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LIFE CYCLE ASSESSMENT OF POLYLACTIC ACID BIOPOLYMER INDUSTRIAL WASTE MANAGEMENT TECHNIQUES IN BELIZE

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THESIS

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ABSTRACT OF THESIS

LIFE CYCLE ASSESSMENT OF POLYLACTIC ACID BIOPOLYMER INDUSTRIAL WASTE MANAGEMENT TECHNIQUES IN BELIZE

In January 2020, the Government of Belize enacted an Implementation Strategy and Action Plan to phase-out single-use plastics and to transition to products like bioplastics. This work investigated the environmental effects of using alternative waste management techniques to manage polylactic acid biopolymer (PLA) waste by using life cycle assessment (LCA). The following treatment options were compared: landfill, landfill expansion, cogeneration, and anaerobic digestion. The landfill and landfill expansion processes both had a global warming potential of 0.01 kg of CO_2 eq. per kg of PLA waste managed compared to the cogeneration and anaerobic digestion processes -0.03 and -0.06 kg of CO_2 eq. per kg of PLA respectively. This difference was due to offsets produced by the cogeneration and anaerobic digestion systems. Additionally, it was shown that construction material requirements of the waste management systems often attribute less than 15% of total burdens to environmental impacts. Through uncertainty and sensitivity analysis it was shown that higher gas capture efficiencies in landfills and higher electrical efficiencies in cogeneration and anaerobic digestion, should be targeted to minimize GWP. Effective use of developed LCA models can assist Belize with strategies for eliminating petroleum single-use plastic and provide waste management strategies to help inform decision makers.

KEYWORDS: Polylactic Acid, Biopolymer, Life Cycle Assessment, Waste Management, Anaerobic Digestion, Belize

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LIST OF ACRONYMS

PLA – Polylactic Acid Biopolymer
LCA – Life Cycle Assessment
EoL – End-of-Life
NEAP – National Environmental Action Plan
NEPS – National Environmental Policy and Strategy
LCI – Life Cycle Inventory
OFMSW – Organic Fraction of Municipal Solid Waste
MSW – Municipal Solid Waste
GHG – Greenhouse Gas
VOC – Volatile Organic Compounds
EPA – Environmental Protection Agency
PET – Polyethylene Terephthalate
GWP – Global Warming Potential
BSWMA – Belize Solid Waste Management Authority
APWC – Atlantic Pacific Waste Consultants
LHV – Lower Heating Value
ISO – International Organization for Standardization
TRACI – Tool for Reduction and Assessment of Chemicals and other environmental Impacts
PAH – Polycyclic Aromatic Hydrocarbons

CHAPTER 1. INTRODUCTION

1.1 Motivation:

Today's society has seen a growing need to promote sustainability in industries to help ensure that our quality of life improves (Piemonte, 2011). Much of the world is searching for plastic solutions that decrease the harmful impact on the environment. This search has led communities to transition from petroleum-based plastics to the ones that are biobased. Biobased plastics or biopolymers are plastics derived from biomass that can be molded into various products. The growth rate for biobased polymers, or biopolymers, is expected to grow from 2.11 million tons in 2019 to 2.42 million tons by 2024 (Bioplastics, 2014). Ideally, these biopolymers should be the obvious choice for replacing their petroleum-based counterparts. This is because biopolymers partially reduce the dependency on fossil resources that cause negative environmental impacts, unlike petroleum plastics (Brehmer et al., 2009). In addition, because of the rising prices of crude oil and natural gas, biopolymers are expected to become more cost-competitive with petroleum based plastics, allowing further growth (Soroudi et al., 2013). In 2000, biopolymers cost around 35 to 100 times more than petroleum-based plastics per ton as compared to only 2 to 5 more times expensive in 2017 (BPM, 2017).

The most common biopolymer produced is poly-lactic acid biopolymer (PLA) which is responsible for over 10% of all biopolymer production (European Bioplastics, 2014). PLA is widely available, has various applications, and technological innovation will likely reveal several new applications for it as well (Barbara G. Hermann et al., 2010). Currently, PLA can be molded into bottles, containers, films, fibers and sheets and is biodegradable (Soroudi et al., 2013). The biodegradability of PLA can depend on how organized its molecular chains are semi-crystalline (organized, tightly packed) or amorphous (disorganized) as shown in many studies (Kolstad et al., 2012; Krause et al., 2016). Owing to its wide range of uses, many studies have begun investigating the environmental effects that coincide with PLA production, use, and disposal. Currently, life cycle assessment (LCA) has emerged as an important tool that facilitates evaluating the environmental profile of bioplastics (Gentil et al., 2010).

LCAs consider the environmental impact of a process or material over its entire life cycle. Many works have studied the processes of cultivation, transportation, and production of the biopolymers extensively. However, when investigating PLA at the end-of-life (EoL), practitioners have used varying methods and assumptions to describe similar waste management systems. There exist several discrepancies between studies related to this stage due to different assumptions on the extent of degradation of biopolymers, allocation of emissions, and differences in technologies such as landfill gas capture (Yates et al., 2013). Being able to accurately assess these waste management scenarios can create improvements in quantifying greenhouse gas (GHG) emissions and other life cycle impact categories (Wurdinger, 2002).

There are two distinguishing categories of biopolymers: biobased polymers and biodegradable polymers. The term biobased means a polymer composed of materials that are produced from biomass, such as corn, beets and sugarcane, as well as biogenic residues and waste (Weiss et al., 2012). A biodegradable polymer is a polymer where enzyme reactions allow it to decompose. Biodegradation is a process that can be expedited in several waste management techniques, under factory-controlled conditions (Veronika, 2018).

The ability for biodegradable plastics to have their energy and biomass resources recovered at the EoL is an integral part of what makes them a favorable choice in reducing their environmental impact (Grigale et al., 2010). However, at EoL, the fate and chemical behavior are not well documented and are believed to be highly variable in the potential impacts (Boyd, 2011). It is important to understand the full potential of biopolymers. For example, (Piemonte, 2011) and (Häkkinen et al., 2010) demonstrated that different waste treatment options have the ability to reduce the global warming potential (GWP) up to 80%. Improvements of this caliber would provide the world with waste management solutions that mitigate impacts on the environment. However, studies that are currently in literature have only partially painted the picture of biopolymer waste management. Therefore, there is a need to investigate the major biopolymer waste management options, including landfilling, composting, incineration, anaerobic digestion, and recycling (Amlinger et al., 2008; Edelmann et al., 2001; Weiss et al., 2012).

One community that could see benefits from this study is Belize. On January 15th, 2020, the Government of Belize enacted an Implementation Strategy and Action Plan to phase-out single-use plastics as well as Styrofoam and to transition to products like bioplastics. It was reported that in 2010, 85.2% of waste in Belize went into uncontrolled landfills and 14.8 percent in uncontrolled combustion (Margallo et al., 2019). However, with the implementation of Belize's Solid Waste Management Plan Phase 1, the waste disposal upgraded to include several transfer sites where waste is sent to the main regional landfill. This landfill collects an average of 114 metric tons of waste per day from the transfer stations and direct hauls to the landfill, where half derives from Belize City, the largest city in Belize (BSWMA, 2019). These transfer stations and the regional landfill are effective in removing waste from urban areas; however, in some rural communities such as the Sittee River Village, a common practice of waste disposal is by burying trash, putting it in the river, or burning it (S. R. Hobbs, 2019).

Developing countries like Belize seek more integrated and sustainable waste management systems as shown by Belize's Waste Management Plan Phase 2 that serves to implement new waste management strategies into the country (G.O.B, 2015b). This plan includes a landfill expansion system, to build upon the original landfill, where bidding on design and construction will begin in January 2021 (G.O.B, 2015b). Additionally, with the combination of new bioplastics and The Ministry of Energy, Science, Technology, and Public Utilities, in 2012, putting forth a strategic plan to reduce Belize's dependence on fossil fuels by 50% by the year 2020, there is an opportunity to investigate the environmental effects of implementing these new bioplastics into the waste stream in Belize. Several scenarios exist where landfill expansion could stifle environmental impact, as well as the utilization of cogeneration systems or anaerobic digestion to help manage the biodegradability of PLA in a way that is more environmentally responsible and allows energy production and a reduction in fossil fuel dependency.

1.2 Background:

Belize has a history of striving to make positive environmental changes through environmental policies and acts. In 1989, the Government of Belize made environmental concerns equal to other traditional ministries with the establishment of the Ministry of Tourism and Environment (G.O.B, 2014). Since this ministry was founded, there have been several initiatives that have attempted to coordinate national efforts to help solve major environmental challenges in Belize and participate in international initiatives (G.O.B, 2014).

The first environmental policy enacted was the Environmental Protection Act in 1992, which established the Department of Environment and gave it the legal mandate to address environmental concerns (G.O.B, 2014). Some of the functions of this department included advising the government on the formulation of policies for good management of natural resources, and encouraging governmental and non-governmental institutions to align their activities with the ideas of sustainable development (G.O.B, 2014).

In response to these new roles, the Department of Environment received funding from the Overseas Development Agency for the First National Environmental Action Plan (NEAP) (G.O.B, 2014). NEAP attempted to solve several environmental issues, such as improper land use and pollution problems and was updated in 1999, but few substantial changes were achieved (G.O.B, 2014). This lack of development was due to not prioritizing its strategies, along with financial constraints and a lack of human participation, which resulted in several recommendations to only partially be implemented (G.O.B, 2015a).

The 2006 National Environmental Policy and Strategy (NEPS) was formed to address the lack of production from NEAP (G.O.B, 2015a). It addressed several problems with insufficient public awareness, insufficient resources, lack of planning, limited databases to inform decision making, and a lack of national strategy to coordinate efforts (G.O.B, 2015a). Since 2006, with more funding and attention, there have been a plethora of positive policies and plans, such as the National Poverty Elimination Strategy and Action Plan, the National Climate Change Adaptation Policy and the National Water Integrated Water Resources Act (G.O.B, 2015a). However, there are still major problems with pollution and poor waste management that since being identified in 1990, have remained a concern to the stakeholders involved in the management of Belize's natural resources and the protection of its environment (G.O.B, 2015a).

The goal of improving waste management was propelled by the Environmental Protection Act, Solid Waste Management Authority Act and the Public Health Act. Under these acts, the Solid Waste Management Plan introduced the first regional landfill and several transfer stations. However, there is still a large problem with litter and plastic pollution (G.O.B, 2015a). NEAP led to the Belize Cabinet approving the Implementation Strategy and Action Plan to phase out single-use-plastics and Styrofoam on March 20th 2018.

There were several expected results of this project (D.O.E, 2019):

- "A reduction in the volume of single-use disposable plastics and Styrofoam becoming waste via regulatory restrictions on importation, production, manufacturing, sale, and possession, through amendments to the Pollution Regulations under the Environmental Protection Act"
- "An improvement in national data quality to aid decision-making and the development of policy for strengthening and promoting the recycling, agro-productive and manufacturing sectors"
- "A transition to using Greener (environmentally-friendly) products, by promoting investment, research and development, production and importation"
- "Monitoring and Evaluating Belize's transition to green products via tracking changes in: importation and production practices, waste stream composition, and consumption habits, attitudes and perceptions relating to single-use disposable plastics and Styrofoam products"

Belize is guided in their environmental concerns by several sustainable development principles, such as the Inter-generational Equity Principle (each generation has a right to the resources of the earth) and the Substitution Principle (products or processes that cause risks to human health or the environment should be avoided, especially when there are less dangerous alternatives that can reasonably be used) (D.O.E, 2019).

Additionally, life cycle approaches are highlighted as a way to help aid in decision making and identify product use patterns and EoL alternatives (G.O.B, 2015a). In January of 2021, the Department of the Environment of Belize called for a Strengths, Weaknesses, Opportunities, and Threats analysis to identify how the NEAP and NEPS have been enacting change in the Belize community (D.O.E, 2019). This project will serve to provide a life cycle approach to help provide information on alternatives for waste management processes for bioplastic wastes and help aid in the decision making of the Government of Belize.

1.3 Research Approach:

This dissertation utilizes LCA to assist Belize with strategies for managing bioplastic wastes in order to provide the Belizean government with valuable waste management strategies. There are several studies that investigate PLA at EoL, however, Belize's climate, infrastructure, and country's needs make it unique to what has already been studied. Further development of these assessments is needed to accurately assess the environmental impacts that can be expected by the Belizean community.

1.4 Intellectual Merit:

This study aims to investigate the environmental impacts of 4 waste management techniques, for managing PLA wastes in Belize, that could offer efficient waste management as well as offsets that provide additional benefits.

Results from this work will provide an effective LCA model that can assist stakeholders with strategies for eliminating petroleum-based single-use plastics and provide methods for managing bioplastic waste with minimal environmental impacts. Additionally, this can serve as a template for other communities who are implementing biopolymers and need solutions to their waste management of biopolymer waste.

The objective of this work is to determine which waste management technique offers the least environmental impact and to provide insight as to how these impacts can be targeted in future operations. Specifically, the questions that this work seeks to answer are:

> 1) Which waste management technique (landfill, landfill expansion, cogeneration, or anaerobic digestion) contributes the least environmental impact for PLA waste?
>
> 2) What elements of the end-of-life of PLA (transportation, materials, and operational requirements) should be targeted to minimize the environmental impacts of the waste management strategies?

To answer these research questions, an LCA was conducted on the EoL of PLA following ISO 14040/14044 standards (ISO, 2006). The life cycle inventory data was collected from the Ecoinvent V3.0 database accessed through SimaPro and supplemented with information from literature. Information obtained from literature was used to model infrastructure that was as similar to Belize's as possible. The life cycle impact assessment was conducted for the waste management systems using the ReCiPe 2016 Midpoint method.

When investigating the amount of PLA that will be managed during the lifetime of the landfill expansion in Belize (500 million kg), hypotheses were formed about the GWP of the waste management systems. Through literature it has shown that anaerobic digestion may have lower GWP impacts than landfilling and incineration (B. G. Hermann et al., 2011). Further, it has shown that transportation requirements may have higher impacts on GWP compared to other aspects of the EoL of PLA (Van der Harst et al., 2013). Given this information, the null hypothesis for this study are:

> Hypothesis 1.1_o: Anaerobic digestion will have a similar GWP to the other waste management systems studied.
>
> Hypothesis 2.1_o: Transportation requirements will have a similar impact on GWP compared to the operational and material requirements of the landfill expansion process.

When managing 500 million kg of PLA, the alternative hypotheses of this study are:

Hypothesis 1.1_a: Anaerobic digestion will have the lowest GWP of the waste management systems studied.

Hypothesis 2.1_a Transportation requirements will be the largest contributor to GWP compared to the operational and material requirements of the landfill expansion process.

The hypotheses were tested using uncertainty analysis (using Monte Carlo methods) via Oracle Crystal Ball implemented in Excel and by conducting a Wilcoxon signed rank test.

1.5 Broader Impacts:

This work presents a framework for identifying the waste management techniques that result in the least amount of environmental impact when managing PLA and the elements of EoL that create these impacts. The LCA model was created using tools that are able to be manipulated for different communities, environments, and situations. Due to many communities making transitions to more environmentally conscious products, it could provide a template for any community that is analyzing the different environmental effects that occur in the EoL of biopolymers. This work can be shared with several stakeholders, such as the Belize Department of Environment and Ministry of Health, and the Belize Solid Waste Management Authority, to provide them with a tool to aid in their transition to biopolymers.

1.6 Structure:

This thesis is structured as follows:

- Chapter 1 introduces the motivation, research approach, and broader impacts of the work that was conducted.
- Chapter 2 provides a review of literature relevant to PLA at EoL. This includes the EoL waste management processes that are available for PLA, the differences in methodologies of how PLA was analyzed at the EoL using LCA, and the results from these LCA studies.
- Chapter 3 details the methodology that was used to address the research questions, including all steps for the LCA, and the relevant assumptions regarding PLA degradation and Belize waste management systems.
- Chapter 4 discusses the outcomes of the LCA and uncertainty and sensitivity analyses.
- Chapter 5 summarizes this work and highlights major conclusions and opportunities for future work.

2.1 Life Cycle Assessment:

Since the beginning of the 1990s, LCA has been used worldwide to investigate and compare waste management strategies (Björklund et al., 2005). The ISO 14040/14044 series has provided guidelines on LCA methodology (Vignali et al., 2017). In these guidelines, it explains that LCA is a method used to assess the potential environmental impacts of a product or process throughout its full life cycle. A product's life cycle is a combination of the activities that go into producing, transporting, using and disposing of that product (ISO, 2006). Oftentimes these cycles could also consider re-use scenarios, recycling, and different offsets produced throughout the life cycle. LCAs help identify possible improvements in environmental effects that could be realized throughout a product's life cycle as well as provide industries with a model to help aid decision-making. The framework of LCA is divided into four main phases:

1. Goal and Scope Definition
2. Inventory Analysis
3. Impact Assessment
4. Interpretation

2.1.1 Goal and Scope

The first phase of LCA is the goal and scope definition. This phase defines the reason that the assessment is being conducted and outlines the system boundaries for the assessment (Gironi et al., 2011). The system boundary is the identification of the processes and activities that make up the system that is under investigation. The functional unit is also defined here to provide a reference to which the inputs and outputs are related. The functional unit chosen should describe the system accurately and ensure the comparability of LCA results (Vignali et al., 2017). The goal and scope phase is the foundation to the entire LCA and will help guide the rest of the project. After this step, the practitioner must gather an inventory of inputs and outputs that create the system.

2.1.2 Inventory Analysis

Inventory analysis, also known as life cycle inventory (LCI), is the phase that defines the inputs and outputs that flow through a system. This step involves data collection and calculation to quantify the flows of the system that are being assessed. These flows will include the use of resources, in addition to the emissions released into the air, water, and land, that are associated with the system. Environmental impacts are generated from the wastes and emissions that are produced inside of the system boundary. These environmental impacts are then normalized to the functional unit.

There are two kinds of LCI data. First is primary data that is specific to the process or material being investigated (e.g., the gallons of diesel fuel used to transport 1 kg of biopolymer). Additionally, there is secondary data that has been collected previously (e.g., databases) and should be limited to minor impacts or to those not variable from case to case (Vignali et al., 2017).

During the LCI phase, allocation procedures are also defined. These procedures are where material and energy flows can be attributed to different products and processes according to procedures that should be clearly stated, documented, and justified. The attributions include offsets and avoided materials that affect the overall system effects. Offsets refer to credits that are allocated to a system for co-producing useful things, such as electricity, heat and secondary materials (Heijungs et al., 2007). After allocations and offsets are considered, the practitioner must use this data to determine environmental effects.

2.1.3 Impact Assessment

The third phase is an impact assessment. In this phase, the data that was quantified in the inventory analysis goes through classification, characterization, and weighting. Classification is the process in which inventory items are assigned to the effects that they have on the environment (ISO, 2006). These inventory items are assigned to different impact categories that can either be midpoint or endpoint (Figure 1). Midpoint categories focus on specific, potential environmental impacts such as ozone depletion. Endpoint categories show effects on three main themes: human health, natural resource consumption, and ecosystem damage; and assess the actual impacts of the midpoint categories such as skin cancer and crop damage that would stem from ozone depletion (UNEP/SETAC, 2011). The midpoint categories are translated into the endpoint category's three themes and each midpoint category can cause impacts on more than one endpoint category (UNEP/SETAC, 2011).

Characterization is the quantification of how much impact the product's and/or service's emissions have on the different impact categories (ISO, 2006). These emissions can have different effects or multipliers depending on the impact category being assessed. Two commonly used impact assessment methods, ReCiPe 2016 and TRACI are used to assist in relating environmental impacts to indicators. Following, is the optional step of weighting in which the impact categories are assigned a value based on how important they are (ISO, 2006). These values can then be used to generate a single score that represents the total environmental impact (ISO, 2006). It is important to note that assigning weighting includes subjectivity and will vary between studies. Next, the information of impacts must be evaluated to ensure that the goal of the study was achieved.

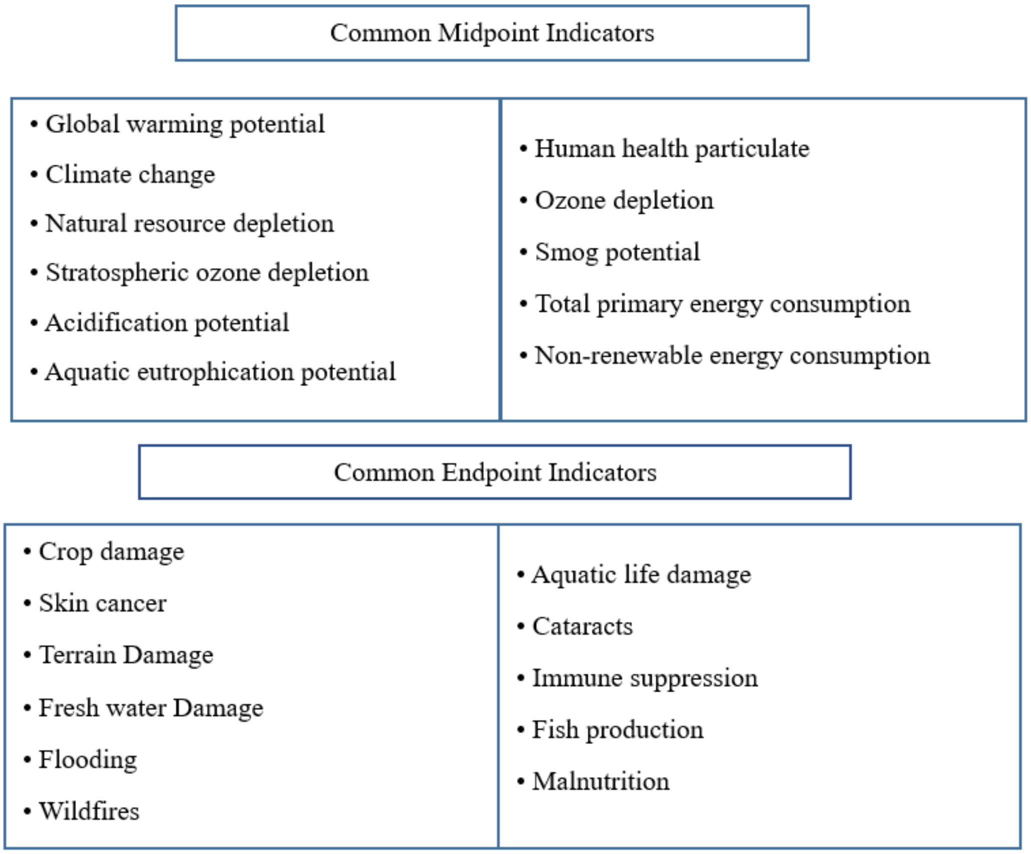

Figure 1 - Common Midpoint and Endpoint Indicators

2.1.4 Interpretation

Interpretation is the final phase that serves to evaluate the entire LCA (UNEP/SETAC, 2011). ISO 14040/14044 requires checks to ensure sensitivity; ensure the assessment is transparent and aligned with the goal and scope; confirm that the data used is accurate and complete; and confirm that all assumptions and allocations are noted (ISO, 2006). The outcome of this phase is a set of conclusions and recommendations for the study. In addition, during this phase the goal and scope of the study should be reviewed to determine if the objective of the study has been met, and to reform the goal and scope if the assessment shows that they cannot be achieved (UNEP/SETAC, 2011).

2.2 End-of-Life Processes of PLA:

The five main waste systems for biopolymers are landfill, industrial composting, incineration, industrial anaerobic digestion and recycling. In each of these systems, PLA is expected to degrade differently and thus create different environmental effects. Throughout these systems biobased carbon can be handled in three different ways (Weiss et al., 2012). The first is considering carbon emissions as carbon neutral because the carbon released by the material is offset by the carbon that was taken up initially. Through this approach, carbon allocation problems are implicitly managed through the carbon content of coproducts (Guinée et al., 2009). Additionally, carbon can be allocated consistently with the allocation of other environmental burdens while still assuming carbon neutrality. Lastly, some may credit carbon emissions through carbon sequestration as the carbon is stored in the biobased materials (Brandão et al., 2011). Knowing what these waste systems are and how PLA behaves in them is essential for understanding why LCA practitioners have found varying results when investigating PLA at EoL. The waste management systems are outlined below.

2.2.1 Industrial Anaerobic Digestion Process

Anaerobic digestion typically involves handling organic solids from municipal wastewater treatment plants (EREF, 2015). The largest portion of the organic fraction of municipal solid waste (OFMSW) is composed of food waste which accounts for over 45% of municipal solid waste (MSW) globally. Anaerobic biodegradation usually indicates degradation at mesophilic (37 °C) or thermophilic (55 °C) biogas plants. In these conditions, a series of metabolic interactions by microorganisms convert organic matter into four main products of methane, carbon dioxide, water and heat (Mohee et al., 2008). To ensure the most ideal conditions for the reaction, the carbon-nitrogen ratio must be balanced in addition to the pH remaining around 7 (Massardier-Nageotte et al., 2006). Once the process is complete, the digestate residue that remains are rich in N, P, and K which are key ingredients in fertilizers. This process produces less heat and biomass compared to aerobic digestion processes such as composting as shown in Figure 2 (Batori, 2018).

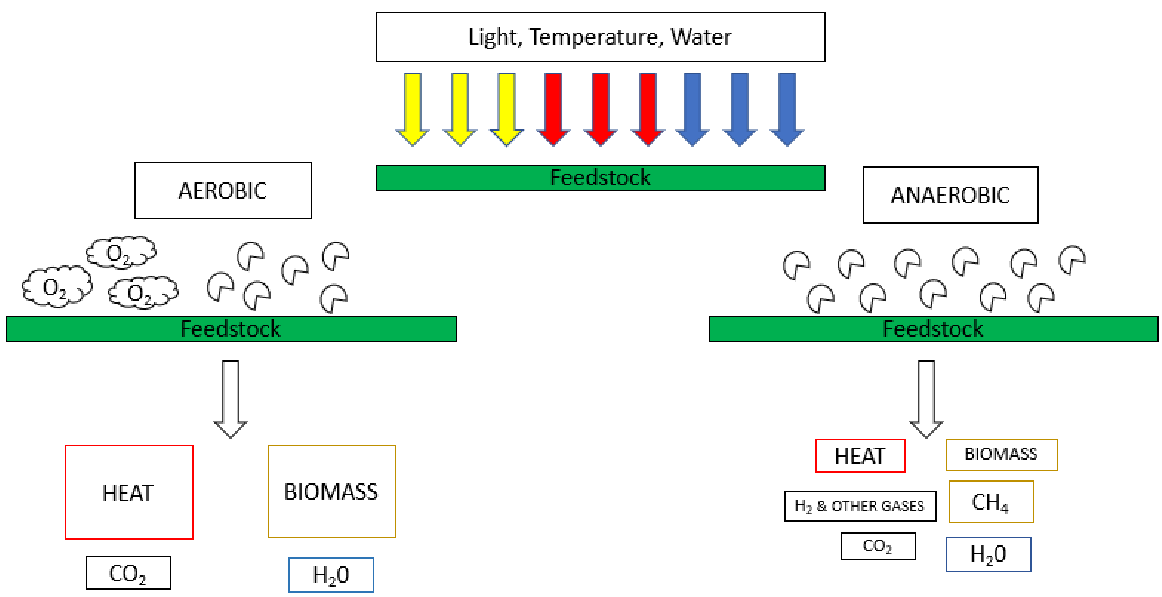

Figure 2 – Anaerobic vs. Aerobic biopolymer degradation

2.2.2 Current State of PLA in Anaerobic Digestion

The research surrounding the anaerobic digestion of biopolymers is still in its infancy (Veronika, 2018). Despite several tests being conducted, the anaerobic digestion of PLA has been achieved with varying degrees of success. Hamad (2015) details that PLA must be hydrolyzed first to reduce the molecular weight before the biodegradation can start. Through this method, a pretreatment is applied to the biopolymer and then combined with OFMSW to form a slurry that can then be anaerobically digested. However, a test from (Itävaara et al., 2002) showed that PLA could degrade rapidly, up to a rate of 60% during waste disposal in anaerobic treatment facilities without pretreatment. However, it was determined that it could take up to 90 days, which is a lengthy process for industrial anaerobic digestion (Kolstad et al., 2012). S. Hobbs (2019) demonstrated that PLA reached near complete solubilization (97% -99%), with alkaline pretreatment applied. Beyond that, (Yagi et al., 2009) showed that PLA was degraded up to 90% in thermophilic temperatures when combined with sludge, without the use of a pretreatment and degraded in mesophilic temperatures although the degradation was much slower. In further tests from (Yagi et al., 2012), they also determined the ideal size of PLA pieces to ensure degradation and concluded that larger pieces of PLA had a faster degradation rate compared to smaller pieces, indicating that its unnecessary to cut PLA into smaller pieces to anaerobically degrade.

