

Research Article

Biodegradation of Biodegradable and Compostable Plastics under Industrial Compost, Marine and Anaerobic Digestion

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Abstract

Biodegradation was measured for biodegradable, compostable, and oxodegradable plastics while exposed to aerobic composting, marine, and anaerobic digestion environments. Biodegradable plastics included, corn-starch based biobag, PHA bag, Ecoflex bag, and PLA lids. Positive and negative controls included, Kraft paper, cellulose, and polyethylene. Other plastics included, oxodegradable plastic bags. For industrial composting environment and according to ASTM 6400 standards, compostable plastic products, along with oxodegradable, cellulose paper, Kraft paper, and polyethylene plastic wrap, were placed in an environment consistent with ASTM 5338 conditions. For the marine environment, the plastic samples were placed in a test environment consistent with ASTM 6691. For anaerobic digestion, plastic samples were placed in an environment consistent with ASTM 5511. The degradation was evaluated by measuring CO₂ gas, which evolves from the degrading plastic samples. For industrial compost conditions, the compostable plastics, namely, PLA, sugar cane, PHA, Ecoflex, and starched-based biobag, biodegraded at least 90% and met the degradation requirement in the ASTM D-6400 standard. The oxodegradable, UV-degradable plastics, and LDPE plastic bag had negligible degradation. Under marine conditions, PHA experienced significant biodegradation. Alternatively, corn-starch-based trash bag, PLA cup, Ecoflex bag, sugar cane lids, UV-degradable plastic ring, and Kraft paper did not exhibit biodegradation under marine conditions. PHA biodegrades by anaerobic digestion in mesophilic conditions.

PHA biodegraded at least 30% and met the degradation requirement in the ASTM D-7081 standard. For anaerobic digestion, PHA biodegraded significantly more than the microcellulose positive control. The gas composition as measured with gas chromatography is about 60% methane and 40% carbon dioxide. Biodegradation terminated after 22 days. Under anaerobic conditions PHA and sugar cane experienced biodegradation, but PLA and polyethylene did not.

Introduction

Plastics can be produced from natural or synthetic materials. Traditional plastics, with an annual world production of approximately 140 million tones, (Masayuki 2001) 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). Most biobased materials are biodegradable, though some are not biodegradable. For example, polyesters can be made from soybean oil, though 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 is not consumed by microorganisms, either. Some petroleum-based plastics are biodegradable polymers since they are consumed by microbes in the soil and biodegrade in compost environments. Aliphatic-aromatic co-polyester polymers from BASF and ϵ -caprolactam are made from petroleum materials and are consumed by microorganisms and are biodegradable.

Compostable plastics biodegrade in composting facilities and break down into carbon dioxide and water. Micro-organisms in the soil or compost degrade the polymer in ways that can be measured by standard tests over specified time-frames. Compostable plastics are defined according to the ASTM D6400 standard 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 leave

no visible distinguishable or toxic residue. Compostable polymers are those that are degradable under composting conditions, which include actions of microorganisms, i.e., bacteria, fungi, and algae, under a mineralization rate that is compatible with the composting process. Polyethylene plastic bags that are produced with starch additives are not certified as compostable plastics since they do not biodegrade into CO₂ in 180 days in a compost environment. The plastics do disintegrate but leave small plastic fragments in the compost, which violates the ASTM D6400 standards. The ASTM D6400 standard differentiates between biodegradable and degradable plastics. Some synthetic polymers, e.g., Low Density Polyethylene (LDPE), can erode over time if blended with an additive to facilitate degradation. These polymers break down into small fragments over time but are not considered biodegradable or compostable since they do not meet the ASTM D6400 standards.

Results

The biodegradation of the sample materials were tested in three

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Received: May 1, 2018; **Accepted:** May 29, 2018; **Published:** June 01, 2018

environments, namely, laboratory compost environment per ASTM D5338 standards, laboratory simulated marine environment per ASTM 6691, and laboratory anaerobic digestion environment per ASTM D5511. The three test methods are compared in Table 1.

Figure 1 shows a schematic of the test procedure for the industrial compost testing.

