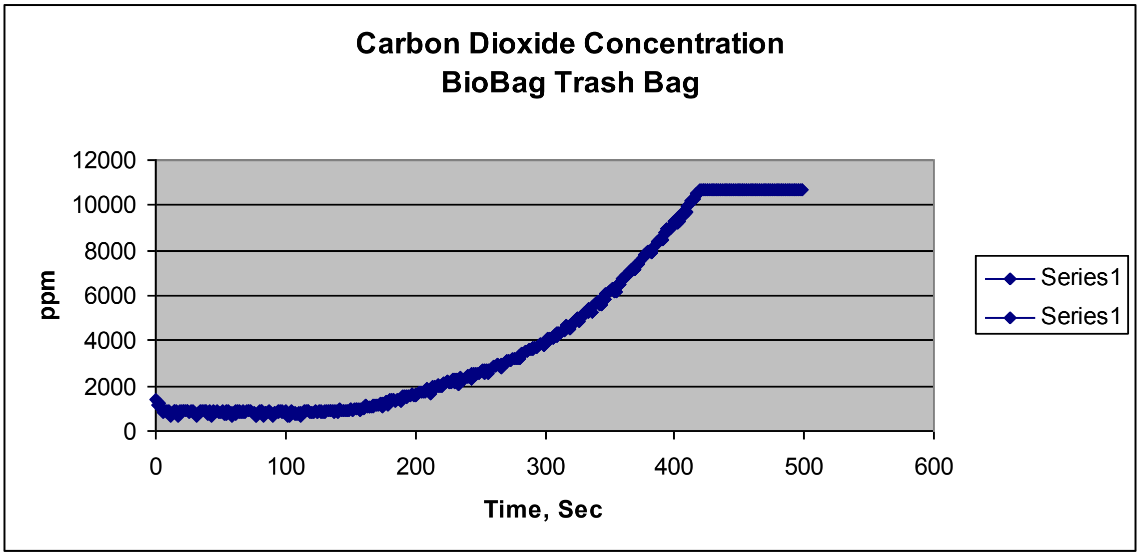


Figure 2. CO_2 ppm concentration of BioBag trash bag on day 21



Carbon Dioxide Concentration Results

As the compostable plastics degrade, CO_2 is produced. However, the initial compostable sample contains moisture and other elements in addition to carbon. For instance, cellulose, which has a compressed chemical formula of $C_6H_{10}O_5$, can have a theoretical maximum carbon content of 42 percent in the original dry sample.

The chemical structures of Kraft paper, corn starch, PLA, and sugar cane are more complex. Kraft paper is made from Kraft pulp, which is 44 percent cellulose. Corn starch's primary carbon source is native amylase corn starch $(C_5H_8O_3)_n$, where *n* is the degree of polymerization. The compressed chemical formula of PLA is $(C_3H_4O_5)_n$. Sugar cane products, such as the lids and bowls, are produced from 100 percent sugar cane fiber.[71] Sugar cane's primary carbon source is from sucrose $(C_{12}H_{22}O_{11})_n$. Bagasse sugar cane consists primarily of water, fiber, and soluble solids, with the fiber consisting of cellulose, pentosans, and lignin.[72]

The percentage of carbon in these, based solely on their chemical formulas, is as follows:

- Kraft paper – 44 percent
- Starch – 55 percent
- PLA – 30 percent
- Sugar cane - 42 percent

The amount of carbon can be less than the theoretical values depending on the amount of other materials added to enable processing into plastic parts or bags.

The amount of carbon can be directly determined experimentally by calorimetry. A bomb calorimeter is a constant-volume device made from stainless steel that measures the change in temperature of a known volume of distilled water as a combustible material is ignited. The bomb calorimeter is capable of withstanding the force of explosive reactions. A Parr Series 1300 Calorimeter with model 1101 stainless steel oxygen bomb was used to measure the carbon content of the samples. The sample was ignited and then the Pasco detector was used to measure the amount of carbon dioxide produced. The volume of the calorimeter was 0.340 liter. The pressure was 25 atmospheres. The carbon content in the sample container was calculated by converting the ppm measurement to mg/m^3 using Equation 3 in Appendix A.

The plastic samples were also measured for moisture content. The combustion results are provided in Table 9. The trash bag and PLA containers had higher heats of combustion than the cellulose material. The Kraft paper and sugar cane plate had lower heats of combustion than the cellulose material. The cellulose, Kraft paper, and sugar cane samples had approximately seven percent moisture content; the trash bag and PLA samples had one percent or less moisture content. The moisture content is the average of three measurements.

Table 9. Carbon content and moisture percent for compostable samples

Material	Bomb Calorimetry % Carbon Content	Moisture %
Cellulose	16.35	6.09
Kraft paper	16.53	7.19
Corn-based BioBag trash bag	21.94	1.03
PLA	17.01	0.37
Sugar cane plate	15.11	6.74
Mirel bag	16.28	3.24
Ecoflex bag	17.99	2.48
Oxodegradable bag	21.29	0.30

Biodegradation Results

Using Equation 5 in Appendix A, the biodegradation rate was determined from the amount of CO_2 measured during the 45 day experiment and the amount of initial carbon present in the sample. Pictures of the degradation experiment are provided in Appendix B. The CO_2 was measured as previously described.

The conversion of the organic materials into CO_2 in each of the eight materials was represented by daily graphing of the total conversion percentage over the 45 day period. See Figures 3 through 12. The results represent an average of three samples per material. Figure 3 illustrates the degradation of the compost material alone. This is well within the measurement error in the experiment and is negligible. The detection limit of the PASCO detector is ten percent of the maximum ppm value of 7000 ppm. The 700 ppm detection limit represents an experimental error of plus or minus 0.04 percent, which is reasonably low for the experiment.

The CO_2 concentrations were measured for four control materials and six degradable plastic samples. The amount of carbon resulting from the CO_2 concentration was calculated for each day. After 45 days the total amount of biodegradation conversion can be found by adding individual daily results. Using these amounts, the percentage of total biodegradation for the entire test was calculated and the results for each of the ten samples are listed in Table 10. The compost alone and the polyethylene (negative control) produced very little CO_2. This resulted in less than two percent conversion of the polyethylene into carbon, which can be accounted for by experimental error. The degradation rate of the compost and polyethylene samples was approximately 0.1 mg/day.

The cellulose and Kraft paper represented positive controls for the experiment. The cellulose degraded 72 percent over the 45 day experiment and the Kraft paper degraded 62 percent. ASTM D5338 requires at least 70 percent degradation of cellulose. The Kraft paper samples had degradation conversion percentages and degradation rates comparable to the Mirel bag, PLA straws, sugar cane plate, BioBag, and Exoflex bag samples. The oxodegradable bag had negligible degradation and was similar to the LDPE control material.

Table 10. Degradation rates for compostable samples

Material	Biodegradation Conversion %	Degradation rate g/day
Cellulose positive control	71.99	0.016
Kraft paper positive control	61.91	0.014
Mirel bag	64.03	0.014
PLA straws	61.22	0.014
Sugar cane plate	61.12	0.014
Corn-based BioBag trash bag	60.47	0.013
Ecoflex bag	60.14	0.013
Blank compost control	1.69	0.000
Polyethylene negative control	1.70	0.000
Oxodegradable bag	2.19	0.000

