Reducing Agricultural Plastics' Environmental Impacts

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Signature Page

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The Group Project is required of all students in the Master of Environmental Science and Management (MESM) Program. The project is a year-long activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Group Project Final Report is authored by MESM students and has been reviewed and approved by:

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Glossary of Acronyms

APW	Agricultural plastic waste
EPA	Environmental Protection Agency
HDPE	High density polyethylene
ISO	International Organization for Standardization
LCA	Life cycle assessment
LDPE	Low density polyethylene
MSW	Municipal solid waste
Mt	Million metric tons
PP	Polypropylene
RTI	Research Triangle Institute
t	Metric ton or tonne

Executive Summary

Plastics are synthetic or naturally occurring materials that consist of polymers, allowing them to be shaped and molded (Andrady & Neal, 2009). Following World War II, their use has increased dramatically. It is estimated that 8,300 million metric tons (Mt) of virgin plastic had been produced to date in 2015 (Geyer et al., 2017). In 2012, annual production of agricultural plastics alone topped 4.4 Mt with an annual growth rate of 7.6% from 2013-2019 (Sintim & Flury, 2017). In agriculture, plastics are used as tunnels, mulch films, and more. Such uses can lead to greater yields, early harvests, reduced chemical inputs, higher quality products, and water conservation (Pazienza & Lucia, 2020). Table 1, shown below, summarizes common agricultural plastics and their uses.

Table 1. Common agricultural field plastics and their key benefits. Categorization of common agricultural plastics by plastic type, color, and benefits.

Common Agricultural Field Plastics			
Field Plastic	**Plastic Type**	**Color**	**Common Uses/Benefits**
Mulch Film	HDPE/LDPE	Mixed	Increase yields, modify soil temperature, protect fruit, reduce food loss, reduce evaporation, maintain soil water levels, and reduce weed establishment
Drip Tape	HDPE/LDPE	Black	Conserve water, decrease fertilizer use, decrease water splash/pathogen spread
Tunnel	HDPE	Clear	Protect crops from adverse weather conditions, extend growing season
Pots	LDPE	Black	Increase yields, extend growing season
Weed Mat	PP	Black	Suppress weed growth
Fumigation	HDPE/LDPE	Clear	Trap fumigants

Many types of agricultural plastics are reused for multiple years and/or mechanically recycled at the end of their life. However, the plastics addressed in this study are in direct contact with the soil and designed for single use. Their single-use nature contributes to the growing volume of plastic waste, as soil contact plastics are disposed of after every growing season. Soil-contact plastics, including mulch film, are difficult to recycle due to their high soil residue levels and thus are sent to landfills where they do not decompose (Piehl et al., 2018). Many US landfills are nearing capacity, which can increase tipping fees for farmers and require further land use change (“Advancing Sustainable Materials Management,” 2021).

As the world's largest berry company, Driscoll's is committed to improving the environmental footprint of their growers' berry production. By partnering with the Bren School, they aim to identify solutions to support their growers in reducing the environmental impact of agricultural plastics while maintaining in-field functionality. To pursue this objective, our team reviewed the literature on solutions that had the potential to reduce the environmental impacts of agricultural plastics. After discussions with Driscoll's, we narrowed our focus to solutions that address end-of-life management of soil-contact plastics (LDPE films). We felt that this was the most appropriate scope for our project because changes to end-of-life management were most likely to be implemented by Driscoll's and their growers.

We identified landfill as the baseline disposal scenario and selected three disposal options to measure and compare against landfill and one another – mechanical recycling, incineration, and plastic-to-fuel technologies, similar to pyrolysis or plastic reformation. Mechanical recycling converts plastic waste back into plastic pellets through washing, grinding and extrusion. Incineration combusts plastic waste and converts the resulting heat into electricity. Finally, plastic-to-fuel uses thermal and mechanical processes to reform plastic back into transportation fuels like diesel and gasoline. Mechanical recycling and incineration are traditional alternatives to landfill while plastic-to-fuel technologies are not yet commonly available, but shows promise in dealing with difficult-to-manage plastic waste.

To evaluate the total impacts of our four end-of-life strategies, we conducted life cycle assessments, or LCAs, according to the methodology provided in ISO 14044. The typical LCA involves modeling all relevant steps of a product system and aggregating total environmental impacts. We began each model with the collection of plastic waste from the field. We then modeled all relevant steps of each waste management process itself. Finally, every method but landfill results in a useful end product, so the benefits of alternative end-of-life processes come not only from avoiding landfill but from the displacement of primary production. In order to consider displaced production, we modeled and subtracted the traditional production process for each scenario's useful end products.