Laboratory Compost Environment

The experimental set up for the laboratory experiment is based upon procedures outlined in ASTM D5338. The biodegradation standards are better explained in a recent book on sustainable plastics. (Greene 2014) Each of the compostable materials was added to compost soil in a 3.8-liter glass jar and placed in an oven maintained at 58°C. Carbon dioxide and oxygen were measured with an IR sensor from Pasco company. The oxygen sensor measures the percentage of oxygen that is present in the container with detection error of +/- 1%.

Cellulose filter paper (Cellupure filter) from FilterQueen™ and Kraft paper were used as positive control materials. Polyethylene plastic sheet, called 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. The materials were added to a 3.8-liter vessel, which was filled with 600 grams of compost and 100 grams of degradable sample. 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% of the container can be filled with the test sample and compost.

The moisture content of the samples was regularly monitored with a digital Satorius moisture analyzer. Distilled water was added, as needed, to achieve an overall moisture content of 50%. The composting vessels were placed in an oven with temperature of 58°C (+/-2°C) for 180 days. CO₂ and O₂ gases were measured with Pasco detectors by Labview data acquisition software. The vessels were rotated and shaken weekly to maintain uniformity. Excess liquid was noted on the daily log and removed by adding air. Oxygen levels ranged between 17% and 21% during the experiment, which met the ASTM requirements of greater than 6% in the containers.

Carbon Dioxide Concentration Results

During biodegradation of the compostable plastics, CO₂ is produced. The initial compostable sample, though, has moisture and other elements besides carbon. For instance, cellulose has a compressed

chemical formula of C₆H₁₀O₅, which can result in a maximum of 42% C 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% cellulose. Corn starch's primary carbon source is native amylase corn starch (C₅H₈O₃)_n, where n is the degree of polymerization. The compressed chemical formula of PLA is (C₃H₄O₃)_n. Sugar cane products, e.g., lids and bowls, are produced from 100% sugar cane fiber. Sugar cane's primary carbon source is from sucrose (C₁₂H₂₂O₁₁)_n. Bagasse sugar cane consists primarily of water, fiber, and soluble solids. The fiber is consisting of cellulose, pentosans, and lignin (Chiparus 2004). The amount of carbon can be less than the theoretical values depending upon the amount of other materials added to the compostable material to enable them to be processed into plastic parts or bags.

Laboratory Compost Biodegradation Results

The biodegradation rate can be determined from the amount of CO₂ measured during the 45-day experiment and the amount of initial carbon present in the sample. The CO₂ was measured according to procedures outlined previously.

The CO₂ concentrations are measured for test material samples. The amount of CO₂ was measured over a 180-day period. The amount of carbon resulted from the CO₂ concentration is calculated for each day. The results are averages of three samples. After 180 days the total amount of biodegradation conversion can be found by adding individual weekly results. The total biodegradation results for the 10 samples are listed in Table 2. The results include the standard error of the mean (SEM).

Cellulose and Kraft paper represented positive controls for the experiment. The cellulose degraded 92% over the 180-day experiment and Kraft paper degraded 92%. ASTM D5338 requires at least 90% degradation of cellulose. The Kraft paper samples had comparable degradation conversion and degradation rates as the PHA 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. The dirt compost alone and polyethylene (negative control) produced very little CO₂ which resulted in less than 3% conversion of the polyethylene into carbon, which can be accounted for by experimental error.

Marine Anaerobic and Aerobic Environment

Marine pollution is a worldwide environmental concern. Marine environmental pollution is regulated by the MARPOL treaty. The treaty prohibits disposal of any plastic waste in the oceans from ships and off shore platforms (Bastioli 2005). Petroleum based plastics can cause environmental concern because of the length of time for the floating plastics to disintegrate in ocean water. Polyethylene plastics, typically, will float in ocean water and can take 100 years to disintegrate completely. Polyethylene did not degrade in marine environment at a temperature of 30°C after 12 weeks (Bastioli 2005). While floating,

Table 1: Three biodegradation test methods.

