Is it Really Zero Waste? Comparative Analysis Between Plastic and Compostable Plastic

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ABSTRACT

In the circular economy, products are made with the intention of reducing waste. Compostable plastic is an example of this and is designed to reintegrate easily back into the environment. Polylactic Acid (PLA) plastic is currently the most commonly used compostable plastic in food ware, but needs to be industrially composted to fully degrade. Because there aren't many industrial compost facilities, PLA plastic can end up as pollution just like petroleum plastic. I ask the question, "How does the circular economy implementation of compostable product design compare to current single-use drinkware in inputs and end-of-life outcomes" to analyze the true benefits and detriments of compostable plastic. Across four Life Cycle Assessments (LCA) comparing petroleum plastic to PLA, I found that for eight major impact categories, except Human Toxicity Potential and Abiotic Depletion of Fossil, petroleum plastic actually outperformed PLA. PLA requires less energy in production than petroleum plastic, but petroleum plastic needs less energy in end-of-life disposal scenarios. I found PLA has similar timelines in decomposing terrestrially and aquatically to petroleum plastic. I focused specifically on these end-of-life timelines because most LCAs do not factor pollution into their output calculations. Lastly, I found three compostable alternatives to PLA that use heat-pressed biomass and had backyard compost timelines of around two months, which all were shorter than the backyard compost timeline of PLA.

KEYWORDS

PLA (Polylactic Acid), Petroleum Plastic, LCA (Life Cycle Assessment), Bioplastic, Circular Economy

INTRODUCTION

Oceanic plastic pollution is currently quantified at about 300 million tons annually (Fadeeva and Van Berkel 2021). UV rays and abrasion from wave currents make ocean plastic brittle, creating microplastics that can be consumed by marine life resulting in intestinal blockage and negative physical effects (Thiel et al., 2018). Plastics are also treated with chemical additives to increase durability or flexibility which can have a negative endocrine effect by altering hormones when consumed (Galloway et al., 2017). The hormonal effects of microplastics in humans reduce growth rates, block enzyme production, lower steroid hormone levels, and affect reproduction (Wright et al., 2013).

Plastic production plays a large part in the linear economy of "produce, use, waste". The linear economy extracts natural resources to produce products that are discarded once they stop being useful (Boonman et al. 2023). Capitalism fuels the linear economy through the ideal of making money. The cheapest product that still performs the same function as its competitors will be purchased more by consumers but results in a lower quality, shorter use phase product (Sakthivelmurugan et al. 2022). In the case of planned obsolescence, some products are even designed to break after a given amount of time so consumers will purchase a new one (Kuppelwieser et al. 2019). Convenience also plays a large part in the linear economy. A disposable single-use cup offers a higher level of convenience for a quick cup of coffee than a reusable mug that needs to be washed and accounted for. Plastic is a desirable material because it is cheap to produce, durable enough to make products out of, and not missed when it is disposed of. In the linear economy, the production and waste phase are the largest legs in the cycle.

A transition away from plastic and towards a circular economy is needed to live in a sustainable environment. Key circular economy strategies include take-back management, recycling, and better product design (Stumpf et al. 2021). Takeback management and recycling both focus on the waste phase of a product and how it can be reintegrated back into production or downgraded into another useful product rather than being landfilled (Stumpf et al. 2021). Better product design entails that products will last longer as well as be made of materials that can readily go back to the earth (Stumpf et al. 2021). One example of circular design that challenges the single-use mindset is the compostable single-use cup. In the past 50 years, petroleum plastic production has increased by 20 times with 9200 million metric tons (Mt) being produced globally (Walker and Fequet 2023). Most single-use cups are made with petroleum plastic, but the cup has been redesigned with natural materials that can go back into the earth more easily and reduce plastic pollution.