Figure 3. Carbon conversion percentage for compost control alone

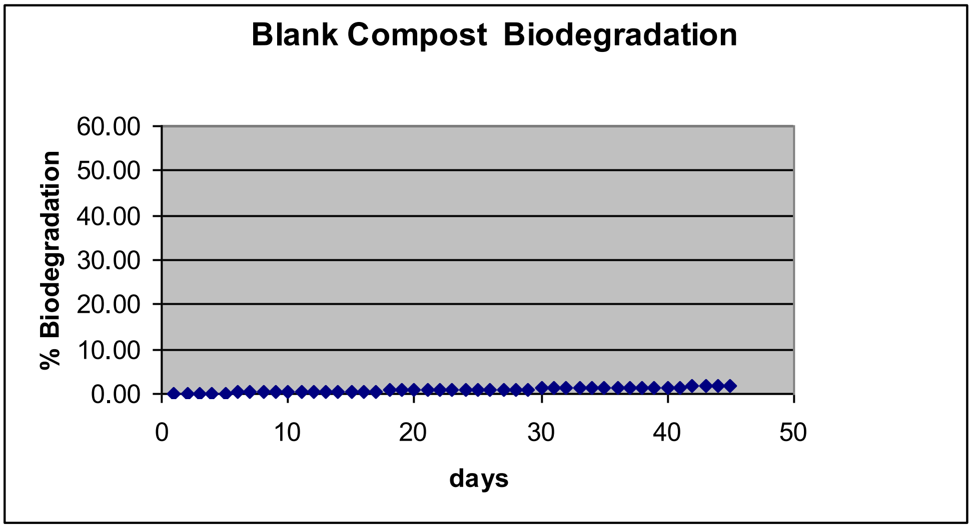


Figure 4. Carbon conversion percentage for cellulose control

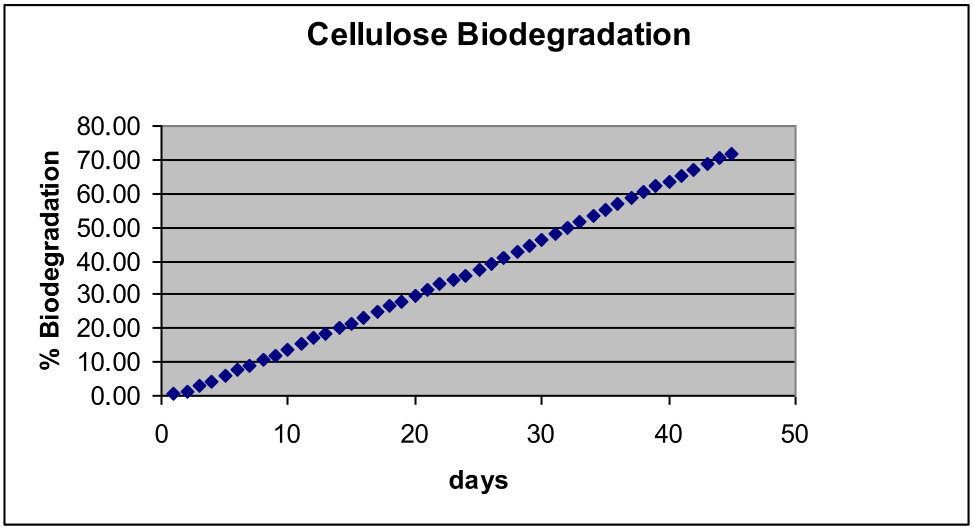


Figure 5. Carbon conversion percentage for Kraft paper control

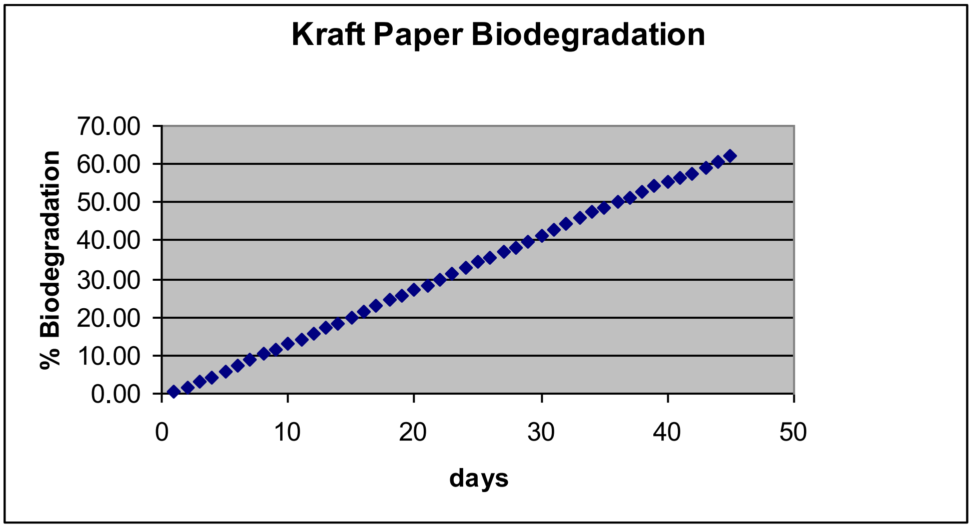


Figure 6. Carbon conversion percentage for polyethylene negative control

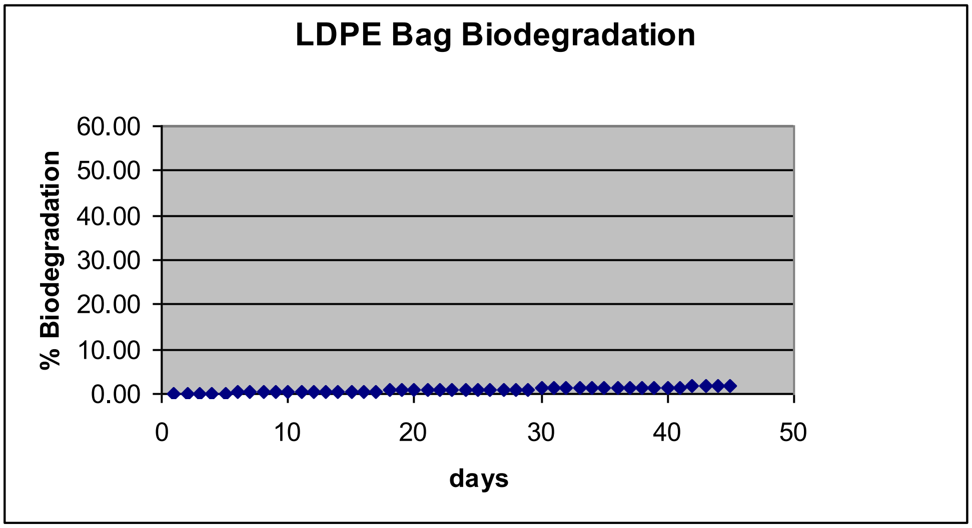


Figure 7. Carbon conversion percentage for corn based BioBag trash bag

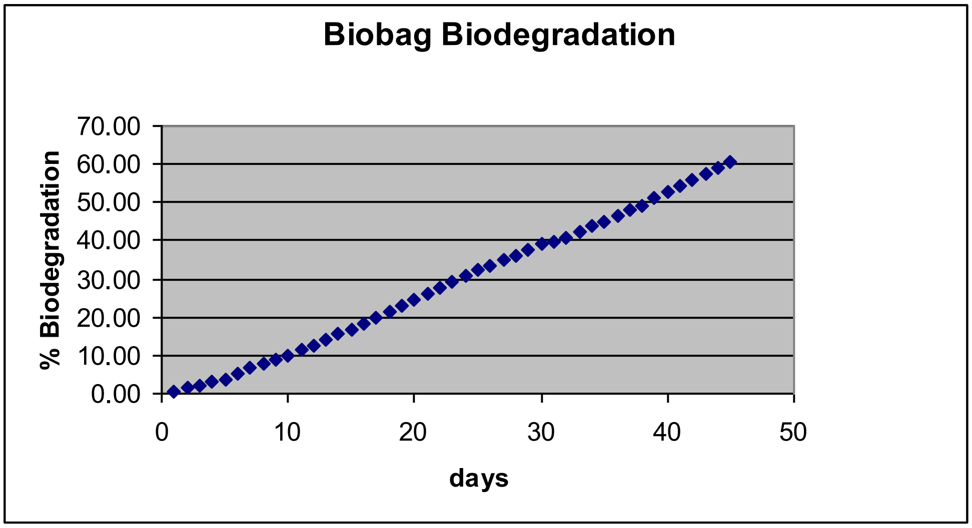


Figure 8. Carbon conversion percentage for PLA straws

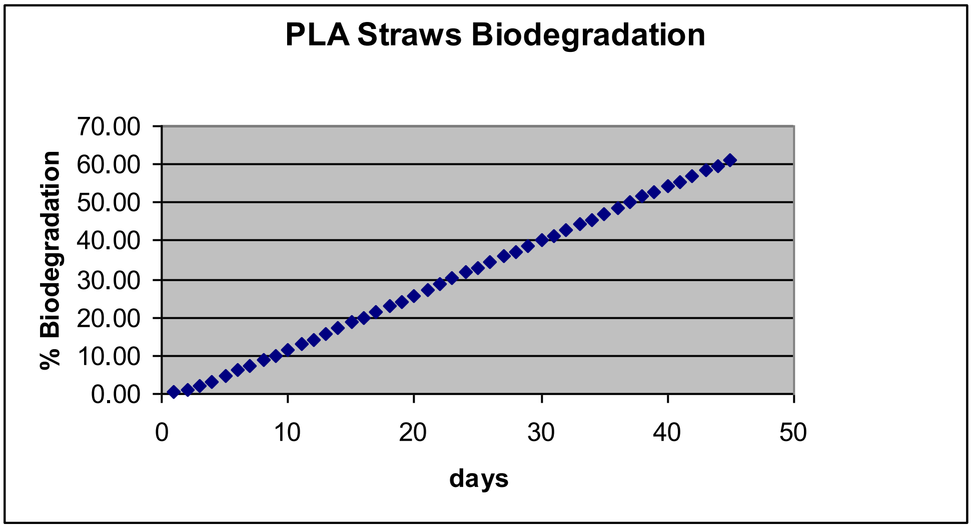


Figure 9. Carbon conversion percentage for sugar cane plate

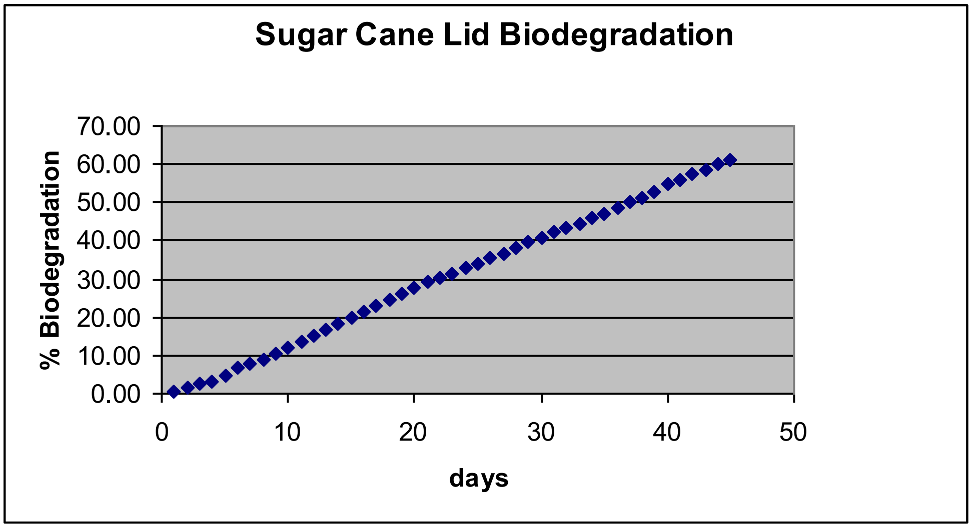


Figure 10. Carbon conversion percentage for Mirel bag

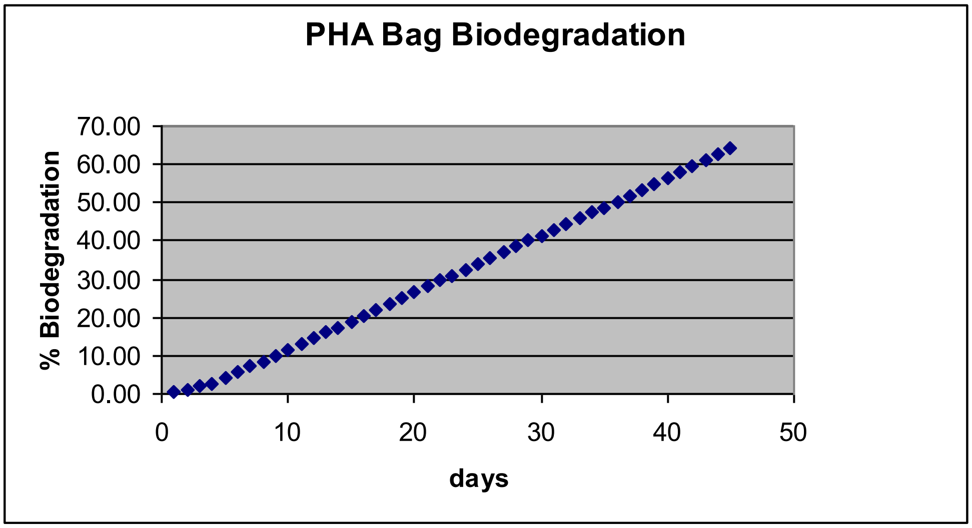


Figure 11. Carbon conversion percentage for Ecoflex bag

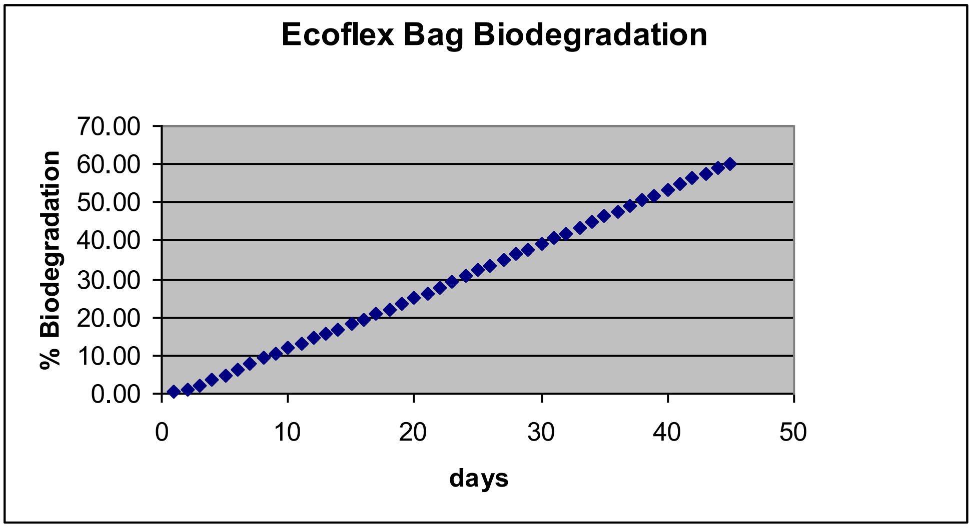
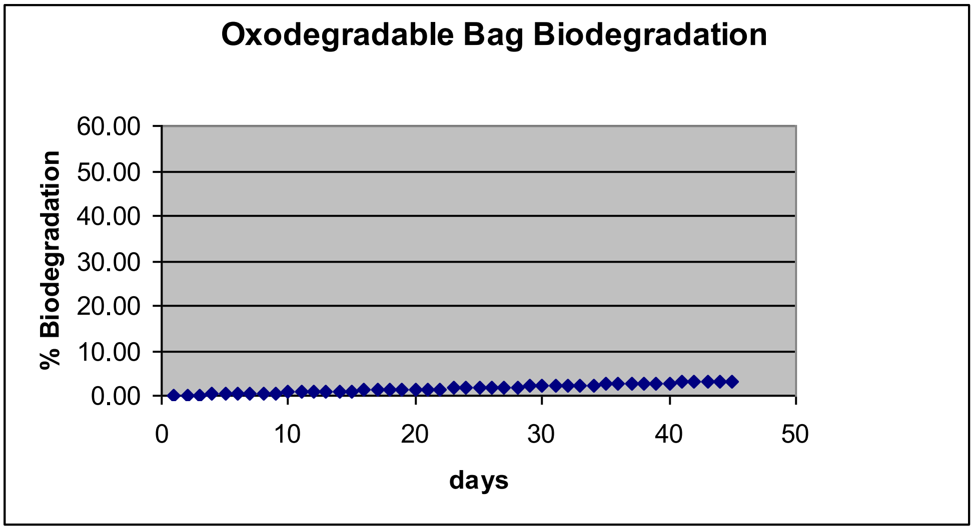


Figure 12. Carbon conversion percentage for Oxodegradable bag



Phytotoxicity Testing

The compostable materials must not release toxic materials into the compost soil during and after degrading. The compost soil can be tested to assess phytotoxicity, which indicates a poisonous environment to plants. The germination of tomato seedlings in the compost soil was evaluated after ten days. The phytotoxicity test was based on the ISO 11269 standard. The tomato seeds, from Vaughan's Seed Company, are a 2006 variety called "Tiny Tim". This variety is used in Biology classes on campus and is known to grow quickly and be robust. Ten were planted in small beverage cups (280 ml) filled with approximately 50 grams of compost from each of the test samples.

The sample containers were placed in a greenhouse with ambient light and watered frequently with tap water. The green house was warm and moist with a temperature of 25°C and relative humidity of 80 percent. After ten days in the green, the number and length of shoots were recorded for each sample. A lack of emerging seedlings would indicate phytotoxicity. The percentage of seeds that germinated and the average length of the seedlings are listed in Table 11. Ten seeds were placed in each container. A germination index is determined by taking the product of percent germination and average length and dividing by 100. All of the samples had tomato seedlings grow and pass the phytotoxicity test.

Similar results resulted with the degraded sugar cane compost using cucumber seeds and cress seeds at 25°C, 80 percent relative humidity, and ambient light for ten days in the greenhouse. The cucumber seedlings exhibited similar germination percentage growth as the tomato seedlings but had much higher growth length. The cress seedlings also had similar germination percentages as the tomato seedlings but had much lower seedling height. The tomato seedlings had the optimum growth height and were adopted as the standard seed source for the experiment.

Table 11. Phytotoxicity of compost soil

Material	Average Germination %	Average Length, mm after 10-days	Average Germination Index	Average pH
Compost control	46.67	24.33	11.35	8.5
Cellulose control	43.33	22.67	9.82	8.8
Avicell cellulose control	83.33	18.33	15.27	8.7
Kraft paper control	66.67	26.67	17.78	8.4
Polyethylene negative control	70	25	17.50	8.63
PLA container	70	20	14	8.5
Sugar cane lid	70	14	9.80	8.77
BioBag corn-starch based bag	60	32.33	19.40	8.63
Mirel bag	63.33	16	10.13	8.83
Ecoflex bag	56.67	18.33	10.39	8.6
Oxodegradable bag	73.33	18.33	13.44	8.8

Heavy Metal Testing