©	Test	ASTM#	Required% biodegradation	Plastic Sample mass	Temp, C	Time
1	Industrial Compost	D6400/5338	90	100g	58	180 days
2	Marine	D7081/6691	30	1g	30	180 days
3	Anaerobic digestion	D5511	None	10g	33	20 days

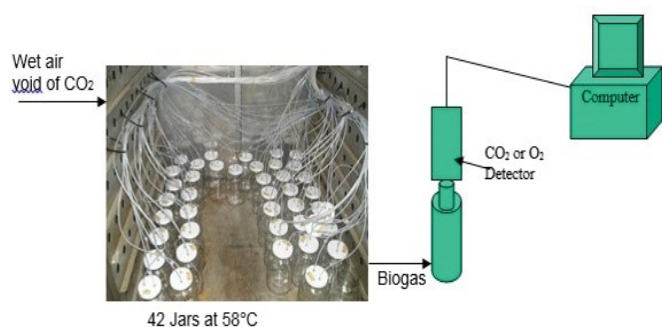


Figure 1: Experimental set-up for biodegradation testing for industrial composting per ASTM 5338.

Table 2: Biodegradation for compostable samples.

Material	SEM	ASTM	Standards
Biodegradation %			
Cellulose positive control	91.99	0.203	Pass
PHA bag	94.03	0.084	Pass
Kraft paper control	91.91	0.151	Pass
PLA straws	91.22	0.178	Pass
Sugar cane plate	91.12	0.154	Pass
Ecoflex bag	90.14	0.265	Pass
Blank compost control	1.69	0.163	None
Oxodegradable LDPE bag	2.19	0.124	Fail
Polyethylene control	1.70	0.118	Fail

low density polyethylene with UV-degradant deteriorated slower in a marine environment than on land (Andrady 1990). Photodegradable LDPE plastic ring connectors can degrade in marine and land environments with a 50% loss in properties in 12 months (Andrady et.al. 2003). Biodegradable plastics can biodegrade much faster than polyethylene due to its ability to absorb water and sink in ocean water. Though, only, PHA, PHB, and poly-ε caprolactone were shown to biodegrade in marine environment (Bastioli 2005).

In the next test environment, samples were tested for marine exposure. The procedure that was used was based upon 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 would demonstrate satisfactory disintegration if after 12 weeks at least 70% 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 CO₂ that is generated during the degradation process be measured. The method and test results are better explained in the recent Sustainable Plastics book. (Greene 2014)

A test sample would demonstrate satisfactory biodegradation if after 180 days 30% 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, approximately, 1 g, 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. Water was held at 5°C for 30 days until testing. During the experiment, the temperature was maintained in an oven at 30°C.

Marine Biodegradation Results

Figure 2 shows the biodegradation results for the samples after ASTM D 6691 test for marine biodegradation. After 180 days in ocean water, the PHA sample had 37% and 47% biodegradation. Cellulose experience 32% biodegradation. There was no biodegradation for polyethylene plastic or PLA.

Landfill Environment

Landfills are typically made with a liner and cover to minimize environmental impact. The US EPA landfill regulations recommends a “dry tomb” approach for municipal solid waste (MSW) management. The approach will minimize leachate generation. Leachate can pollute groundwater. However, “dry tomb” approach to landfills can cause some pollution problems for groundwater (Lee and Jones (1992). Most landfills are packed tightly and are anaerobic, which practically

eliminates biodegradation of organic materials. Thus, very little methane, carbon dioxide is produced from the biodegradation of organic materials due to the limited amount of oxygen and water, as well as low temperatures. In fact, some research in 25-year old landfills, have found still recognizable hot dogs, corn cobs and grapes, as well as newspapers with readable print (Rathje 1992). Biodegradable plastics and compostable plastic biodegrade in compost environments but not in landfill environments due to lack of moisture, temperature and oxygen. Oxodegradable plastics should behave as other polyethylene plastics and not degrade or fragment in landfill conditions due to lack of oxygen.

The degradable samples, 1g each, were combined with food waste in 1-liter bottles. Each reactor bottle was purged with helium gas for 5 minutes to ensure anaerobic conditions. All experiments were performed in duplicate under thermophilic conditions at 50oC. The initial pH of all reactors 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. 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 by measuring the displacement of water in the large tubes as shown in Figure 4.

Methane and carbon dioxide contents of the biogas produced in each reactor was periodically measured using gas chromatography, HP 5890 A, with 1.8 × 0.32 mm Alltech carboxpher column. Helium was the carrier gas at a flow rate of 60 ml/min. The temperatures of oven and thermal conductivity detector were 100 and 120C, 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% methane and 40% carbon dioxide was used to calibrate the reactors.