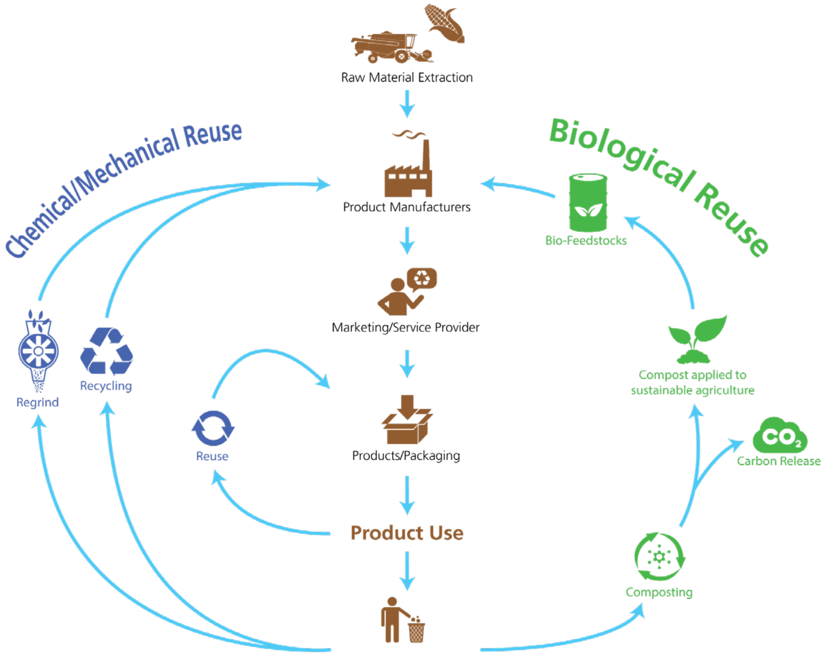

Figure 1. Visualization of Circular Economy (https://naturbag.com/circular/).

PLA (polylactic acid), is the most commonly used form of compostable plastic because of its attractive qualities, but it also has its own drawbacks. PLA is a biopolymer primarily made from corn or sugar cane (Dieterle and Ginter 2022). PLA is durable and visually similar to petroleum plastic, but it also leads consumers to mix compostable plastic with petroleum plastic in trash bins, contaminating waste streams, and forcing compost facilities to send everything to the landfill (Garlotta, 2002; Shah et al., 2008; Edgar 2019a). PLA plastic also needs to be heated to temperatures of at least 140 degrees Fahrenheit to fully break down into nontoxic components which is unable to be done in everyday backyard compost and can only be done in an industrial compost facility ("Is PLA Actually Biodegrable?" 2021). Because they cannot compost in backyard compost, industrially compostable plastic bags have been found to leave behind microplastic particles in soil (Accinelli et al. 2020). Compostable plastics have also been shown to not biodegrade in marine conditions and therefore can create as much oceanic microplastic pollution as petroleum plastic (López-Ibáñez and Beiras 2022). There are existing life cycle analyses comparing petroleum plastic and compostable plastics in terms of production inputs and end-of-life disposal streams, but there is little research about the end-of-life analysis of pollution, environmental absorbability, and better alternatives to PLA plastic.

My Central Research Question (CRQ) is as follows: How does the circular economy implementation of compostable product design compare to current single-use food ware in inputs and end-of-life outcomes? My first subquestion (SQ1) is as follows: How does compostable plastic compare to single-use plastic in terms of energy and resource usage? My second subquestion (SQ2) is as follows: How does compostable plastic compare to single-use plastic in terms of end-of-life timelines, focusing on pollution? My third subquestion (SQ3) is as follows: Are there alternative viable compostable product designs that have shorter end-of-life timelines than the commonly used PLA plastic?

BACKGROUND

Factors That Affect the Success of Circular Economies

Circular economy is an innovative alternative to the linear economy, but there are barriers to implementation as well as factors that help its adoption. Here are a few case studies that display examples of factors of success for circular economies. For modular construction projects in Hong Kong, effective supply chain management, competence and early commitment, and collaboration and information management were success factors in the implementation of the circular economy (Wuni and Shen 2022). For steel recycling in Thailand, circular economy education, environmental commitment, and social willingness to recycle affect the success of circular economy practices (Akkalatham and Taghipour 2021). In the UAE, ethical leadership need management control systems to enable the uptake of circular economy practices (Cheffi et al. 2023). Education, communication, management, and commitment are all factors that contribute to the success of circular economies.

Scope of Bioplastic

Compostable plastic allows for the utility of single-use plastic while preventing petroleum plastic pollution. There were 2.11 million tons of bioplastic produced in 2018, but that made up only 1% of all plastic produced (European Bioplastics, 2018). Forty percent of the bioplastic market in 2020 was made up of polylactic acid (PLA), polyhydroxyalkanoates (PHAs), and thermoplastic starch (TPS) (UNEP 2020).