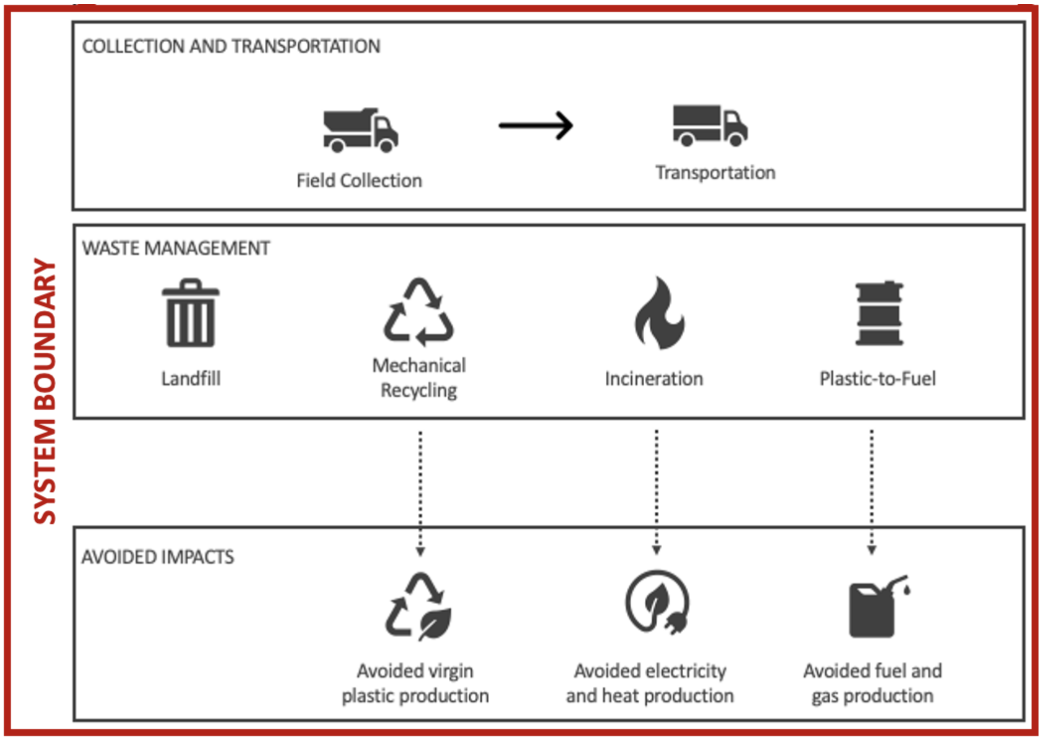

Figure 1. System boundaries for LCA models of end-of-life scenarios. For each model, the system begins with field collection and transportation, continues with waste management or reprocessing, and ends with displaced production. The initial production and use phases are left out because they are consistent across each end-of-life scenario and therefore do not affect the results.

We used the following framework to evaluate the life cycle impacts of our different scenarios, represented by the equation below:

$$E^{i}_{\text{Net}} = \underbrace{E^{i}_{\text{Coll}} + E^{i}_{\text{Trans}} + E^{i}_{\text{Rep}}}_{E^{i}_{\text{Direct}}} - E^{i}_{\text{Virgin}} - E_{\text{Land}}$$

where i = respective end-of-life scenario

The *direct* impacts from each scenario are the sum of impacts from collection, transportation, and end-of-life reprocessing. We account for avoided burdens by subtracting the environmental impacts of primary production and landfill, and assume useful end products displace virgin production on a 1:1 basis and plastic waste would be sent to landfill if not for an alternative scenario. We are left with E_{Net}, or the net environmental impacts of a given process compared to landfill.