Laboratory experiment was conducted by mixing PHA with an inoculum coming from an industrial digester to study its biodegradability. One blank (only inoculum), a positive control, and a negative control were used for this experiment.

The total solids and volatile solids contents of the substrates and sludge are shown in Table 3. 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 Mirel PHA bag had 99.99 percent Volatile Solids (VS).

Figure 3 depicts the accumulative biogas production of sugar cane plate, paper bag, and cellulose, from the digesters with an initial loading of 50% degradable sample and 50% food waste. Figure 3 demonstrates that biogas is produced for the first 15 days from the digestion of the food waste. After the food waste is consumed in each

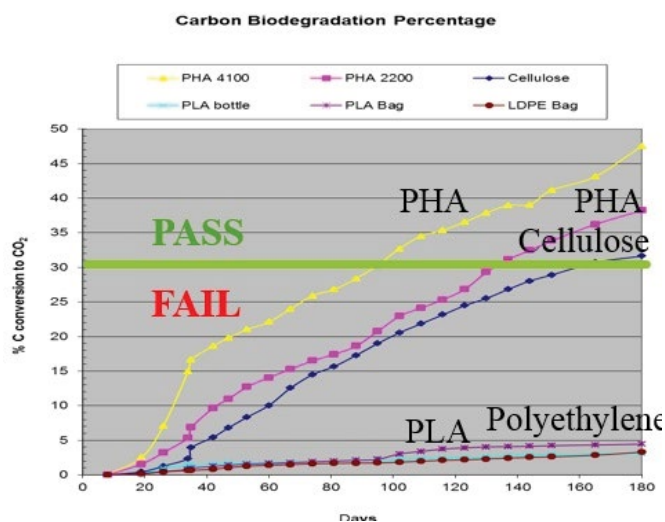


Figure 2: ASTM D6691 test results for marine biodegradation.

Table 3: Characteristics of the substrates and sludge.

Material Type	Total Solids, %	Volatile Solids/ Total Solids %
Oxodegradable-bag	99.99	96.18
Ecoflex bag	99.96	90.57
PLA cups	99.6	99.98
PLA straws	99.59	94.9
Mirel PHA bag	99.03	99.99
UV degradable Clear plastic bag	97.75	99.91
Kraft paper control	96.64	95.72
Sugar cane plate	94.21	99.43
Bio-bag	93.48	99.58
Food waste control	19.17	92.83
Sludge control	0.24	47.59

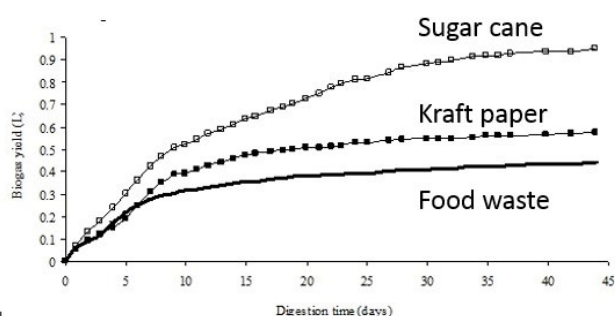


Figure 3: Cumulative biogas production from the anaerobic digestion after 20 days.

of the jars, the Mirel PHA and sugar cane samples continue to produce new biogas and thus are biodegraded in the anaerobic vessel.

The other samples do not produce any additional biogas after day 15, which indicates very little biodegradation occurring for the Kraft paper, PLA, corn starch, Ecoflex, Oxodegradable, and UV-degradable samples. Except for Mirel and sugar cane there was a little difference between the daily biogas production and food waste. The biogas yields at the end of the digestion time, after 43 days, from degradable samples alone was calculated as the difference between the biogas produced from reactors treating food waste and degradable samples and that treating food waste alone.

Biogas from the reactors has on average 60% methane gas and 40% carbon dioxide gas. The percentage of biodegradation is calculated by multiplying each samples resultant biogas volume by 40%, then multiplying by the density of carbon dioxide, and lastly dividing by the amount of carbon available in each sample.