- PLA - polymerized lactic acid from crop biomass
    - used mainly for disposable tableware
    - most biodegradable thermoplastic
    - too fragile and cannot be used for other packaging manufacturing processes
- PHA- polymer produced by microorganisms
    - can be produced from methane and waste biomass
    - biobased and biodegradable with access to elevated temperature and moisture
    - naturally digestible by marine microorganisms
- TPS - contains starch and a plasticizer to improve physical qualities
    - starch - biodegradable, thermal stable, but is hydrophilic
    - biodegradable, cheap, acquired from renewable plant resources
    - poor water resistance and inferior mechanical properties

Descriptions of these bioplastics were sourced from these papers (Atiwesh et al. 2021) (Nandakumar et al. 2021).

Replacing petroleum plastic with bioplastic could potentially reduce greenhouse gas emissions by up to 225% (Liptow and Tillman, 2012; Tsiropoulos et al., 2015; de Oliveira et al., 2021; Benavides, Lee, and Zare`-Mehrjerdi, 2020; Alvarenga et al., 2013)). The crops used to make bioplastic also act as carbon sinks due to the uptake of CO2 (Rostkowski, Criddle, and Lepech, 2012; Vink et al.,2003; Kim and Dale, 2008). There also exist petrochemical plastics that are biodegradable and bioplastics that are non-biodegradable displayed in table 1.

Table 1. Plastics and Levels of Degradability (Brizga et al. 2020).

	Petrochemical Plastics	Blended Plastics	Bioplastics
Biodegradable	PBS, PBAT, PVA, PVOH, PCL, PGA	starch and PLA blends	PLA, PHA, cellulose-based plastics, lignin-based polymer composites
Non-biodegradable	PE, PP, PET, PS, PVC, PA, PUR, other	drop-in plastics, e.g., bio-PET, bio-PA, bio-PTT	bio-PA 11, bio-PE

Recycling and End-of-Life

The current recycling rate for petroleum plastic is only 27.2 % while landfill and incineration are both 36.4 % (Vieira et al., 2022). Plastic recycling could be a viable circular economy strategy to reduce waste but because plastic sorting is an expensive process, landfill and incineration are more commonly used (Lim et al. 2022; Dastjerdi et al., 2021; Gradus et al., 2017; Hopewell et al., 2009; Kim and Jeong, 2017). Plastic sorting is expensive because plastic must be sorted to at least 99.98% purity and dirt, glues, and labels must be removed (Kosior and Mitchell 2020). There is also a lack of motivation to recycle because of a lack of environmental concern, lack of awareness on how to recycle correctly, and inconvenience (Fogt Jacobsen et al. 2022). As a result, around 80% of plastics ended up in landfill or as pollution between 1950-2015 (Geyer, Jambeck, and Law, 2017). Even though recycling has complications, the infrastructure is established, unlike industrial compost facilities, and could be used as a viable additional waste stream for PLA plastic if consumer behavior toward recycling increases (Fredi and Dorigato 2021).

METHODS

Data Collection Methods

Literature Review

I conducted a systematic literature review to explore the research questions using published LCAs on single-use plastic cups. Literature reviews are a type of research that is helpful in analyzing information that is already in the field and bringing attention to current gaps in the literature where further research could be taking place. (Leite et al. 2019). I consolidated data from multiple different sources, analyzed, and synthesized this into my own conclusions.

Life Cycle Assessment (LCA)

I conducted a systematic analysis of four life cycle assessments. When assessing the impact of a product, companies consider the impact within each life cycle stage of their products, from raw material extraction to product disposal. Comparative LCAs define a functional unit to provide a baseline to compare products (van der Harst et al. 2014). For example, if the functionality of a single-use cup were to provide a single cup of coffee, a comparative analysis between PLA and PET plastic could be based on the functional unit of one cup.