If E_{Net} is negative for a given environmental indicator, we can infer that that process is a net environmental benefit compared to landfill. With that logic, the most negative E_{Net} is the most environmentally friendly strategy for that indicator. Our analysis resulted in the following net environmental impacts for each waste management strategy:

Table 2. Net environmental impacts from each end-of-life scenario. Net impacts include the avoided burden of using virgin material for each end-of-life process

Comparative LCA Results: Net Impacts				
Indicator	**Landfill**	**Mechanical Recycling**	**Incineration**	**Plastic to Fuel**
Acidification (kg SO_2 eq.)	—	-3.41	-0.76	-0.74
Ecotoxicity (CTU eq.)	—	-855.00	-8.40	-330.28
Eutrophication (kg N eq.)	—	-3.10	-0.01	-0.41
Global Warming (kg CO_2 eq.)	—	-1,521.20	2,809.70	-287.20
Human Health (kg PM2.5 eq.)	—	-0.43	-0.02	-0.07
Human Toxicity (CTUh)	—	0.00	0.00	0.00
Smog Formation (kg O_3 eq.)	—	-77.61	-2.48	-10.68

When we calculate overall net impacts (direct impacts minus impacts from landfill and virgin production), we find that each strategy is a net environmental benefit compared to landfill, with the exception of incineration with respect to its global warming potential. Overall, mechanical recycling has the lowest environmental impacts in every category, followed by plastic to fuel and then incineration.

These results are associated with each individual process's expected method for soil-contact plastic removal, location, and soil residue levels. We conducted scenario analyses to test our results' sensitivity to different levels of transportation, location, soil residue, and displacement ratios, and found that in almost every scenario, the results remain the same – mechanical recycling has the lowest environmental impacts. The plastic-to-fuel technology becomes the preferable option for global warming potential only when we test a scenario in which its end products offset 100% of virgin production but end products from mechanical recycling displace less than 25-50% of virgin plastic production.

While our models clearly showed that mechanical recycling is the preferable option in terms of environmental impacts, this solution has economic, technical, and political constraints. The United States currently lacks sufficient infrastructure to recycle plastics at a large scale, and there are concerns about the existence of profitable secondary markets for recycled plastics, especially when oil prices are low. In addition, the added cost to clean soil-contact plastics before they can be processed represents another barrier for this technology. Our models also rely on the assumption that the useful end products completely displace virgin plastic production instead of expanding existing markets or simply creating a market for a new product altogether. Plastic-to-fuel and incineration, on the other hand, have more certain end markets and may be more financially feasible in the short term.

Considering net impacts and the many socioeconomic factors at play, we recommend that Driscoll's considers both plastic-to-fuel technologies and mechanical recycling as viable alternatives to landfill, with a preference for recycling when economically possible. Driscoll's plans to use these recommendations to inform their sustainable agriculture plastic strategy.

Significance and Objective

Although consumer-facing food packaging has largely been the focus of the public discourse around plastics, agricultural systems use plastics for a variety of purposes. From seedling transport, to irrigation systems, to in-field structures, plastic is an effective tool to improve yields and increase input efficiency on farms (Kasirajan & Ngouajio, 2012; Freeman & Gnayem, 2005). Berry production, due to the highly perishable nature of the fruit, has a particularly high reliance on agricultural plastics.

However, agricultural plastics also come with negative environmental impacts throughout their life cycle. Driscoll's is committed to supporting their independent growers in reducing the environmental impact of agricultural plastics while maintaining the in-field functionality plastics provide. Driscoll's also recognizes that different solutions have tradeoffs between social, environmental, and functional objectives. As the world's largest berry company, Driscoll's is dedicated to improving the environmental footprint of their berry production. After a thorough review of the literature and discussions with Driscoll's environmental team, we identified the following research question and objective:

Research Question:

What opportunities are there to reduce the environmental impacts of the agricultural plastic use in Driscoll's berry production?

Objective:

Use life cycle assessment to identify the environmental impacts of and tradeoffs between various end-of-life management methods of soil-contact plastics.

Background

Plastics Overview

Plastics are a group of synthetic or naturally occurring materials consisting of polymers that can be shaped and molded. While there are hundreds of plastic materials available, six main commodity plastics, those produced at high volumes and low prices, account for 90 percent of total plastic demand. These include low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), and polyethylene terephthalate (PET) (Andrady & Neal, 2009).

Following their growth in popularity after World War II, annual global production of plastics has increased from two million metric tons (Mt) in 1950 to 380 Mt in 2015, totaling 7800 Mt in that time span (Geyer et al., 2017). Plastic use in agriculture also began in the 1950s (Espi et al., 2006) and has grown substantially; the annual global use of agricultural plastic was estimated at 4.4 Mt in 2012 with the market growing annually at a rate of 7.6% from 2013-2019 (Sintim & Flury, 2017). Agricultural plastics are typically made from LDPE, PP, HDPE, or linear low-density polyethylene (LLDPE) and have helped increase yields in previously unproductive areas (Hurley, 2008; Espi et al., 2006).