The biodegradation results are presented in Table 4. Mirel PHA and sugar cane samples had biodegradation of 38% and 24 % respectively. The other materials had negligible biodegradation. The average final pH ranged from 6.33 and 6.87 for all of the samples.

Materials in Anaerobic Digestion Experiments

Polyhydroxyalkanoates (PHA) PHA-4100 was supplied by Metabolix (USA). Polylactide plastic (PLA) was supplied by NatureWorks.™ The carbon content in this PHA was 46.15%. Cellulose Avicel PH-101 was used as a positive control and LDPE was used as a negative control. PHA and PLA were blended into 1-2mm wide pellets using a regular kitchen blender.

Inoculum

The inoculum (pH = 7.76; FOS = 1.08g/L; TAC = 6.49g/L (Lossie, 2008)) was stored one week at 37°C before the beginning of the experiment to let it degas. Methanogen archaea in this mixture are mainly Methanosarcina and Methanobrevibacter.

Table 4: Cumulative biogas production from the anaerobic digestion after 20 days.

Material Type	% C biodegradation	Biogas Yield (L/gVS)
Mirel PHA bag	38	0.82
Sugar cane plate	24	0.53
Kraft paper control	6	0.18
PLA straws	6	0.02
PLA cups	6	0.01
Ecoflex bag	6	0.01
Bio-bag	5	0.18
Oxodegradable-bag	0	0.01
UV degradable Clear plastic bag	0	0.05
Food waste control	Not applicable	Not applicable
Sludge control	Not applicable	Not applicable

The inoculum came from a 2 stages mesophilic semi-continuous anaerobic digester owned by North State Rendering (Oroville, California). The plant was composed of 2 hydrolysis tanks and one digester. The inoculum was withdrawn on the bottom of the digester. The main feeding of this installation were cheese waste, olive waste and food waste.

Equipment

The experiments required the following equipment:

- 6 glass bottles (2.75 L)
- An incubator with an opening on the top to connect the bottles to an external sensor
- A thermocouple (OMEGA, MODEL 660)
- 6 PVC pipe closed with a PVC cap (2" wide and 2'6" long ; Volume = 1.6L)
- Gas Chromatograph SRI310
- A pH meter
- An electronic scale
- Standard gas (15% Nitrogen, 35% Carbon dioxide, 50% Methane)
- Biogas titration manager (HACH)

Biodegradation under mesophilic anaerobic digestion

The method used, as shown in Figure 4, was based on the Standard Test Method for Determining Anaerobic biodegradation of Plastic Materials Under High-Solids Anaerobic-Digestion Conditions ASTM 5511-02 (ASTM International, 2012). The system temperature was set to 37°C (±2°C). To match the usual feeding rate at the North State Rendering plant the plastic concentration was chosen between 4 g/L to 16g/L. The usual concentration is 4g/L but various concentrations were tested to observe the effect its effect on the degradation. The laboratory scale batch reactors were connected to a plastic pipe designed to collect the gas produced. The plastic pipes were sealed on one side and put upside down in a bucket filled with water. The pipe was filled with water every time it was full of gas. Hydrochloric acid was added to the water to keep the pH under 2 to avoid the carbon dioxide to dissolve into it.

At the beginning of the experiment, atmospheric oxygen was present inside the headspace of the reactor. This oxygen was rapidly consumed during the initial stages of degradation and the reactor quickly became anaerobic. Moreover, the experiment has been designed so the headspace volume was small (0.25L). The bottles were all closed with rubber tape and silicon to ensure that they were gas tight. The experiment was run until the gas production stopped (21 days). The gas production (volume) and gas composition were daily

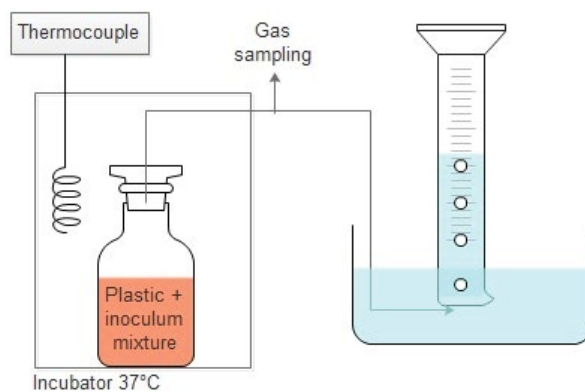


Figure 4: Experimental set-up.

analyzed.