The degraded materials should not leave any heavy metals in the compost soil after degradation. The compost soil from each of the degraded samples was tested for lead (Pb) and cadmium (Cd). Additionally, the compost soil from the blank compost control and the oxodegradable plastic samples were tested for residual cobalt (Co). The acceptable limit is 30 mg/kg for Pb and 0.3 mg/kg for Cd. There are no limits in the US for Co. The compost soil for each sample was put into solution and the heavy metal in the compost soil was measured by flame atomic absorption spectrometry and Fisherbrand [73] hollow cathode single-element two inch diameter lamps with elements for lead and cadmium and cobolt.

Lead and cadmium absorption was measured at 283.3 nm and 228.8 nm respectively. The background correction was measured at 281.2 nm for Pb and at 226.5 nm for Cd. The detection limits are 0.02 ppm Pb, 0.005 ppm Cd, and 0.02 ppm Co in the analytical solution. For a 1 gram sample, the detection limits are 0.2 ppm Pb, 0.2 ppm Co, and 0.05 ppm Cd. The soil samples that were used during the phytotoxicity tests were also used to measure lead and cadmium levels. Approximately 10 grams of compost soil from each sample were dried for 24 hours at 105 °C. The average moisture loss was about 30 percent. About three grams of each dried sample was weighed into a 150 mL beaker to which 50 mL of 8 M HNO_3 was added. The samples were heated for 4 hours at 85 °C with occasional stirring. After four hours, 50 mL of deionized water was added to each sample followed by vacuum filtration through a Whatman GF/A glass filter with one percent (v/v) HNO_3. The filtrate was quantitatively transferred to a 250-mL volumetric flask and filled to the mark with 1 percent (v/v) HNO_3. The resulting samples all had a relatively intense orange-red appearance.

Sample preparation included adding a 0.8239 g sample of $Pb(NO_3)_2$ to a 500-mL volumetric flask, dissolved and diluted to the mark with 1 percent (v/v) HNO_3 yielding a 1099.5 ppm Pb^{2+} solution. Various standard solutions in the range of 0.220 to 1.10 ppm Pb^{2+} in one percent (v/v) HNO_3 were prepared along with a 1 M HNO_3 solution. Standard solutions were prepared by dissolving 0.2460g Cd in approximately 3 mL of 6M HCl and approximately 2 mL of 8M HNO3 in a 250 mL volumetric flask and diluted to the mark with 1 percent HCl (v/v) yield on 984 ppm Cd solution. Various standard solutions including a blank from mature compost alone were prepared from 0.0984ppm to 9.840 ppm Cd in one percent HCl.

The standard solutions and eight sample solutions were analyzed using a ThermoElectron S Series Flame Atomic Absorption Spectrophotometer using an air-acetylene flame and equipped with a Pb hollow-cathode lamp detecting at 283.3 nm, a Co hollow-cathode lamp, and a Cd hollow-cathode lamp. The sample solutions gave absorbances at or very near the lowest standard employed which was just above the detection limit of the instrument. Using 0.022 ppm Pb^{2+} as the detection limit leads to an upper limit of 20 ppm Pb^{2+} in the original soil samples. The 20 ppm value equates to 0.02 mg/kg for Pb. The Cd concentrations were lower than 1ppm which equates to 0.001 mg/kg Cd. All of the soil samples from the compostable materials had lead concentrations much lower than the limit of 30 mg/kg Pb and Cd concentrations lower than the limit of 17 mg/kg Cd. In fact, the measured values for Pb and Cd were at the lower detection limits of the Pb and Cd detectors. Similarly, the cobalt concentrations were very low in both the control and the oxodegradable samples.