There are four steps in an LCA: 1. Goal and Scope Definition, 2. Inventory Analysis, 3. Impact Assessment, and 4. Results and Interpretation (Santos et al. 2022). The first step establishes the goal of the study and the system boundary which bounds the different aspects of a product's impact (Santos et al. 2022). For example, an LCA on a plastic cup may consider the greenhouse gas emissions released by trucks during the transportation of the cup, but it may not consider the greenhouse gasses emitted in the creation of the truck that transported the cups. The second step quantifies the inputs and outputs of all life cycle stages within the system boundary (Santos et al. 2022). The third step converts the raw data within the inventory into conceivable environmental impacts (Santos et al. 2022). For example, the gigatons of greenhouse gas emissions released in the production of the cup receive a symbolic quantity of how much it contributes to the impact category: Global Warming Impact. The fourth step looks at the data and readdresses the goal defined in the first step (Santos et al. 2022).

Methodology

I gathered four life cycle assessments between petroleum and PLA and qualitatively compared them. A systematic analysis between multiple LCAs was the best way to serve my first and second sub-questions in comparing compostable drinkware to petroleum drinkware in inputs and outputs. If I were to create an LCA on my own comparing the two, I would lack the resources, funds, time, and extensive ability to create an accurate LCA. I would also only have one data point. Scraping data from existing LCAs gives me a more well-rounded view of the same problem from four different sources. The disadvantages of scraping existing LCAs for data results in the loss of control of the boundaries of the system and how they are defined. I then gathered data on end-of-life timelines for both backyard compost and ocean degradation for all plastics studied. This addresses the gap in the literature on how improperly disposed plastic that ends up as pollution is not considered in calculating an LCA. I conducted a literature review for my third question in searching for alternative viable compostable product designs. This was the best way to conduct a broad search for alternatives rather than surveying different restaurants for what they use or interviewing bioplastic producers.

My main data collection method was going onto ScienceDirect and collecting papers that would be useful to my research. I typed in the keywords “LCA (Life Cycle Assessment)” and “PLA (Polylactic Acid)” and then chose the first four papers that met my criteria for analysis. The criteria are as follows; LCAs that had PLA as a bioplastic alternative and LCAs that broke down impact category estimations by life phase.

I then found data to quantify backyard compost and ocean degradation timelines for plastic and bioplastic. I typed in the keywords “PLA”, “plastic”, and “degradation” to find papers that quantified how long PLA plastic takes to degrade in backyard compost conditions compared to other materials. I typed in the keywords “PLA”, “plastic”, “ocean”, and “degradation” to find papers that quantified how long PLA plastic lasts in the ocean compared to other types of plastic. Finally, I found three papers describing compostable plastic alternatives by typing in the words “compostable”, “plastic”, and “drinkware”.

Data Analysis Methods

To determine how compostable plastic compares to single-use plastic in terms of energy and resource usage, I created table 2 comparing the four LCAs by extracting data on their boundaries and functional units. From this, it was easier to analyze which materials each LCA was comparing, and which end-of-life outcomes they modeled for their data. I created table 3 listing all of the impact categories each LCA mentioned and how each material performed within each impact category in comparison to each other. In my documentation, “material 1” > “material 2”, material 1 performed better than material 2, meaning it had a lower score within the impact category. I created table 4 as a meta-table and listed all of the impact categories that were mentioned in at least 2 LCAs. I then listed which material performed the best from each LCA. The last column of the table documents a simple majority in which material performed the best for the same impact category across multiple LCAs. Because each LCA considered different materials, I considered all petroleum-based materials as one material versus PLA as another material of which to grant a majority ruling. If one impact category was only used by 2 LCAs and each LCA mentioned a different best-performing material, there is no simple majority and I wrote the test results “inconclusive”. I created table 5 that listed how different materials compared in energy consumption in the production stage of the product. Analysis was done within each LCA to quantitatively compare which material required the least amount of energy to produce. In some LCAs, I simply acknowledged a graph, in some LCAs I had to do a few simple calculations to derive which material required the least amount of energy.

To determine how compostable plastic compares to single-use plastic in terms of end-of-life timelines, focusing on pollution, I created table 6 to compare end-of-life performances between all materials considered between all LCAs. I extracted the data from the four LCAs on different materials and their end-of-life strategies and how they performed in comparison to each other in terms of energy usage and emissions. I created table 7 to compare end-of-life timelines between all materials considered between all LCAs. I listed the materials that were compared in the LCA and timelines for how long each will take to decompose in the soil. I then listed timelines for how long it will take to decompose in marine ecosystems.