Table 5 lists the experimental set up for the biodegradation testing. It lists the type of plastic, mass, amount of carbon in the sample, the volume of the inoculum, and the plastic concentration of g of plastic per liter of inoculum. Typical concentrations should be 4 or 8 grams of plastic sample per liter of inoculum for best results.

Biodegradation calculation

The biodegradation rate was determined by the carbon loss and according to the reactions equations 1, 2, 3, and 4. The carbon loss corresponds to the gas produced. The volume of gas produced has been measured all along the experiment. The biogas produced by anaerobic digestion is mostly composed of methane and carbon dioxide (Rasi, Veijanen, & Rintala, 2007). This calculation was driven by the hypothesis that the gas produced was only composed by methane and carbon dioxide. Each mole of gas produced contained one mole of carbon. Those two reactions do not represent the biodegradation reactions but were used to calculate the material balance.



$$\text{Biodegradation (\%)} = \frac{\text{gas produced by the anaerobic digestion}}{\text{amount of carbon tested}} * 100$$

Equation 3

The gas produced by the anaerobic digestion was determined by the difference between the gas measured in the tested bottle and the gas produced by the blank bottle with no plastic.

$$\text{Biodegradation (\%)} = \frac{\text{gas produced by the test} - \text{gas produced by the blank}}{\text{amount of carbon tested}} * 100$$

Equation 4

Table 6 lists the mass of each sample for the anaerobic digestion along with the mass of carbon and the mols of carbon in the experiment.

Gas chromatography

The methane production from each reactor was measured every day by using a 500µL gas tight syringe (Hamilton Company, Reno, Nevada). The gas collected was injected into a gas chromatograph (SRI Model 310) to analyze its methane and carbon dioxide content. These measurements were run according to the standard ASTM E 260. The gas chromatograph was equipped with a thermal conductivity detector and helium gas was used as a carrier. The oven temperature was 85°C and the inlet pressure was 50psi. The gas was calibrated before each use by doing a calibration with a standard gas mixture (15% Nitrogen,

35% Carbon dioxide, and 50% Methane).

The gas produced was calculated considering that it was only composed of methane and carbon dioxide because the other gas produced do not represent a big part of the all gas production (e.g. ammonia). It was chosen to ignore the other gases produced to make the gas composition calculation easier (e.g. : the gas measured is 20% nitrogen, 40% methane and 40% carbon dioxide ; the gas produced is considered as 50% methane and 50% carbon dioxide). This method of calculation has been used to consider that a certain amount of nitrogen present in the headspace stayed in it during the all experiment, and the gas was sampled in the headspace.

Biodegradation of plastics

PHA and cellulose biodegradation started after 2 days. This time corresponds to how long it takes for the material to hydrolyze. Oxygen is used up during the breakdown of organic material; once it is used up the reaction becomes anaerobic. The positive control was microcellulose. The negative control was LDPE. Figure 5 shows the biodegradation of PHA, PLA, LDPE, and cellulose during anaerobic digestion.

Both negative control and positive control showed that the experiment was working. However the cellulose (positive control) biodegradation slowed down after 5 days. Nothing in particular was changed at this moment. PHA1 and PHA2 were close to be totally degraded (102% and 95%). The fact that the PHA1 biodegradation is above 100% shows that the methane and carbon dioxide production are not the only reaction happening in the reactor or could come from a measure uncertainty.

Gas composition

The gas composition of the blank, the positive control and the negative control were measured but they do not appear on the next graph because they are not very relevant. Furthermore, the blank and the negative control barely produced gas. Figure 6 lists the volume

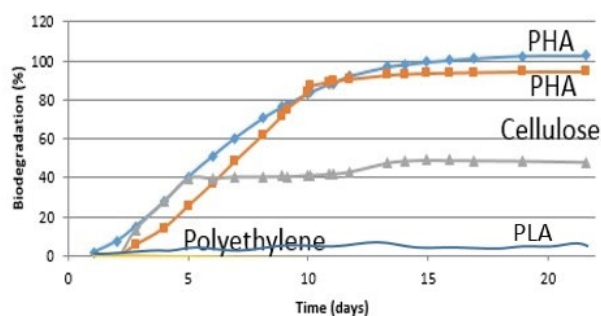


Figure 5: Biodegradation of PHA, PLA, Cellulose, and LDPE in anaerobic digestion.