It is important to note that biopolymers must meet the conditions of existing biogas and anaerobic digestion plants to help continue the processes already established. The C:N ratio, which is essential in anaerobic digestion, could be increased due to the use of PLA which is shown to have a ratio of 20:1 to 30:1 which could help increase the overall value of the process and increase production. However, it has also been discovered that biopolymers such as PLA have a higher hydraulic retention time than OFMSW which could hinder implementation (Veronika, 2018).

2.2.3 Landfilling Process

Landfilling is the mass burial of wastes, often with a bottom liner separating the wastes from the ground and a covering of soil. This process can occur over decades and throughout this time, the system can undergo many fluctuations in pH, oxygen levels, and temperature (Kjeldsen et al., 2002). Some advanced landfills have technology to capture gases that are produced due to the wastes decaying, which help limit greenhouse gas emissions (EPA, 1997). Landfills act as a primary reservoir of plastic waste as well as paper products, organics, and other items, which break down under anaerobic conditions in landfills (Su et al., 2019).

Many communities are seeking more integrated and sustainable waste management systems. Even though landfilling may have a higher environmental impact than other MSW treatment alternatives, such as recycling or incineration, it is still the backbone of waste management in many countries (Laurent et al., 2014). This is because it is relatively inexpensive, well-known technology with lower environmental, economic impacts when compared to uncontrolled dumpsites (Laurent et al., 2014). Many countries in Latin

America, such as Mexico and Brazil, have found success with several open dumpsites being converted into controlled landfills (Manfredi et al., 2009).

2.2.4 Current state of PLA in landfills

In landfill conditions, wastes undergo anaerobic degradation. As mentioned in Section 2.2.2, the research surrounding the anaerobic digestion of PLA is in its infancy and has been met with mixed results. It has been shown by several studies that PLA will degrade, at least partially, under thermophilic (55 °C) landfill conditions. Kolstad et al. (2012) highlighted that amorphous PLA degradation would emit up to 260 ml of methane per gram of PLA and (Krause et al., 2016) found that PLA would emit between 185 and 372 ml of methane per gram of PLA. Kolstad et al. (2012) also asserted that semi-crystalline PLA would not degrade in landfill conditions whereas (Krause et al., 2016) claimed that semi-crystalline PLA, could be anaerobically digested in thermophilic landfill conditions, which landfills in warm, tropical climates are known to reach.

2.2.5 Incineration Process

Incineration is a process where a feedstock such as polymers are converted to steam using a boiler, which is then used to convert to energy through a generator (Gongora, 2018). Like petroleum-based polymers, PLA can be incinerated, and the steam can be used in energy production as well as district heating. Using renewable resources is crucial for the CO_2 neutrality of energy recovery (Kreindl, 2012). The overall efficiency of these systems can exceed 80% making incineration a great method of power generation. Despite these benefits, incineration is expensive in terms of operation and maintenance; it is also known to cause environmental impacts such as GHG emissions from the burning of petroleum and biobased feedstocks; and substantial impact on water depletion that is needed for the incineration process (Kamate et al., 2009; Zhang et al., 2018).

2.2.6 Current State of Incineration of PLA

Biopolymers have high heating values, and since they are renewable, the energy recovery competes with other forms of waste management (Lorber et al., 2015). Zhang has shown success in incinerating biopolymers as shown by his experiments (Zhang et al., 2018). Furthermore, biopolymers can be considered CO_2 neutral when burned because the carbon released by the material is offset by the carbon that was in the biobased feedstock initially, which results in a lower GWP (Brandão et al., 2011).

Carbon cascading is a process where biomass is used for material purposes and then incinerated at the EoL to recover energy and maximize the GHG emission savings of the material (Weiss et al., 2012). The energy released from the biopolymer comes from solar energy and through gasification is converted to heat. Most of the CO_2 consumed during the photosynthesis is released into the environment and the amount of captured solar energy through biomass gasification may fully support the heat and electricity required to produce the biopolymer. Hence, no fossil resource would be needed to supply energy for the polymer synthesis.

2.2.7 Composting Process

This process is where organic matter decomposes under controlled aerobic conditions to form a fertilizer or soil-enriching product (Ruggieri et al., 2008). Composting is a beneficial waste management system, particularly where landfill sites are sparse, and in cities with dense populations (Papong et al., 2014). Composting is spurred through a diverse group of microorganisms that use nutrients such as carbon, nitrogen, and phosphorus found in the organic matter to grow. The carbon to nitrogen ratio is critical in the process, as this serves as an indicator of the nutritional balance and the optimum ratio for composting. Typically, the C:N ratio is between 25:1 and 35:1. Composting usually occurs in a high-oxygen environment, and the heat released during this process is not able to be collected because it requires continuous turning of the biomass for a healthy microbial community (Bernal et al., 2009). This compost continues to degrade over time, however at a much slower rate during the initial waste treatment (B. G. Hermann et al., 2011). One of the benefits of compost is the long-term carbon storage to help replenish carbon losses in soil due to agricultural farming (Rothamsted, 2006). Therefore, there is a clear value that corresponds to using compost and digestate as soil conditioners (B. G. Hermann et al., 2011).

2.2.8 Current State of PLA in Composting

Using composting for the disposal of PLA wastes has been widely studied. Hydrolysis is the central mechanism for degradation of PLA. This process is catalyzed by temperature and results in bacterial decomposition of the fragmented residues (Farrington et al., 2005). The first phase of PLA degradation in compost is surface hydrolysis; called the hydrolytic phase. After this, the second phase of enzymatic degradation begins and the polymer undergoes random decomposition (Armentano et al., 2013; Fortunati et al., 2010).During this process, the polymer is used as a carbon and energy source for microorganisms, which creates the biproducts of carbon dioxide, water, and compost (Colon, 2009). Any carbon that is not metabolized by microorganisms remains stored in the compost. Disintegration in compost occurs through aerobic fermentation, which results in CO_2 and humus rich soil; thus, composting would be a waste management option for packaging plastics, such as PLA, at EoL (Arrieta et al., 2014). It has also been reported that plasticizers could speed up the disintegration of PLA in composting conditions (Arrieta et al., 2014).

2.2.9 Recycling Process

Recycling is a method of waste management where materials that would be discarded are turned into new products. There are two types of recycling, which are mechanical and chemical recycling. Mechanical recycling is the collection, sorting, grinding, and washing of plastics that are then used in the production of new plastic. Chemical recycling changes the molecular structure of the plastic, where it is depolymerized into smaller molecules, which are then polymerized to form the recycled plastic (Lorber et al., 2015). Recycling offers a unique way for products to be incorporated into a, “Circular Economy” where a material’s value is retained in the economy for an extended period, while minimizing the amount of waste created (Commission, 2015a). Additionally, through the recycling of organic wastes, biodegradable products have an alternative at EoL that effectively sequesters carbon (Carus et al., 2018).

2.2.10 Current State of PLA in Recycling

PLA in recycling scenarios has been found to be a reliable way of managing PLA wastes. However, mass recycling of biopolymers is difficult because there is no large-scale infrastructure to do so (Soroudi et al., 2013). Recycling has seen major reductions in the life cycle impacts of bio-based polymers. The decrease in GWP and fossil fuel depletion is accentuated when using biobased feedstocks rather than petroleum-based feedstocks (Meeks, 2015).

For chemical recycling, PLA is hydrolyzed at high temperatures to obtain lactic acid (Mohd-Adnan et al., 2008). Another process is the thermal degradation of PLA into L-lactide, a cyclic dimer, that can be used to make new PLA (Fan, 2004; Fan et al., 2003; Nishida et al., 2005). The lactic acid obtained is pure again and can be used to create new PLA. This process can be seen as cradle-to-cradle because it closes the loop and prevents further resource extraction from the environment (Helfenbein, 2011; Nishida et al., 2005). Currently, chemical recycling of virgin PLA waste generated during polymerization can be proceeded in the production process, but it is also a future option for the recovery of used post-consumer PLA packaging materials (Papong et al., 2014).

Mechanical recycling has been used extensively for petroleum-based plastics and has gained attention for biopolymers such as PLA. Only thermoplastics such as PLA are suitable for mechanical recycling because the polymer chain does not degrade when melted down (Lorber et al., 2015). Lopez established in his experiments that biodegradable bioplastics will have manageable losses in mechanical and thermal properties when recycled up to five times. (Lopez et al., 2012). When recycled, the PLA is tuned into pellets that can be added in 20-50% blend with virgin PLA to reduce the material cost and send less to landfills (Soroudi et al., 2013). Several studies have found mechanical recycling to have the maximum potential for reducing environmental impacts when compared to other waste management strategies (Papong et al., 2014; Rossi et al., 2015).

2.3 Life Cycle Assessments of PLA at EoL:

LCAs that consider PLA at EoL differ in how they determine PLA degradation, how they allocate any electricity production and offsets. Additionally, the final results of environmental effects and which waste management techniques they see as the least harmful to the environment vary. These different methodologies were studied across 13 different LCAs that considered PLA and the results will be outlined below as well as in Tables 1 and 2.

Table 1 - PLA End-of-Life Waste Management Methodologies (NC-Not Considered, NM-Methodology not Specified)

PLA End-of-Life Waste Management Methodologies			
Reference	**Landfill**	**Incineration**	**Anaerobic Digestion**
Hermann et al. (2010)	With gas recovery	With energy recovery	NM
Hermann et al. (2011)	NC	Carbon credits for power and heat generation. 11% of LHV power exported, net export of heat 22% of LHV	40% carbon stored in soil, carbon credits assigned for soil conditioner replacement. 36% electricity generation efficiency. 28% exported. Carbon credits assigned for soil derived electricity displacement
Piemonte (2011)	NC	Energy Utilized but efficiency not mentioned.	85% degradation of PLA and MaterBi assumed. 95% gas recovered. 36% efficiency in converting to electricity
Gironi (2011)	85 % degradation of PLA 25% recovery of gas. 36% efficiency for electricity generation from gas burning	26 MJ of electric and 53.3 MJ of thermal energy from 1000 PLA bottles	NC
Rossi Cleeve-Edwards (2015)	1% degradation of PLA in 100 years, 3.76gCH_4/kg PLA in 100 years, 22% gas recover, 6.1% landfill gas energy into	LHV 19.5 MJ/ kg PLA, substituted electricity by MSWI Production, 0.78kWh/kg PLA, substituted heat by MSWI production 8.25 MJ/kg PLA, sub heat by DFS	85.7 percent carbon degradation, 60% CH_4 and 40% CO_2 in biogas, 17.2 MJ/kg PLA recovered, 397g/kg PLA digestate generated,

PLA End-of-Life Waste Management Methodologies			
Reference	**Landfill**	**Incineration**	**Anaerobic Digestion**
	electricity, and 3% into useful heat	prod 19.5 MJ/kg PLA, 14% net electric, 41.2% thermal efficiencies	credits assigned to peat for compost, heat, and energy, 10 percent emissions for post-digestion composting
Papong (2014)	100 percent degradation, 334 g CH_4/kg PLA, 10% oxidized in the soil. 60 percent methane recovered and combusted, 30% energy efficiency for methane burned	30% electricity efficiency, 20 kWh of electricity are considered for incineration of 1000 PLA Bottles; electricity substitutes the grid electricity of Thailand	NC
Benetto (2015)	NC	not specified	NC
Van der Harst (2013)	not specified, credits given	not specified, credits given	NC
Madival (2009)	not specified, no credits	not specified, no credits	NC
Lorite (2017)	No degradation, no landfill gas to be collected or utilized, no credits (Best Case scenario for GWP)	Incineration of waste plastic as the base, avoided products. 11% of the net calorific value is transformed into electric energy and 23% to thermal energy	NC
Kruger (2006)	no degradation, no gas capture	11% recovery as electricity, 30% as thermal energy. Substitutes European grid	NC

PLA End-of-Life Waste Management Methodologies			
Reference	**Landfill**	**Incineration**	**Anaerobic Digestion**
		electricity, and thermal energy serves as process heat replacing heat generated by 50 percent light fuel oil and 50 percent natural gas	
Ingrao (2015)	NC	NC	NC
Hottle (2017)	37% degradation over 100 years, and no degradation over 100 years. High emission was modeled as an environmental flow rather than estimating a gas capture efficiency and combustion to make high end bounding scenario	NC	NC
EPA (2020) "WARM Tool"	No degradation, no gas capture. Credited for carbon sequestration	Energy value of 0.0176 MBTU/ kg of PLA; 17.8% combustion efficiency, avoided products of electricity produced	NC
Hobbs (2017)	Ecoinvent process of sanitary landfill was used. Landfill gas and leachate collection included	NC	Treated Scenario: Complete Hydrolysis of PLA Untreated Scenario: 53% degradation of PLA

Table 2 - PLA EoL Waste Management Methodologies (NC-Not Considered, NM-Methodology not Specified)

PLA End-of-Life Waste Management Methodologies		
Reference	**Industrial Composting**	**Recycling**
Hermann et al. (2010)	NM	NC
Hermann et al. (2011)	carbon credits for peat and straw replacement, ratio 1:3 ratio	NC
Piemonte (2011)	50% of compost displaces 20% of synthetic fertilizer used for agricultural stage, 60% degradation, 95% of this degrades to CO_2, 5% into CH_4	90% used to make a lower grade product which is incinerated after use or same product.
Gironi (2011)	60% degradation. 95% of this degrades to CO_2, 5% into CH_4	100 percent closed loop recycling with same efficiency as PET 1kg PLA recycled with 90% efficiency
Rossi Cleeve-Edwards (2015)	1kg H20/kg PLA, 80% carbon content degraded fraction in composting 500g C/kg PLA, 1.03 g CH_4/kg PLA, 1464g CO_2/kg PLA, 400g compost/kg PLA, 62g CO_2/kg PLA, long term CO_2 emissions from compost	0.83 ratio of primary to secondary PLA. 8 percent material loss during process, 10 percent quality loss leading to lower ability of substitution of primary material.
Papong (2014)	87% degradation of PLA, 13% remaining used as soil conditioner. Assumes 100 percent of carbon to CO_2 which makes it carbon neutral	90% PLA waste can be converted, 0.6Mj/kg PLA to convert 0.76kgPLA/kg PLA (Chemical recycling)

PLA End-of-Life Waste Management Methodologies		
Reference	**Industrial Composting**	**Recycling**
Benetto (2015)	NC	not specified, no credits
Van der Harst (2013)	not specified, credits given	NC
Madival (2009)	NC	not specified, no credits
Lorite (2017)	100% composting managed as composting of common-biowaste and avoided composts via Ecoinvent	NC
Kruger (2006)	50% fresh compost in an encapsulated system, 50% treated in an open system. Assumed methane and other VOC's are emitted.	NC
Ingrao (2015)	Avoided production of chemical fertilizers such as N .007kg/kg of compost and P .0006kg/kg, K 0.004kg/kg. Compost spreading was not considered	NC
Hottle (2017)	60% carbon degradation, 95% in CO_2, 5% in methane, rest of carbon in compost but credits not mentioned.	NC
EPA (2020) "WARM Model"	100% composting, Avoided fertilizer offset, carbon storage with composting, 52% of compost passive, 0.14MTCO$_2$E/ ton PLA managed	NC

PLA End-of-Life Waste Management Methodologies		
Reference	**Industrial Composting**	**Recycling**
Hobbs (2017)	Untreated Scenario: 6.25% degradation, PLA remaining sent to landfill Treated Scenario: Treated by CSA-Biproduct, Credit for landfill avoidance	NC

2.3.1 Landfilling LCA Methodologies

In many communities landfilling is an obvious inclusion in the waste stream because they are commonly used to dispose of conventional petroleum-based plastics. Of the 15 LCAs assessed, 11 of them considered landfilling at the EoL. Only 7 of these studies specified the assumptions made when modeling landfills and 4 of them considered landfill gas capture as an offset (Gironi et al., 2011; Barbara G. Hermann et al., 2010; Papong et al., 2014; Rossi et al., 2015). The studies that did not, (Kruger et al., 2006), (EPA, 2020) and (Lorite et al., 2017), assumed that there would be no degradation of PLA so there would be no landfill gas to be captured. Kruger et al. (2006) specified that they wanted the best-case scenario in terms of GWP for PLA hence they used no degradation.

Throughout the studies that considered landfilling, models differed because of the PLA degradation expected, the gas capture efficiency, recovery percentage, electricity production and thermal recovery. The degradation of PLA ranged from 0% degradation to 100% degradation. EPA (2020) used 0% degradation and the study by (Hottle et al., 2017), used two different scenarios: One low emission scenario with 0% degradation, and a high emission scenario of 37% degradation to cover the estimates offered by (Krause et al., 2016) and (Kolstad et al., 2012). Rossi et al. (2015) has specified 1% degradation from the estimates by (Kolstad et al., 2012) in addition to (Gironi et al., 2011) specifying 85% PLA degradation. Lastly, (Papong, 2014) who desired a worst-case scenario, assumed 100% degradation with emissions found through stoichiometry. Depending on the system and country they were operating in, the efficiencies used for gas recovery varied between 20% and 60%, and the electrical efficiency between 20% and 40% (Papong et al., 2014; Rossi et al., 2015). For the LCAs that considered the CH_4 capture, (Gironi et al., 2011; Barbara G. Hermann et al., 2010; Hottle et al., 2017; Lorite et al., 2017; Papong et al., 2014; Rossi et al., 2015), burning credits were given to the system by assuming they would need less regional electricity production resulting in less fossil fuel consumption.

2.3.2 Incineration LCA Methodologies

Of the studies considered, 12 of the 15 assessed incineration as a waste management technique. Of these studies, 5 did not specify if credits for electricity were given, or neglected to mention the efficiency and values that were (Benetto et al., 2015; Barbara G. Hermann et al., 2010; Madival et al., 2009; Piemonte, 2011; Van der Harst et al., 2013). Studies by (EPA, 2020), (Gironi et al., 2011) and (Rossi et al., 2015), specified the exact energy values that were provided for a defined amount of PLA. EPA (2020) specified 3.46 Mj of electricity per kg of PLA, Gironi et al. (2011) specifies 26 Mj of electricity and 53.3 Mj of thermal energy from 1000 PLA bottles and (Rossi et al., 2015) specified 19.5 Mj electricity and .78kWh thermal production per kg of PLA. In the LCAs by (Kruger et al., 2006); (Lorite et al., 2017); and (B. G. Hermann et al., 2011), they specified 11% efficiency for electricity generation whereas (Papong et al., 2014) specified 30% efficiency. For thermal energy offsets (B. G. Hermann et al., 2011); (Lorite et al., 2017); and Kruger (Kruger et al., 2006) specified 22, 23, 30% efficiencies respectively. These values were taken as a proportion of PLA's higher heating value.

2.3.3 Anaerobic Digestion LCA Methodologies

Of the studies considered, only 5 studies addressed anaerobic digestion. Barbara G. Hermann et al. (2010) did not outline any specific information on the methodology that was used. (B. G. Hermann et al., 2011) provided credits for the carbon replacement in digestate that would be used for soil remediation. Continuing, they estimated 36% electricity generation efficiency and 28% of the electricity being exported after internally powering the digester. Herman assumed 100% degradation of carbon of PLA with 40% degrading to CO_2, 40% to methane, and 20% remaining in the digestate. Piemonte (2011) assumed that 85% of PLA would degrade, and 95% of the gas would be recovered. It also specified a 36% efficiency in converting to electricity, which would serve as an offset to the process. Rossi et al. (2015) noted an 85.7% carbon degradation with 60% methane and 40% CO_2 in the biogas that was credited. S. R. Hobbs (2017), detailed 53% of PLA degradation in an untreated scenario and used experimental data to outline the emissions from the PLA. Lastly, (Rossi et al., 2015) assigned credit for substituting peat in digestate and added 10% more emissions from burdens for post-digestion composting with 0.11% methane production.

2.3.4 Industrial Composting LCA Methodologies

Of the studies considered, 13 investigated the use of industrial composting in eliminating PLA waste. For most of these studies, credits were given for the compost replacing either fertilizer, or the contents that typically go into fertilizer such as peat and straw. (B. G. Hermann et al., 2011) replaced the peat and straw at a ratio of 1:3. Piemonte (2011) estimated that 50% of compost displaces about 20% of synthetic fertilizer used during the agriculture stage of PLA production and was credited accordingly. B. G. Hermann et al. (2011) and Piemonte (2011) also predicted 60% degradation of PLA where 95% would degrade to CO_2 and 5% into CH_4. Hottle et al. (2017) and Gironi et al. (2011) also used

60% degradation where the 40% that was not degraded would be put into the digestate residue. However, (Hottle et al., 2017) did not give credit to it as a soil fertilizer while (Gironi et al., 2011) and (EPA, 2020) did. Papong et al. (2014) estimated 87% degradation of PLA where the 13% remaining would be credited as soil conditioner and assumed all of the carbon inside was degraded into CO_2. Rossi et al. (2015) supported that 80% of the PLA carbon would be degraded and went a step further to inspect the compost degradation when it is used and identified that it would emit an additional 301g of CO_2/kg of PLA. Lorite et al. (2017) established that 100% of the compost managed would be managed as common biowaste and 100% of the compost would be added as avoided products. EPA (2020) also established that PLA would degrade 100% and used the compost as fertilizer. (Ingrao et al., 2015) avoided the production of a chemical fertilizer of nitrogen, phosphorus, and potassium per kg of compost.

2.3.5 Recycling LCA Methodologies

There are 5 studies that considered recycling at the EoL; and 4 of them specified the methodology used. Piemonte (2011) assumed 90% of PLA could be used to make a lower grade product which would then be incinerated after use. Gironi et al. (2011) assumed a 100% closed loop recycling with the same efficiency as PET plastic with 90% efficiency. Rossi et al. (2015) assumed a 0.83 ratio of primary to secondary PLA with an 8% loss of material during processing and a 10% quality loss leading to a lower ability of substituting primary material. Papong et al. (2014) was the only study that specified a chemical recycling process where 90% of PLA waste could be converted and a 0.76 ratio of new PLA to old PLA could be created. Each of these practitioners used the PLA created from the process as credited to the system.

2.3.6 Environmental Impacts of Waste Management Techniques

As discussed in the previous section, the methodologies vary widely on how to manage PLA biopolymers at EoL. The studies investigated mostly used GWP (normalized to kg CO_2) as well as single score points, or several midpoint indicators to indicate environmental impact. The values that were explicitly stated, or estimated from figures, have been tabulated in the Table 3. However, many of the studies combined the environmental effects from the EoL with the rest of the life cycle, and without separation, EoL impacts specifically, are impossible to identify. Some studies used functional units such as 1000 PLA bottles (Gironi et al., 2011) or 1000 clamshells (Benetto et al., 2015) and in these events, values were converted to reflect those of 1kg of PLA to help aid in comparison. In addition, as with (Gironi et al., 2011) the GWP gave credit to energy production but did not couple the values with the environmental effects and kept them separately, which also affected GWP. Lastly, the credits that were given sometimes reflect production processes that varied earlier in the PLA life cycle.

Owing to these inconsistencies, it is difficult to come up with a definitive expectation of environmental impact that could be expected throughout the EoL processes. Besides EPA (2020) considering the sequestration of the PLA,, the lowest reporting impacts from the landfill process was from (Hottle et al., 2017), with the low emission scenario contributing 0.05 kg CO_2/kg PLA with the highest reporting from (Papong et al., 2014) with 5.07 kg CO_2/kg PLA (without energy recovery). With incineration, the GWP could be expected to be between -0.17 kg CO2/kg PLA as reported from (Papong et al., 2014) to 1.4 kg CO_2/kg PLA as reported from (Gironi et al., 2011). Anaerobic digestion based on the studies can be expected to be between 0.84 kg/ kg PLA CO_2 (B. G. Hermann et al., 2011) and 0.95 kg CO_2/ kg PLA from (Rossi et al., 2015). Industrial composing was found to be anywhere between .064 kg CO_2/kg PLA from (Papong et al., 2014) to 2.5 kg CO_2/kg PLA as reported from (Rossi et al., 2015). Recycling values reported from (Rossi et al., 2015) and (Gironi et al., 2011) are -0.4 and 0 kg CO_2/kg PLA respectively showing that the environmental GWP impact for recycling methods could likely be less than the others.

Due to discrepancies in values between studies, it can be difficult to see the general trends that correlate with which waste management techniques have the least environmental impact. Much of this is determined by the location where these processes take place, and the assumptions that are made. The general trend among these studies is that because of the offsets of reusing the plastic at high efficiency recycling becomes a clear favorite in managing PLA waste at EoL.

Table 3 - GWP Values per 1 kg of PLA (Landfill, Incineration, Anaerobic Digestion)

Global Warming Potential Values per 1 kg of PLA (Landfill, Incineration, Anaerobic Digestion (AD)					
Reference	**Functional Unit**	**System Boundary**	**Landfill**	**Incineratio n**	**AD**
Hermann et al. (2011)	1 kg of PLA	Only waste treatment, excluding use and transportation		1.24 kg CO_2 w/ credits	(GWP) 0.75 kg CO_2 w/ credits
Gironi (2011)	1000 Bottles (12.2 kg)	Waste collection, sorting, and treatment of used bottles	4.66 kg CO_2, - 2.45 MJ energy	1.4 kg CO_2, - 6.63 MJ (produced)	
Rossi Cleeve-Edwards (2015)	1 kg of PLA	Waste collection, transportation, and treatment	0.1 kg CO_2	0.9 kg CO_2	0.95 kg CO_2

Papong, (2014)	1000 Bottles (16.35 kg)	Waste collection and treatment	5.07 kg CO_2 w/o energy recovery , 1.67 kg CO_2 w/ energy recovery	about -0.17 kg CO_2	
Van der Harst, (2013)	PLA Cup	Production, use, transportation, and disposal	Landfilling Less than 2 percent total GWP	about -20 percent GWP	
Ingrao (2015)	1 kg of PLA	Only waste treatment, excluding use and transportation			
Hottle (2017)	1 kg of PLA	Waste collection, transportation, and treatment	Landfill high, 2.75 kg CO_2, Low, 0.05kg CO_2		
EPA (2020)	1 ton of PLA	Transportation, Treatment, Offsets	-1.8 kg CO_2	-6.9E-4 kg CO_2	
Hobbs (2017)	1 kg of PLA and food waste	Collection, Transportation, Treatment, Offsets	About 1 kg CO_2		Treated Scenario: About-0.1 kg CO_2 Untreated Scenario: about 2 kg CO_2

Table 4 - GWP Values per 1 kg of PLA (Industrial Composting and Recycling)

Global Warming Potential Values per 1 kg of PLA (Industrial Composting and Recycling)				
Reference	**Functional Unit**	**System Boundary**	**Industrial Composting**	**Recycling**
Hermann et al. (2011)	1 kg of PLA	Only waste treatment, excluding use and transportation	(GWP) 1.6 w/ credits	
Gironi (2011)	1000 Bottles (12.2 kg)	Waste collection, sorting, and treatment of used bottles	2.57 kg CO_2, 0.285MJ energy	0.37 kg CO_2, -47.2MJ energy
Rossi Cleeve-Edwards (2015)	1 kg of PLA	Waste collection, transportation, and treatment	1.8 kg CO_2	-0.4 kg CO_2
Papong, 2014	1000 Bottles (16.35 kg)	Waste collection and treatment	0.064 kg CO_2	0.0086 kg CO_2
Van der Harst, 2013	PLA Cup	Production, use, transportation, and disposal	about 7 percent of total GWP	
Ingrao, 2015	1 kg of PLA	Only waste treatment, excluding use and transportation	0.22 kg CO_2	
(Hottle, 2017)	1 kg of PLA	Waste collection, transportation, and treatment	0.3 kg CO_2	
EPA (2020)	1 kg of PLA	Transportation, Treatment, Offsets	-9.93E-4 kg CO_2	

Hobbs (2017)	1 kg of PLA and food waste	Collection, Transportation, Treatment, Offsets	Untreated Scenario: About 5 kg CO_2 Treated Scenario: About 5 kg CO_2	

2.4 Discussion:

The reviewed studies differ widely from each other as most, if not all, assumptions about system boundaries, functional units, and allocations vary greatly (Table 3). There were no corrections for the differences in these choices and assumptions as this study was just an attempt to give an overarching view of PLA at the end of its life cycle and how practitioners are managing it. It is also important to note that the databases and information used are vital to LCAs and may create inconsistencies (Van der Harst et al., 2013). These inconsistencies add variability to the studies, especially when methodologies are not clearly specified, which hinders the reliability of LCA studies as a tool that supports decision making. Decision-makers need consistent and well-grounded LCA studies if they are to implement them in their judgement (Van der Harst et al., 2013).