To determine if there are alternative viable compostable product designs that have shorter end-of-life timelines than the commonly used PLA plastic, I created table 8 that lists compostable alternatives to PLA. The first column describes the material and the manufacturing process. The second column lists an end-of-life timeframe for composting in backyard conditions.

RESULTS

I identified the boundaries and functional unit for each LCA I studied in Table 2. The boundaries included which materials were studied and a basic breakdown of how the life cycle is defined for each. For LCA 1 and 4, the weights of each material compared were noted within the functional unit. In both cases, PP was the lightest material.

Table 2. LCA Breakdown by Boundaries and Functional Unit. Paper (PA), Polylactic Acid (PLA), Polypropylene (PP), Polystyrene (PS), Polyethylene terephthalate (PET)

LCAs	**Boundaries**	**Functional Unit**
LCA 1 (Gao and Wan 2022)	PP, PLA, PA straws Production>Transport (500km)>Straw Production>Transport (500km)> Distribution & Use> Disposal: Landfill/Incineration	Functional unit - (5E+8 no./d) Weight PP - (.52 g/straw) PLA - (.81g/straw) PA - (1.15g/straw)
LCA 2 (Genovesi et al. 2022)	PLA, PP, PS plates PP/PS - Production of Raw Materials>Crockery>Landfill PLA - Production of Raw Materials>Crockery>Composting Plant/Landfill	Functional Unit - 1000 plates, cups, cutlery
LCA 3 (Madival et al. 2009)	PLA, PS, PET clamshell containers PLA - Corn growing/harvesting>Lactic Acid Production>Extrusion/Thermoforming>Distribution>Consumption>Incineration/Recycling/Landfill/Composting>Energy Recovery PS/PET - Crude Oil>Extrusion/Thermoforming>Distribution>Consumption>Incineration/Recycling/Landfill>Energy Recovery	Functional unit -1000 clamshell containers to pack .4536kg (1 lb) of strawberries
LCA 4 (Moretti et al. 2021)	PLA, PP, PET cups PLA - Corn Cultivation and Harvest in USA/Sugarcane Cultivation and Harvest in Thailand>Lactic Acid Production>Thermoforming in Europe> Use Phase in Europe>End-of-Life in Europe (15% Recycling, 15% Composting, 39% Incineration, 31% Landfilling) PP/PET - Natural Gas/Crude Oil Extraction and Refining>Polymerisation>Thermoforming>Use Phase>End-of-Life (30% Recycling, 39% Incineration/31% Landfilling)	Functional unit - 1000 single-use cups with 200 ml volume used to contain cold drinks Weight - PP (2.9–3.5 g) PLA (4.1–4.7 g) PET (5.5–6.4 g).

I tabulated all the impact categories considered for each LCA and how each material performed in comparison to each other in Table 3. For LCA 1 and 4, PP performed the best the majority of the time. For LCA 2, PLA performed the best and for LCA 3, PS performed the best.

This means across all LCAs, petroleum plastic performed the best on average. I then created a meta-table comparing the same impact categories across the 4 LCAs and which material performed the best in Table 4. Only 3 impact categories overlapped between the 4 LCAs including Global Warming Potential, Acidification, and Eutrophication. Across all the impact categories and LCAs, PP performed the best the majority of the time.

Table 3. Impact Categories and Material Performance. Paper (PA), Polylactic Acid (PLA), Polypropylene (PP), Polystyrene (PS), Polyethylene terephthalate (PET)