Marine Testing

Background

Marine pollution is a worldwide concern. Marine environmental pollution is regulated by the MARPOL treaty. The treaty prohibits ocean disposal of any plastic waste from ships and off shore platforms. [74] Petroleum-based plastics can cause environmental concern because they remain floating in the water for a long time before disintegrating. Poly-ester-urethane had a significant weight loss in sea water within 12 months, whereas, poly-ether urethane did not experience any weight loss in 12 months. [75]

Polyethylene plastics typically float in ocean water and can take 100 years to disintegrate completely. Polyethylene did not degrade in a marine environment at a temperature of 30°C after 12 weeks.[76] Floating, low density polyethylene with a UV-degradant deteriorated slower in a marine environment than on land.[77] Photodegradable LDPE plastic ring connectors can degrade in marine and land environments with a 50 percent loss in properties in 12 months.[78],[79]

Biodegradable plastic will biodegrade much faster than polyethylene due to its ability to absorb water and sink in ocean water. However, only PHA, PHB, and poly-ε caprolactone were shown to biodegrade in marine environment. [80] The use of biodegradable plastics has been studied for biodegradation in marine environments. [81] The biodegradation of biodegradable plastics is essential for the plastics to be used for fishing nets and other aquatic applications. Polyhydroxyalkanoates (PHA), polyhydroxyvalerate (PHV) and polyhydroxybutyrate (PHB) have been studied extensively for biodegradation in marine environments. PHB biodegraded in sea water at a rate of 0.6 μg/week at 25°C. However, PLA did not biodegrade in sea water at the same temperature. [82] PLA did not biodegrade in an anaerobic liquid environment, either. PHB biodegraded rapidly in three weeks, though Mirel degraded more slowly. [83]

Test Procedures

There were two marine tests conducted. The sample materials for the first marine test included: Kraft paper and low density polyethylene controls, UV-degradable six-pack rings, ecosafe and eco-friendly oxodegradable plastic trash bags, PLA straws, corn starch trash bags, Mirel bags, Ecoflex bags, and Stalk Market sugarcane lids.

The samples were tested for marine exposure using procedures based on ASTM D6691 and ASTM D7081. ASTM D6691 is a test method for determining aerobic biodegradation of plastic materials in the marine environment by defined microbial consortium. A test sample material demonstrates satisfactory disintegration if after 12 weeks, at least 70 percent of the material disintegrates. ASTM D7081 is a standard specification for non-floating biodegradable plastics in marine environments. Both standards also require that the amount of CO_2 generated during the degradation process be measured. A test sample demonstrates satisfactory biodegradation if after 180 days, 30 percent or more of the sample is converted to carbon dioxide. The sampling and specimen preparation are identical in both standards.

The degradable samples were prepared according to ASTM D7081. A small sample, 0.030g, of each material was placed in a jar with 100 ml of ocean water. Ocean water was retrieved in July from Big Sur beach in California and held at 5°C for 30 days until testing started. The samples were placed in an oven maintained at 30°C. The mass of the material was recorded after 30 days and 60 days. After 30 days, the samples were removed from the jar and allowed to dry overnight. After weighing the samples were placed in jars with new ocean water and then placed in the oven again.

A second test was conducted using larger samples (3 g) that sink. This caused more carbon dioxide to be generated than with the 0.030 g sample size specified in ASTM D7081 standard. The amount of carbon dioxide produced during the second experiment was measured with the PASCO detector. The samples were kept in an oven and held at 30°C for three weeks. The samples included Kraft paper control, Mirel bag, Ecoflex bag, BioBag, sugar cane, and PLA. Carbon dioxide was measured with the computer controlled equipment from the ASTM D5338 compost testing. Dry air, void of CO_2, was added to 3.8 L jars containing 3 g of each sample along with 300 ml of ocean water and 10 ml of ocean soil. The LabView software controlled the opening of valves and recorded the amount of CO_2 as measured with the PASCO detectors.

Results

For the first test, after 30 days in ocean water, the Mirel sample had 36 percent disintegration. There was no disintegration of the oxodegradable and UV-degradable plastic trash bags, LDPE control, Kraft paper control, PLA straws, sugar cane lids, corn starch trash bags, or Ecoflex bag.

Similarly, after 60 days in ocean water, the Mirel sample had 60 percent disintegration. The other samples still did not experience any disintegration. There was no disintegration of the oxodegradable and UV-degradable plastic trash bags, LDPE control, Kraft paper control, PLA lids, sugar cane lids, corn starch trash bags, or Ecoflex bag. The materials that sank in the marine water were Kraft paper control, PLA straws, Mirel bag, Ecoflex bag, and cornstarch bag. The materials that floated included the LDPE control, sugar cane lid, oxodegradable bag, UV-degradable bag, and UV-degradable soda rings.

The UV-degradable six-pack ring polyethylene samples experienced no weight loss in 14 days, but did become more brittle. Three plastic rings were placed in ocean water and exposed to sunlight and temperatures between 15°C and 35°C. Likewise, three plastic rings were placed in a wooden box without sea water and also exposed to sunlight and temperatures between 15°C and 35°C. None of the six samples experienced any weight loss after 14 days. Several of the samples could be pulled apart and broken. This was most likely due to polymer chain scission from exposure to ultra violet light. Additional research is needed to better understand the breakdown of UV degradable plastics in marine water and land environments.

The results of the second marine testing are similar to the first round of testing in that none of the samples had detectable amounts of CO_2 other than the Mirel PHA bag and sugar cane lid. After 21 days, the amount of carbon biodegradation was six percent for the Mirel bag and two percent for the sugar cane lid. The other compostable plastics, e.g., PLA, BioBag, Ecoflex, and Kraft paper had less than one percent biodegradation which is within experimental error limits.

The amount of biodegradation was less in the second experiment due to several factors including: insufficient original sample mass, improper ratio of sample mass to ocean water volume, and other experimental conditions. Future experiments should be modified to improve the measurement techniques. Additional research is needed to better understand the biodegradation of compostable and biodegradable polymers in the marine environment.

Anaerobic Digestion

Degradable plastics can also break down in anaerobic conditions. Anaerobic digestion occurs when organic materials are broken down by bacteria in the absence of oxygen.[84] Anaerobic digesters are commonly used for sewage treatment or for managing animal waste on farms. Organic materials that can be anaerobically digested include waste paper, grass clippings, food waste, sewage and animal waste.

Many factors affect the biodegradability of polymers, including pH, bacterium type, temperature, molecular weight, chemical linkages, and access of the material to the enzymatic system.[85] Several kinds of commercial biodegradable plastics were shown to degrade under aerobic and anaerobic conditions. Biodegradable plastics derived from natural polymers, such as starch or cellulose, contain recalcitrant components that can inhibit microbial degradation. Results have shown that degradation behavior of commercial biodegradable plastics is different from pure polymers due to the additives used to improve the performance of the final product.[86] Thermophilic anaerobic digestion of the organic fraction of municipal solid waste has been successfully applied in lab-scale[87] and full scale anaerobic digesters.[88]

Materials

The degradable polymers were evaluated under anaerobic conditions and characterized with methods established for digestion of food waste.[89] The degradable materials included PLA cup and straw, sugar cane plate, corn starch based BioBag, Mirel bag, Ecoflex bag, oxodegradable bag, UV degradable bag, and Kraft paper as a control. BioBag is made from a Novamont resin, derived from corn starch, in combination with fully biodegradable aliphatic polyesters, aliphatic/aromatic polyesters or in particular polylactic acid. Ecoflex is an aliphatic-aromatic copolyester based on 1,4-butanediol and the dicarboxylic acids, adipic acid and terephthalic acid. Biogas production from these seven substrates was compared with that produced from Kraft paper. Food waste was added to provide a source for the macro and micro elements necessary for microorganism growth

Test Procedures

The degradable samples, 1g each, were combined with food waste in one-liter bottles. Each reactor bottle was purged with helium gas for five minutes to ensure anaerobic conditions. All experiments were performed in duplicate under thermophilic conditions at 50°C. The initial pH of all the materials was 7.4. Total solids and volatile solids of the sludge and food waste were measured according to the ASTM D5630 and Amirel standard methods for 43 days. Pressure was measured daily in each of the batch reactors headspace using a WAL-BMP-Test system pressure gauge. The biogas in the reactors headspace was released under water to prevent any gas exchange between the reactor and the air. Biogas volumes of each reactor were determined with the following equation:

$$V_{\mathrm{Biogas}} = \frac{PV_{\mathrm{head}}\,C}{R.T} \qquad \textbf{Equation 1}$$

Where V_{Biogas} = daily biogas volume (L),
P = absolute pressure difference (mbar),
V_{head} = volume of the head space (L),
C = molar volume (22.41 L mol^{-1}),
R = universal gas constant (83.14 L.mbar.K^{-1}.mol^{-1}),
T = absolute temperature (K).

The amounts of methane and carbon dioxide produced in each reactor were periodically measured using gas chromatography, HP 5890 A, with 1.8 × 0.32 mm Alltech carbosphere column. Helium was the carrier gas at a flow rate of 60 ml/min. The temperatures of the oven and thermal conductivity detector were 100° and 120° C, respectively. The gas flowed into a helium filled column where a thermal conductivity detector measured the amount of methane and carbon dioxide in the sample. A gas standard with 60 percent methane and 40 percent carbon dioxide was used to calibrate the reactors.

Results

The percentages of total and volatile solids (VS) for each of the substrates and sludge are shown in Table 12. The oxobiodegradable plastic bag did not show any loss of organic matter after being heated at 105°C for 24 hours. The total solids of the Mirel PHA bag had 100 percent VS.

Table 12. Characteristics of the substrates and sludge

Material Type	Total Solids, %	Volatile Solids/ Total Solids,%	% C biodegradation
Food waste control	19.17	92.83	Not applicable
Sludge control	0.24	47.59	Not applicable
Kraft paper control	96.64	95.72	6
PLA straws	99.59	94.90	6
PLA cups	99.60	99.98	6
Sugar cane plate	94.21	99.43	24
Mirel PHA bag	99.03	99.99	38
Bio-bag	93.48	99.58	5
Ecoflex bag	99.96	90.57	6
Oxodegradable-bag	99.99	96.18	0
UV degradable Clear plastic bag	97.75	99.91	0

The digesters started with an initial loading of 50 percent degradable sample and 50 percent food waste. Figures 13 and 14 depict the accumulated biogas production after the initial load. These figures demonstrate that biogas was produced for the first 15 days from the digestion of the food waste. After the food waste was consumed in each of the jars, the Mirel PHA bag and sugar cane samples continued to produce new biogas and thus were biodegraded in the anaerobic vessel. The other samples (Kraft paper, PLA, corn starch, Ecoflex, oxodegradable and UV-degradable bags) did not produce any additional biogas after day 15, indicating very little biodegradation occurred. Except for Mirel and sugar cane, there was a little difference between the daily biogas production of the samples and that of the food waste.