Studies on PLA have reported results that vary substantially, and sometimes these even result in conflicting conclusions on which EoL process is the preference. These discrepancies come from a series of problems discussed in detail in this section. Some of these are related to the assumptions made about the degradation potential of PLA, the system efficiencies, the impact method used, and the overall point of the paper.

In some studies, details on methodological choices are vague, which makes coming to a definitive conclusion as to why inconsistencies exist, difficult. Overall methodology might be addressed, however, details on data sources, allocation methods, and efficiencies are sometimes neglected. Also, as alluded to before, some studies combined final environmental impacts together without separation, making a delineation about the waste management effects impossible. In scenarios where the waste treatments are separated, sometimes the results are reported in single-score units. This does not allow for direct comparison with other studies, but rather overall trends for the treatment methods that were used. Lastly, functional units play a critical role in determining the overall effects of the systems and comparing different functional units can create further variance.

Many practitioners of LCA have focused on gaining most of their information through databases such as Ecoinvent and adjusting these values to fit for their study. However, these values can vary greatly from values that are garnered from site specific data, which again, can create differences. Studies on PLA have used data from NatureWorks, or other published articles. NatureWorks is leading producer of PLA that has published three LCA studies. Each study produced findings that presented a reduction in environmental impact per kg of PLA. Therefore, older studies may overestimate the non-renewable energy use (NREU) and GWP of PLA (Yates et al., 2013).

Allocation makes a large difference in terms of overall environmental impact. Some studies assume worst- or best-case scenarios due to the differences of studies in reporting the actual degradation potential of PLA. These can lead to extremely large emission differentials at the EoL stage. In addition, allocations of electricity production for some studies consider only the offset of the creation of fossil fuel derived electricity while some include the renewable energy credits. Discrepancies can result between studies based on their choice of electricity source for example, the study by (Barbara G. Hermann et al., 2010) used European energy whereas (Gironi et al., 2011); (Piemonte, 2011) have used US grid electricity mix from Ecoinvent.

In summary, there are many sources of discrepancies in LCA, not all which can be attributed to a lack of detail. They include true differences in environmental impact in addition to the differences caused by methodological choices. Depending on system boundaries and the waste management system assessed, the EoL stage can represent less than a 5% change in GWP when compared to the entire production and transportation processes of PLA (Van der Harst et al., 2013). However, EoL processes still play a critical role regionally, where improper and inefficient waste disposal can cause a host of other problems. Additionally, EoL processes can create closed loop systems that can create a drastic reduction in resource extraction. Systems such as recycling, which have been shown to have the least environmental impact, provide a way to reuse polymers to stifle the need for harvesting resources. Another idea that could be presented to decision makers, is to consider both the 100-year, and the long-term impact of scenarios implying long term biodegradation (Rossi et al., 2015).

2.5 Conclusion and Broader Impacts:

This review of the LCA methodologies used to assess PLA at EoL has demonstrated that there exist vast differences in how PLA is managed in these assessments. Due to these discrepancies, only further research on how PLA behaves in waste management systems could help alleviate any incongruencies. Additionally, the differences in methodologies and their resulting impacts doesn't make one LCA study more credible than another. Adjustments must be continuously made to account for differences in factors such as the infrastructure that is available and different climates. Many communities are growing and building new infrastructure in addition to looking for alternatives for conventional petroleum plastics.

CHAPTER 3. METHODOLOGY

3.1 Goal and Scope:

There is an opportunity to evaluate how biopolymer waste can be managed throughout its end-of-life (EoL). An integral part of this is to investigate the environmental impacts of existing and new waste management systems that can manage polylactic-acid (PLA) wastes. In this study, it is assumed that the waste stream of single-use petroleum plastic is replaced with PLA. Hence, the goal of this study is to determine which waste management technique creates the lowest environmental impact and to highlight the biggest influences in the EoL of PLA in Belize. Only the EoL was investigated because in Belize there is a significant amount of waste that is disposed of incorrectly via burning or burying (S. Hobbs, 2018a). Investigating better waste management practices would not only provide a way to help eliminate pollution at EoL but also generate benefits from the biodegradability of PLA. It is assumed that PLA will be divided out of the normal waste stream because Belize implements "Pickers" or, waste sorters, which will allow for materials to be isolated by hand (BSWMA, 2015).

To accomplish this goal, an attributional LCA was used to investigate the global environmental burdens from the relevant flows of the PLA waste management systems. An attributional LCA is an approach where inputs and outputs are attributed to the functional unit of a system by totaling the unit processes of the system (UNEP/SETAC, 2011). Additionally, LCA followed the ISO 14040-44 methodology which includes 4 main steps: Goal and scope definition, inventory analysis, impact assessment, and interpretation.

Even with a consistent methodology, when forming conclusions about LCA, results are often provided in a way that makes comparisons between different studies difficult. Therefore, throughout this LCA it was essential to make values, assumptions and results transparent. The functional unit of this LCA was 1 kg of PLA which allowed a base of reference for waste management systems in this study and worked in parallel with functional units from other studies (Table 3) to allow comparisons. The system boundary begins with transportation of PLA waste from the Belize City transfer station and ending with the offsets and or environmental burdens that are produced by the respective waste management scenarios. This system boundary is outlined in Figure 3.

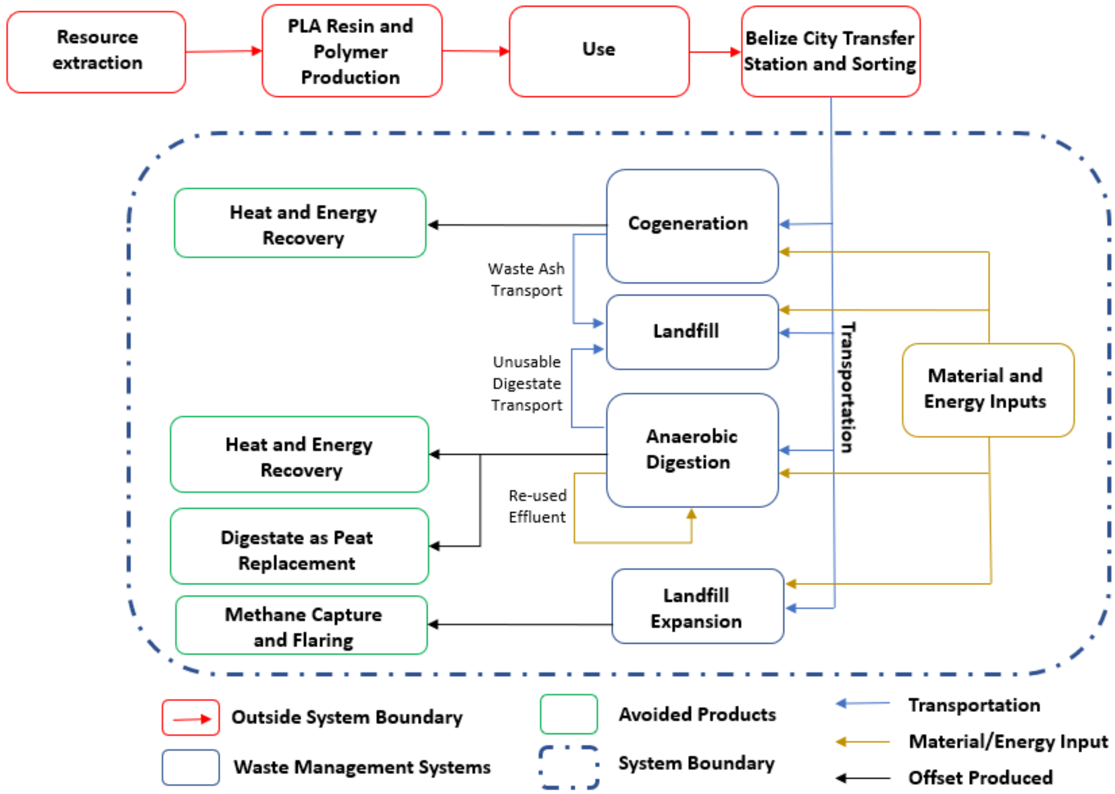

Figure 3 - System Boundary

3.2 Life Cycle Inventory:

The waste management options of cogeneration, landfill, anaerobic digestion and landfill expansion that were considered for this study are outlined in the system boundary in Figure 2. Landfilling and cogeneration were considered because Belize currently has these options available to dispose of wastes. Further, because the Government of Belize plans to incorporate better wastewater management in their communities, anaerobic digestion was considered (Grau et al., 2013). This could provide PLA with another route of disposal in addition to providing electricity, digestate for soil amendment, and disposal of organic wastes. Lastly, a landfill expansion scenario was modeled because Belize plans to make expansions to the existing landfill with the goal of reducing its environmental impact (BSWMA, 2016). Recycling was not considered because there is not a large-scale infrastructure available to recycle PLA (Hottle, 2017). Lastly, composting was not considered because through literature review there were no indications of plans for a large-scale composting facility in Belize. For each of the waste management scenarios that were studied, they require a different inventory of materials and resources for each of the processes.

Sources of information for the materials and resources were provided through the Belize Solid Waste Management Authority (Belize, 2016), NatureWorks (NatureWorks, 2020) and other literature sources that were aimed at quantifying the amount of materials and energy that related to infrastructure in Belize. Ecoinvent V3.0, an LCI database that was accessed through SimaPro V9.0, provided further information on resource requirements and allowed the total emissions for each waste management system to be quantified. Ecoinvent V3.0 is a database that houses the emissions of the resources and is continually updated to ensure accurate data, however, many of the processes used were changed to match the Belize infrastructure as much as possible. For example, the electricity process for the operation of the systems was changed to a Mexico mix to represent the energy that Belize imports from Mexico. To aid in the manipulation of these processes, Microsoft Excel was utilized to house and edit the model. Furthermore, this study focused on the cut-off system model for processes offered by Ecoinvent V3.0. This cut-off model is defined by Ecoinvent as an approach where the production of materials is allocated to the primary user of the material. Continuing, the primary producer does not receive any credit for the provision of any additional offsets which ensures that the waste management systems in this study will receive the credits for any offsets produced (Ecoinvent, 2020). Further details on the changes that were made, and all of the Ecoinvent processes that were used are available in Appendix 1. The values for the degradation of PLA and the offsets produced in the different waste management systems were detailed from literature sources including (S. Hobbs, 2019; Krause et al., 2016; Yagi et al., 2009). Details of the systems and their assumptions are outlined below.

3.2.1 Landfill

To model the landfill system, an inventory of the resources that were needed by the system was created as opposed to changing the default landfill processes in the Ecoinvent V3.0 database. This ensured that the landfill model did not include any technology that is unavailable in Belize such as landfill gas collection and energy production. Several sources were used to find the different types and amounts of materials that were used to construct and operate the landfill in Belize. Information from BSWMA provided information on the acreage of the site, 270 acres, and waste cell, 5 acres (Authority, 2021). Furthermore, it detailed the use of geotextiles and liners as well as the total amount of waste that arrived at the landfill per month on average in 2019 as shown in Table 5 (Authority, 2021). Next, the Government of Belize outlined the 15-year expected lifetime of the project (BSWMA, 2016), and the APWC detailed the percentage of plastic waste that was collected in the landfill (Petterd et al., 2019). This helped delineate the total input of waste transported to the landfill and helped define the burden that would result from PLA waste. Lastly, the Government of Belize detailed information on the depth of waste cells and the typical landfill cell lining system that was used (BSWMA, 2016). Ecoinvent V3.0 values from landfills were used to help determine the operational requirements of electricity and fuel. Google Earth was used to estimate transportation distances using a 21 metric ton landfill process in Ecoinvent V3.0.

Table 5 - Flow of Solid Waste to Landfill (Adapted from BSWMA, 2019)

Flow of Solid Waste to Landfill in 2019		
Month	**Total Metric Tons to Landfill**	**Total Tons of Plastic to Landfill**
Jan-19	4099	778
Feb-19	3081	586
Mar-19	3131	595
Apr-19	3219	611
May-19	3450	656
Total	**16980**	**3226**
Average Per Month	3382	643
Average Per Day	113	22

In addition to the landfill infrastructure requirements, PLA degradation was assessed. The degradation of PLA in the landfill environment would result in air emissions such as methane (CH_4). The baseline percentage of degradation used was 0% as offered from Kolstad, 2012. Additionally, the uncertainty analysis assessed an uncertainty presented by (Kolstad, 2012), with 37% of PLA being degraded in thermophilic landfill conditions. As described before, thermophilic temperatures are above 55 °C, which landfills in hot environments, such as Belize, are known to reach (Grillo, 2014). The theoretical ultimate methane potential per kg of PLA was 467 liters (at standard temperature and pressure) of methane stoichiometrically (Equation 1), therefore there would be 172 liters of methane emitted per kg of PLA that is landfilled if 37% degraded. This landfill process did not include any gas capture, so it received no credit for energy production.

$$C_6H_8O_4 + 2H_2O \rightarrow 3CO_2 + 3CH_4$$

Equation 1 - Theoretical Methane Generation Potential of PLA from Stoichiometric Reaction

Combining the inventory from the infrastructure and degradation of PLA, led to the creation of a landfill process with the total amount of resource requirements and emissions that would be produced by the landfilling system throughout its lifetime. These totals were then normalized into the resource requirements and emissions that results from managing 1 kg of PLA.

3.2.2 Landfill Expansion

The modeling of the landfill expansion system was created using an inventory of the various resources that were needed by the system as opposed to changing the default landfill processes in the Ecoinvent database. This ensured that the landfill expansion that was modeled did not include any technology that is unavailable in Belize such as energy production. The Government of Belize provided information on the acreage of the expansion, and the volume of the new waste cells (BSWMA, 2016). The same details of landfill cell lining systems provided for the original landfill were used. The APWC detailed that the expected lifetime of the landfill expansion would be 66 years due to the larger capacity than the original landfill process (Petterd et al., 2019). Continuing, it was assumed the percentage of wastes that was plastic assumed to be the same as the original landfill at 19%.

The values of PLA degradation remained the same as in the original landfill with PLA degrading 0%. However, the landfill expansion included the addition of landfill gas capture and flaring. To account for the infrastructure required, a steel extrusion process was used to estimate the environmental burden of the incinerator. Additionally, a CH_4 capture efficiency of 60% was used (EPA, 1997). CH_4 emissions from the PLA are flared into CO_2 that is released into the atmosphere.

Correspondingly to the original landfill, the inventory of infrastructure and degradation of PLA led to the creation of a landfill expansion process with the total number of resource requirements and emissions that would be produced by the operation throughout its lifetime. These totals were then normalized into the resource requirements and emissions that results 1 kg of PLA.

3.2.3 Cogeneration

The cogeneration model was created using a combination of literature and assumptions using Ecoinvent V3.0 processes. Cogeneration is similar to incineration however there is heat that is recovered from the process in addition to electricity. The cogeneration plant in Belize is centered around the burning of bagasse residuals from sugarcane production. For infrastructure, an Ecoinvent V3.0 process, "Bagasse, from sugarcane (RoW) | treatment of, in heat and power co-generation unit, 6400kW thermal | Cut-off, U", that used a 6400 kW heat and power cogeneration unit was used as this was the same unit that was used in the cogeneration system in Belize (Harris, 2010). Additionally, an Ecoinvent process containing the cogeneration building was included to account for the rest of the site's infrastructure resource requirements.

Estimates of the amount of chemicals that were required to incinerate bagasse, wood and plastic were able to be modeled in Ecoinvent V3.0 by making them a function of the amount of energy that was produced by the feedstocks. Therefore, the same equation was used as the rest of the processes based on the lower heating value (LHV) of PLA. The emissions of water, CO, CO_2 and residuals that resulted from the incineration of PLA was provided by (NatureWorks, 2020). The residues that resulted from burning PLA were sent to the landfill.

The energy efficiency of 84% was established for the cogenerator as well as an electrical efficiency of 14% (Kamate, 2009). NatureWorks (2020) provided the LHV of PLA which was 3795 (BTU) per kg of PLA. Offsets from energy production were accounted by assuming that electricity produced during the process would replace the electricity that is typically imported from Mexico to Belize.

3.2.4 Anaerobic Digestion

There are no existing anaerobic digesters at the wastewater treatment plant in Belize, however, there were plans to advance Belize's water resources infrastructure that could include an anaerobic digestion (Grau et al., 2013). Therefore, Ecoinvent processes were used to model and predict what using an anaerobic digestion system would look like with PLA as a feedstock along with municipal sludge in an anaerobic digester. An Ecoinvent process called, "Anaerobic digestion plant, for sewage sludge (RoW)| construction | Cut-off, U" was chosen that has a capacity of 1400 m^3, a lifetime of 25 years, and mesophilic temperatures (Jungbluth, 2007). The material requirements for this system were also referenced from Ecoinvent as the main components to build the anaerobic digester and its facility (Jungbluth, 2007).

The methane potential for the PLA in the industrial anaerobic digestion system was scaled up to industrial size based on the studies from (S. Hobbs, 2019; Yagi et al., 2009). They described values of PLA degradation under mesophilic temperatures and concluded that the degradation percentage would be between 50% and 55% with a retention time of 30 days. This translates to around 234 L of CH_4 being produced during the process with an ultimate methane potential of 467 L.

The amount of pretreatment, sodium hydroxide (NaOH), that would be required was based on studies from (S. Hobbs, 2019). Additionally, an equal amount of hydrochloric acid (HCl) was assumed to be needed to balance the pH of the anaerobic digester sludge (S. Hobbs, 2018b, 2019). The energy requirements for heating the anaerobic digester was based on the heat capacity equation shown in Equation 2. In this equation it was assumed the sludge had the same heat capacity of water. The energy that can be produced via the anaerobic digestion process is based on the percentage of methane in the biogas produced. Methane contains 10 kwh of energy per m^3. It was estimated that around 60% of the gas in biogas is CH_4 (Dayton et al., 2020). Therefore, 6 kwh of energy per cubic meter of biogas was estimated. The CO_2 in the biogas does not provide any heat or electricity. Additionally, the energy efficiency of the burning of biogas was assumed to be 30% (Papong, 2014). The amount of digestate that was created was assumed to be the PLA that was not degraded, and this was sent to the landfill. The energy efficiency was further assessed in the sensitivity analysis to further assess its effects on the waste management system.

$$Q = mc\Delta T$$

Where:

$$Q = Heat\ [J]$$
$$m = Mass\ [kg]$$
$$c = Specific\ Heat\ Capacity\ \left[\frac{J * K}{kg}\right]$$
$$\Delta T = Change\ in\ Temperature\ [K]$$

Equation 2 - Heat Capacity Equation

3.3 Life Cycle Impact Assessment:

The life cycle impact assessment is aimed at classifying, characterizing and weighting the environmental impacts of the inventory items to their environmental impacts. In some environmental conditions (anaerobic environments) PLA may not degrade or may release CH_4 which results in positive greenhouse gas emissions (Hottle et al., 2017). In this study, for the baseline scenario, biogenic carbon in PLA was considered to be CO_2 neutral and excluded from environmental burden (Pawelzik et al., 2013). The unit impacts from the inventory items were provided through the use of the ReCiPe 2016 Hierarchist model in SimaPro V9.0. The unit impacts were totaled in Microsoft Excel to find the total environmental effects of the waste management processes. ReCiPe 2016 was utilized because it is typically used in scientific models and the impacts from this method are investigated outside of the United States where many stakeholders of this project are located (Huijbregts, 2016). Additionally, this method provides 18 impact categories that allow detailing of specific environmental impacts caused by the processes. These midpoint indicators are not classified into the endpoint indicators because the midpoint impacts are normalized into units of each impact category, outlined in Table 4, which makes comparison between studies possible. A description of the 18 midpoint indicators that were assessed are outlined below.

Table 6 - Impact Category Normalization Units (Adapted from Huijbregts, 2016)

Impact Category Normalization Units	
Impact category	**Unit**
Global warming	kg CO_2 eq
Stratospheric ozone depletion	kg CFC11 eq
Ionizing radiation	kBq Co-60 eq
Ozone formation, Human health	kg NOx eq
Fine particulate matter formation	kg PM2.5 eq
Ozone formation, Terrestrial ecosystems	kg NOx eq
Terrestrial acidification	kg SO_2 eq
Freshwater eutrophication	kg P eq
Marine eutrophication	kg N eq
Terrestrial ecotoxicity	kg 1,4-DCB
Freshwater ecotoxicity	kg 1,4-DCB
Marine ecotoxicity	kg 1,4-DCB
Human carcinogenic toxicity	kg 1,4-DCB
Human non-carcinogenic toxicity	kg 1,4-DCB
Land use	m2a crop eq
Mineral resource scarcity	kg Cu eq
Fossil resource scarcity	kg oil eq
Water consumption	m3

- Global Warming – The GWP is calculated by the total amount of radiation caused by 1kg of greenhouse gas (GHG) emissions. This expresses the amount of additional energy that is absorbed by an emission of 1kg of GHG relative to the energy absorbed over that same time, caused by the release of 1 kg of CO_2. This may create environmental burdens, such as sea level rise in addition to burdens on humans and the environment (Agency, 2021; Steinmann et al., 2020)

- Stratospheric ozone depletion – Manmade chemicals that contain fluorine, brome, and chlorine groups can increase the rate of ozone destruction in the stratosphere. The stratosphere functions to absorb UV radiation from the sun and increasing its rate of destruction can cause the ozone layer to thin and have adverse effects on human health and ecosystems (Steinmann Zoran et al., 2020b).

- Ionizing radiation – Ionizing radiation is created when radionuclides decay. Radionuclides may be ingested by humans or dissolved in water due to human activity, such as the burning of fossil fuels. This can cause the DNA of organisms to be altered. The unit kBq Co-60 is used to denote the number of atom nuclei that decay per second (Steinmann Zoran et al., 2020a).

- Human health/Terrestrial Ecosystems Ozone formation – Ozone formation starts with an emission of NOx to the atmosphere where these substances are formed into ozone. The tropospheric ozone can be inhaled by humans or taken up by plants, leading to mortality in humans as well as damage to terrestrial ecosystems (Rosalie van Zelm et al., 2020).

- Fine particulate matter formation – Particulate matter formation begins with NOx, NH_3, SO_2, or primary PM2.5 to the atmosphere. These substances are then transformed into secondary aerosols that can be inhaled and negatively affect human health (Rosalie van Zelm et al., 2020).

- Terrestrial acidification – Acidification marks changes in soil chemical properties by the deposition of nutrients, such as nitrogen and sulfur in acidifying forms. This can cause adverse effects, including the decline of the soils pH. This effect can lead to an increase in plant tissue yellowing and reducing photosynthesis rates (Ligia B. Azevedo et al., 2020).

- Freshwater/Marine eutrophication – Discharge of nutrients into soil, freshwater bodies and marine environments can cause a rise in nutrient levels (such as phosphorus and nitrogen). The excess nutrients are utilized by autotrophic organisms which can result in a decrease in (Azevedo et al., 2020).

- Marine/Freshwater/Terrestrial ecotoxicity – Hundreds of chemicals are emitted during industrial processes which may be toxic to humans or ecosystems. Ecotoxicity measures the fate of chemicals and the toxicity related effects that result from them (Fantke et al., 2020).

- Human carcinogenic toxicity – Hundreds of chemicals are emitted during industrial processes which may be toxic to humans or ecosystems. Human carcinogenic toxicity measures that amount of substances with strong evidence for carcinogenicity (Fantke et al., 2020).

- Human non-carcinogenic toxicity - Chemicals emitted during the processes may contain hundreds of toxins which can have impacts on humans or ecosystems. Human non-carcinogenic toxicity concerns the fate of chemicals and the toxicity related effects that result from them that are not carcinogenic (Fantke et al., 2020).

- Land use – Land use is a main cause of biodiversity loss. During transformation and occupation of land, environments are modified and used so that it cannot develop towards its natural state (Abhishek Chaudhary, 2020).

- Mineral/Fossil resource scarcity – Minerals and fossil fuels extracted from the environment can cause resource shortages especially when their demand is increasing (Mark A.J. et al., 2020).

- Water consumption – Water consumption in processes decreases water's availability for other uses such as agriculture and drinking which may result in human health impacts such as malnutrition or environmental burdens.

3.4 Interpretation:

All interpretations made were within the ISO 14040-44 standards where interpretation should be constantly evaluated with the goal and scope of the study to remain consistent throughout the impact assessment (ISO, 2006). These standards also require a completeness and sensitivity check, while also ensuring that the same iterative steps are used throughout the project to maintain transparency (ISO, 2006). Uncertainty analysis (using Monte Carlo methods) and sensitivity analysis were executed in Microsoft Excel, using Oracle Crystal Ball. The variables being assessed, including the degradation rates of PLA, were randomized within the ranges outlined in Table 7. These ranges of values were randomly entered into the model in 10,000 different iterations to record differences in the final impacts and detail the uncertainty. Using Spearman's rank correlations to rank the 10,000 combinations of the variables used in the uncertainty analysis, the sensitivity analysis was performed. This served to help identify the impacts that the variables had on the system, and ensured the results were robust so meaningful conclusions could be drawn. The results from the sensitivity and uncertainty analysis were used to compare the environmental impacts of each PLA waste management technique and highlight notable influences in the effects and how they can be improved. Furthermore, the hypotheses of this study were tested using a Wilcoxon signed rank test which also ranked 100 different iterations of the uncertain variables (keeping the transportation distances the same between the waste management systems) to determine the acceptance or rejection of the hypotheses. Conclusions formed with this information can prove invaluable for BSWMA, as this could provide better insight to the GWP effects of managing large amount of PLA waste.

Table 7 – Table of Uncertainty and Sensitivity Analysis Parameters

Uncertainty and Sensitivity Analysis Parameters						
Parameter	Unit	Waste Management System	Distributions	Minimum Value	Maximum Value	Citation
Biogas to Electricity Efficiency	%	Anaerobic Digestion	Uniform	0.24	0.36	(Kolstad, 2010; Krause and Townsend)
Distance from AD to Landfill	km	Anaerobic Digestion	Uniform	28.0	42.0	Google Earth
Distance from Belize City Transfer Station	km	Anaerobic Digestion	Uniform	12.0	18.0	Google Earth
Electricity to heat efficiency	%	Anaerobic Digestion	Uniform	0.24	0.36	Kamate, 2009
Percentage Degradation	%	Anaerobic Digestion	Uniform	0.50	0.55	(Hobbs, 2019; Yagi, 2009)
Distance from Cogen to landfill	km	Cogeneration	Uniform	56.0	84.0	Google Earth
Distance from Belize City Transfer Station	km	Cogeneration	Uniform	56.0	84.0	Google Earth
Electrical Efficiency Cogen	%	Cogeneration	Uniform	0.14	0.28	Kamate, 2009
Energy Efficiency Cogen	%	Cogeneration	Uniform	0.84	0.92	Kamate, 2009
Distance from Belize City Transfer Station	km	Landfill Expansion	Uniform	32.0	48.0	Google Earth Estimation
Percentage Degradation of PLA (decimal) Expansion	%	Landfill Expansion	Uniform	0.00	0.37	(Kolstad, 2010; Vargas, 2009)

Percentage of Methane into air (Decimal) Expansion	%	Landfill Expansion	Triangular	Min: 0.15 Average: 0.25	0.40	EPA, 2002
Distance from Belize City Transfer Station	km	Landfill	Uniform	32.0	48.0	Google Earth Estimati on
Percentage Degradation of PLA (decimal) Landfill	%	Landfill	Uniform	0.00	0.37	(Kolstad , 2010; Krause and Townse nd, 2016)

CHAPTER 4. RESULTS AND DISCUSSION

4.1 Contribution Analysis:

The contributions from the material, operation, and transportation requirements of the waste management systems are outlined in Figures 4-6. The operational requirements of the waste management systems were the main contributors for most impact categories. Reducing these energy requirements while maximizing the offsets produced will provide environmental benefits throughout the waste management systems. The transportation requirements contributed larger percentages to the terrestrial, freshwater and marine ecotoxicity burdens because of the emissions that are related to transporting wastes. Furthermore, transportation impacts had a larger proportion of environmental impact on all of the environmental impact categories of the landfill and landfill expansion systems. This is due to the relatively small operational requirements of the landfill and landfill expansion processes.

The environmental burdens of building the infrastructure and collecting the materials are minimal as compared to the operational and transportation requirements of managing their PLA waste. For most of the waste management systems, the material requirements contribute less than 15% to the burdens of the environmental impact categories. The impact categories that were more affected by material requirements were the water consumption and mineral resource scarcity. The water consumption impacts are catalyzed by upstream processes from the production of materials such as plastic liners for the landfills. Additionally, the mineral resource scarcity is highly impacted by the processes of the heat and power cogeneration infrastructure.