LCAs	Impact Categories Considered	Impact Categories Performance
LCA 1	1. Global Warming Potential	1. PP>PLA>PA
	2. Acidification Potential	2. PP>PA>PLA
	3. Eutrophication Potential	3. PP>PA>PLA
	4. Ozone Depletion Potential	4. PA>PLA>PP
	5. Freshwater Toxicity Potential	5. PP>PA>PLA
	6. Human Toxicity Potential	6. PP>PLA>PA
	7. Terrestrial Toxicity Potential	7. PP>PA>PLA
	8. Abiotic Depletion of Fossil	8. PA>PLA>PP
LCA 2	1. Global Warming Potential	1. PLA>PP>PS
	2. Ozone Depletion	2. PP>PS>PLA
	3. Ozone Formation	3. PLA>PP>PS
	4. Acidification	4. PLA>PP>PS
	5. Aquatic Eutrophication	5. PP>PS>PLA
	6. Human toxicity Water	6. PLA>PP>PS
	7. Ecotoxicity water chronic	7. PP>PLA>PS
LCA 3	1. Global warming	1. PS>PLA>PET
	2. Aquatic Acidification	2. PS>PET>PLA
	3. Ozone layer depletion	3. PS>PLA>PET
	4. Aquatic Eutrophication	4. PS>PLA>PET
	5. Respiratory organics	5. PS>PET>PLA
	6. Respiratory Inorganics	6. PS>PET>PLA
	7. Aquatic ecotoxicity	7. PLA>PS>PET
	8. Energy	8. PLA>PS>PET
	9. Land Occupation	9. PS>PLA>PET
LCA 4	1. Climate change	1. PP>PLA>PET
	2. Particulate matter	2. PP>PET>PLA
	3. Photochemical ozone formation	3. PP>PET>PLA
	4. Acidification	4. PP>PET>PLA
	5. Terrestrial Eutrophication	5. PP>PET>PLA
	6. Resource use fossil fuels	6. PLA>PP>PET

Table 4. Meta-Table Impact Categories Comparison. Paper (PA), Polylactic Acid (PLA), Polypropylene (PP), Polystyrene (PS), Polyethylene terephthalate (PET)

All Impact Categories (at least 2 LCAs shared)	**LCA1**	**LCA2**	**LCA3**	**LCA4**	**Majority**
Global Warming Potential	PP	PLA	PS	PP	Petroleum (PP)
Acidification Potential	PP	PLA	PS	PP	Petroleum (PP)
Eutrophication Potential	PP	PP	PS	PP	Petroleum (PP)
Ozone Depletion Potential	PA	PP	PS		Petroleum
Freshwater Toxicity Potential	PP	PP	PLA		Petroleum (PP)
Human Toxicity Potential	PP	PLA			inconclusive
Abiotic Depletion of Fossil	PA		PLA	PLA	PLA
Ozone Formation		PP		PP	Petroleum (PP)

I took the data collected from each LCA and found how much energy each material took to produce in comparison with each other in Table 5. Across the 4 LCAs, PLA took the least amount of energy to produce on average. I also found how much energy each material used in end-of-life disposal in comparison with each other in Table 6. Each LCA had different end-of-life pathways, and petroleum plastic used the least amount of energy in end-of-life disposal on average.

Table 5. Energy Inputs Comparison. Paper (PA), Polylactic Acid (PLA), Polypropylene (PP), Polystyrene (PS), Polyethylene terephthalate (PET)

	LCA1	**LCA2**	**LCA3**	**LCA4**
Energy total input (acquiring material & forming product)	Abiotic depletion of fossil - landfill PA>PLA>PP Abiotic depletion of fossil - incineration PA>PLA>PP	Global warming PLA>PP>PS	Energy PLA>PS>PET	Resource use fossil fuels PLA>PP>PET

Table 6. Energy Outputs Comparison. Paper (PA), Polylactic Acid (PLA), Polypropylene (PP), Polystyrene (PS), Polyethylene terephthalate (PET)

	LCA1	**LCA2**	**LCA3**	**LCA4**
EOL Strategies	Landfill incineration	Landfill for all Composting included for PLA	Different scenarios 40R/30I/30L 100L 100R 50I/50L 23.5I/76.5L (current)	PLA 15R/15C/39I/31L PP and PET 30R/39I/31L
EOL Performance	Abiotic depletion fossil Landfill - PP>PLA>PA Incineration - PP>PLA>PA	Global warming potential PLA=PP=PS	Energy Consumption PLA>PS>PET Except if 100R PLA>PET>PS	Resource use, fossil fuel PET>PP>PLA All negative

I compared end-of-life timelines in soil and ocean conditions for each material compared across all LCAs in Table 7. PA had the shortest end-of-life timeline in both conditions and PLA had a comparable timeline to the other petroleum plastics and does not degrade. I found end-of-life timelines in soil for alternatives to PLA in Table 8. All alternatives were made of biomass and had backyard compost timelines of around 2 months which are much shorter than PLA.