Figure 13. Cumulative biogas production from anaerobic digestion

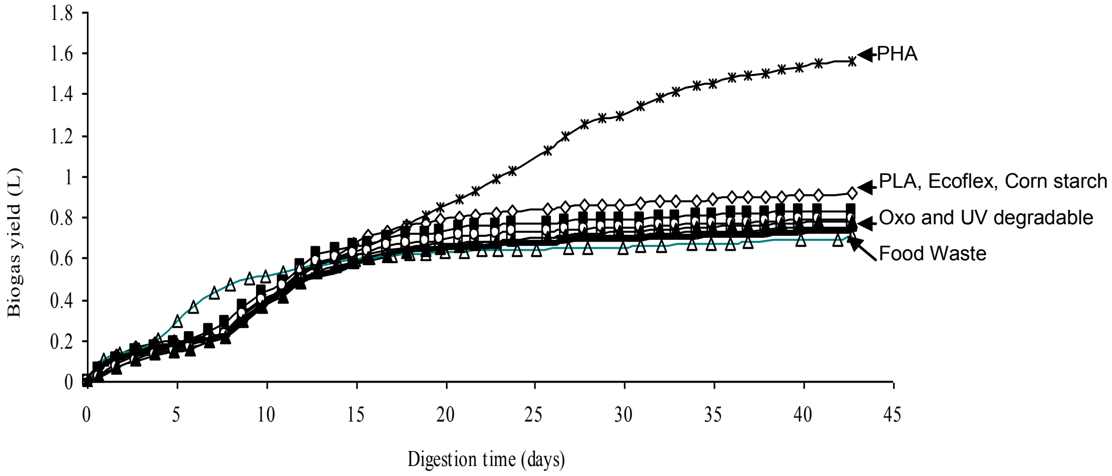
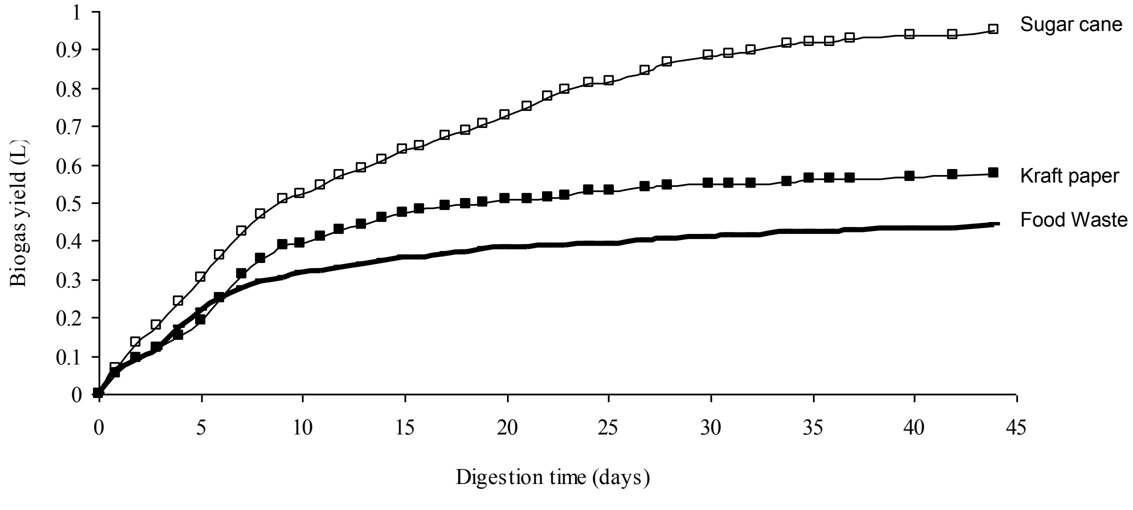


Figure 14. Cumulative biogas production from anaerobic digestion



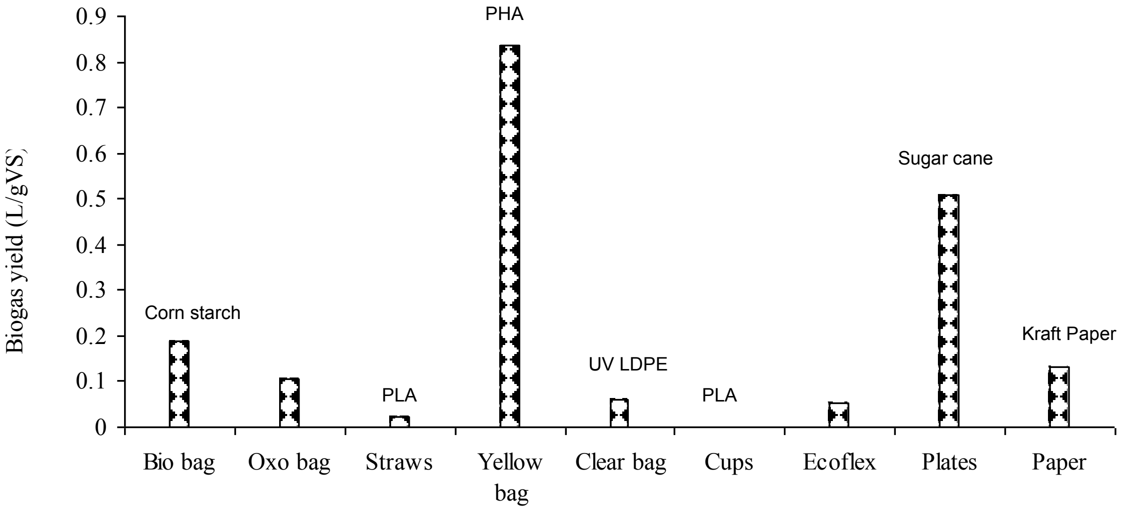
The biogas yields from degradable samples alone were calculated as the difference between the biogas produced from reactors treating a mixture of food waste and degradable samples and that treating food waste alone. The results are shown in Figure 15.

Biogas from the reactors has on average 60 percent methane gas and 40 percent carbon dioxide gas.[90] The percentage of biodegradation (BDG) is calculated by multiplying each samples resultant biogas volume (Vol) by 40% , then multiplying that by the density of carbon dioxide (dCO2). The resulting product is then divided by the amount of carbon available in each sample (C). See Equation 2. The biodegradation results are presented in Table 10. The Mirel PHA bag and sugar cane samples had biodegradation of 38 percent and 24 percent respectfully. The other materials had negligible biodegradation. The average final pH ranged from 6.33 to 6.87 for all samples.

$$\%BDG = \frac{(Vol \times 40\%) \times dCO2}{C} \qquad \textbf{Equation 2}$$

Where *%BDG* is the percentage of biodegradation
Vol is the biogas volume of the sample
dCO2 is the density of carbon dioxide
C is the amount of carbon available in each sample

Figure 15. Biogas yield at day 43 from anaerobic digestion



Composting Environments

The biodegradable and oxodegradable materials were placed in four compost environments, including, traditional windrow, in-vessel manure, in-vessel food waste, and in-vessel municipal solid waste. All of the compost facilities are commercial operations and produce compost for the public.

City of Chico Municipal Compost Facility

The City of Chico municipal compost facility is located on a 10-acre site that produces 500,000 cubic yards of compost each year via aerobic windrow compost. The compost is mixed using a windrow turner. The turning machine straddles a windrow of approximately eight feet high by 13 feet across. Turners drive through the windrow at a slow rate of forward movement. A steel drum with paddles turns the compost rapidly. As the turner moves through the windrow, fresh air (oxygen) is injected into the compost by the drum/paddle assembly and waste gases produced by harmful bacteria are removed. The oxygen feeds the beneficial composting bacteria and thus speeds the eventual composting process. This process is then extended by windrow dynamics.[91] The facility accepts green yard waste, which includes lawn clippings, leaves, wood, sticks, weeds, and pruning. Testing in commercial compost facilities allows the compostable plastics to be exposed to active compost that has a high degree of enzyme activity and high temperatures.

Materials and Procedures

The food waste and plastic products from the cafeteria experiment were placed in the compost with oxodegradable plastic bags and Kraft paper on May 10, 2006. Also buried were contaminants including: paper cups with polyethylene liners, paper plates, plastic cups, plastic water bottles and plastic trash bags. Portions of the waste collected from the one week bio-plastics demonstration at Chico State University cafeteria were sent to the municipal compost site. Approximately, 1.5 yd^3 was sent to the compost facility on a dirt pad. During the experiment, the compost was turned with a windrow turner.

During the experiment, the moisture content of the compost was between 35 and 55 percent and the temperature of the compost ranged from 48°C to 65°C. The temperature of the outside air ranged from 35°C to 43°C. Pictures of the plastic fragments during this experiment are provided in Appendix C.

After 120 days, the compost pile was screened to remove the debris. The compost was tested for moisture percentage, temperature, pH, compost maturity, and percent solids. The compost maturity index can be defined as compost that is resistant to further decomposition and free of compounds, such as ammonia and organic acids, that can be poisonous to plant growth. The disintegration of products was monitored for sample fragments after 30, 60, 90 and 120 day test intervals.

Results

After 90 days, the PLA spoons, knives, and lids had completely disintegrated. The compostable plastics, including, sugar cane, BioBag, PLA containers, PLA cups, and sugar cane plates had noticeable biodegradation and were broken into fragments. The oxodegradable and UV-degradable plastics were completely intact and did not show any signs of disintegration.

After 120 days, PLA forks, spoons, knives, and lids, sugar cane lids and plates were completely biodegraded and no fragments were found. Small fragments of PLA cups, PLA container, and corn starch trash bags were visible. The small PLA fragments resulted from the way in which the PLA container and cup broke down and were turned by the auger machine. The fragments had a higher surface area than the PLA forks, spoons, and straws. The higher surface area made the PLA cup and container fragments less dense and susceptible to gathering on the surface of the compost pile rather than below the surface. Biodegradable polymers, like PLA, will degrade very little when not in a hot compost environment.

Approximately, 750 PLA cups, 500 clamshell containers, and 15 trash bags were buried in the municipal compost site. Approximately, four PLA cup and container fragments were found. The four fragments would equal the mass of one cup for an overall PLA degradation rate of 99.92 percent.