Despite identifying the trends of percent contributions that can be expected from the material, operation, and transportation requirements of the systems, comparisons were still made between the waste management systems with the offsets that are produced included. Totaling the environmental impacts from all aspects of the waste management systems allows conclusions to be drawn on the environmental impact that could be expected from the waste management scenarios when managing PLA waste.

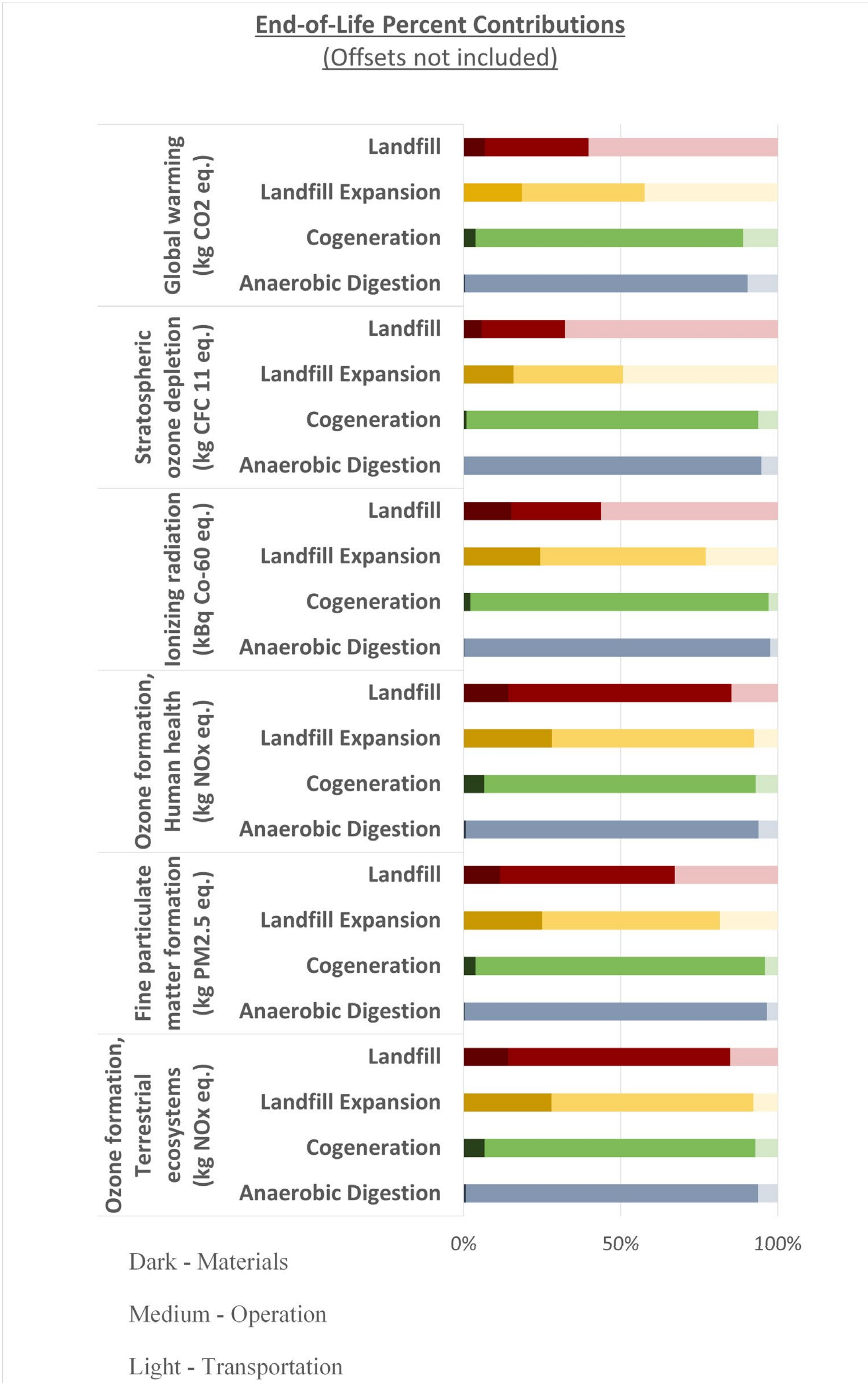

Figure 4 - End-of-Life Contribution Analysis

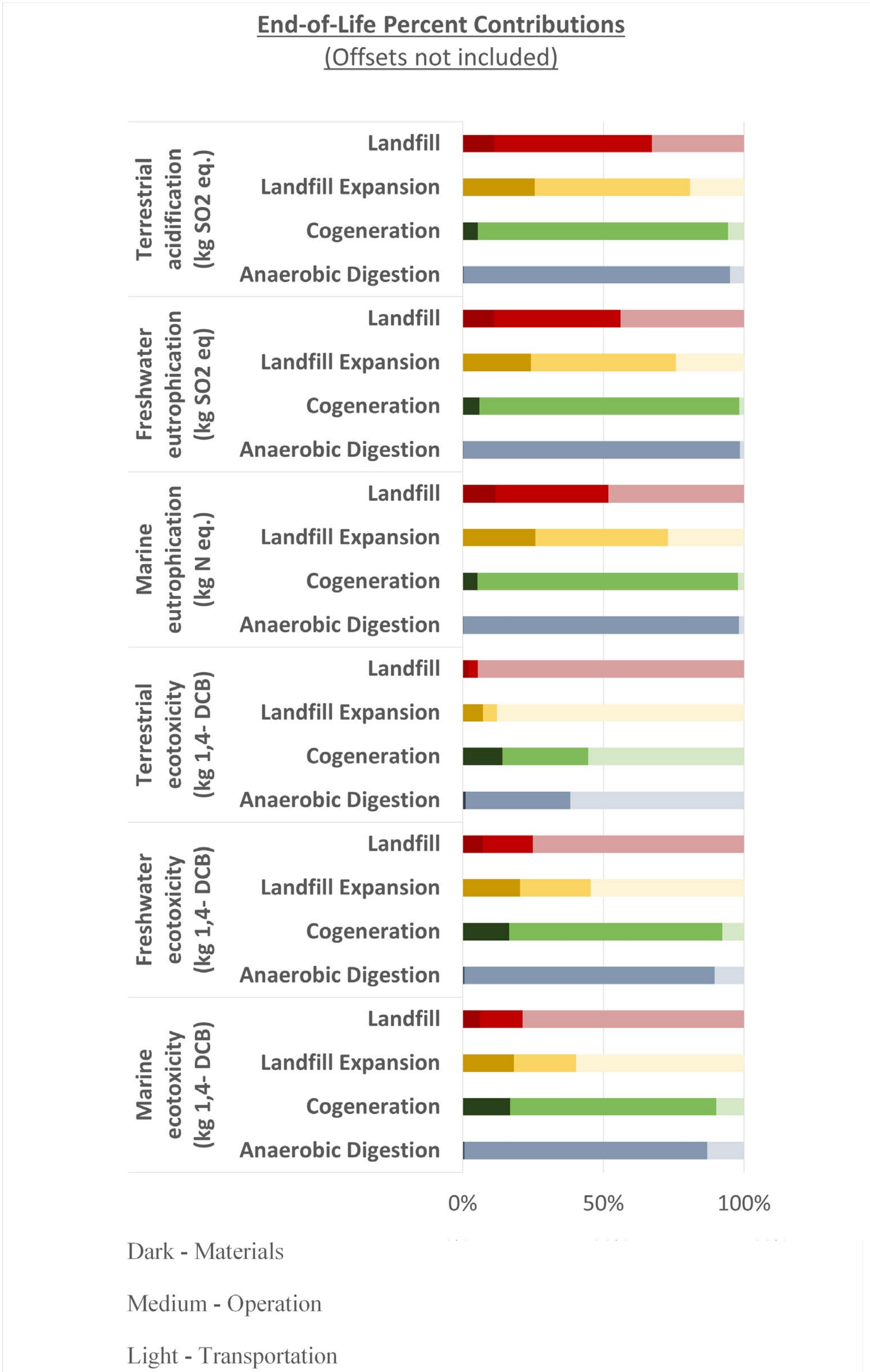

Figure 5 - End-of-Life Contribution Analysis

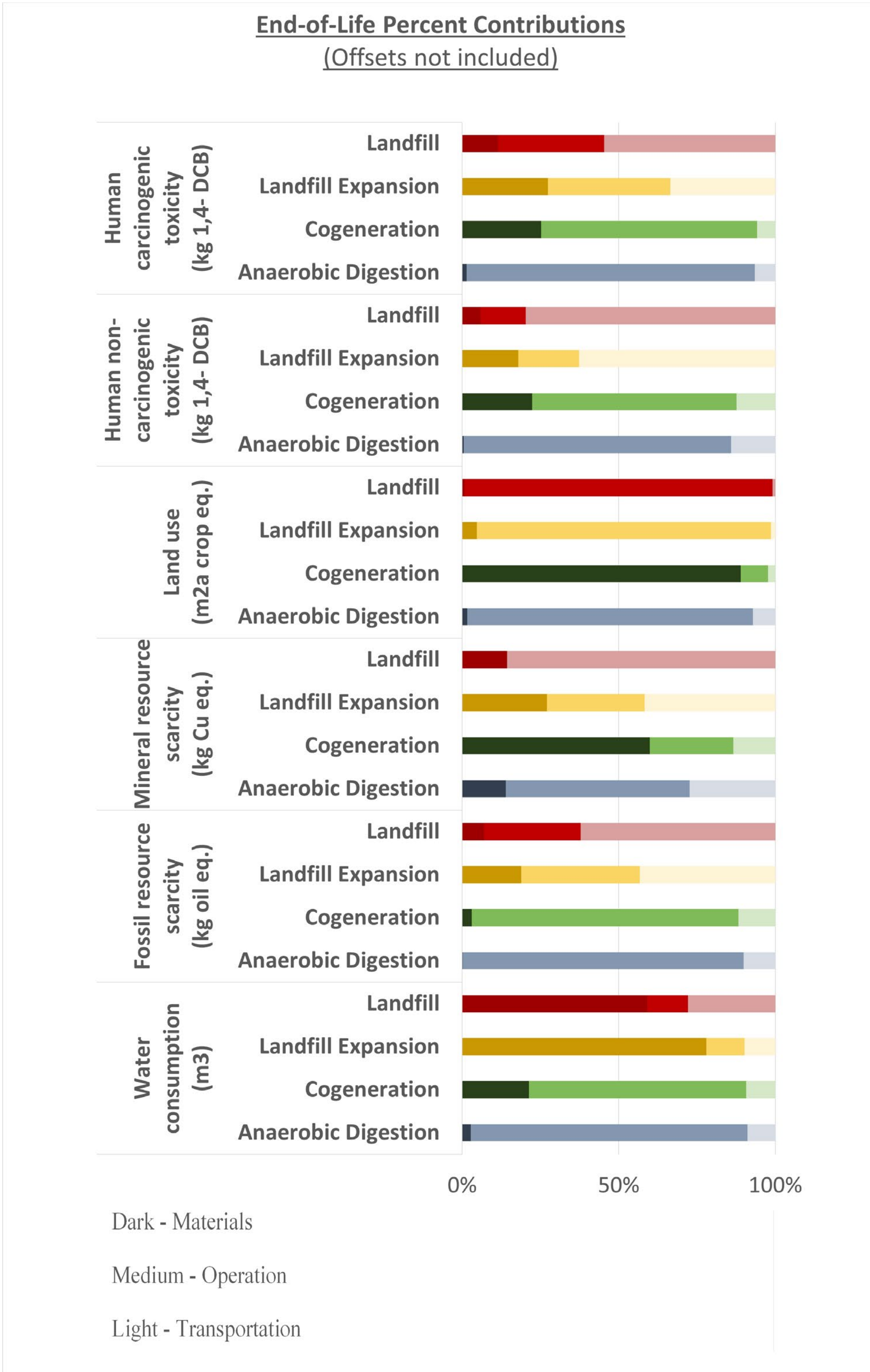

Figure 6 - End-of-Life Contribution Analysis

4.2 Comparison of Waste Management Alternatives:

For each of the 18 environmental midpoint ReCiPe categories (outlined in Section 3.3) the environmental impacts of the waste management systems were compared to each other when managing the functional unit of 1 kg of PLA (Figures 5-20). The green error bars in Figures 5-20 show the lower 5% and top 95% of values that were calculated during the uncertainty analysis (outlined in Table 7) and are discussed in more detail in Section 4.3. Additionally, a negative value for the environmental impact indicates that there are environmental benefits in using the waste management system. Most studies surrounding the EoL of PLA focus on carbon footprint and GWP and the other impact ReCiPe midpoint categories were not previously studied. Therefore, comparisons between other studies was limited to the GWP impact category.

Throughout the 18 environmental impact categories, anaerobic digestion had the lowest net environmental impact in each category. Furthermore, the anaerobic digestion system provided a net environmental benefit in all 18 of the categories except for land use. The environmental benefits are a result of the biogas that is produced during the process that outweighs the electricity requirements of operating the system and heating the digester. The cogeneration process requires a high amount of energy for operation, however, the offset of electricity and heat that it produces often results in a net environmental benefit in many of the impact categories as well. The landfill expansion process has a larger environmental impact than the landfill process in most of the impact categories because of the additional operational energy requirements that the landfill does not have. The details for each of the 18 environmental impact categories are outlined below with insight also garnered from Figures 4-6 to help explain the comparisons of the waste management systems.

4.2.1 Global Warming Potential

The GWP impacts from the waste management systems that were studied were compared (Figure 7). The landfill and landfill expansion processes both had a GWP of 0.01 kg of CO_2 eq. per kg of PLA compared to the cogeneration and anaerobic digestion processes -0.03 and -0.06 kg of CO_2 eq. per kg of PLA respectively. In the baseline scenario this impact is due to the operational requirements of the systems when the degradation of PLA was assumed to be 0%. This assumption corresponds with (Lorite et al., 2017), (Kruger et al., 2006) and, (EPA, 2020) that also asserted that crystalline PLA would not degrade in the landfill.

The cogeneration scenario resulted in the complete combustion of the PLA. The impact from this scenario resulted from the operational burdens of the system. However, some the burdens were offset by the heat and electricity produced from the burning of PLA. This production of electricity was assumed to offset the energy that Belize imports from Mexico.

Similar effects to the cogeneration process were shown in the anaerobic digestion processes. Its GWP resulted from the heat and energy requirements of the anaerobic digestion plant. These requirements were offset by the production of biogas; however, the fraction of the PLA that was not degraded was sent to the landfill. The biogas from the process is credited towards energy production which created an environmental benefit.

Compared to literature, the GWP predicted for the landfill and landfill expansion model were consistent within the range of values determined from other studies (Hottle, 2017; Rossi-Cleave, 2015). These studies predicted a 0.05 kg CO_2 eq. per kg of PLA and a 0.1kg CO_2 eq. per kg of PLA for each scenario where PLA did not degrade. The cogeneration process followed similar trends from other studies as well showing it to produce a benefit in terms of GWP (Papong 2011; Van Der Harst 2012). The anerobic digestion process resulted in GWP values less than those observed by (B. G. Hermann et al., 2011) and (Rossi et al., 2015). Rossi et al., (2015) predicted a 0.95 kg CO_2 eq per kg of PLA compared to this studies -0.06 kg CO_2 eq per kg of PLA. This difference can be attributed to longer transportation distances used from Rossi et al., (2015) and additional emissions that resulted from PLA degradation from post digestion composting that was not considered in this study.

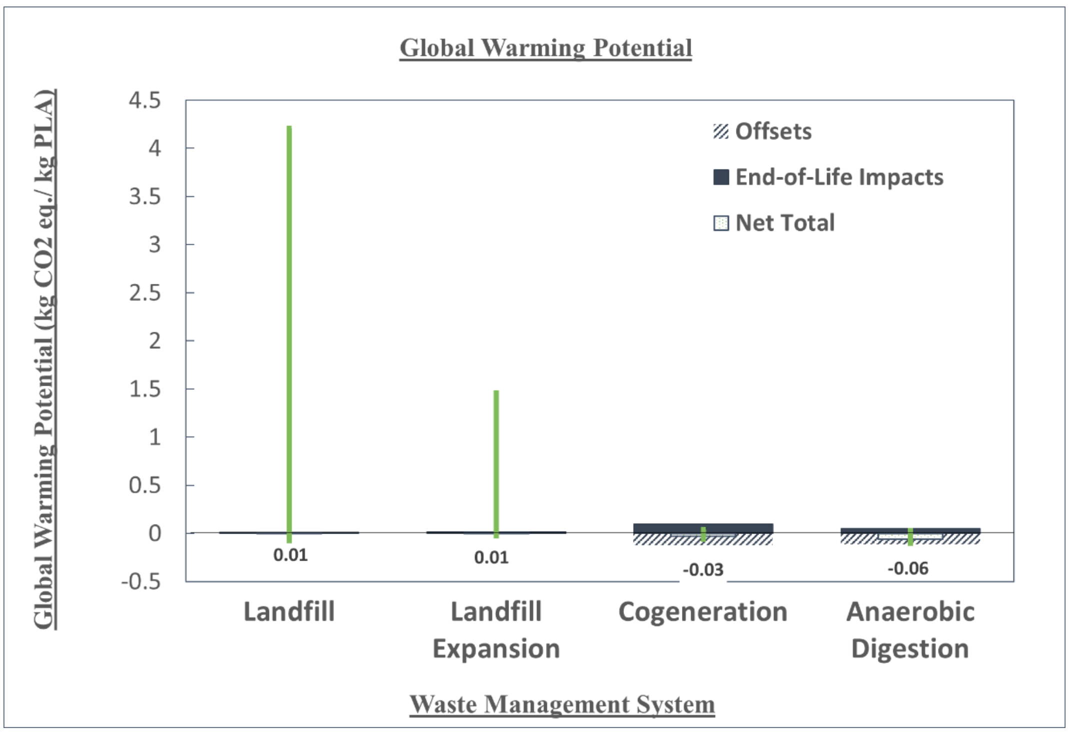

Figure 7 - Global Warming Potential Impacts

Green Error Bars represent 5th/95th percentile of Net Totals, EoL Impacts include burdens from Materials, Operation, and Transportation. Offsets include Electricity, Heat, and Burdens from Residuals. The values shown are the Net Total of the base scenario's Offsets and EoL Impacts

4.2.2 Stratospheric Ozone Depletion

The stratospheric ozone depletion impact category of the waste management systems is outlined in Figure 8. The anaerobic digestion process was the most favored because the offsets produced outweighed the initial heat and electricity requirements that caused most of its potential stratospheric ozone depletion burdens. The cogeneration process faced greater initial burdens from transporting the PLA and its own energy requirements. The landfill and landfill expansion processes had smaller impacts than the cogeneration and anaerobic digestion processes when offsets are not considered. This is due to low operational requirements with less electricity and diesel fuel required to manage the wastes; however, landfill and landfill expansion were had larger net burdens because they do not produce any offsets.

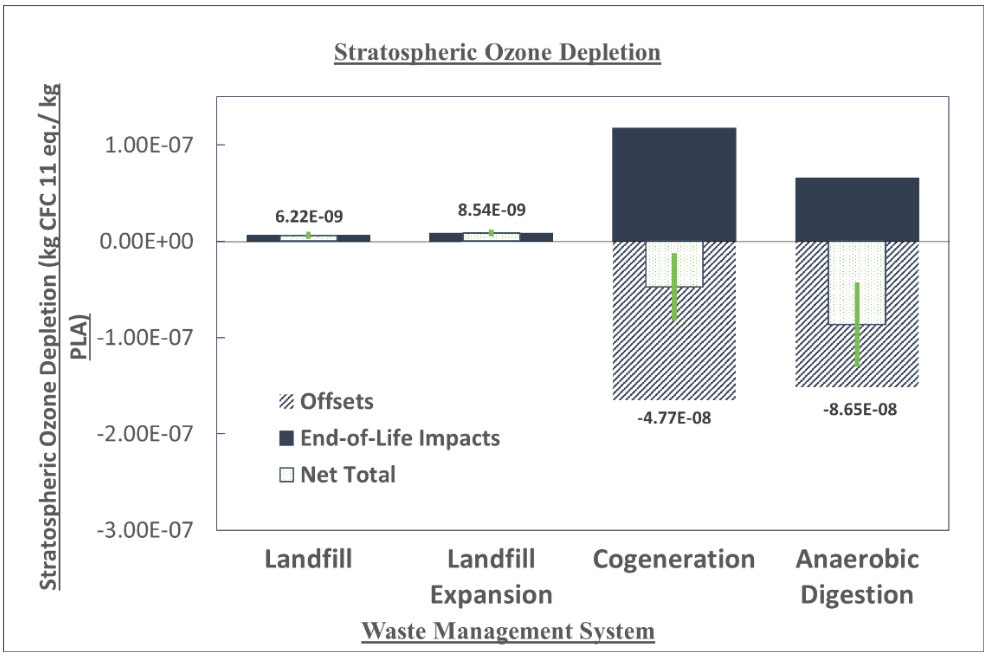

Figure 8 - Stratospheric Ozone Depletion Impacts

Green Error Bars represent 5th/95th percentile of Net Totals, EoL Impacts include burdens from Materials, Operation, and Transportation. Offsets include Electricity, Heat, and Burdens from Residuals. The values shown are the Net Total of the base scenario's Offsets and EoL Impacts

4.2.3 Ionizing Radiation

Figure 9 shows the burdens in the ionizing radiation impact category for the waste management systems. The landfill expansion process resulted in the greatest ionizing radiation potential. More than 50% of this impact resulted from the burdens of the operation of the landfill and the additional energy and infrastructure requirements for capturing the CH_4 produced. The landfill process had the next highest ionizing radiation potential with more than half of the impact coming from the transportation of PLA. The anaerobic digestion process has would provide an environmental benefit in this category because of the biogas that is produced. Similarly, the cogeneration system produces heat and energy which outweighed the operational burdens that created most of its burdens.

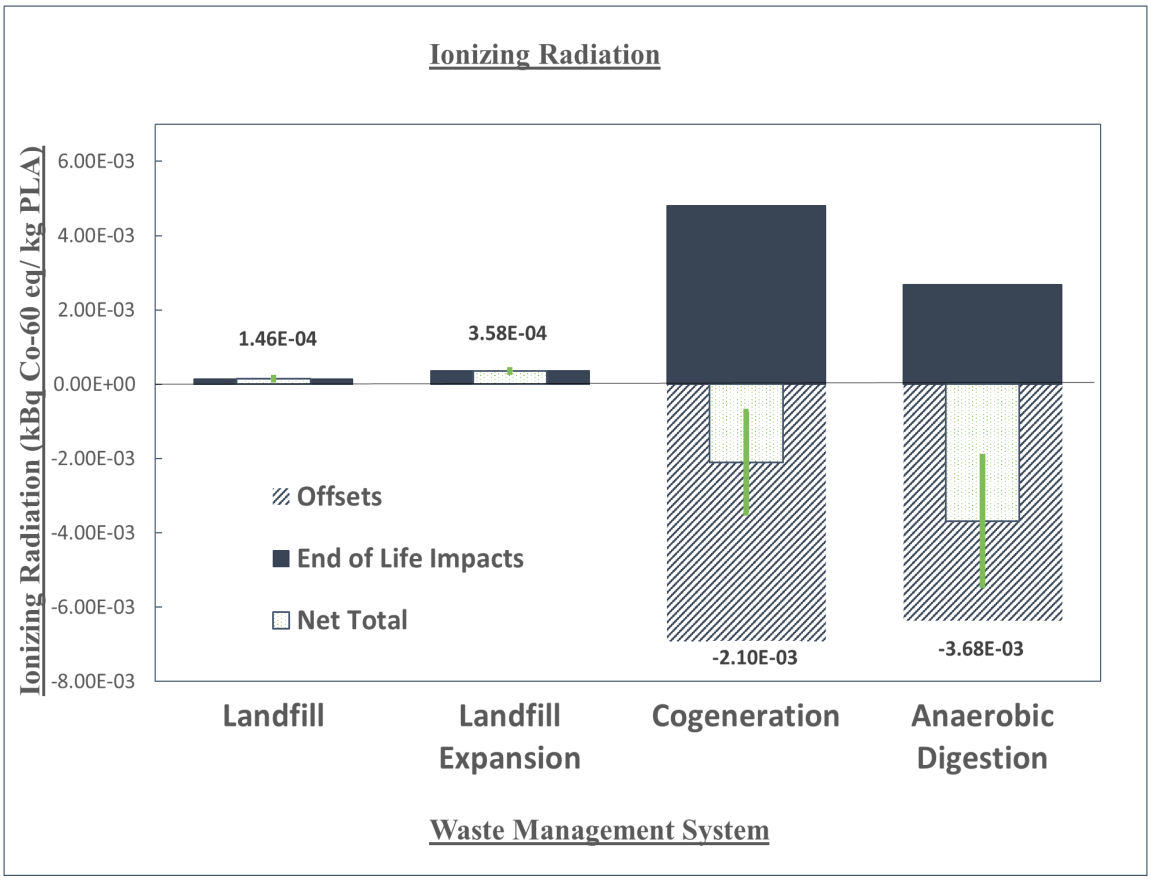

Figure 9 - Ionizing Radiation Impacts

Green Error Bars represent 5th/95th percentile of Net Totals, EoL Impacts include burdens from Materials, Operation, and Transportation. Offsets include Electricity, Heat, and Burdens from Residuals. The values shown are the Net Total of the base scenario's Offsets and EoL Impacts

4.2.4 Ozone formation, Human Health and Terrestrial Ecosystem

The ozone formation impacts on human health from the waste management systems is shown in Figures 10. Ozone formation, human health and terrestrial ecosystem followed the same trend and had similar values. Through these impacts it is apparent that the combustion of diesel fuels has a large impact on the ozone formation potential. The landfill and landfill expansions processes faced large contribution from the diesel burdened when compacting the wastes inside the landfills which was the largest burden for their ozone formation potential. For the anaerobic digestion system and the cogeneration system, the negative effects that are derived from their operational burdens were outweighed by the offsets that were produced. The anaerobic digestion process was had the largest environmental benefit of the waste management systems investigated.

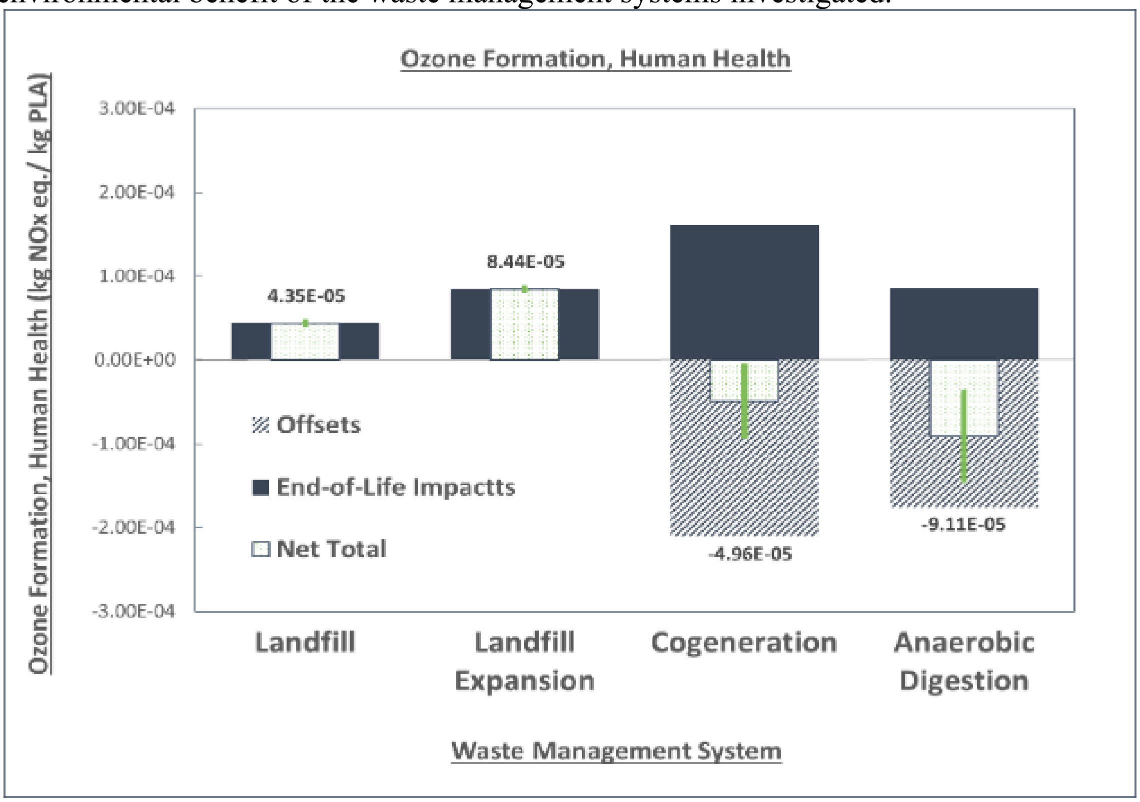

Figure 10 - Ozone Formation Impacts

Green Error Bars represent 5th/95th percentile of Net Totals, EoL Impacts include burdens from Materials, Operation, and Transportation. Offsets include Electricity, Heat, and Burdens from Residuals. The values shown are the Net Total of the base scenario's Offsets and EoL Impacts

4.2.5 Fine Particulate Matter Formation

Figure 11 shows the fine particulate matter formation potential of the waste management systems. The landfill expansion process creates the most particulate matter formation potential. The landfill and landfill expansion processes burn diesel during the operation of the landfill which contribute to most of their fine particular matter formation. The cogeneration process created the most particulate matter formation without offsets because of the burdens of transportation and heat and electricity operational requirements, but with the offsets became an environmental benefit in this category. The anaerobic digestion process has the greatest net benefit in this scenario because of the offsets from the biogas that is produced that outweighed its operational requirements.