Table 7. End-of-Life Timelines in Soil and Ocean for Materials. Paper (PA), Polylactic Acid (PLA), Polypropylene (PP), Polystyrene (PS), Polyethylene terephthalate (PET)

Materials Compared	**PA**	**PLA**	**PP**	**PS**	**PET**
EOL Backyard Compost Timelines (Solano et al. 2022)	85% reduced at 31 weeks	2% at 78 weeks	does not degrade	does not degrade	does not degrade
Ocean degradability timelines (Gerritse et al. 2020)	8% reduced per year	≤ 1% per year	≤ 1% per year	≤ 1% per year	3–5% per year

Table 8. Alternatives to PLA.

Alternatives	**Description**	**Backyard Compost EOL Timeline**
Alternative 1 Cassava Starch (Casarejos et al. 2018)	Woody shrub whose tuberous root is rich in starch Manufacturing process is cassava starch pulp preparation, mold filling, pressurized cooking, and mold removal	75-135 days
Alternative 2 Hybrid Sugarcane and Bamboo Fibers (Liu et al. 2020)	Blend long bamboo fibers with the short sugarcane bagasse fibers to enhance mechanical properties The manufacturing process is mixing sugarcane bagasse fibers with bamboo fibers, cold-press formation, hot-press drying, and packing	60 days
Alternative 3 Areca leaf (Nayak et al. 2021)	Areca are mainly grown for its seed and is used as an herbal drug, also are grown as an ornamental plant. The manufacturing is the sheaths are heat pressed into shapes of plates and dried out	60 days

DISCUSSION

Over the course of my research, I analyzed inputs, outputs, and alternatives to PLA and petroleum plastic across four Life Cycle Assessments. I found that for all impact categories except Human Toxicity Potential and Abiotic Depletion of Fossil, petroleum plastic outperformed PLA. PLA needs less energy to produce than petroleum plastic with only PA (paper) needing less energy to produce than PLA in LCA 1. I found that petroleum plastic needed the least amount of energy in end-of-life disposal scenarios and PA had the shortest timeline in decomposing terrestrially and aquatically. I found three compostable alternatives using heat-pressed biomass that had backyard compost timelines of around two months which all were shorter than the backyard compost timeline of PLA. While other LCAs comparing plastic to compostable plastic do not consider pollution as an end-of-life outcome and do not factor it into their calculations, I have synthesized data on how long each plastic would last after being disposed of improperly to see a more comprehensive view of each material's impact on the environment.

Inputs

PP outperformed PLA and other types of petroleum plastic repeatedly. This is most likely due to the low density, meaning there is a lower mass requirement to fulfill the functional unit, and a lower impact in all life cycle stages (Moretti et al. 2021). Even with the fossil fuels and energy needed to farm biomass, PLA outperforms petroleum plastic in terms of energy usage during production. This is consistent with findings of other LCA studies about PLA's lower carbon footprint and energy consumption than other plastics and having a lower impact in the Global Warming Potential category (Ghomi et al., 2021; Franklin Associates, 2006). This is likely because PLA has a lower specific heat and heat of fusion which means it will require less energy during thermoforming (Madival et al. 2009). But, producing biomass can have negative effects such as eutrophication or acidification which is why PLA performed worse than petroleum plastic for all other impact categories. This is in line with the findings of the studies previously published (Binder and Woods, 2009; Potting and van der Harst, 2015).

Outputs

Each LCA had different end-of-life strategies that resulted in different outcomes that I have described in Table 6. These strategies included landfill, incineration, recycling, and composting. LCA 4 also considers the energy gained from incineration resulting in negative end-of-life values for energy consumption. Incineration increases air pollution but landfill increases toxic leachate (Nanda and Berruti, 2021). This is why the variation in end-of-life strategy can alter performances in different impact categories such as Global Warming Potential or Eutrophication. Petroleum plastic on average needs less energy in end-of-life than PLA plastic but values were tied for LCA 2. These tied values for greenhouse gas emissions between PLA and PP were also found in other studies when considering landfilling as an end-of-life scenario (Bohlmann, 2004).