The green Eco-safe oxodegradable bags were broken into pieces from the windrow turner, but did not appear to degrade. The oxo-biodegradable plastic bags were full-sized and did not appear to experience any degradation. The plastic waster bottles did not degrade nor did the polyethylene lined paper soft drink cups.

University Farm In-vessel Compost Facility

The university farm uses cow manure and straw to create a compost material that is sold commercially. The university farm environment represents a commercial compost facility with very active manure-based compost that should provide a high degree of enzyme activity and nutrients for the compostable materials to degrade. The University Farm at California State University Chico produces 250-tons of compost from dairy manure and rice straw annually using conventional windrow methods. The nutrient composition, or NPK, is 1.2 parts Nitrogen to 0.5 parts Phosphorous to 1.5 parts Potassium. The organic matter content is approximately 30 percent and the pH is 8. The fecal coli forms count is 0, the E. coli is 0 counts, and Salmonella is 0 counts. The heavy metals content of the compost was negative for arsenic, lead and mercury. [92]

Materials and Procedures

The materials buried at the university farm compost site were food waste and biodegradable products including: PLA cups, forks, spoons, knives, clamshell containers, lids, and straws, sugar cane plates, and corn starch trash bags. Also buried were contaminants which included paper cups with polyethylene liners, paper plates, plastic cups, plastic water bottles and plastic trash bags.

The food waste, plastic products, and compost were placed in the compost mound. The temperature and moisture of the compost were measured and the ambient temperature and weather conditions were recorded. Portions of the waste collected from the one week bio-plastics demonstration at Chico State University cafeteria were sent to the farm compost site. Approximately, 0.5 yd^3 was sent to the university farm site and buried on May 9, 2006, under an in-vessel Ag-bag environment on a concrete surface pad. After 30-days the in-vessel was removed and the compost was turned in a traditional windrow operation for 90 days. The compost was tested for moisture percentage, pH, compost maturity, and percent solids. The disintegration of products was monitored after 30, 60, 90 and 120 day test intervals.

During the experiment, the moisture content of the compost was between 35 and 55 percent and the temperature of the compost ranged from 48°C to 64°C. The temperature of the outside air ranged from 35°C to 43°C. Pictures of the plastic fragments during this experiment are provided in Appendix D.

Results

After 120 days, the materials that completely degraded were similar to the green-yard waste compost results and included PLA forks, spoons, knives, and lids, sugar cane lids and plates. Small fragments of PLA cups and PLA container, and corn starch trash bags were visible. As in the green yard-waste compost site, the small PLA fragments resulted from the way in which the PLA container and cup broke down and were turned by the auger machine. Approximately, 250 PLA cups, 160 clamshell containers, and six trash bags were buried in the municipal compost site. Approximately, three PLA cup and container fragments were found. The three fragments would equal the mass of half of a cup for an overall PLA degradation rate of 99.88 percent.

Vacaville In-vessel Food-waste Compost Facility

The facility is operated by Jepson Prairie Organics (JPO), a wholly owned subsidiary of Norcal Waste Systems, Incorporated. The facility processes 80,000 tons of kitchen trimmings, plate scrapings, and other food scraps from San Francisco restaurants, hotels, and food scraps gathered from the City residents. The Jepson Prairie's facility transforms the food waste into 30,000 tons of organic compost a year.

Materials and Procedures

The food waste and plastic products from the cafeteria experiment were placed in the compost with oxodegradable plastic bags and Kraft paper. Approximately, 4 yd^3 was sent to the compost facility on a dirt pad. Originally, the degradable samples were placed in the compost pile in their native form. However, due to the large amount of debris in the compost pile, identification of the biodegradable and degradable samples was difficult and the experiment was stopped.

Alternatively, the biodegradable and degradable samples were placed in a burlap sack along with municipal solid waste (MSW) from the compost site and then buried in the in-vessel compost on June 13, 2006. The degradable and compostable samples were mixed with other MSW and placed on the dirt under an 8-mil thick plastic bag for the in-vessel composting operation. The compostable samples included, corn starch based BioBag, Mirel bag, Biotuf Ecoflex bag, Husky bag, PLA lids, sugar cane lids, and Kraft paper. Also buried were polyethylene shrinkwrap, UV degradable plastic bag, and oxodegradable plastic bag. Additionally, contaminants were buried including: paper cups with polyethylene liners, paper plates, plastic cups, plastic water bottles and plastic trash bags.

After 30-days the in-vessel was removed and the compost was turned in a traditional windrow operation for an additional 30 days. At the end of 60 days the compost was screened and the separated compost was placed in a static pile for 60 to 120 days. The compost was turned with a windrow turner twice per week to aerate the compost pile. The temperature and moisture of the compost in the bag were measured and the ambient temperature and weather conditions were recorded.

After 60 days, the compost pile was screened to remove the debris. Due to partial tearing of the burlap sacks, they were removed after 60 days and buried in a perforated plastic bag in a static pile. The compost was tested for moisture percentage, temperature, pH, compost maturity, and percent solids. The disintegration of products was monitored for sample fragments after 30, 60, 90 and 180-day test intervals.

During the experiment, the moisture content of the compost was between 30 and 55 percent and the temperature of the compost ranged from 55°C to 70°C. The temperature of the outside air ranged from -5°C to 40°C. Pictures of the plastic fragments during this experiment are provided in Appendix E.

Results

After 180 days, the materials that completely degraded included PLA lids, Mirel bags, Ecoflex bags, Husky bags, and corn starch trash bags. Small fragments of sugar cane lids and Kraft paper were visible. The sugar cane and Kraft paper fragments were very moist and disintegrated when picked up.

The Kraft paper and sugar cane fragments did not completely biodegrade as there was no mechanical agitation while in the plastic sacks. If the materials were placed in the compost soil, higher degradation would occur due to better interaction with the compost soil.

The oxo-biodegradable plastic bags, LDPE plastic bags, and UV-degradable plastic bag did not appear to experience any degradation.

Mariposa County In-vessel MSW Compost Facility

This composting facility is located at the Mariposa landfill. The 50,000 ft^2 facility can accept approximately 40 tons of municipal solid waste (MSW) per day. The in-vessel composting process utilizes the Engineered Compost System (ECS).[93] The SV Composter™ features excellent control of temperature and moisture in an enclosed room made from concrete and stainless steel. The MSW is placed in the room and air is evenly distributed to the composting materials through perforated floor covers. Moisture and water runoff is collected in the floor and drained to a sump. The water removal helps reduce anaerobic conditions. The ECS in-vessel composting process has a PC-based system control that measures the temperature, and pressure from several locations in the compost pile and compost vessel. The MSW materials undergo a temperature regime that destroys pathogens in the first three days and then maximizes composting over the next three weeks with proper aeration, drainage, and temperature control. The in-vessel compost is typically heated to 60°C for three days and then maintained at 58°C for 14 to 21 days. The composting process typically reduces the volume of the MSW by 30 to 60 percent.

Materials and Procedures

Biodegradable, compostable, controls, and oxodegradable samples were placed in burlap sacks along with municipal solid waste (MSW) from the compost site and then buried in the in-vessel compost. Approximately, 80 g of full-sized samples were mixed with approximately, 1 kg of MSW. As with the Vacaville compost experiment, the samples included, corn starch based BioBag, Mirel bag, BioTuf Ecoflex bag, Husky bag, PLA lids, sugar cane lids, and Kraft paper. Also buried were polyethylene shrink-wrap, UV degradable plastic bag, and oxodegradable plastic bag. Debris included plastic water bottles, plastic cups, paper cups, plastic straws, newspaper, glass bottles, metal lids, miscellaneous paper products, and plastic bags.

The compostable and degradable plastics were buried on September 30, 2006. After 14 days the experiment had to be restarted due to problems with the compost that resulted in low temperatures. Green yard waste and manure were added to the vessel and the process was restarted on October 15, 2006. The temperature and moisture of the compost were recorded by the process control unit. After 50 days the materials were removed from the ECS vessel and placed on a concrete pad to cool and aerate. Biofilters remove noxious gases from the compost. The experiment ended on December 3, 2006.

Typically, the compost pile is screened for recyclable materials, e.g., glass, metal, and plastic, and for debris. The recyclable materials are recovered and the debris waste is sent to the landfill. The screened compost is used as cover for the landfill. In our experiment, the compostable and biodegradable samples were removed from the burlap sacks and placed in perforated plastic bags. Some of the burlap sacks had holes in them. The samples and bags were relocated to the Vacaville compost site and placed in the static pile for further composting for an additional 120 days.

During the experiment, the average top temperature was 56.4°C, the average bottom temperature was 56.3°C, the supply pressure was 1.5 in H_2O, the air supply temperature was 28.2°C, and the exhaust temperature was 34.7°C. Pictures of the plastic fragments during this experiment are provided in Appendix F.

Results

After 180 days, the results were identical to the Vacaville in-vessel compost results. The materials that completely degraded included PLA lids, Mirel bags, Ecoflex bags, Husky bags, and corn starch trash bags. Small fragments of sugar cane lids and Kraft paper were visible. Similar to the Vacaville compost results, the sugar cane and Kraft paper fragments were very moist and would disintegrate when picked up. The Kraft paper and sugar cane fragments did not completely biodegrade due to the segregation in the plastic sacks. If the materials were placed in the compost soil, higher degradation would occur due to better interaction with the compost soil.

The oxo-biodegradable plastic bags, LDPE plastic bags and UV-degradable plastic bag did not appear to experience any degradation.

Contamination Effects of Degradable Plastics on Recycled Plastics

Polyvinyl chloride (PVC) is a contaminant to polyethylene terephthalate (PET) and high density polyethylene (HDPE). PVC concentrations as low as 200 ppm can significantly degrade PET during the compounding extrusion process. PVC contamination can also cause discoloration of the PET, lower intrinsic viscosity, and cause black streaks and specks in molded products.[94] Also, PVC contamination can lead to excessive corrosion of the processing equipment due to the evolution of hydrochloric acid from the degraded PVC.[95] LDPE can be contaminated with HDPE, which can cause severe processing problems in plastic bag manufacturing. HDPE containers can be contaminated with PVC, PS, PP, and glues from labels.