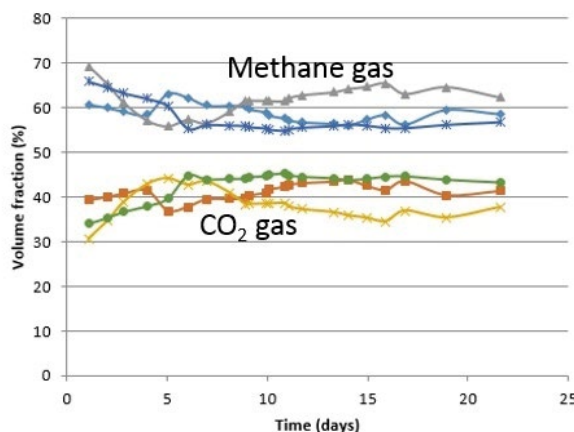


Figure 6: Gas composition as measured with a GC.

Table 5: List and characteristic of the samples.

	Type of plastic	Mass of plastic (g)	Amt of C (mol)	Volume of inoculum (L)	Plastic concentration (g/L)
PHA1	PHA	10	3.85	2.5	4
PHA2	PHA	20	7.69	2.5	8
PHA3	PHA	40	15.4	2.5	16
Blank	X	X	X	2.5	X
Positive control	Cellulose	10	4.44	2.5	4
Negative control	LDPE	10	8.57	2.5	4

Table 6: Amount of carbon per bottle.

	PHA1	PHA2	PHA3	Positive control	Negative control
Mass (g)	10	20	40	10	10
w (g carbon/g)	0.462	0.462	0.462	0.444	0.857
Carbon quantity (mol)	0.39	0.77	0.54	0.37	0.71

percentage of methane and carbon dioxide for the experiment. The gas composition was typically 60% methane gas and 40% carbon dioxide gas.

The gas composition was almost the same for the 3 samples. The average gas composition of the 3 tests was 60% methane and 40% carbon dioxide.

Conclusions and Recommendations

Compostable plastics, including, PLA lids, PHA bags, Ecoflex bags, Husky Eco-Guard plastic bags, Kraft paper, and cellulose paper completely biodegraded into CO₂ and water in a laboratory compost environment and met the biodegradation requirements of ASTM D-6400. However, oxodegradable, UV-degradable, and polyethylene plastics do not degrade under laboratory compost conditions and do not meet the ASTM D-6400 for biodegradation in compost environment. Compostable plastics biodegraded in commercial compost environment after 180-days. Oxodegradable and UV-degradable plastics did not degrade while under composting environment in 180-days. PHA experienced significant disintegration in a simulated marine environment. Alternatively, corn-starch-based trash bag, PLA cup, Ecoflex bag, sugar cane lids, UV-degradable plastic ring, and Kraft paper did not exhibit disintegration in marine environment.

PHA biodegrades by anaerobic digestion in mesophilic condition. Its biodegradation is above 90% after 11-12 days and can reach 95%-100%. The results also show that PHA biodegraded significantly more than the microcellulose positive control. According to the gas composition analysis with gas chromatography, the gas composition is about 60% methane and 40% carbon dioxide. Biodegradation

terminated after 22 days. Under anaerobic conditions PHA, cellulose, and sugar cane experienced biodegradation, but PLA and polyethylene did not.

Compostable plastic materials could be very economical for organizations and institutions that service a controlled population, e.g., hospitals, correctional facilities, schools, and cruise lines. The cost of disposal of waste at these locations can be offset by the use of compostable plastics, which have a compost nutrient value. Compostable plastics can be a boon to compost operators by having an organic nutrient source that can be a beneficial soil amendment.

Acknowledgements

The authors would like to thank the following people who have helped develop this research work: Dr. Cindy Daley (CSU, Chico), Dr. Randy Miller (CSU, Chico), and Mr. Jeremy Vaughn (CSU, Chico). Funding for the research was provided by the Rice Research Board.

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