PA (Paper) has the fastest timeline to degrade with PLA behaving similarly to petroleum plastic in being unable to degrade. Other studies have also concluded that plastic is non-degradable and paper is completely marine degradable (Chamas et al., 2020; Chitaka et al., 2020).

Alternatives

The alternatives I researched all involved biomass that would normally be discarded and used heat and pressure to form it into food ware. While the backyard compost timeline is considerably shorter than PLA and petroleum alternatives, the energy needed for inputs was not calculated and the marine degradation timelines were not considered. Judging from the fact that PLA and PA need less energy to produce than petroleum plastic even when considering the energy needed to acquire biomass, it is likely that these biomass alternatives will not exceed petroleum plastic in terms of energy inputs shown in table 5. But because biomass cultivation involves fertilizer, water consumption, and a plethora of other resources, these biomass alternatives could perform worse in impact categories such as eutrophication and toxicity in comparison to petroleum plastics.

Limitations

My experimental design did address the Central Research Question, but is limited by the number of LCAs I compared. Because there were only four LCAs and they only compared three materials at a time, there was not a lot of data. The benefit of only comparing four LCAs is the reduction in the amount of spread between the data. Each LCA had many differences from each other in how they defined their boundaries and integrating more LCAs could have convoluted the data and produced inconclusive results. My study design also sufficiently addressed the energy needed for inputs and outputs between compostable and petroleum plastic, but it could have thoroughly considered other impact categories/factors in determining which plastic performed the best. I chose to base my design around comparing energy needed because even though each LCA compared different impact categories, Global Warming Potential was always one of the impact categories mentioned.

Future Directions

Future research could conduct complete LCAs on each biomass alternative so that a comprehensive overview can be done comparing petroleum plastic and PLA.

PHB

PHAs are biodegradable polyesters formed by microorganisms with the most popular of those being Poly(3-hydroxybutyrate) (PHB). PHB has high biodegradability, but low ductility, is expensive, and isn't heat resistant (Briassoulis et al. 2021). Unlike PLA, PHB is backyard compostable and even enrichs the soil (Nandakumar et al. 2021). PHAs are also more degradable in water than in soil (Nandakumar et al. 2021). Though PLA is the incumbent for food ware bioplastic, PHB reintegrates better into the environment and further research should include conducting a full LCA on PHB versus PLA to determine if it could be a viable alternative to PLA.

Chemical Contamination and Negative Effects

Although bioplastic is seen as a cleaner and healthier alternative to petroleum plastic because it is made of natural materials, they are also laced with harmful chemicals. These chemicals are also designed for water and grease resistance or flexibility and can leach into the environment (Oregon gov). Bioplastic and conventional plastics have been shown to have similar toxicity levels (Zimmermann et al. 2020). Further research could be done to quantify chemical contamination and toxicity and integrate this factor into LCAs for PLA as well as petroleum plastics to have a broader view of what kind of impact each material has.

Broader Implications

My research discussed the benefits and detriments of one example of the Circular Economy. My research helped fill the gap for plastic that is not accounted for when it is improperly disposed of as pollution by focusing on end-of-life timelines on land and in water. Conducting research like this gives policymakers a more comprehensive overview of making sustainable decisions to move forward with new materials to replace petroleum plastic. PLA plastic is designed to be industrially composted but infrastructure needs to be constructed and consumer diligence for accurate disposal has to be developed. Petroleum plastic recycling centers could be scaled to recycle PLA plastic but the purity of waste streams have to be maintained for this to be a feasible solution. PLA plastic may use less energy to produce but has many detriments in other impact categories and is unable to degrade in soil or marine environments. It should not be seen as the go-to alternative and more research into other materials is needed. Cost is always a factor in making a business decision and because petroleum products are so cheap, it is hard to upend the status quo. Even if PLA cups were better for the environment, they are much more expensive to produce. This is why it's important to look into other cheaper materials. For example, bamboo sugar cane fiber cups were 2 times cheaper than PLA cups and a bit more expensive than PS cups (Liu et al. 2020). Plant fibers in general, especially those that have no other uses and would end up as biomass waste are low-cost and can have diverse appliances (Nayak et al. 2021). Research like this is useful in providing a full background when moving toward the circular economy.

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