Contamination effects are minimized by improved sorting techniques and by regular testing of incoming materials. Automated sorting methods efficiently and quickly sort the plastic using spectroscopic techniques. Hundreds of identifications per second can help sort plastics with more than 99 percent accuracy[96] at throughput rates of 2,000 kg per hour.[97]

Post consumer resin (PCR) quality can be improved with a quality assurance protocol that provides efficient, reliable and practical test methods for PCR.[98] The testing includes melt index, density, and moisture percent of PCR.[99]

Degradable plastics can negatively affect the quality and mechanical properties of recycled plastics if they are mixed with the recycled plastics. The contamination of degradable, biodegradable, and oxodegradable plastics can be treated as other contamination to plastics. The effects of the degradable contamination can be evaluated by measuring physical properties and mechanical properties of the plastics. In particular, PET contaminated with PLA, HDPE contaminated with PLA, LDPE contaminated with oxodegradable plastic, and LDPE contaminated with corn-starch based biodegradable plastic can all be evaluated. The effects are measured for melt index, density, moisture percentage, and voids and bubbles in 1” film. The mechanical properties include tensile and impact properties.

Test Procedures

The effects of contamination were evaluated by mixing contaminants with the appropriate recycled plastic material and then injection molding them into tensile and impact bars. The LDPE and HDPE post-industrial recycled plastic material was provided by Bay Polymers. PLA was dry mixed with PET and HDPE at 5 percent and 10 percent by weight concentrations. Unfortunately, injection molding of the PET was not successful due to the very high melt index of the PET. HDPE was injection molded successfully. Oxodegradable and biodegradable BioBag were first cut into small pieces and then placed in an infrared oven where they softened. The plastic pieces were pressed into thin sheets and then chopped in a grinder to create a master batch of 100 percent plastic pellets. The master batch plastic pellets were dry-mixed with LDPE pellets and then injection molded.

The pellets were injection molded into tensile bars with an Arburg 320-A 55-ton injection-molding machine. The LDPE and HDPE tensile bars were produced with the following conditions: rear temperature of 200°C, center zone temperature of 230°C, front zone temperature of 240°C, nozzle temperature of 240°C, injection pressure of 203 MPa, pack pressure of 105 MPa, cool time of 35 seconds, injection time of one second, and pack time of one second. Thirty tensile-bar and impact bar samples were molded for each material with a purge of Insta-purge between each material type.

Results

The moisture was very low in all of the plastic materials. The oxodegradable plastic had the same moisture content as LDPE. PLA-HDPE and biodegradable BioBag-LDPE plastics had slightly higher moisture content than HDPE and LDPE alone. The moisture content of the plastic samples was measured with a Satorius moisture analyzer. The moisture of LDPE and HDPE were less than 0.3 percent. LDPE with the oxodegradable plastic bag was also less than 0.3 percent. LDPE with the biodegradable BioBag plastic was between 0.4 and 0.8 percent. HDPE with PLA was between 0.3 and 0.6 percent. The moisture content of PET was also significantly increased with the addition of PLA. Increased moisture in PET could be deleterious.

Specific gravity was measured with an electronic density instrument: model MD-300S from Qualitest Incorporated. See Table 13 for results. When mixed at 20 percent, oxodegradable plastic and BioBag biodegradable plastics increased the density of the recycled LDPE plastic by 2.2 and 5.2 percent. PLA increased the density of recycled HDPE plastic by 5.3 percent with the addition of 10 percent contaminant. The average density of PLA straws was measured as 1.19 g/cc with a standard deviation of 0.03 g/cc.

The melt index is an indication of the viscosity of the material.[100] The melt index of the samples was measured with an LMI 4002 series melt flow indexer from Qualitest Incorporated. Plastic pellets were added to a heated chamber and flowed through a tubular die as a weighted plunger moved through the top of the cylinder. The melt index, with units of g/10-min, is recorded for materials based upon plastic flow during a 10-minute time interval at a prescribed temperature and mass of plunger.[101] The procedure for running the test is detailed in ASTM D-1238. The melt index test for polyethylene is run at 190°C with a 2.16 kg plunger load. The melt index was significantly changed with the addition of oxodegradable plastics to LDPE, cornstarch based biodegradable plastics to LDPE, and PLA added to HDPE. The melt index of PET was also significantly increased with the addition of PLA. Concentration variation in the samples caused the melt index results to have some inconsistencies. Future research work can better evaluate the causes of the variations in melt index.

The quality test results for the materials are also given in Table 13. The melt index, density, and moisture results were averaged over five samples. The results indicate that melt index is significantly affected with the addition of oxodegradable and biodegradable plastic contaminants. Density is moderately affected by the contaminants and moisture content is minimally affected by the presence of degradable contaminants.

The contamination effects on film properties were evaluated for haze, opacity, and dart impact. The physical appearance of the clear LDPE was dramatically affected by the addition of the oxodegradable and BioBag plastic contaminants. The mixed plastic had streaks of green and other dark colors. The amount of light passing through the film was measured with an opacity meter. The contaminants reduced the opacity of LDPE and made it appear more opaque. The impact strength of the plastic film was reduced 20 to 50 percent with the addition of ten percent and 20 percent biodegradable and oxodegradable plastic contaminants. With the addition of 20 percent oxodegradable plastic contaminant, it was impossible to produce a plastic bag with LDPE due to bubble instabilities.

Table 13. Quality test results for LDPE and HDPE with oxo- and bio-contamination

Material	Melt Index (g/10 min)	Density (g/cc)	Opacity	Thickness (mils)	Impact (Max drop g)
LDPE - neat	0.711	0.906	19.8	3.2	226
LDPE - 10% oxodegradable	0.597 (-16%)	0.911 (0.55%)	19.7	3.4	102
LDPE - 20% oxodegradable	0.664 (-6.6%)	0.926 (2.2%)	17.9	N/A	N/A
LDPE - 10% BioBag	0.646 (-9.1%)	0.929 (2.5%)	19.7	3.5	192
LDPE - 20% BioBag	0.778 (9.4%)	0.953 (5.2%)	19.5	4	177
HDPE- neat	11.07	0.945			
HDPE - 5% PLA	11.57 (4.5%)	0.958 (1.4%)			
HDPE - 10% PLA	4.154 (-62.5%)	0.995 (5.3%)			

The tensile bars were tested with an MTS tensile test machine, MTS QT/50, with 50 kN Load Cell and Q-test software. The samples were pulled in a tensile mode at a rate of 1.5 in/min at room temperature. The mechanical test results for the materials are given in Tables 14 and 15. The results indicate that oxodegradable plastic had very little effect on LDPE tensile strength.

The oxodegradable plastic reduced the tensile modulus between 10 and 15 percent and increased the elongation at break between 23 and 28 percent. The differences are a result of the different LDPE plastic formulations in the oxodegradable bag and the Bay Polymer.

The biodegradable plastic had a negative effect on the LDPE with a nine percent reduction of tensile strength and eight percent reduction in modulus for the sample with 20 percent biodegradable plastic contamination. Additional testing in the future can provide better understanding of the effects of contamination on the recycled plastics.

Table 14. Mechanical test results for LDPE and HDPE with oxo- and bio-contamination

Material	Maximum tensile stress, psi	Elongation at break, %	Tensile modulus, psi	Impact strength, ft-lbs
LDPE- neat	1,689	138	10,791	9.6
LDPE 10% oxodegradable	1,744	170	9,667	9.4
LDPE 20% oxodegradable	1,738	178	9,278	9.4
LDPE 10% BioBag	1,680	154	9,300	9.2
LDPE 20% BioBag	1,540	127	10,247	9.3
HDPE- neat	2,830	23	59,197	5.2
HDPE 5% PLA	2,708	27.7	61,284	3.2
HDPE 10% PLA	2,568	46.22	48,912	3.6

Table 15. Mechanical tests results for LDPE and HDPE with oxo- and bio-contamination

Material	Tensile strength	Ultimate Elongation	Tensile Modulus	Impact strength
	% change	% change	% change	% change
LDPE- neat	0	0	0	0
LDPE 10%oxodegradable	3.26	23.19	-10.42	-2.08
LDPE 20% oxodegradable	2.90	28.99	-14.02	-2.08
LDPE 10% BioBag	-0.53	11.59	-13.82	-4.17
LDPE 20% BioBag	-8.82	-7.97	-5.04	-3.13
HDPE- neat	0	0	0	0
HDPE 5% PLA	-4.31	20.43	3.53	-30.77
HDPE 10% PLA	-9.26	100.96	-17.37	-38.46

Conclusions and Recommendations

In developing state and local policy related to the environmentally beneficial uses of degradable plastics, decision-makers should first consider the implications of any policy or program decision on the affected waste diversion and disposal systems, and those that use it. This is because improvement in one area of a system can sometimes adversely affect another part of the system. For example, it is clear that compostable plastic products could significantly increase food scrap and greenwaste diversion because food service ware could be composted along with food scraps, and the bags used to collect greenwaste would not need to be separated before composting. However, degradable plastics could also contaminate the existing plastic recycling stream if they are not properly collected and composted, thus reducing plastic recycling opportunities. Further, while compostable bags meeting ASTM standards will degrade in a compost environment (based on the experimental conditions of this study), most will not break down if released as litter into the land or marine environments. Thus, it is important to understand that biodegradable or compostable plastics are not a panacea for waste or litter reduction.

It is recommended that additional research be performed to:

- Better understand the fate of degradable plastics in land and marine environments and to understand the effect that degradation residues may have on wildlife, plants, and marine life.
- To assess the environmental risks and fate of intermediate products of other biodegradable plastics in composting environments.
- Assess the life cycle costs incurred during the manufacturing, collection, and reprocessing of compostable bags compared to the costs incurred managing conventional plastics through processing, recycling, and disposal. Local governments need this information to make informed decisions on uses for compostable bags.
- Propose a law requiring the development of an identification code for compostable bags and containers to help identify and separate compostable plastics from recyclable plastics. The presence of degradable plastic material in regulated rigid plastic packaging containers and trash bags would make compliance with present law very difficult and, as indicated above, would reduce plastic recycling opportunities.
- Evaluate other degradable plastics, including oxodegradable materials, in commercial compost operations that utilize aerobic in-vessel composting.
- Further investigate degradability in marine environments and life cycle assessments of the degradable plastics.
- Better understand the biodegradation of compostable and biodegradable polymers in the marine environment.
- Further evaluate the effects of contamination of the degradable plastics on recycled plastics.
- Better evaluate the variations in melt index.