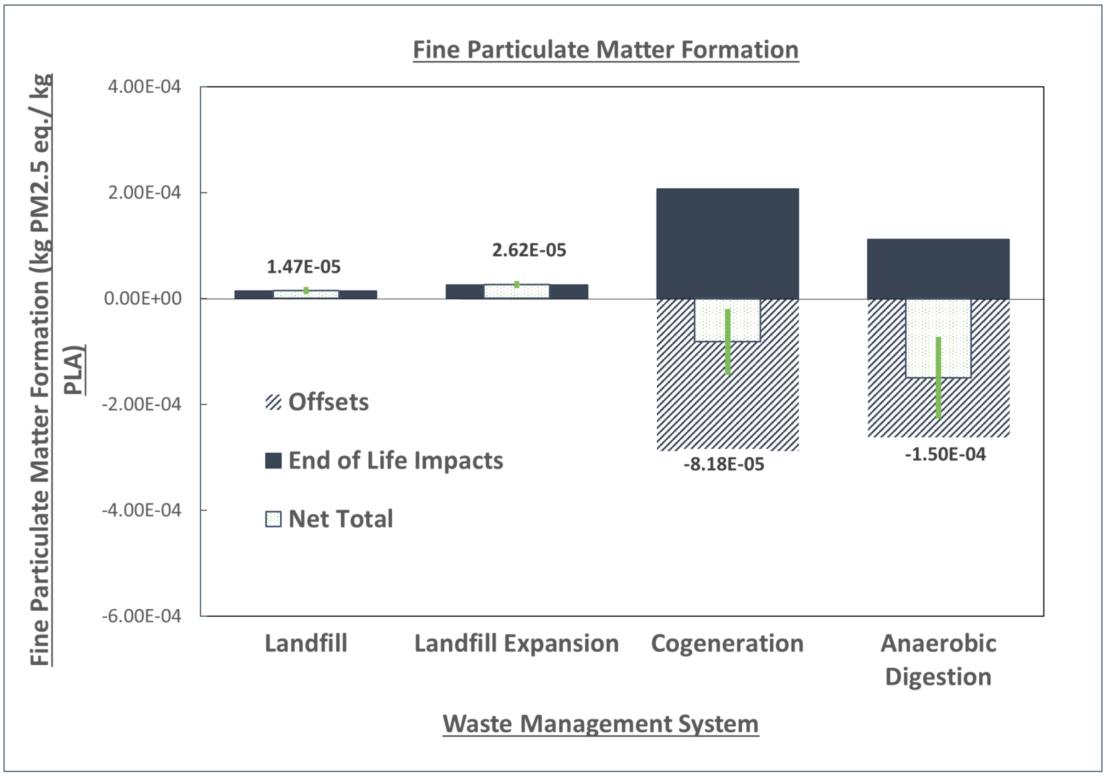

Figure 11 - Fine Particulate Matter Formation Impacts

Green Error Bars represent 5th/95th percentile of Net Totals, EoL Impacts include burdens from Materials, Operation, and Transportation. Offsets include Electricity, Heat, and Burdens from Residuals. The values shown are the Net Total of the base scenario's Offsets and EoL Impacts

4.2.6 Terrestrial Acidification

The terrestrial acidification impacts follow the same trend as ozone formation and fine particulate matter formation where the diesel being burned in the processes creates the greatest environmental burdens in the landfill and landfill expansion process (Figure 12). This means that the operational requirements from the landfill and landfill expansion process creates the largest burden and the transportation processes. The offsets from cogeneration and anaerobic digestion outweigh the environmental burdens. The anaerobic digestion process is the most favored between the waste management impacts studied.

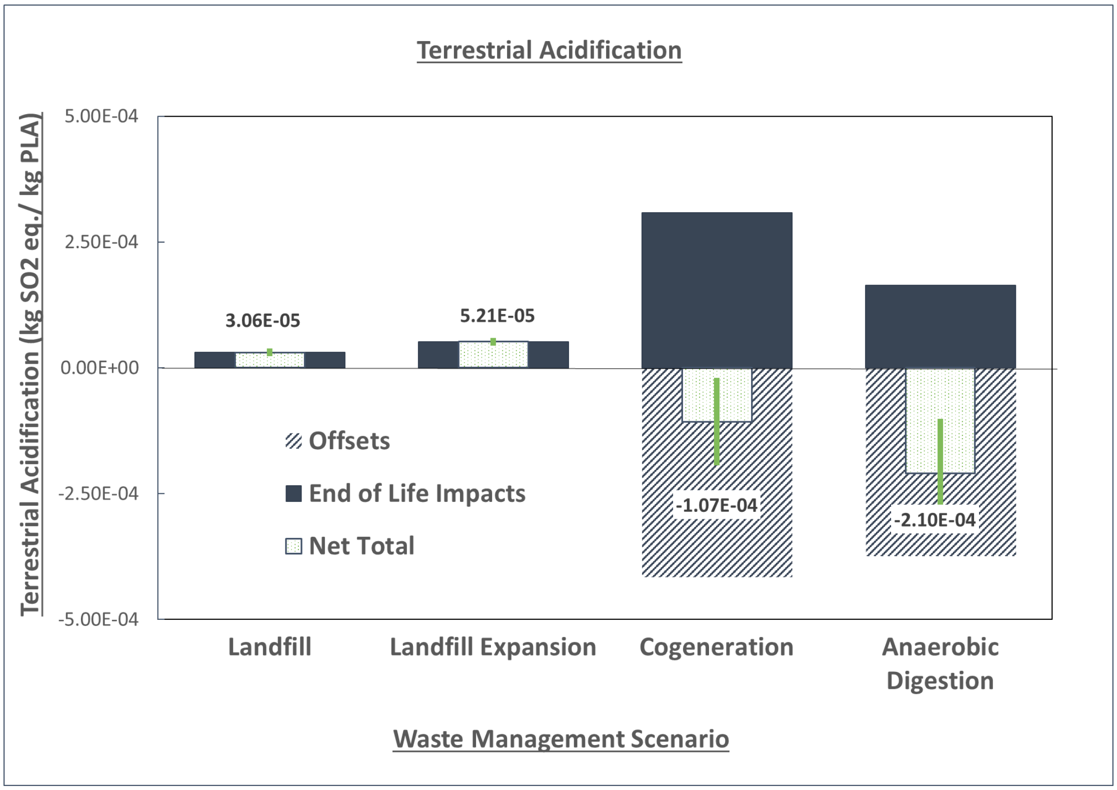

Figure 12 - Terrestrial Acidification Impacts

Green Error Bars represent 5th/95th percentile of Net Totals, EoL Impacts include burdens from Materials, Operation, and Transportation. Offsets include Electricity, Heat, and Burdens from Residuals. The values shown are the Net Total of the base scenario's Offsets and EoL Impacts

4.2.7 Freshwater and Marine Eutrophication

Figure 13 shows the freshwater eutrophication impacts of the waste management systems studied. The freshwater and marine eutrophication impacts follow the same trends of their burdens. This also follows the same trend as the acidification, ozone potential, and fine particulate matter formation for which the electricity and diesel requirements dictate the environmental impacts in this category. The anaerobic digestion process is the provides the least environmental burden for this impact category.

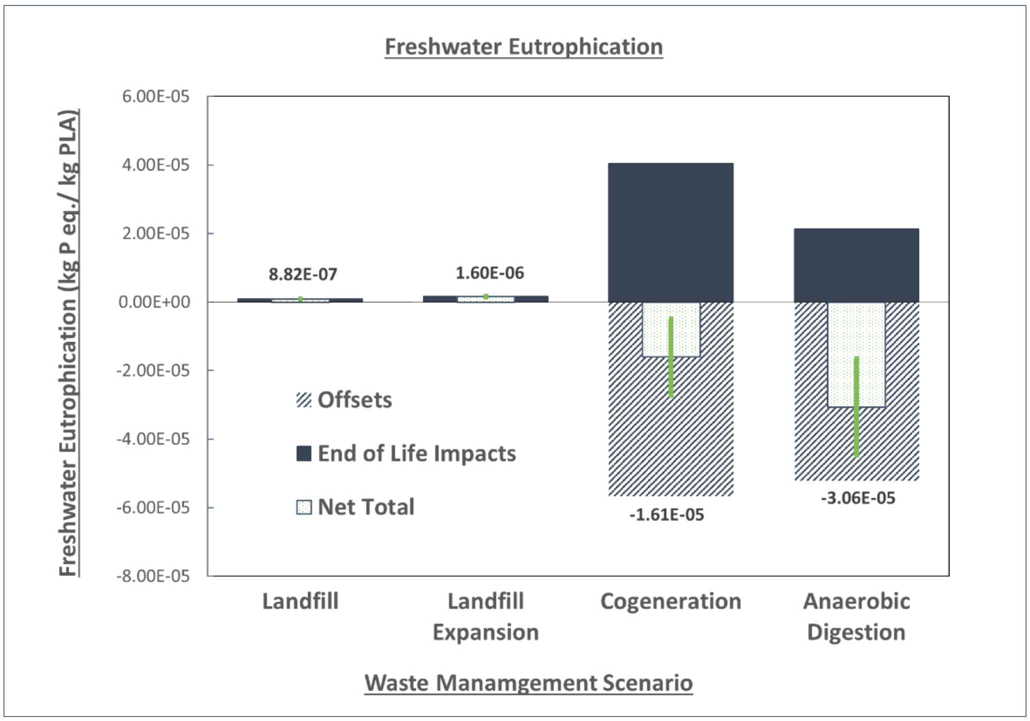

Figure 13 - Freshwater Eutrophication Impacts
Green Error Bars represent 5th/95th percentile of Net Totals, EoL Impacts include burdens from Materials, Operation, and Transportation. Offsets include Electricity, Heat, and Burdens from Residuals. The values shown are the Net Total of the base scenario's Offsets and EoL Impacts

4.2.8 Terrestrial Ecotoxicity

Figures 14 shows the terrestrial ecotoxicity impact from the waste management studies investigated. The terrestrial ecotoxicity impacts were more than 50% based on transportation for all of the processes which resulted in a high impact of the cogeneration system in that midpoint category. This is due to the cogenerator in Belize being the farthest system away from the transfer station. Additionally, for the cogeneration of PLA, naphthalene and the other polycyclic aromatic hydrocarbons (PAH) are emitted when the PLA is burned (Chien et al., 2012). The anerobic digestion process shows an environmental benefit because the offsets from the electricity produced outweigh the transportation burdens of the process as it is the closest waste management system to the transfer station.

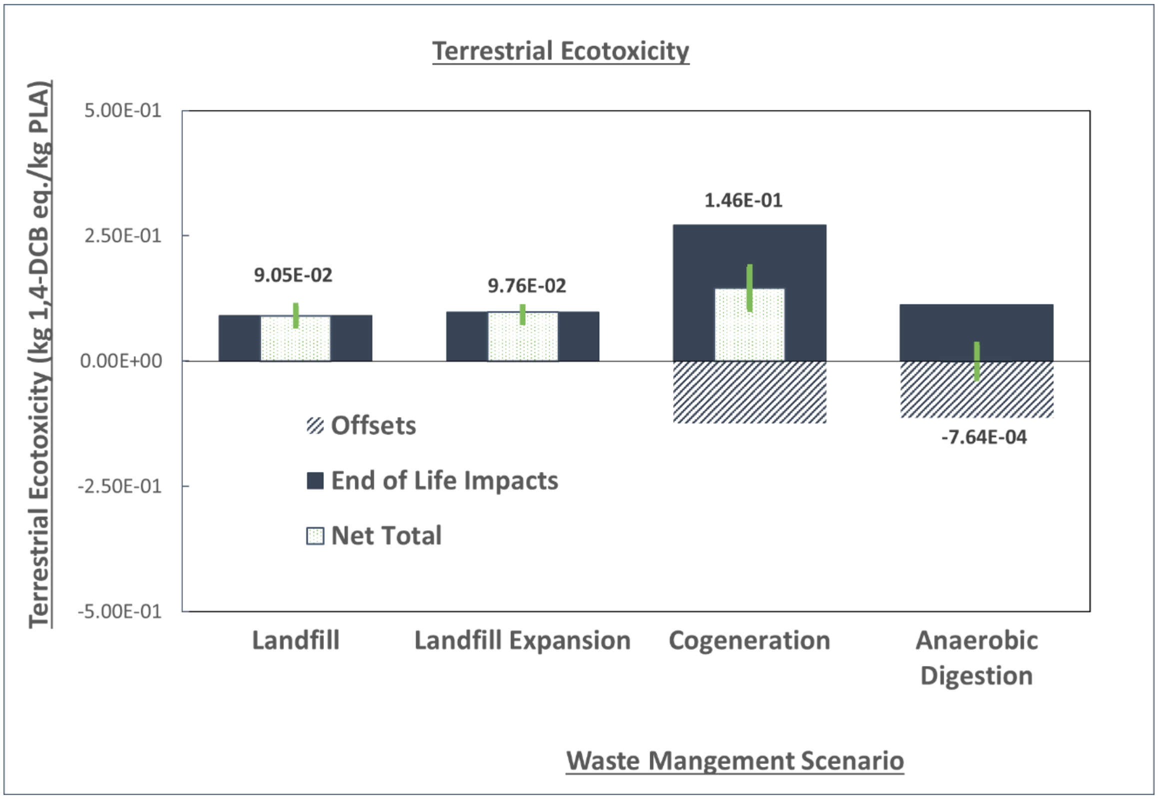

Figure 14 - Terrestrial Ecotoxicity Impacts

Green Error Bars represent 5th/95th percentile of Net Totals, EoL Impacts include burdens from Materials, Operation, and Transportation. Offsets include Electricity, Heat, and Burdens from Residuals. The values shown are the Net Total of the base scenario's Offsets and EoL Impacts

4.2.9 Marine, and Freshwater Ecotoxicity

Figure 15 shows the freshwater ecotoxicity impacts of the waste management systems. In the freshwater and marine ecotoxicity impacts, the trends are the same. The landfill and landfill expansion process both have over 50% of impacts from the transportation requirements of transporting the PLA to the landfill. Additionally, 10% of the total burdens for anerobic digestion and cogeneration resulted from transportation impacts. The offsets from the cogeneration process and anaerobic digestion process outweighed the impacts from the environmental burdens from the operational and transportation requirements.

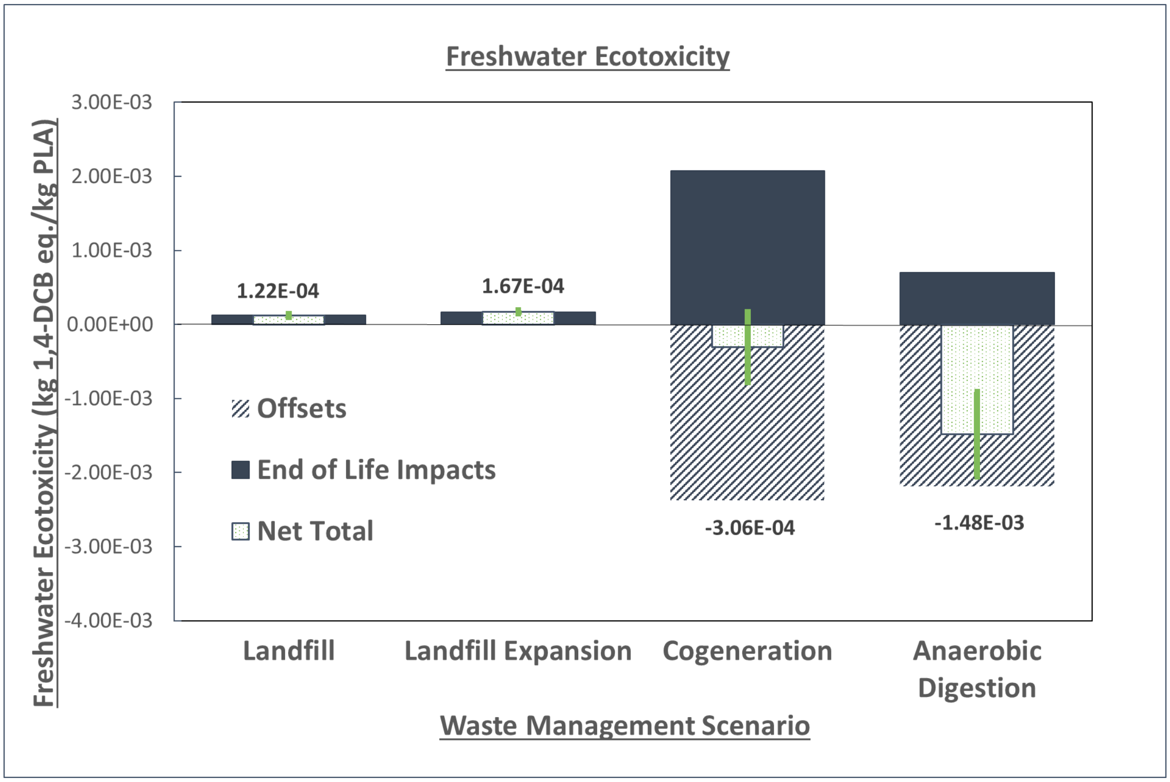

Figure 15 - Freshwater Ecotoxicity Impacts

Green Error Bars represent 5th/95th percentile of Net Totals, EoL Impacts include burdens from Materials, Operation, and Transportation. Offsets include Electricity, Heat, and Burdens from Residuals. The values shown are the Net Total of the base scenario’s Offsets and EoL Impacts

4.2.10 Human Carcinogenic Toxicity

Figure 16 depicts the human carcinogenic toxicity impacts from the waste management systems that were studied. The largest amount of human carcinogenic toxicity resulted from the landfill expansion process. This was due to operational burdens of the landfill expansion and transportation of the PLA to the landfill. Additionally, the excavation processes for creating the landfill expansion contributed to 20% of the impacts. Around 50% of the human carcinogenic toxicity associated with the landfill resulted from the transportation of the material to the landfill. The anaerobic digestion process was the most favored of the processes because of the offsets produced. The cogeneration process had a high amount of environmental burdens because of the operational requirements and the material requirements of steel and gravel. The cogeneration process also experienced more burdens because of the PAHs that were accounted for in the process (Chien et al., 2012). However, the offsets that were produced still produced a net environmental benefit in this impact category.

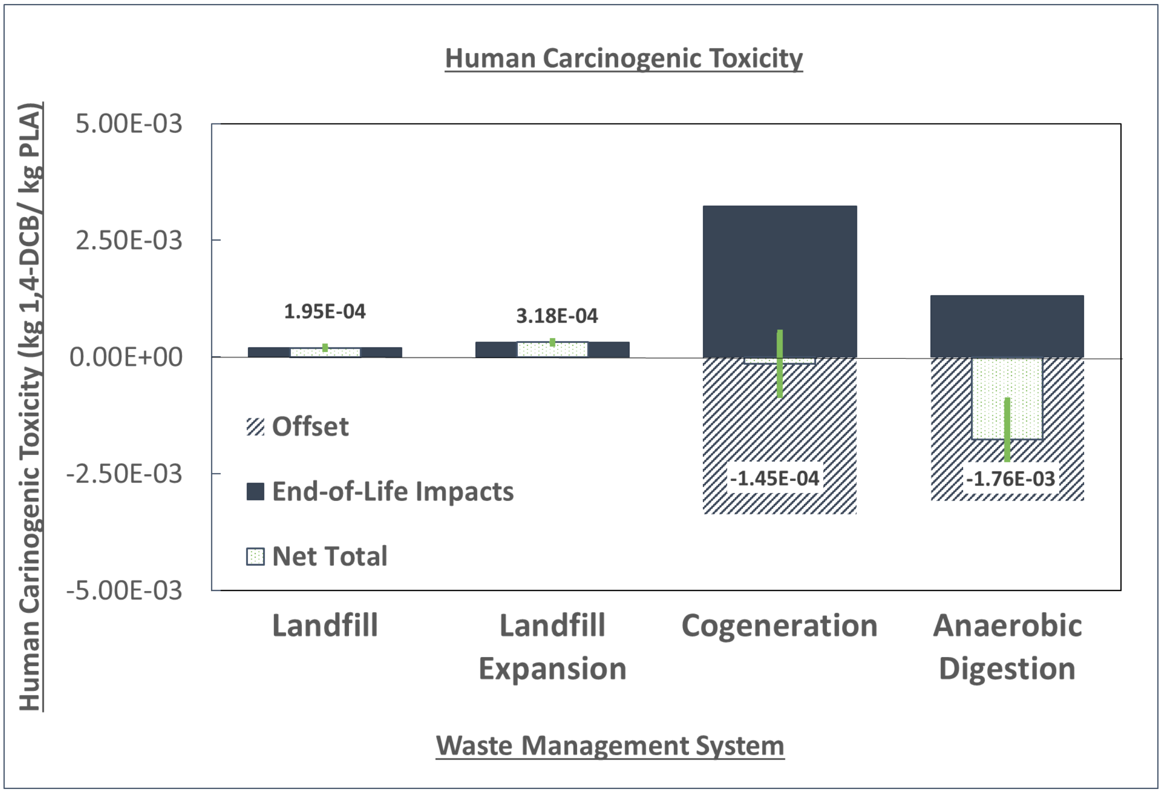

Figure 16 - Human Carcinogenic Toxicity Impact
Green Error Bars represent 5th/95th percentile of Net Totals, EoL Impacts include burdens from Materials, Operation, and Transportation. Offsets include Electricity, Heat, and Burdens from Residuals. The values shown are the Net Total of the base scenario's Offsets and EoL Impacts

4.2.11 Human non-carcinogenic Toxicity

Figure 17 shows the human non-carcinogenic toxicity impacts. The human non-carcinogenic toxicity is impacted largely by the transportation effects from the landfill and landfill expansion systems and the electricity requirements for the cogeneration and anerobic digestion systems. Additionally, the PAHs included in the cogeneration scenario contribute a small portion to the systems impacts (Chien et al., 2012). The offsets created from the anaerobic digestion system, results in net environmental benefits whereas the landfill, landfill expansion, and cogeneration systems have net environmental burdens.

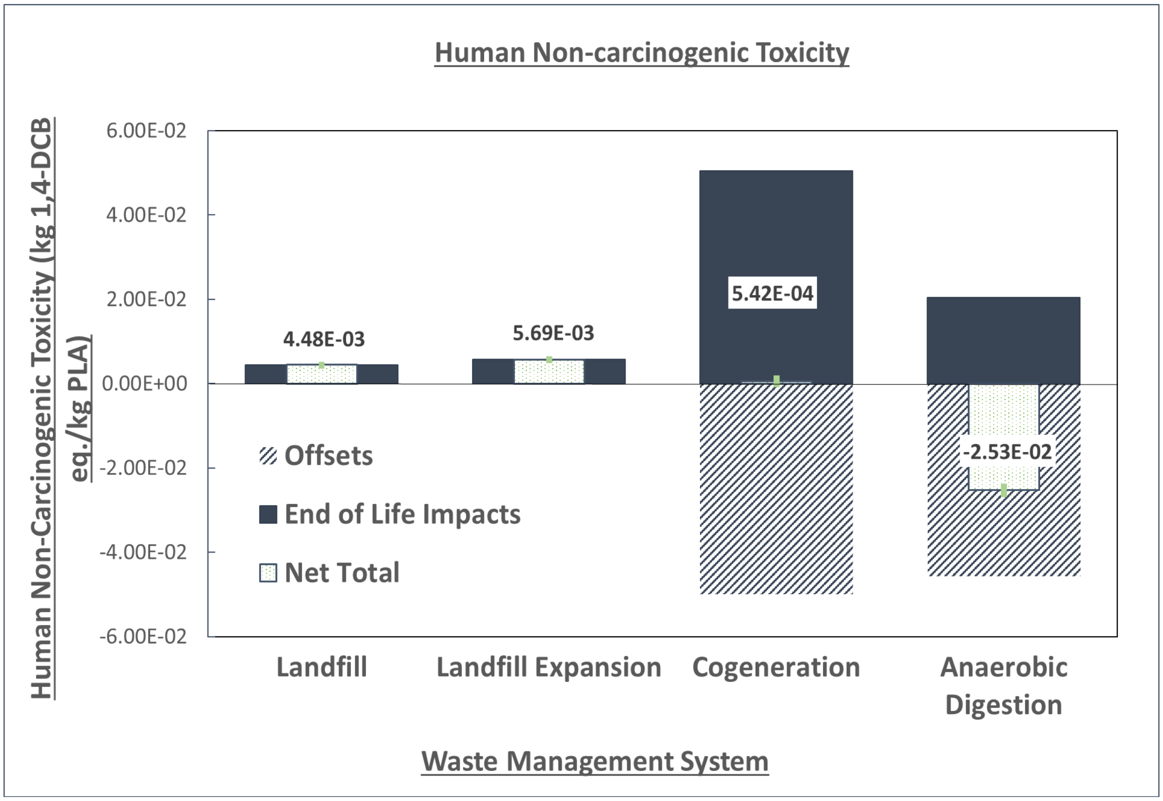

Figure 17 - Human Non-carcinogenic Impacts

Green Error Bars represent 5th/95th percentile of Net Totals, EoL Impacts include burdens from Materials, Operation, and Transportation. Offsets include Electricity, Heat, and Burdens from Residuals. The values shown are the Net Total of the base scenario's Offsets and EoL Impacts

4.2.12 Land use

Figure 18 shows the land use impacts which are led by the landfill and landfill expansion processes. In this category the landfill has the highest impact because of the small waste cell as compared to the entire acreage of the site. The landfill expansion has larger waste cells with more utilization of the entire site therefore it has a smaller land use impact per kg of PLA. The anerobic digestion system has an environmental burden for the offsets because the digestate was said to go to the landfill which produced an environmental burden.