Appendices

Appendix A. Calculations

The concentration of CO_2 in the compost container is found by converting the ppm concentration that is measured in the 320-ml measurement bottle to a ppm concentration of the compost 3.8L container. First, the amount of g-mols of CO_2 present in the 320-ml measurement bottle is determined from the ppm concentration difference between the 320-ml bottle with a known amount of CO_2 from the compost containers and the background ppm concentration of CO_2 in the room. The difference represents the amount of g-mols that was added to the 320-ml container.

The flow rate of gas is measured with a flow tube. The slope of the ppm measurement versus time is calculated. The amount of gas added to the 320-ml container is calculated based on the time required to reach the maximum ppm level and the flow rate of gas.

Second, the concentration, in g-mols/ml, that is the concentration of CO_2 in the compost container, can be converted to ppm concentration of CO_2 with using the Ideal Gas Law relationship, described in Equation 3. [102] The gram-molecular weight for CO_2 is 44 g/mol.

$$ppm = \frac{RT}{P \times MW} \times mg / m^3 \qquad \textbf{Equation 3}$$

Where P is the pressure in the vessel in mm Hg
R is the universal gas constant, 62.4 (L- mmHg)/(°K -mol)
T is the temperature in Kelvin
MW is the gram molecular weight, g/mol

Third, the concentration of CO_2 (in ppm) can be converted to mg/m^3 by multiplying the ppm measurement by the gram molecular weight of CO_2 and then dividing by 24.45. This is valid when measurements are taken at 25°C and atmospheric pressure of 760 torr (760 mm Hg). For temperatures and pressures different than this, the concentration of carbon dioxide can be converted from ppm to mg/m^3 as described in Equation 3. The total amount of carbon is the concentration of carbon in grams per liter times the volume of the gas in the chamber of 1 liter, as described in Equation 4.

$$mg / m^3 = \frac{P}{(RT)} \times MW \times ppm \qquad \textbf{Equation 4}$$

Where P is the pressure in the vessel in mm Hg
R is the universal gas constant, 62.4 (L- mmHg)/(°K -mol)
T is the temperature in Kelvin
MW is the gram molecular weight, g/mol

Fourth, the grams of CO_2 can be converted to grams of Carbon by multiplying by the atomic mass of Carbon (12g) and then dividing by the molecular weight of CO_2 (44g), as described in Equation 5.

$$g_C = g_{CO_2} \times \frac{12}{44}$$ **Equation 5**

Last, the percentage of biodegradation of the materials is calculated by dividing the average net gaseous carbon production of the test compound by the original average amount of carbon in the compostable sample and multiplying by 100, as described in Equation 6.

$$\%\, biodegradation = \frac{meanC_{g,test} - meanC_{g,blank}}{C_i} \times 100$$ **Equation 6**

Where Cg,test is the amount of gaseous-carbon produced in sample, g
Cg,blank is the amount of gaseous-carbon produced in blank compost soil alone, g
C_i is the amount of carbon in test compound added, g

An alternative method to calculate the amount of carbon that is present in the ppm concentration involves a simpler calculation that relates the density of CO_2 and the density of air in the different volumes of gas. The calculation addresses the volume percent of CO_2 in the initial measurement container compared to the volume percent after adding sample of the compost gas.

First, the gas ppm concentration in the 320-ml measurement container is converted to volume percent CO_2, using Equation 6. Note that ppm is mass of substance divided by 1 million times the mass of solution. Thus, 400 ppm of CO_2 represents 0.004% CO_2.

$$vol\%_{CO_2} = ppm_{CO_2} \frac{\rho_{air}}{\rho_{CO_2}} \times 100$$ **Equation 7**

Where ρ air is the density of air, 1.2928 g/cc at 25 °C and 1 atmosphere pressure
ρ_{CO2} is the density of CO_2, 1.9768 g/cc at 25 °C and 1 atmosphere pressure

Second, the volume fraction of CO_2 present in the initial concentration is multiplied by the 320-ml volume to yield the volume of CO_2, which is converted to mass of CO_2. Similarly, the ppm concentration after gas sample is added is also converted to mass of CO_2.

Third, the two mass values are subtracted to obtain the mass of CO_2 that is present in the container.

Last, the mass concentration is multiplied by the volume of the compost container to yield the mass of CO_2 that is present from the biodegradation process. As before, the mass of CO_2 can be converted to mass of carbon that will determine biodegradation rate of the composting materials.

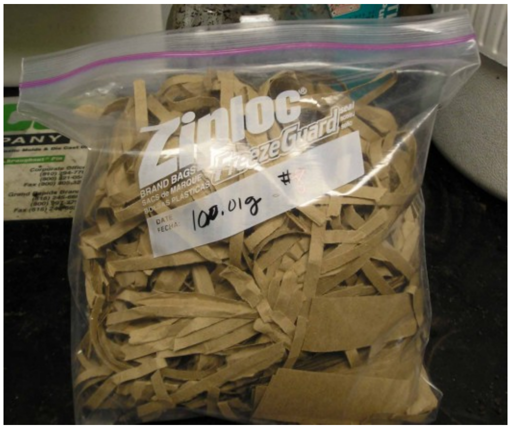
Appendix B. Pictures of Samples at the CSU Chico Experimental Laboratory

PLA Container (120 days)

Corn Starch Bag (120 days)

Cellulose Start

End (45 days)



Kraft Paper Start

End (45 days)

LDPE Bag Start

End (45 days)

BioBag Start

End (45 days)

PLA Start

End (45 days)

Sugar Cane Start

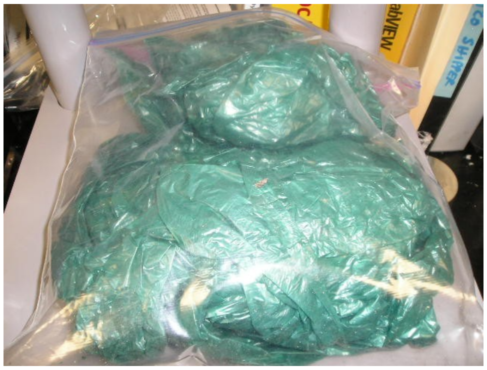
End (45 days)

Mirel PHA Start

End (45 days)

Ecoflex Start

End (45 days)



Oxodegradable plastic start

End (45 days)

Appendix C. Pictures of Samples at the CSU Chico Farm

In-vessel compost

Windrow – University Farm

In-vessel sample open

Incoming trash

PLA Container (120 days)

Corn starch bag (120 days)

Appendix D. Pictures of Samples at the City of Chico Municipal Compost Facility

Windrow compost pile – first day

City of Chico Compost Facility

Windrow compost pile (120 days)

Incoming trash

PLA Container (120 days)

Corn starch bag (120 days)

Oxodegradable bag (120 days)

Oxodegradable bag (120 days)

Plastic bottle debris (120 days)

Plastic debris (120 days)

Appendix E. Pictures of Samples at the Vacaville In-vessel Compost Facility

In-vessel compost pile (first day)

Windrow compost pile (30 days)

Static pile(60 days)

Burlap sacks

Kraft paper and sugar cane (180 days)

Oxodegradable and UV degradable (180 days)

Appendix F. Pictures of Samples at the Mariposa In-vessel Compost Facility

ECS in-vessel compost vessel

Inside chamber with samples and MSW

Static pile at Vacaville compost site

Kraft paper and sugar cane (170 days)

Oxodegradable plastic bag (170 days)

Oxodegradable, UV degradable, LDPE bag, and debris (170 days)

Appendix G. Experimental Protocol for Composting Sites

The experimental protocol for the commercial composting sites is as follows:

1. Chico green yard-waste compost facility
    - Place samples in compost pile and mix with green yard waste.
    - Turn compost twice a week with industrial sized windrow turner.
    - Remove compost sample for soil testing, including pH, percentage moisture, percentage solids, and maturity index.
    - Observe fragmentation and disintegration once a month and record with digital camera.
    - After 120 days, remove compost sample for soil testing, including pH, percentage moisture, percentage solids, and maturity index.

2. University farm manure compost facility
    - Place samples in compost pile and mix with manure and straw waste.
    - Place Ag bag over compost.
    - After 30 days remove Ag bag.
    - Turn compost twice a week with industrial sized windrow turner.
    - Remove compost sample for soil testing, including pH, percentage moisture, percentage solids, and maturity index.
    - Observe fragmentation and disintegration once a month and record with digital camera.
    - After 120 days, remove compost sample for soil testing, including pH, percentage moisture, percentage solids, and maturity index.

3. Vacaville in-vessel food-waste compost facility
    - Place samples in perforated plastic bag and place in compost pile with food waste and municipal waste.
    - Place Ag bag over compost.
    - After 30 days remove Ag bag.
    - Turn compost twice a week with industrial sized windrow turner.
    - Remove compost sample for soil testing, including pH, percentage moisture, percentage solids, and maturity index.
    - Observe fragmentation and disintegration once a month and record with digital camera.
    - After 60 days, remove degradable sample bags from compost pile and place in static pile.
    - Every 30 days, remove degradable samples from bags and observe fragmentation and disintegration. Record with digital camera.
    - After 180 days, remove compost sample for soil testing, including pH, percentage moisture, percentage solids, and maturity index.

4. Mariposa County in-vessel municipal solid waste (MSW) compost facility
    - Place samples in perforated plastic bag and place in compost pile with MSW in concrete composting chamber from ECS.
    - After 30 to 45 days remove samples from ECS chamber.
    - Turn compost twice a week with industrial sized windrow turner.
    - Remove compost sample for soil testing, including pH, percentage moisture, percentage solids, and maturity index.
    - Observe fragmentation and disintegration once a month and record with digital camera.
    - After 60 days, remove degradable sample bags from compost pile and place in static pile.
    - Every 30 days, remove degradable samples from bags and observe fragmentation and disintegration. Record with digital camera.
    - After 170 days, remove compost sample for soil testing, including pH, percentage moisture, percentage solids, and maturity index.

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