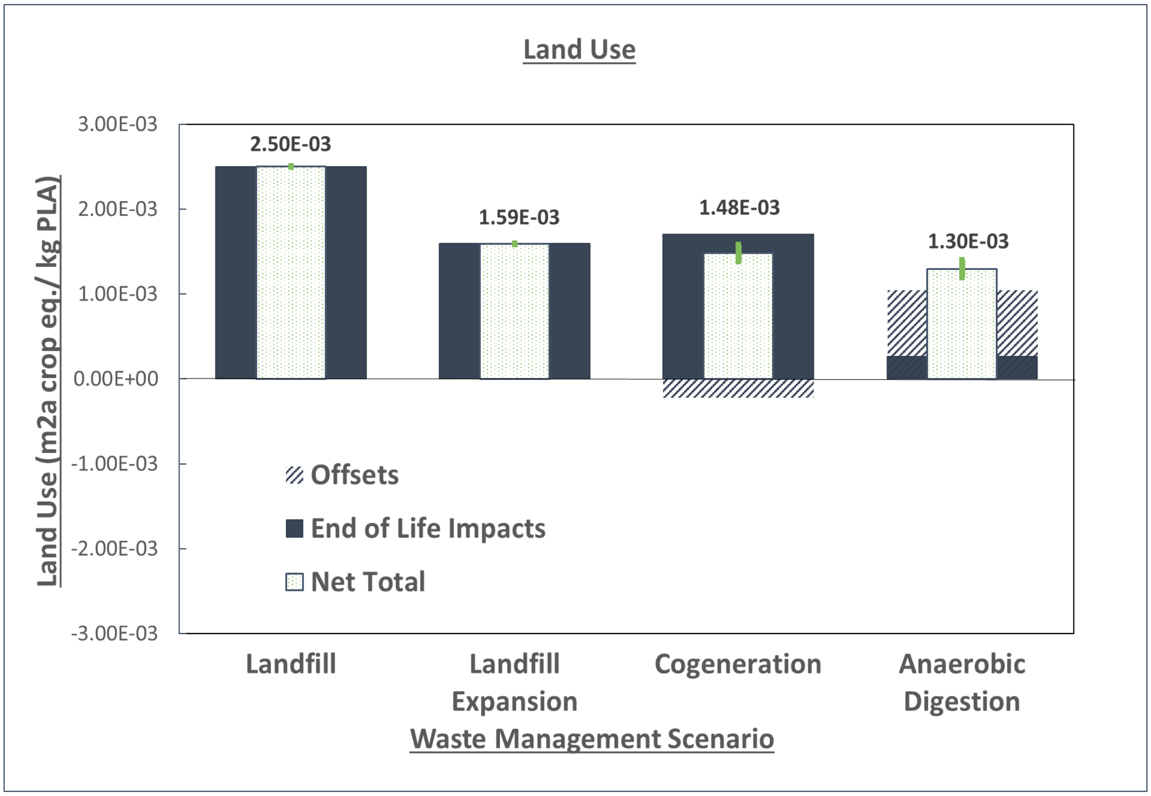

Figure 18 - Land Use Impacts

Green Error Bars represent 5th/95th percentile of Net Totals, EoL Impacts include burdens from Materials, Operation, and Transportation. Offsets include Electricity, Heat, and Burdens from Residuals. The values shown are the Net Total of the base scenario's Offsets and EoL Impacts

4.2.13 Mineral Resource Scarcity

The anaerobic digestion process has an environmental benefit in mineral resource scarcity after offsets are allocated (Figure 19). The cogeneration system sees a large impact on the mineral resource scarcity from the components to the heat and power cogeneration infrastructure. The operational and transportation burdens were the largest contributors in the landfill, landfill expansion, and anaerobic digestion processes. In this impact category anaerobic digestion was the only system to provide an environmental benefit.

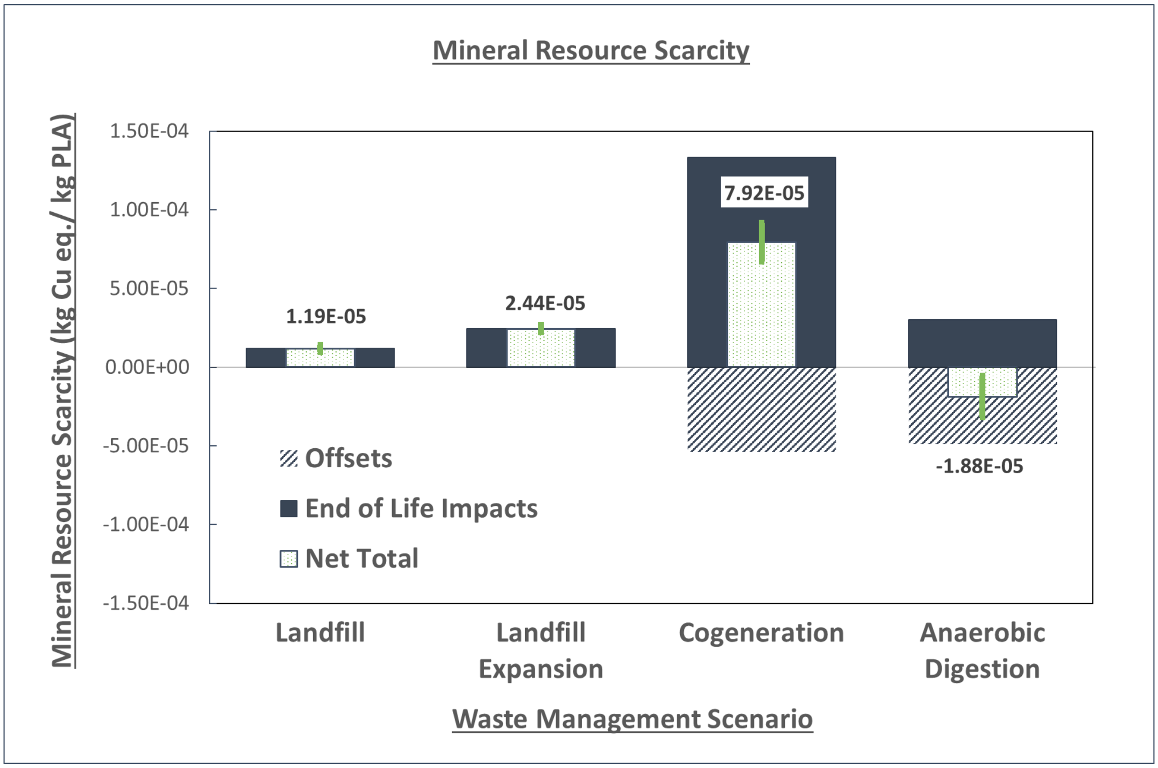

Figure 19 - Mineral Resource Scarcity Impacts

Green Error Bars represent 5th/95th percentile of Net Totals, EoL Impacts include burdens from Materials, Operation, and Transportation. Offsets include Electricity, Heat, and Burdens from Residuals. The values shown are the Net Total of the base scenario's Offsets and EoL Impacts

4.2.14 Fossil Fuel Depletion

The fossil fuel depletion is depicted in Figure 20. The contribution to fossil fuel depletion is mainly based on the processes that burn fossil fuels. Parallel to other impacts the operational burdens of the anaerobic digestion process and the cogeneration process are the main contributors to fossil resource scarcity. Therefore, the transportation burdens from all of the processes and the operational burdens for the landfill and landfill expansion processes create the largest impacts. The offsets that are created from the anaerobic digestion and cogeneration process create an environmental benefit in this category.

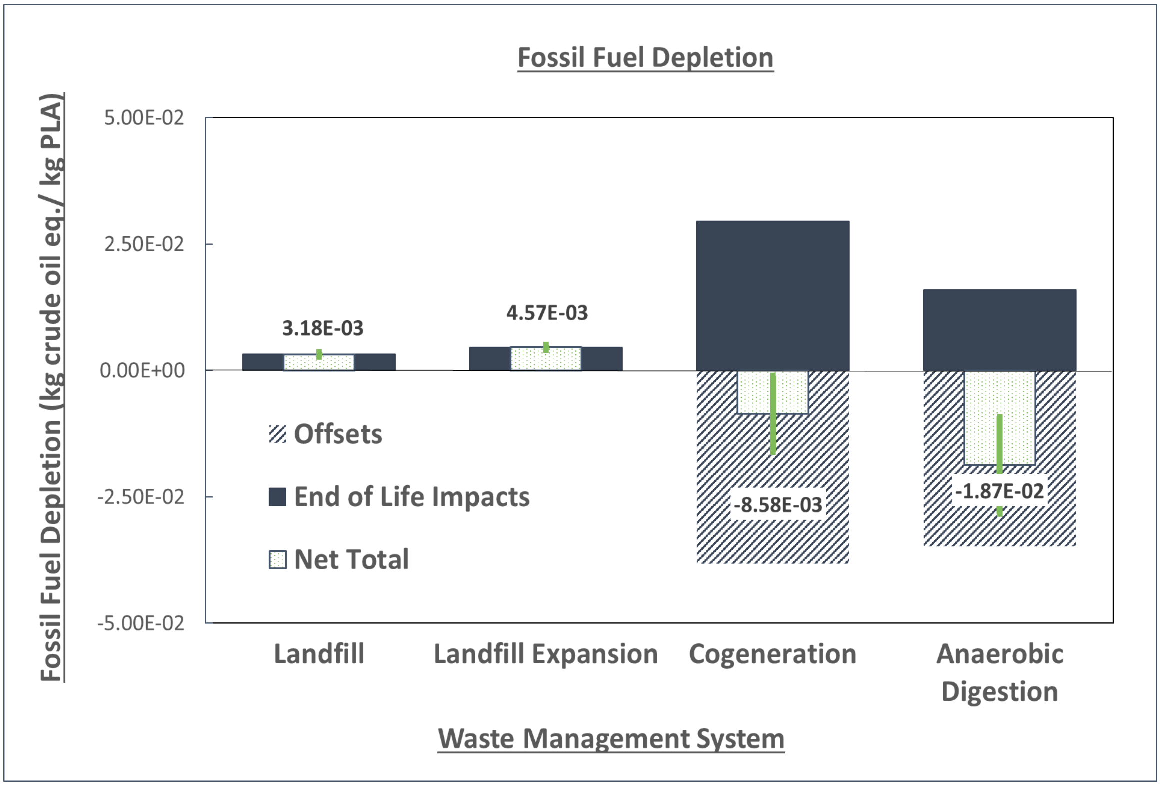

Figure 20 - Fossil Fuel Depletion Impacts

Green Error Bars represent 5th/95th percentile of Net Totals, EoL Impacts include burdens from Materials, Operation, and Transportation. Offsets include Electricity, Heat, and Burdens from Residuals. The values shown are the Net Total of the base scenario's Offsets and EoL Impacts

4.2.15 Water Consumption

The water consumption impact of the landfill expansion scenario was the largest of the waste management scenarios assessed (Figure 21). This resulted from the material inputs such as polyethylene plastic, geotextile, and gravel drainage layer that required water upstream. The landfill process had the next greatest water consumption net total that also resulted from the impacts from the same material requirements of the landfill expansion. The anaerobic digestion process had the lowest net environmental burden. In the anaerobic digestion process, it was assumed that there were no burdens of water for the PLA as it was just added to the already established process of anaerobic digestion for municipal sludge. The offsets produced by the cogeneration and anaerobic digestion systems the environmental impacts burdens, so it had a negative water consumption value.

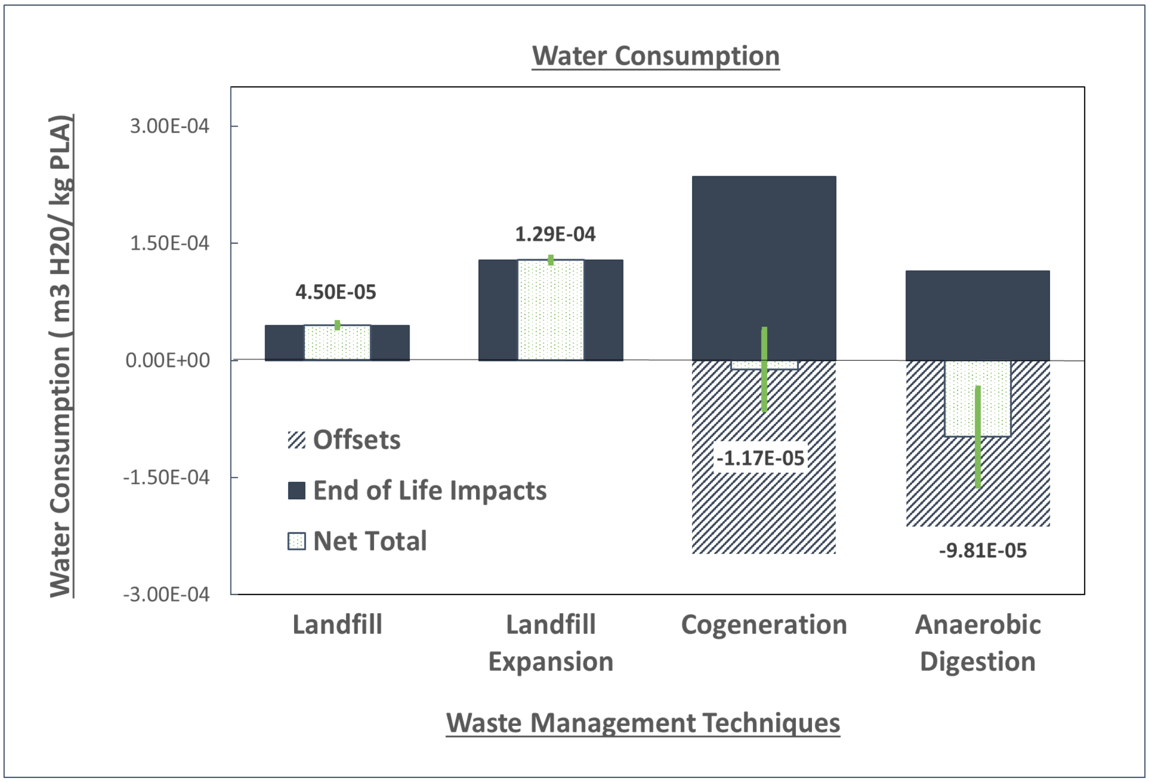

Figure 21 - Water Consumption Impacts
Green Error Bars represent 5th/95th percentile of Net Totals, EoL Impacts include burdens from Materials, Operation, and Transportation. Offsets include Electricity, Heat, and Burdens from Residuals. The values shown are the Net Total of the base scenario's Offsets and EoL Impacts

4.3 Uncertainty and Sensitivity Analysis:

Identifying the degradation of PLA and determining how the emissions are attributed is pivotal in determining the environmental impacts of the systems in which it is managed. There is an ongoing discussion on classifying the carbon content of the PLA as anthropogenic (man-made) or biogenic (from nature). This plays a direct role in waste management systems because the methods in which emissions are attributed can cause significant changes to environmental emissions. In the landfill scenario it is a deciding factor in whether landfill gas capture should be a necessity when highlighting GWP as an environmental concern.

Moreover, the complete degradation of PLA and the other trace gases that are produced during its decomposition must be studied more to identify other environmental impacts that are possible. The effects of these emissions can be shown on the marine, freshwater, and terrestrial ecotoxicity impact categories of the cogeneration system where there are burdens from PAHs that are released from PLA combustion. Other pollutants may be present in more abundance during the combustion of PLA (Chien et al., 2012). Additionally, there are microplastics that could result from the degradation of PLA in addition to trace gas emissions that typically result from the anaerobic degradation of biomass that should be identified (Shruti et al., 2019). The uncertainty and sensitivity analysis functioned to use the available information that is known on PLA degradation combined with the efficiencies and distances of the infrastructure in Belize to form conclusions on ways that these variables can be enhanced in each of the waste management systems.

4.3.1 Landfill Uncertainty and Sensitivity

The landfill uncertainty and sensitivity analysis investigated the degradation of PLA and the distance from the landfill to the transfer station to predict the amount of variance in the landfill process (Figure 22). Values from the Spearman's rank correlation demonstrate that all of the environmental impact categories, disregarding GWP, were highly sensitive (Spearman's rank correlation coefficient of ~1.0) to transportation distance. This is due to the emissions associated with transportation of PLA. The GWP was mainly impacted by the degradation of PLA. Some experimental researchers state that 37% degradation of PLA is possible in thermophilic landfill conditions (Kolstad et al., 2012; Krause et al., 2016). This is addressed in the uncertainty of this system where the GWP of the landfill process increases to over 4.0 kg of CO_2 eq. per kg of PLA when the PLA degrades up to 37%. Hottle (2017) also reported a high emissions scenario that matched the degradation and emissions from the uncertainty of this study. This high uncertainty is a direct result of the amount of CH_4 that is released into the air without CH_4 capture. The percentage degradation of PLA had a high Spearman's rank correlation coefficient of almost 1.0 for the GWP impact category. This indicates that the GWP had a high sensitivity to the degradation of PLA due to the release of CH_4. This sensitivity data shows that decreasing the transportation burdens would help stifle the other environmental impacts from this system. Additionally, more information must be garnered to predict the impact that PLA degradation would have on other environmental impact categories outside of the GWP.

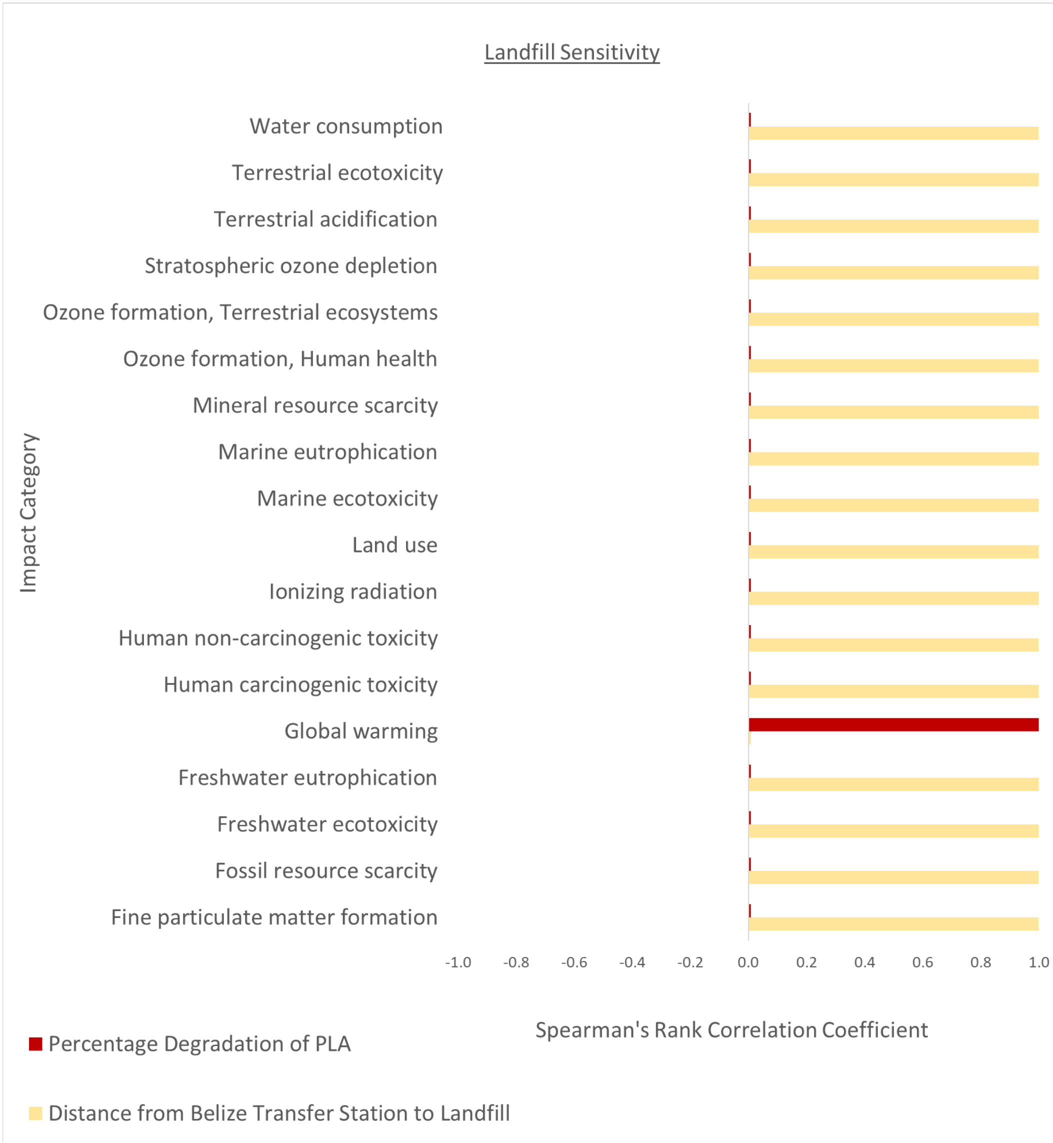

Figure 22 - Landfill Sensitivity Analysis

4.3.2 Landfill Expansion Uncertainty and Sensitivity

The landfill expansion uncertainty and sensitivity analysis investigated the degradation of PLA, the percentage of CH_4 into the air (this is the percent of CH_4 that was not captured), and the distance from the landfill to the transfer station (Figure 23). Similar to the landfill scenario, all of the impact categories besides the GWP were very sensitive to the distance from the landfill to the transfer station (Spearman's rank correlation coefficient of ~1). This is due to the emissions that result from the transportation of PLA. As with the landfill scenario, the landfill expansion scenario investigated the uncertainty of PLA degrading up to 37% (Kolstad et al., 2012; Krause et al., 2016). The uncertainty from the degradation of PLA and the CH_4 capture resulted in a GWP which grew to a maximum of 2.0 kg of CO_2 eq. per kg of PLA. The GWP for the landfill expansion had a high sensitivity (Spearman's rank correlation coefficient of 0.96) to the percentage degradation of PLA and had a weak correlation to the percentage of CH_4 into the air (Spearman's rank correlation coefficient of 0.23). This shows that the degradation of PLA in the landfill scenario plays a critical role on GWP because of the CH_4 that is released into the environment. Additionally, this highlights that when advanced technology such as landfill CH_4 capture is utilized, the GWP of the landfill expansion process can be reduced.

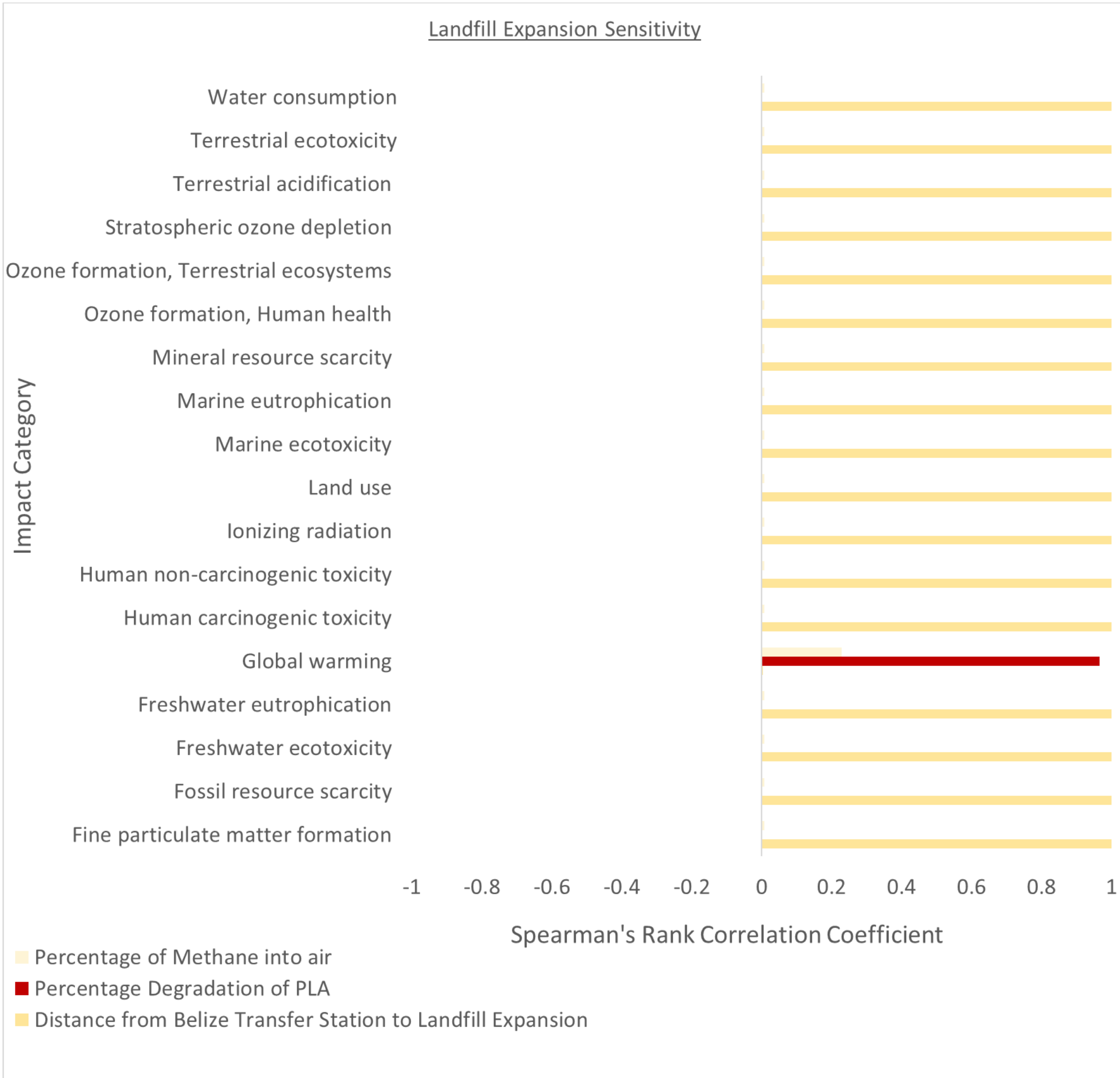

Figure 23 - Landfill Expansion Sensitivity Analysis

4.3.3 Cogeneration Uncertainty and Sensitivity

The cogeneration uncertainty and sensitivity analysis investigated the distance from the cogenerator to the landfill, the distance from the transfer station to the cogenerator, the electrical efficiency, and the energy efficiency of the system (Figure 24). The energy efficiency of the cogeneration process was used to account for the amount of infrastructure required. Therefore, there was a high correlation between the energy efficiency and the mineral resource scarcity (Spearman's rank correlation coefficient of ~0.9) where material requirements had a large impact. Additionally, there was weak correlation between the energy efficiency and land use impacts (Spearman's rank correlation coefficient of 0.35) because with more infrastructure, there was more land required. The terrestrial ecotoxicity was sensitive to the distance from transfer station to cogenerator (Spearman's rank correlation coefficient of ~0.83) because the transportation of PLA heavily impacted the terrestrial ecotoxicity impact category. All of the impacts (excluding the land use and terrestrial ecotoxicity) had a high correlation (Spearman's rank correlation coefficient of -0.6 to -1.0) to the electrical efficiency of the cogenerator. This is due to the offsets produced, when the system was more efficient there were less environmental burdens. The distance from the cogenerator to the landfill had a very weak correlation to any impact category, because it only transported a small amount of waste ash per kg of PLA that was treated. The uncertainties expressed throughout the impact categories show that there is still environmental benefits that could be realized through improving efficiencies and reducing transportation burdens. Through the sensitivity analysis it is apparent that for the system to minimize environmental burdens, higher electrical efficiency should be targeted which would create additional offsets. Additionally, finding a transportation solution that contributes less emissions would help benefit the terrestrial ecotoxicity of the cogeneration system.

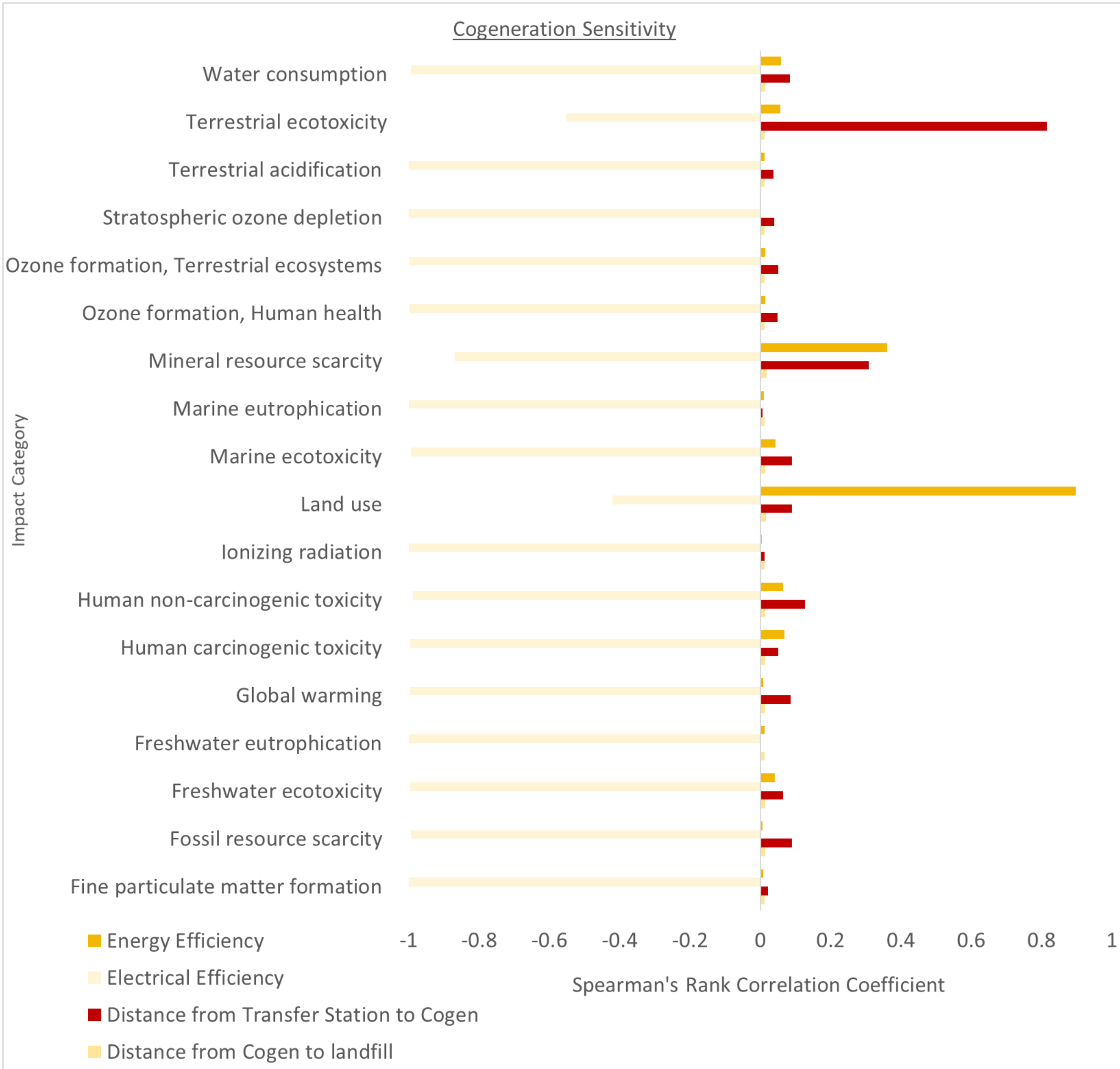

Figure 24 - Cogeneration Sensitivity Analysis

4.3.4 Anaerobic Digestion Uncertainty and sensitivity

The anaerobic digestion uncertainty and sensitivity analysis investigated the biogas to electricity efficiency, the distance from the anaerobic digester to landfill, the distance to the transfers station to the anaerobic digester the electricity to heat efficiency and the percentage degradation of PLA (Figure 25). The uncertainty in the anerobic digestion impacts shows a consistent trend where higher efficiencies and lower transportation distances would create less environmental burden and vice versa. Through the sensitivity analysis it is shown that in most of the environmental impact categories, there is a high sensitivity to the biogas to electricity efficiency (Spearman's rank correlation coefficient of less than -0.8). This is because the electricity production represents a large offset to the environmental burdens of the system and more electricity can be produced with higher efficiencies.

The degradation of the PLA in the system impacts the land use category because the PLA that wasn't degraded was sent to the landfill. The degradation of PLA and the electricity to heat efficiency also have a weak correlation to the overall environmental impact of the systems (Spearman's rank correlation coefficient of -0.25 and a -0.35 respectively). This is because when there is more degradation of PLA, there is an increase in the amount of biogas as an offset. A higher electricity to heat efficiency means that it takes less energy to heat the anerobic digester which was a major operational burden across the impact categories. The distance from the transfer station to the anaerobic digester has a weak correlation (Spearman's rank correlation coefficient of ~0.22) to the terrestrial ecotoxicity impact category. Similarly, the distance from the anaerobic digester to the landfill has a weak correlation to the terrestrial ecotoxicity impact category (Spearman's rank correlation coefficient of ~0.21). This shows that even though there is a correlation between transportation distances and the terrestrial ecotoxicity, to maximize benefits for anaerobic digestion, it should not be the focal point of improvement.

Through this analysis it shows that to improve the benefits of managing PLA waste via anaerobic digestion, the amount of electricity produced from the biogas is a cornerstone in producing a lower net environmental impact. Additionally, increasing the electricity to heat efficiency and realizing a higher amount of PLA degradation would serve to increase the amount of benefits from this system as well. If an anaerobic digester was heated to thermophilic temperatures efficiently it would help PLA degrade more and maximum benefits may be achieved.

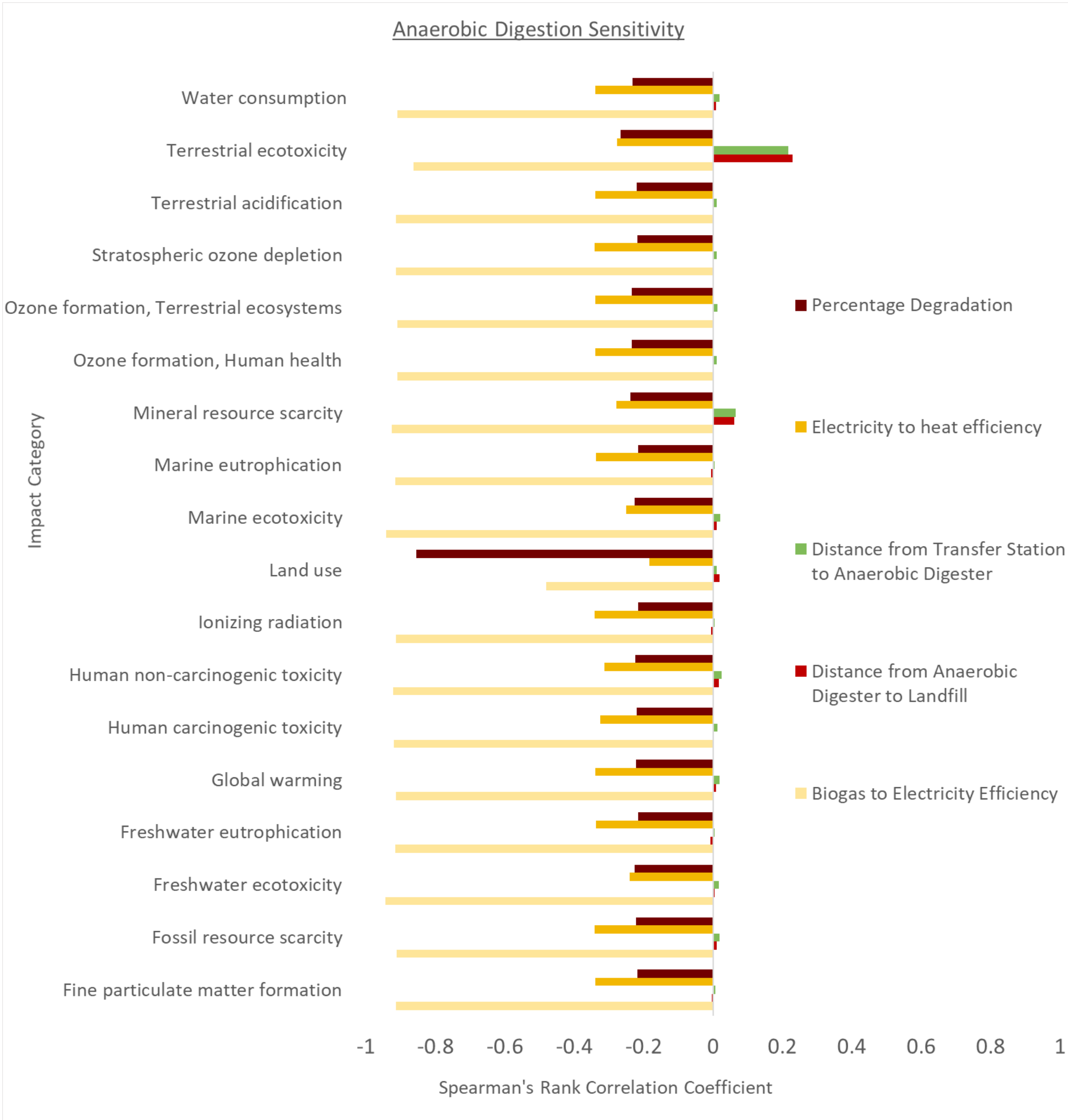

Figure 25 - Anaerobic Digestion Sensitivity Analysis

4.4 Hypothesis Testing:

A Wilcoxon signed rank test was used to investigate the differences of GWP when 500 million kg of PLA was managed via the waste management systems that were studied (Appendix 2). The null hypothesis 1.1_o stated that anaerobic digestion will have a similar GWP to the other waste management systems studied when large amounts of PLA are managed. Results show that GWP of anaerobic digestion was lower than the cogeneration, landfill and landfill expansion ($p\text{-value} \leq 0\ .05$) meaning the null hypothesis was rejected. The p-value was about 0 when anaerobic digestion was compared to the landfill and landfill expansion scenarios and the p-value was 0.0002 when compared to the cogeneration system. This indicated that the anaerobic digestion process did have significantly lower GWP of the waste management systems studied and the alternative hypothesis 1.1_a was accepted.

A Wilcoxon signed rank test was used to investigate the impacts that the transportation requirements had on the GWP of the landfill expansion process when 500 million kg of PLA was managed (Appendix 2). The null hypothesis 2.1_o stated that transportation requirements will have similar impacts to GWP compared to the material and operational requirements. Results show that transportation has lower environmental impact when compared to materials ($p\text{-value} = 0$; $p\text{-value} \leq 0.05$). However, when comparing transportation GWP to operational requirements, the $p\text{-value} \geq 0.05$. Therefore, the alternative hypothesis is rejected, and the operational requirements had a higher impact than the transportation for the GWP of the landfill expansion process.

Through investigating the hypotheses, it is shown that the anaerobic digestion process, when managing 500 million kg of PLA, would produce the least amount of global warming potential of the waste management systems studied. Additionally, through the second hypothesis it is shown that when the landfill expansion process managed 500 million kg of PLA, the operational requirements would have the largest effects on the GWP. These findings communicate that anaerobic digestion would provide the least GWP when large amounts of PLA is managed. Additionally, when managing large amounts of waste in the landfill expansion process, the operational requirements of the landfill is a cornerstone on the GWP from this process. Despite these results, it is important to note that the capacity of an anaerobic digester is much less than the landfill, landfill expansion and cogeneration systems. When scaling to manage one year of PLA waste produced in Belize within a year anaerobic digestion becomes less feasible.

4.5 Waste Management of 1 Year of PLA Waste

There is around 7,710 tons of plastic waste that is sent to the landfill in Belize per year (BSWMA, 2019; Petterd et al., 2019). When assuming that all of this plastic waste is going to be replaced with PLA, there would be too much PLA to be managed from one anaerobic digestion system. As shown in section 4.2.1, when anaerobic digestion is used to manage small amounts of PLA wastes with offsets considered, it could provide environmental benefits. However, when estimating the total amount of materials that would be required from each waste management system (landfill, landfill expansion, cogeneration, anaerobic digestion) to manage the yearly amount of PLA waste, anaerobic digestion becomes less feasible.

When managing 7,710 tons of PLA within a year, it would require 65 anaerobic digesters if using the same temperature, capacity, ratio of PLA to municipal sludge, and 30-day retention time (Equation 3). The landfill, landfill expansion and cogeneration systems would be able to manage 7,710 tons of PLA waste with just one system. Therefore, when investigating the environmental impacts of the total amount of materials that would be required, it shows that anaerobic digestion system would have higher environmental burdens from materials and infrastructure than the rest of the waste management systems studied. The additional materials and land use that would be required for 65 anaerobic digesters show that anaerobic digestion may not be feasible for large amounts of PLA waste.

$$\frac{7{,}710{,}000\ kg\ of\ PLA\ Waste\ per\ year}{120{,}000\ kg\ PLA\ managed\ per\ Digester\ per\ year} = 65\ Anaerobic\ Digesters\ Required$$

Equation 3 – Anaerobic Digesters Required for One Year of PLA Waste

As highlighted in Figure 26, the anaerobic digestion systems land use requirements would reach over 1,280 acres throughout its life cycle. This land use is over 3 times the amount required by the landfill expansion system and 18 times more land required than the cogeneration system. Furthermore, there are similar trends throughout the mineral resource scarcity, human carcinogenic toxicity, marine ecotoxicity, freshwater and terrestrial ecotoxicity, and freshwater eutrophication impacts where the material requirements of the anaerobic digestion system create significant environmental burdens that are greater than the other waste management systems. The landfill expansion process still sees large environmental impacts for infrastructure requirement where the excavation of land for the landfill causes a large environmental burden in the global warming potential, stratospheric ozone depletion, ionizing radiation, ozone formation impacts, fine particulate matter and terrestrial and marine ecotoxicity burdens. Despite any offsets that could be produced from anaerobic digestion, the material requirements and land requirements could prove insurmountable when other constraints such as economic and social factors are considered.

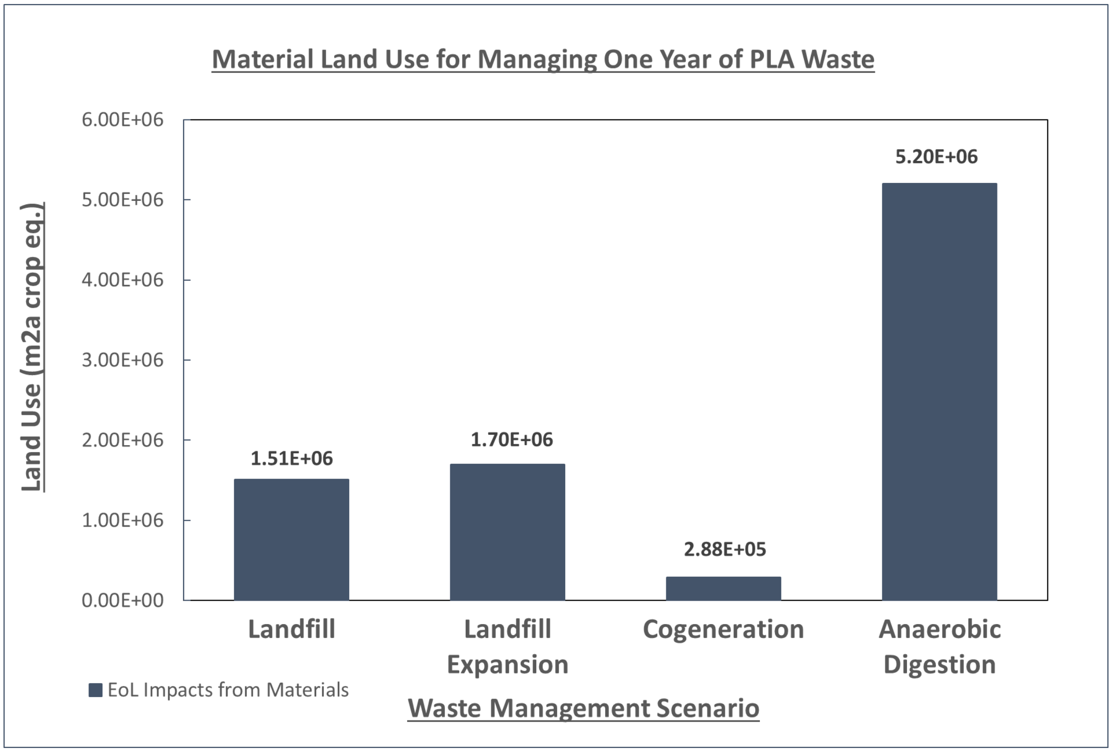

Figure 26 - Land Use Total for Managing One Year of PLA Waste

CHAPTER 5. CONCLUSIONS AND FUTURE WORK

In January 2020, the Government of Belize enacted an Implementation Strategy and Action Plan to phase-out single-use plastics as well as Styrofoam and to transition to products like bioplastics. Biopolymers, the most common of which is PLA, are plastics derived from biomass that can be molded into various products. The addition of these new biopolymers creates an opportunity to utilize its biodegradability to help manage its wastes with less harmful environmental impact. This work aimed to investigate the environmental effects of using alternative waste management techniques to manage PLA waste by using life cycle assessment.

The first objective of this study was to determine which waste management technique (landfilling, cogeneration, or anaerobic digestion) contributes the least environmental impact for PLA waste. After conducting this study, it was established that the anaerobic digestion of PLA would result in the least amount of environmental burden throughout the 18 impact categories per kg of PLA waste that was managed. This was largely due to the offsets that were produced from the system. Additionally, as shown via the hypothesis testing, when managing a large amount of PLA waste (500 million kg) there would still be large benefits in GWP when using anaerobic digestion over the other waste management systems studied. Despite this, it may become unfeasible to manage this much PLA waste because of the amount of materials and land use that would be required to manage the large amounts of PLA waste. In future work, it could be beneficial to investigate the impacts of larger digesters and thermophilic temperatures being used in anaerobic digestion. This would provide an opportunity to manage more PLA waste in addition to producing additional offsets.

The second objective of this study was to investigate what elements of EoL (material, operation, and transportation requirements) should be targeted to minimize the environmental impacts of the waste management strategies. Through the study it was shown that the infrastructure requirements played a minimal role in the net environmental burdens of the waste management systems. Therefore, to minimize the environmental burdens, there must be a focus on the operational requirements (electricity, heat, fuel) of the waste management systems. Increasing the electrical efficiency of the cogeneration system and the electricity to heat efficiency of the anaerobic digestion system could reduce the environmental burdens from the systems greatly. The operational requirements of the landfill and landfill expansion systems were relatively low compared to the cogeneration and anerobic digestion systems. Due to this, and the likely degradation of PLA, there is an opportunity to not only capture this methane but to use it for energy as well. This could see large environmental benefits in terms of GWP and, as discussed, there would likely not be a large environmental burden from the infrastructure required.

Further investigation of these waste management systems should also involve the social and economic aspects of the projects as well. There are many stakeholders in Belize that would have different requirements and needs for waste management so it is important to weigh all of the different variables to make a complete interpretation on the strategies that could be used to manage wastes. Life cycle costing is a tool that investigates the costs that occur over a product or systems lifetime which could be used to identify economical tradeoffs of the waste management systems. Additionally, social life cycle assessment is a method of investigating the social effects of processes. However, these assessments can involve a lot of data that is specific to the sites that are being studied which would require extensive research. Considering all 3 aspects of sustainability (environmental, social, and economical) would allow for consideration of sustainability trade-offs to best inform decision making.

APPENDICES

APPENDIX 1. LCI Assumptions

This appendix outlines the LCI of the Landfill, Landfill Expansion, Cogeneration, and Anaerobic Digestion system. This includes the assumptions that were made and the sources that were used for the assumptions.

Landfill

<u>Design Calculations</u>

- PLA Ultimate Methane Potential (UMP) at standard temperature and pressure
  - Equation: $C_6H_8O_4 + 2H_2O \rightarrow 3CO_2 + 3CH_4$
  - MW of C6H8O4 = 144 grams

$$1000g\text{C6H8O4} * \frac{\text{1molC6H8O4}}{\text{144gramsC6H8O4}} * \frac{\text{3molCH4}}{\text{1molC6H804}} * \frac{\text{22.4 liters}}{\text{1molCH4}} = UMP$$

    - Total: 467 Liters Methane/kg of PLA
- Max Percentage Degradation of PLA
  - Source: (Kolstad et al., 2012)
    - Empirical data: 37%
- Methane yield from PLA Biogas:
  - Equation: % degradation * ultimate methane potential = methane yield
    - Total: 172.79 Liters methane per kg PLA
- Conversion from Liters to Kg of Methane
  - Equation:

$$\text{1LCH4} * \frac{\text{1molCH4}}{\text{22.4 L}} * \frac{\text{16gCH4}}{\text{1molCH4}} * \frac{\text{1kg}}{\text{1000g}} = 7.14E - 4kg$$

    - Total: 7.14E-4 kg of methane
- Lifespan of Landfill
  - Source: (BSWMA, 2016)
    - Data: 15 Years
- Percentage of Waste that is Plastic
  - Source: (Petterd et al., 2019)("Combined" Category, Figure 19)
    - Data: 19%
- Waste Per Month
  - Source: (BSWMA, 2019)
    - Data: 3382 Tons/month
- Months Per Year
    - Data: 12 months/year
- Area of Site
  - Source: (B. S. W. M. A. BSWMA, 2020)
    - Data: 370 Acres
- Area of Waste Cell

    - Source: (B. S. W. M. A. BSWMA, 2020)
        - Data: 5 Acres
- Area of Treatment Ponds
    - Google Earth Estimation
        - 3500m^2
- Wide Side of Waste Cell
    - Source: Google Earth Estimation
        - Data: 215 Meters
- Short Side of Waste Cell
    - Source: Google Earth Estimation
        - 100 Meters
- Depth of Waste Cell
    - Source: (Stantec, 2008) (Lowest depth of bore hole)
        - 13 Meters (Based on maximum depth of drills for land)
- Typ. Depth of Treatment Pond
    - Source: (Youcai, 2018)
        - 5 Meters (Assumed middle of range 3 to 7 meters)
- Distance from Belize Transfer Station to Land
    - Source: Google Earth Estimation
        - Data: 40 km
- Depth of Gravel Layer
    - Source: (Stantec, 2008)
        - Data: 0.3 Meters
- Density of Gravel
    - Source: (Daniel Kellenberger et al., 2007)
        - Data: 1650 kg/m3
- Thickness of PE Sheet
    - Source: (Stantec, 2008)
        - Data: 0.0015 Meters
- Density of High Density Polyethylene
    - Source: (Europe, 2021) (Average value from range of 0.93-0.97)
        - Data: 935 kg/m3
- Thickness of Geotextile
    - Source: (Perkins, 2007)
        - Data: 2.54E-4 Meters
- Density of HDPE Geotextile
    - Source: (Europe, 2021)
        - Data: 935 kg/m3
- Pipe Length in Landfill
    - Equation: Length of Landfill waste cell
        - Data: 315 m
- Pipe length to pond
    - Source: Google Earth Estimation

        - Data: 200 m
- Total kg of Waste in Landfill
    - Equation: Lifespan of Landfill*Waste per Month*Months Per year*kg per ton=Total kg of Waste
        - Data: 6.09E8 kg
- Total kg of PLA in Landfill
    - Equation: Total kg of Waste in Landfill * Percentage of waste that is plastic=Total kg of PLA
        - Data: 1.16E8 kg

<u>Life Cycle Inventory</u>

- Land Occupation
    - Process: Occupation, Land Unknown
        - Equation: Area of Site
            - Data: 370 Acres
        - FU Equation: Area of site / (Total kg of Plastic Waste * Percentage of Waste that is plastic) = Land occupation per kg of PLA
            - Data: 2.46E-3 m^2
- Excavation of Landfill (Divided by 2 because each excavation method was said to excavate half of the landfill)
    - Process: Excavation, hydraulic digger (RoW) | market for | Cut-off, U
        - Equation: (Depth of waste cell*Area of waste cell + Area of treatment pond*Depth of treatment pond)/2 = Excavation of landfill total
            - Data: 2.37E5 m^3
        - FU Equation: Excavation of landfill total / (Total kg of Waste in Landfill* Percentage of waste that is plastic) = Excavation of landfill burdens per kg of PLA
            - Data: 3.90E-4 m^3
- Excavation, skid-steer loader (RoW)| market for | Cut-off, U
    - Process: Excavation, skid-steer loader (RoW)| market for | Cut-off, U
        - Equation: (Depth of waste cell*Area of waste cell + Area of treatment pond*Depth of treatment pond)/2 = Excavation of landfill total
            - Data: 2.37E5 m^3
        - FU Equation: Excavation of landfill total / (Total kg of Waste in Landfill* Percentage of waste that is plastic) = Excavation of landfill burdens per kg of PLA
            - Data: 3.90E-4 m^3
- Extrusion for Plastic sheet (2 different sheets so multiplied by 2)
    - Process: Extrusion, plastic film (RoW)| market for | Cut-off, U
        - Equation: Thickness of PE sheet for sealing*Area of waste cell*Density of PE sheet*2 = Plastic Extrusion for sheet total
            - Data: 5.68E4 kg

- FU Equation: Plastic extrusion for sheet total / (Total amount of waste in landfill*Percentage of waste that is plastic) = Extrusion of plastic sheet burdens per kg of PLA
  - Data: 9.32E-5 kg

❖ Gravel
- ➢ Process: Gravel, round (RoW)| market for gravel, round | Cut-off, U
  - ▪ Equation: Depth of gravel layer* Density of gravel* Area of waste cell = Total gravel burdens
    - Data: 1.00E7 kg
  - ▪ FU Equation: Total gravel burdens / (Total amount of waste in landfill*Percentage of waste that is Plastic) = Total burdens of gravel per kg of PLA
    - Data: 1.65E-2 kg

❖ Waste Transportation
- ➢ Process: Municipal waste collection service by 21 metric ton lorry (RoW)| processing | Cut-off, U
  - ▪ Equation: Total waste that is plastic*Distance from Belize Transfer station to landfill= Total transportation burdens
    - Data: 4.63E9 kgkm
  - ▪ FU Equation: Total Transportation burdens / (Total amount of waste in landfill*Percentage of waste that is plastic) = total transportation burdens per kg of PLA
    - Data: 40 kgkm

❖ Piping for Landfill
- ➢ Process: Polyethylene pipe, corrugated, DN 75 (RoW)| production | Cut-off, U
  - ▪ Equation: Pipe Length in landfill + Pipe length in pond = total pipes for landfill
    - Data: 515 m
  - ▪ FU Equation: Total pipes for landfill / (Total amount of waste in landfill*Percentage of waste that is plastic) = Total pipes for landfill per kg of PLA
    - Data: 8.46E-7 m

❖ Operational requirements of landfill (Includes landfill compaction and leachate collection)
- ➢ Process: process-specific burdens, residual material landfill
  - ▪ Data: 1 ea
  - ▪ FU Equation: 1/(Total amount of waste in landfill * Percentage of waste that is plastic) = burdens of operations per kg of PLA
    - Data: 1 ea

❖ Geotextile for landfill (Multiplied by 2 because there are two sheets)
- ➢ Process: Polyethylene, high density, granulate (RoW)| production | Cut-off, U
  - ▪ Equation: Density of geotextile*Thickness of Geotextile*Area of site*2= Total amount of polyethylene
    - Data: 1.42E4 kg

- FU Equation: Total amount of polyethylene/ (Total amount of waste in landfill * Percentage of waste that is plastic) = Polyethylene burden per kg of PLA
    - Data: 4.43E-6 kg

- Maximum Methane Emissions
  - Process: Methane Emission of PLA
    - Equation: Methane Yield*total kg of plastic in landfill*Conversion of Liters to kg at STP = Total methane produced
      - Data: 143E7 kg
    - FU Equation: Total methane produced / Total amount of waste in landfill that is plastic = Total methane emissions per kg of PLA
      - Data: .12 kg

Landfill Expansion

<u>Design Calculations</u>

- PLA Ultimate Methane Potential (UMP) at standard temperature and pressure
  - Equation: $C_6H_8O_4 + 2H_2O \rightarrow 3CO_2 + 3CH_4$
  - $1000g\text{C6H8O4} * \frac{1\text{molC6H8O4}}{144\text{gramsC6H8O4}} * \frac{3\text{molCH4}}{1\text{molC6H804}} * \frac{22.4\text{ liters}}{1\text{molCH4}} = UMP$
    - Total: 467 Liters Methane/kg of PLA
- Max Percentage Degradation of PLA
  - Source: (Kolstad et al., 2012)
    - Empirical data: 37%
- Methane yield from PLA Biogas:
  - Equation: % degradation * ultimate methane potential = methane yield
    - Total: 172.79 Liters
- Percentage of methane into air
  - Source: (EPA, 1997) (60 percent gas capture)
    - Data: 40%
- Conversion from Liters to Kg of Methane
  - Equation:

  $1\text{LCH4} * \frac{1\text{molCH4}}{22.4\text{ L}} * \frac{16\text{gCH4}}{1\text{molCH4}} * \frac{1\text{kg}}{1000\text{g}} = 7.14E - 4kg$

    - Total: 7.14E-4 kg of methane
- Lifespan of Landfill Expansion
  - Source: (Petterd et al., 2019)
    - Data: 66 Years
- Percentage of Waste that is Plastic
  - Source: (Petterd et al., 2019)
    - Data: 19 Percent
- Waste Per Month
  - Source: (BSWMA, 2019)
    - Data: 3382 Tons Per Month
- Months Per Year
    - Data: 12 months/year
- Area of Site
  - Source: (B. S. W. M. A. BSWMA, 2020)
    - Data: 370 Acres
- Area of Waste Cells
  - Source: (BSWMA, 2016)
    - Data: 89 Acres
- Area of treatment ponds
  - Google Earth Estimation
    - 3500 m^2
- Wide Side of Waste Cell

- Source: (BSWMA, 2016) (Estimated from Figure 28)
  - Data: 270 Meters

- Short Side of Waste Cell
  - Source: (BSWMA, 2016) (Estimated from Figure 28)
    - 220 Meters
- Depth of Waste Cell
  - Source: (Stantec, 2008) (Lowest depth of bore hole)
    - 13 Meters
- Depth of Treatment Pond
  - Source: (Youcai, 2018) (Averaged typical depth between 3 and 7)
    - 5 Meters
- Distance from Belize Transfer Station to Landfill
  - Source: Google Earth Estimation
    - Data: 40 km
- Depth of Gravel Layer
  - Source: (Stantec, 2008)
    - Data: 0.3 Meters
- Density of Gravel
  - Source: (Daniel Kellenberger et al., 2007)
    - 1650 kg/m^3
- Thickness of PE Sheet
  - Source: (Stantec, 2008)
    - Data: 0.0015 Meters
- Density of Polyethylene
  - Source: (Europe, 2021)
    - Data: 935 kg/m3
- Thickness of Geotextile
  - Source: (Perkins, 2007)
    - Data: 2.54E-3 Meters
- Density of Geotextile
  - Source: (Perkins, 2007)
    - Data: 935 kg/m3
- Pipe Length in Landfill
  - Equation: Width of Landfill Cell * 6 (Number of waste Cells)
    - Data: 315 m
- Pipe length to pond
  - Source: (BSWMA, 2016) (Estimated from Figure 28)
    - Data: 400 m
- Total kg of Waste in Landfill
  - Equation: Lifespan of Landfill*Waste per Month*Months Per year*kg per ton = total kg of waste in landfill
    - Data: 2.68E9 kg
- Total kg of PLA in Landfill

- Equation: Total kg of Waste in Landfill * Percentage of waste that is plastic = total kg of PLA in landfill
  - Data: 5.09E8 kg
- CO2 produced from combustion methane
  - Equation: $CH_4 + 2O_2 \rightarrow 2H_2O + CO_2$
    - Data: $1\text{g } CH4 * \frac{1\text{molCH4}}{16\text{gramsCH4}} * \frac{1 \text{ mol CH4}}{1\text{mol CO2}} * \frac{44\text{grams CO2}}{1\text{mol CO2}} = 2.75\ grams\ CO2$

  Life Cycle Inventory
- Land Occupation
  - Process: Occupation, Land Unknown
    - Equation: Area of Site
      - Data: 1.50E6 m^2
    - FU Equation: Area of site / (Total kg of Plastic Waste * Percentage of Waste that is plastic) = Land occupation per kg of PLA
      - Data: 5.59E-4 m^2
- Excavation of Landfill (Divided by 2 because each excavation method was said to excavate half of the landfill)
  - Process: Excavation, hydraulic digger (RoW)| market for | Cut-off, U
    - Equation: (Depth of waste cell*Area of waste cell + Area of treatment pond*Depth of treatment pond)/2 = Excavation of landfill total
      - Data: 4.00E6 m^3
    - FU Equation: Excavation of landfill total / (Total kg of Waste in Landfill* Percentage of waste that is plastic) = Excavation of landfill burdens per kg of PLA
      - Data: 1.49E-3 m^3
- Excavation, skid-steer loader (RoW)| market for | Cut-off, U
  - Process: Excavation, skid-steer loader (RoW)| market for | Cut-off, U
    - Equation: (Depth of waste cell*Area of waste cell + Area of treatment pond*Depth of treatment pond)/2 = Excavation of landfill total
      - Data: 4.00E6 m^3
    - FU Equation: Excavation of landfill total / (Total kg of Waste in Landfill* Percentage of waste that is plastic) = Excavation of landfill burdens per kg of PLA
      - Data: 1.49E-3 m^3
- Extrusion for Plastic sheet (Multiplied by 2 because there are 2 sheets)
  - Process: Extrusion, plastic film (RoW)| market for | Cut-off, U
    - Equation: Thickness of PE sheet for sealing*Area of waste cell*Density of PE sheet*2= Plastic extrusion for sheet total
      - Data: 1.04E6 kg
    - FU Equation: Plastic extrusion for sheet total/ (Total amount of waste in landfill*Percentage of waste that is plastic) = Extrusion of plastic sheet burdens per kg of PLA
      - Data: 3.87E-4 kg

- Gravel
  - Process: Gravel, round (RoW)| market for gravel, round | Cut-off, U
    - Equation: Depth of gravel layer *Density of gravel* Area of waste cell = Total gravel burdens
      - Data: 1.64E8 kg
    - FU Equation: Total gravel burdens / (Total amount of waste in landfill*Percentage of waste that is Plastic) = Total burdens of gravel per kg of PLA
      - Data: 6.13E-2 kg
- Waste Transportation
  - Process: Municipal waste collection service by 21 metric ton lorry (RoW)| processing | Cut-off, U
    - Equation: Total waste that is plastic*Distance from Belize Transfer station to landfill = Total transportation burdens
      - Data: 2.321E10
    - FU Equation: Total Transportation burdens/ (Total amount of waste in landfill*Percentage of waste that is plastic) = Transportation required per kg of PLA
      - Data: 40 kgkm
- Piping for Landfill
  - Process: Polyethylene pipe, corrugated, DN 75 (RoW)| production | Cut-off, U
    - Equation: Pipe Length in landfill + Pipe length in pond = Total pipes for landfill
      - Data: 3.43E3 m
    - FU Equation: Total pipes for landfill / (Total amount of waste in landfill*Percentage of waste that is plastic) = Total pipes for landfill per kg of PLA
      - Data: 3.45E-5 m
- Operational requirements of Landfill (Includes landfill compaction, Leachate capture, Methane Capture and flaring)
  - Process: process-specific burdens, Sanitary landfill RoW
    - FU Equation: 1 ea
      - Data: 1 ea
- Total amount of polyethylene (Multiplied by 2 because 2 layers of Polyethylene Sheets)
  - Process: Polyethylene, high density, granulate (RoW)| production | Cut-off, U
    - Equation: Density of geotextile*Thickness of Geotextile*Area of site*2 = Total amount of polyethylene
      - Data: 2.52E5 kg
    - FU Equation: Total amount of polyethylene/ (Total amount of waste in landfill*Percentage of waste that is plastic) = Polyethylene burden per kg of PLA
      - Data: 1.79E-5 kg
- Max Methane Emission of PLA

    - Equation: Methane Yield*total kg of plastic in landfill*Conversion of Liters to kg at STP = Total methane produced
        - Data: 2.51E5 kg
    - FU Equation: Total methane produced / Total amount of waste in landfill that is plastic = Total methane emissions per kg of PLA
        - Data: 4.94E-2 kg
- CO2 Emission from burning methane
    - Equation: Methane Yield*(1-Methane into air)*total kg of plastic in landfill*CO2 produced from combustion of methane*Conversion of kg to liters at STP= Total CO2 emitted
        - Data: 1.04E7 kg
    - FU Equation: Total CO2 emitted / (Total amount of waste in landfill*Percentage of waste that is plastic) = CO2 emitted per kg of Methane
        - Data: 2.04E-1 kg

Co-generation

<u>Design Calculations</u>

- Lifetime
  - Source: (Jungbluth et al., 2007)
    - Data: 20 years
- PLA LHV
  - Source: (NatureWorks, 2020)
    - Experimental Data: 8368 btu
- Energy per kg of PLA
  - Equation: PLA LHV/ 0.453592 kg per lb
    - Data: 18448.297 btu
- Energy Efficiency
  - Source: (Kamate et al., 2009)
    - Data: 84%
- Electrical Efficiency
  - Source: (Kamate et al., 2009)
    - Data: 14%
- Thermal Efficiency
  - Source: (Kamate et al., 2009)
    - Equation: Energy efficiency – Electrical efficiency = Thermal efficiency
      - Data: 70%
- Percentage of energy Exported
  - Source: (IDB, 2006)
    - Data: 33.33%
- Conversion from BTU to MJ
    - Data: 947.81 Btu/MJ
- MJ End Energy from PLA Co-generation
  - Equation: Energy per kg of PLA*Energy Efficiency/Conversion from BTU to MJ = MJ end energy
    - Data: 16.35 MJ
- MJ End heat from PLA Co-generation
  - Equation: Energy per kg of PLA*Thermal Efficiency*Conversion from BTU to MJ = MJ end heat
    - 13.62 MJ
- Capacity of Co-generator
  - Source: (Jungbluth et al., 2007)
    - Data: 4.67E7 MJ/y
- Capacity Utilization Rate
  - Source: (Jungbluth et al., 2007)
    - Data: 0.85%
- MJ of end heat produced in Wood Chip Process
  - Source: (Jungbluth et al., 2007)

        - Data: .767 MJ
- Distance from transfer station to Co-generator
    - Source: Google Earth Estimate
        - Data: 70 km
- Distance from Co-generator to landfill
    - Source: Google Earth Estimate
        - 70 km
- Conversion from kwh to btu
        - Data: .00029307 kwh per btu
- Energy Exported
    - Equation: Energy per kg of PLA * Electrical Efficiency * Percentage of energy exported
        - Data: 860.92 btu/kg PLA

Life cycle inventory

- Electricity Produced
    - Process: 1 kWh Electricity, high voltage (mx)| heat and power co-generation, biogas, gas engine | Cut-off, U
        - Equation: Energy Exported/kg PLA*Conversion from btu to kwh = Energy Exported per kg of PLA
            - Data: 0.76 kwh
- Heat Produced
    - Process: 1 kWh Heat, central or small-scale, other than natural gas (mx)| heat and power co-generation, biogas, gas engine | Cut-off, U
        - Equation: Energy per kg of PLA*Thermal Efficiency*Conversion from kwh to btu*Heat to power ratio*conversion from kwh to btu = Heat produced per kg PLA
            - Data: 3.78 kwh
- Electricity Required (66% of energy produced is used for system operation)
        - Source: (IDB, 2006)
    - Process: 1 kWh Electricity, high voltage (mx)| heat and power co-generation, biogas, gas engine | Cut-off, U
        - Equation: Energy produced *.66 = Electricity Required
            - Data: 0.50 kwh
- Chemicals used for Co-generation of 1 kg of PLA
    - Process: Chemical, organic (RoW)| market for | Cut-off, U
        - Chemicals used for Co-generation of 1kg of Wood Chips
            - Data: 5.74E-6 kg
        - Equation: Chemicals used for Co-generation of 1kg of wood chips/MJ of end heat produced by wood chips * MJ of end heat produced = Chemicals used for Co-generation of 1 kg of PLA
            - Data: 1.02E0-4 kg
- Chlorine Used for Co-generation of 1 kg of PLA

- Process: Chlorine, liquid (RoW)| market for chlorine, liquid | Cut-off, U
  - Chlorine used for Co-generation of 1kg of Wood Chips
    - Data: 3.28E-7 kg
  - Equation: Chlorine used for Co-generation of 1kg of wood chips/MJ of end heat produced by wood chips * MJ of end heat produced = Chlorine used for Co-generation of 1 kg of PLA
    - Data: 5.83E-6 kg

- Heat and power Co-generation infrastructure (Building lifetime is 80 years [4 times longer than boiler and turbine])
  - Process: Heat and power co-generation unit, 6400kW thermal, building (RoW)| construction | Cut-off, U
    - Heat and power Co-generation infrastructure used in Co-generation of 1kg of Wood Chips
      - Data: 2.93E-9 ea
    - Equation: Energy MJ of end energy produced from PLA Co-generation/(Capacity of Co-generator *Capacity Utilization Rate*Lifetime*4)=Infrastructure required for 1 kg of PLA
      - Data: 5.15E-9 ea
- Heat and power Co-generation infrastructure (boiler & turbine)
  - Process: Heat and power co-generation unit, 6400kW thermal, common components for heat + electricity (RoW)| construction | Cut-off, U
    - Heat and power Co-generation used in for Co-generation of 1kg of Wood Chips
      - Data: 1.17E-8 ea
    - Equation: Energy MJ of end energy produced from PLA Co-generation/(Capacity of Co-generator *Capacity Utilization Rate*Lifetime*) = Infrastructure required for 1 kg of PLA
      - Data: 2.06E-8 ea
- Heat and power Co-generation infrastructure (Generator and control board)
  - Process: Heat and power co-generation unit, 6400kW thermal, components for electricity only (RoW)| construction | Cut-off, U
    - Heat and power Co-generation used in for Co-generation of 1kg of Wood Chips
      - Data: 1.17E-8 ea
    - Equation: Energy MJ of end energy produced from PLA Co-generation/(Capacity of Co-generator *Capacity Utilization Rate*Lifetime*) = Infrastructure required for 1 kg of PLA
      - Data: 2.06E-8 ea
- Sodium chloride used in Co-generation process
  - Process: Sodium chloride, powder (RoW)| market for | Cut-off, U
    - Sodium Chloride used for Co-generation of 1kg of Wood Chips
      - Data: 4.1E-6 kg

- Equation: Sodium Chloride used for Co-generation of 1kg of wood chips/MJ of end heat produced by wood chips *MJ of end heat produced = Sodium Chloride used for Co-generation of 1 kg of PLA
  - Data: 7.28E-5 kg

- Water used in Co-generation
  - Process: Water, decarbonized, at user (RoW)| market for | Cut-off, U
    - Water used for Co-generation of 1kg of Wood Chips
      - Data: 7.87E-4 kg
    - Equation: Water used for Co-generation of 1kg of wood chips/MJ of end heat produced by wood chips *MJ of end heat produced = Water used for Co-generation of 1 kg of PLA
      - Data: 1.40E-2 kg
- Municipal solid waste produced
    - Municipal solid waste produced in 1 kg of wood chips
      - Data: 3.28E-6 kg
    - Equation: Municipal solid was produced in Co-generation of 1kg of wood chips/MJ of end heat produced by wood chips *MJ of end heat produced = Municipal solid waste produced for Co-generation of 1 kg of PLA
      - Data: 5.83E-5 kg
- Waste Mineral oil produced
    - Equation: Waste Mineral Oil produced in 1 kg of wood chips
    - Data: 3.28E-6 kg
    - Equation: Waste mineral oil produced in Co-generation of 1kg of wood chips/MJ of end heat produced by wood chips *MJ of end heat produced = Waste mineral oil produced for Co-generation of 1 kg of PLA
    - Data: 5.83E-5 kg
- Ashes left after burning PLA
  - Source: (NatureWorks, 2020)
    - Data: .001 kg per kg of PLA
- Total Waste Produced per kg of PLA
  - Equation: Ashes left after burning PLA + Waste mineral oil produced + municipal solid waste produced = Total waste produced per kg of PLA
- Waste Transportation to Co-generator
  - Process: Municipal waste collection service by 21 metric ton lorry (RoW)| market for | Cut-off, U
    - Equation: Distance from Co-generator to transfer station* 1 kg of PLA = Transportation burdens per kg of PLA
      - Data: 70 kgkm
- Waste Transportation from Co-generator to landfill
  - Process: Municipal waste collection service by 21 metric ton lorry (RoW)| market for | Cut-off, U
    - Equation: Total waste produced per kg PLA*Distance from Co-generator to landfill = Transportation of wastes to landfill per kg of PLA

        - Data: 7.82E-2 kgkm
- Landfill Waste Treatment
  - Process: Treatment of Wastes in Landfill
    - Equation: Total waste produced = Total kg of waste to landfill per kg of PLA
      - Data: 1.76E-4 kg
- Carbon dioxide released from incineration of 1kg of PLA
  - Process: Carbon dioxide, biogenic
    - Source: (NatureWorks, 2020)
      - Data: 2.02 kg
- Carbon monoxide released from incineration of 1 kg of PLA
  - Process: Carbon monoxide, biogenic
    - Source: (NatureWorks, 2020)
      - Data: 6.53E-5 kg
- Naphthalene released from incineration of 1 kg of PLA
  - Process: Naphthalene
    - Source: (Chien et al.)
      - Data: 98E-6 grams / kg PLA
- PAH's released from incineration of 1 kg of PLA
  - Process: Polycyclic Aromatic Hydrocarbons
    - Source: (Chien et al.)
      - Data: 23.02E6 grams / kg PLA
- Water released from burning 1 kg of PLA
  - Process: Water
    - Source: (NatureWorks, 2020)
      - Data: 0.26 Liters

Anaerobic Digestion

Design Calculations

- Capacity
  - Source: (Jungbluth et al., 2007)
    - Data: 1400 m^3
- Temperature
  - Source: Hobbs, 2016
    - Data: 35° (Mesophilic)
- Retention Time
  - Source: (Yagi et al., 2009); (Veronika, 2018)
    - Data: 30 days
- Lifetime
  - Source: (Jungbluth et al., 2007)
    - Data: 25 Years
- Lifetime Usage Total (360 days per year because 30 days per month assumed)
  - Equation: Capacity*(360 days/Retention time)*Lifetime = Lifetime usage total
    - Data: 420000 m^3 of feedstock
- PLA Ultimate Methane Potential (UMP) at standard temperature and pressure
  - Equation: $C_6H_8O_4 + 2H_2O \dashrightarrow 3CO_2 + 3CH_4$
  - $1000g\text{C6H8O4} * \frac{\text{1molC6H8O4}}{\text{144gramsC6H8O4}} * \frac{\text{3molCH4}}{\text{1molC6H804}} * \frac{\text{22.4 liters}}{\text{1molCH4}} = UMP$
    - Total: 467 Liters Methane per kg of PLA
- Percentage Degradation
  - Source: Hobbs, 2016, Yagi, 2008
    - Data: 50%
- Methane produced per kg of PLA
  - Equation: Ultimate Methane Potential per kg * Percent degradation = Methane produced per kg of PLA
    - Data: 233.5 l/kg of PLA
- Distance from AD to landfill
  - Source: Google Earth Estimation
    - Data: 35 km
- Distance from transfer station to AD
  - Source: Google Earth Estimation
    - Data: 15 km
- Density of NaOH
  - Source: (NCB, 2021)
    - Data: 1.515 g/ml
- Density of PLA
  - Source: (NatureWorks)
    - Data: 1240 kg/m3
- Density of Sludge

- Source: (Walton, 2010)
    - Data: 720 kg/m^3
- Sludge input
  - Source: (Yagi et al., 2009)
    - Data: 1.4 liters = .0014 m3
- PLA Input
  - Source: (Yagi et al., 2009)
    - Data: 10 grams
- PLA Input (Unit Conversion)
  - Equation: PLA Input (g) / 1000g per kg* Density of PLA
    - Data: 8.06 E-6 m3
- Sludge influent reused
  - Source: (Yagi et al., 2009)
    - Data: .06 liters
- Sludge PLA Reuse Percentage
  - Source: (Yagi et al., 2009)
    - Equation: Sludge-PLA Influent reused/Sludge input = Sludge PLA Reuse Percentage
    - Data: 4.3%
- Heat Capacity of Sludge
  - Assumption: Identical to water
    - Data: 4.184 C°*J/g
- Electricity to heat efficiency
  - Source: Literature Review
    - Data: 30%
- Energy per m^3 of biogas (60% CH4 - 40% CO2)
  - Equation: 0.1 kwh* % of methane in m^3 biogas = Energy per m^3 of biogas
    - Data: 6 kwh per m^3 of biogas
- PLA in digester per retention
  - Equation: Capacity / (Sludge input/PLA Input) = PLA in digester each retention
    - Data: 8.065 m^3
- Sludge in digester
  - Equation: Capacity – PLA in digester per retention = Sludge in digester
    - Data: 1391.94 m^3
- Ratio of PLA to sludge in digester
  - Source: PLA in digester per retention/sludge in digester = Ratio of PLA to sludge in digester
    - Data: .005793743 m^3/m^3
- New sludge per retention
  - Equation: sludge in digester – (Sludge PLA reuse percentage* Sludge in digester) = New sludge per retention
    - Data: 1332.28 liters
- Methane generated from PLA per retention

- Equation: PLA in digester per retention* density of PLA * Methane produced per kg of PLA = Methane generated from PLA
  - Data: 2.34E6 liters
- Biogas produced (Assumed 60% CH4, 40% CO2in biogas)
  - Equation: Methane Generated from PLA/ Ratio of Methane to CO2 produced = Biogas Produced
    - Data: 3.89E6 liters
- Heat required for digester per gram of sludge
  - Source: Heat capacity*Temperature = Heat capacity per gram of sludge
    - Data: 146.44 joules/gram
- Heat required for one retention
  - Equation: (Capacity*Heat required per gram of sludge in digester *1000 grams/kg*Density of Sludge/1E6 joules per MJ)
    - Data: 12372.672 MJ
- Electricity needed for heat
  - Equation: Heat Required for One retention/Electricity to heat efficiency = Electricity required to heat anaerobic digester for one retention
    - Data: 5.41E5 MJ
- PLA degradation
  - Source: (Yagi et al., 2009) (Hobbs, 2016)
    - Data: 50%
- Pretreatment Required (Multiplied by 5 x amount of pretreatment than PLA by weight)
  - Source: Hobbs, 2016
    - Equation: PLA in digester per retention * Density of PLA* 5 = Total amount of Pretreatment used
    - Data: 5.00E4 kg
- Digestate produced due to PLA per retention
  - Source: (B. G. Hermann et al., 2011)
    - Equation: (1-Degradation of PLA) per kg*Density of PLA*PLA in digester per retention = Digestate Produced per retention
    - Data: 3970 kg
- Total amount of digestate residue
  - Equation: Digestate produced per retention*Lifetime*360/retention time*Density of PLA
    - Data: 1.48E9 kg
- Total PLA treated over lifetime
  - Equation: PLA in digester per retention*Lifetime*360/Retention time*Density of PLA
    - Data: 3000000 kg
- Total mass treated over lifetime
  - Equation: (Sludge in digester per retention*Lifetime*360/retention time*Density of PLA) + Total PLA treated over lifetime
    - Data: 3.00E6 kg

Life Cycle Inventory

- Concrete for Digester (Jungbluth et al., 2007)
  - Data: 406 kg
  - Process: Concrete, normal (RoW)| market for | Cut-off, U
    - FU Equation: Concrete for digester* Volumetric Ratio of PLA to sludge in Digester*(Density of PLA/Density of Sludge)/Total PLA treated over lifetime = Concrete for digester/kg of PLA
      - Data: 7.84E-7 kg
- Cast Iron for Digester (Jungbluth et al., 2007)
  - Data: 504 kg
  - Process: Cast iron (RoW)| market for | Cut-off, U
    - FU Equation: Cast iron for digester*Volumetric Ratio of PLA to sludge in Digester*(Density of PLA/Density of Sludge)/Total PLA treated over lifetime= Cast iron for digester/kg of PLA
      - Data: 1.67E-6 kg
- Steel for Digester (Jungbluth et al., 2007)
  - Data: 1970 kg
  - Process: Steel, Chromium steel 18/8, hot tolled (RoW)| Market for | Cut-off, U
    - FU Equation: Steel for digester*Volumetric Ratio of PLA to sludge in Digester*(Density of PLA/Density of Sludge)/Total PLA treated over lifetime= Steel for digester/kg of PLA
      - Data: 6.55E-6 kg
- Reinforcing Steel for digester (Jungbluth et al., 2007)
  - 24300 kg
  - Process: Reinforcing steel (RoW)| market for | Cut-off, U
    - FU Equation: Reinforcing steel for digester*Volumetric Ratio of PLA to sludge in Digester*(Density of PLA/Density of Sludge)/Total PLA treated over lifetime= Reinforcing Steel for digester/kg of PLA
      - Data: 8.08E-5 kg
- Occupation (Jungbluth et al., 2007)
  - 78000 m^2
  - Process: Occupation, Land use, Unknown
    - FU Equation: Occupation Total*Volumetric Ratio of PLA to sludge in digester*(Density of PLA/Density of Sludge)/Total PLA Treated over lifetime = Occupation of anaerobic digester per kg of PLA
    - Data: 0.000150637 m^2
- High voltage electricity required for digester
  - Process: Electricity, High voltage (mx)| market for | Cut-off, U
    - Equation: Electricity required per retention *Lifetime*360/retention time*Ratio of PLA to sludge in digester = Electricity required over lifetime for PLA
      - Data: 9.41E5 MJ

        - FU Equation: Electricity required over lifetime for PLA/Total PLA Treated over lifetime) = High voltage electricity required per kg of PLA
            - Data: 1.82E-3 MJ
- Low voltage electricity required for digester (Systems, monitoring)
    - .002135 MJ per kg of sludge
    - Process: Electricity, low voltage (mx)| market for | Cut-off, U
        - FU Equation: Low voltage electricity required for digester*(Ratio of PLA to sludge in digester/Total PLA Treated over lifetime) = low voltage electricity required per kg of PLA
            - Data: 4.12E-12 MJ
- Heat Required for digester
    - Process: Heat, district or industrial, natural gas (RoW)| market for heat, district or industrial, natural gas | Cut-off, U
        - Equation: Heat required per retention *Lifetime*360/retention time*Density of PLA = Total heat required
            - Data: 2.82E5 MJ
        - FU Equation: Total heat required*(Ratio of PLA to sludge in digester/Total PLA Treated over lifetime) = Heat required for digester per kg of PLA
            - Data: 5.45E-4 MJ
- Transportation from Transfer station to AD
    - Process: Municipal waste collection service by 21 metric ton lorry (RoW)| processing | Cut-off, U
        - Equation: Distance from Ad to Transfer station*1 kg of PLA = Transportation required per kg of PLA
            - Data: 15 kgkm
- Pretreatment Required
    - Process: NaOH Pretreatment
        - Equation: Pretreatment Required
            - Data: 5E-4 kg
        - FU Equation: Pretreatment required*(Ratio of PLA to sludge in Digester*(Density of PLA/Density of Sludge)/Total PLA treated over lifetime = NaOH required per kg of PLA
            - Data: 1.66E-4 kg
- HCl Required
    - Process: HCL Acid Balancing
        - Equation: HCL Required
            - Data: 5E-4 kg
        - FU Equation: HCl acid required*(Ratio of PLA to sludge in Digester*(Density of PLA/Density of Sludge)/Total PLA treated over lifetime = HCl required per kg of PLA
            - Data: 1.66E-4 kg
- Digestate residue produced
    - Process: Digestate Residue

    - Equation: Digestate Residue per retention * 360/retention time*Lifetime = Total digestate residue produced from PLA
        - Data: 1.19E6 kg
    - FU Equation: Total/Total PLA waste digested = Digestate produced per kg of PLA
        - Data: 0.5 kg

- Biogas Produced
  - Process: Biogas
    - Equation: Biogas per retention * 360/retention time*Lifetime = liters of biogas produced
        - Data: 1.17E9 liters
    - FU Equation: liters of biogas produced/Total amount of PLA Digested = biogas produced per kg of PLA
        - Data: 389.1667 liters
- Transportation from AD to Landfill
  - Process: Municipal waste collection service by 21 metric ton lorry (RoW)| processing | Cut-off, U
    - Equation: Digestate Residue * Distance from AD to landfill = Transportation of Wastes per kg of PLA
        - Data: 13.9 kgkm
- Electricity Produced From biogas
  - Process: Electricity, high voltage (mx)| heat and power co-generation, biogas, gas engine | Cut-off, U
    - Equation: Biogas Produced/1000liters per m^3*energy per m3 of biogas*Electricity to heat efficiency = Total electricity produced from biogas
        - Data: 2.1E6 kwh
    - FU Equation: Total electricity produced from biogas/Total amount of PLA degraded = Electricity produced from biogas per kg of PLA
        - Data: 7.01E-1 kwh
- Heat produced from biogas
  - Process: Heat, district or industrial, natural gas (RoW)| market for heat, district or industrial, natural gas | Cut-off, U
    - Equation: Biogas produced/1000 liters per m^3*(1-electricity to heat efficiency) *energy per m^3 of biogas = Heat produced from biogas
        - Data: 4.90E6 kwh
    - FU Equation: Heat produced from biogas/ Total kg of PLA Treated = Heat produced from biogas per kg of PLA
        - Data: 1.63 kwh
- Landfill Burdens from digestate
  - Process: landfill burdens from digestate
    - FU Equation: .5 kg / kg PLA

APPENDIX 2. Wilcoxon Signed Rank Test

This appendix summarizes the calculations of the Wilcoxon Signed Rank test that was used to test the hypotheses.

$$Z = \frac{x - \left(\frac{n(n+1)}{4}\right)}{\sqrt{\left(\frac{n*(n+1)(2n+1)}{24}\right)}}$$

X = minimum between the sum of negative ranks and the sum positive ranks

N = number of trials

Anaerobic Digestion Comparison Between Waste Management Systems			
	Anaerobic Digestion vs. Cogeneration	Anaerobic Digestion vs. Landfill Expansion	Anaerobic Digestion vs. Landfill
Sum of Negative Differences	3551	5050	5050
Sum of Positive Differences	1499	0	0
Number of Trials	100	100	100
Z-Score	-3.53E+00	-8.68E+00	-8.68E+00
P-Value based on Z-score	0.0002	0	0

Landfill Expansion (Materials, Transportation, Operation) Comparison		
	Transportation vs. Material Requirements	Transportation vs. Operational Requirements
Sum of Negative Differences	0.00E+00	5050
Sum of Positive Differences	5.05E+03	0
Number of Trials	100	100
Z-Score	-8.68E+00	2.98E+00
P-Value based on Z-score	0	0.9986

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