Benefits of Agricultural Plastics

In agriculture, certain polymers serve particular functions; the most common plastics used in berry production, and thus those of interest to Driscoll's, are shown below in Table 3.

Table 3. Common agricultural field plastics and key benefits. Categorization of the key plastics used in fields by plastic type, color, and benefits.

Common Agricultural Field Plastics			
Field Plastic	**Plastic Type**	**Color**	**Common Uses/Benefits**
Mulch	HDPE/LDPE	Mixed	Increase yields, modify soil temperature, protect fruit, reduce food loss, reduce evaporation, maintain soil water levels, and reduce weed establishment
Drip Tape	HDPE/LDPE	Black	Conserve water, decrease fertilizer use, decrease water splash/pathogen spread
Tunnel	HDPE	Clear	Protect crops from adverse weather conditions, extend growing season
Pots	LDPE	Black	Increase yields, extend growing season
Weed Mat	PP	Black	Suppress weed growth
Fumigation	HDPE/LDPE	Clear	Trap fumigants

The functional use of any particular polymer is dependent on its resulting material properties. Plastic tunnels are often used in berry production to protect the fruit from adverse weather conditions such as rain, frost, hail, and sandstorms. These tunnels are made from HDPE and vary in height and thickness depending on growing conditions (Freeman & Gnayem, 2008). Plastic mulch increases yields, modifies soil temperature, protects fruit, reduces food loss, reduces evaporation, maintains soil water levels, and reduces weed establishment - all of which strongly influence plant growth and yield. Different types and colors alter the optical properties in a way that optimizes the mulch's effectiveness for a given microclimate (Kasirajan & Ngouajio, 2012). Drip irrigation systems utilize plastic tubing called drip tape to optimize water and nutrient efficiency. These systems deliver water directly to each plant, preventing excess evaporation and overwatering, which can reduce water usage by up to 40% compared to traditional sprinklers (Freeman & Gnayem, 2008). Drip irrigation may also protect against pathogen dispersal by preventing water contaminated with pathogens from splashing onto leaves. (Durner et al., 2002). Weed mats help suppress weed growth in the field. Fumigation plastic allows for more efficient use of fumigation compounds and reduced climate impacts (Pazienza & Lucia, 2020). Finally, some farmers are turning to container production agriculture, where berries are grown in plastic pots containing organic substrates like coconut fiber as opposed to soil. Container production agriculture eliminates the need for certain fumigants, and has shown potential to increase yields, use water more efficiently, and extend the growing season (Lopez-Medina et al., 2004).

Impacts of Agricultural Plastics

While plastics provide agronomic benefits to agricultural systems, their production is associated with greenhouse gas emissions, contributing to climate change. Plastic production begins with the extraction and transportation of crude oil, which then leads to polymerization and plasticization that produces plastic pellets to be sold to manufacturers ("Plastics and Climate," 2019). Researchers estimate that resin production results in an average of 1.65 kg CO_2e/kg resin for LDPE and HDPE, the agricultural industry's two most common plastics (Posen et al., 2017).

A study completed in China found that soil-contact plastics like mulch film and weed mats that are left on the field can collect rainwater and create a smooth pathway for water to flow, contributing to soil erosion and pesticide or nutrient runoff (Zhang et al., 2020; Griffin & Bromley, 1982). While most farmers in North America remove soil-contact plastics after each growing season, a small amount can be unintentionally left in fields. These residues break down into microplastics and may leak additives into soil and groundwater, which can reduce crop quality or harm human and animal health (Moreno et al., 2014; Erkekoglu & Kocer-Gumusel, 2014; He et al., 2018). Managing the use phase impacts of agricultural plastics requires careful consideration of the costs and benefits of agricultural plastic use.

Finally, end of life management is an ongoing challenge for agricultural plastic. Due to their single-use nature, some agricultural plastics must be constantly produced and disposed of. In the United States, plastic waste is either landfilled, recycled, or incinerated (Figure 2). Because they have high soil residue rates, soil-contact plastics are often difficult to recycle and thus are most often sent to a landfill where they do not fully decompose (Figure 2; Piehl et al., 2018). There are concerns that many US landfills are nearing capacity, which can increase tipping fees for farmers and require more land use change ("Advancing Sustainable Materials Management," 2020).

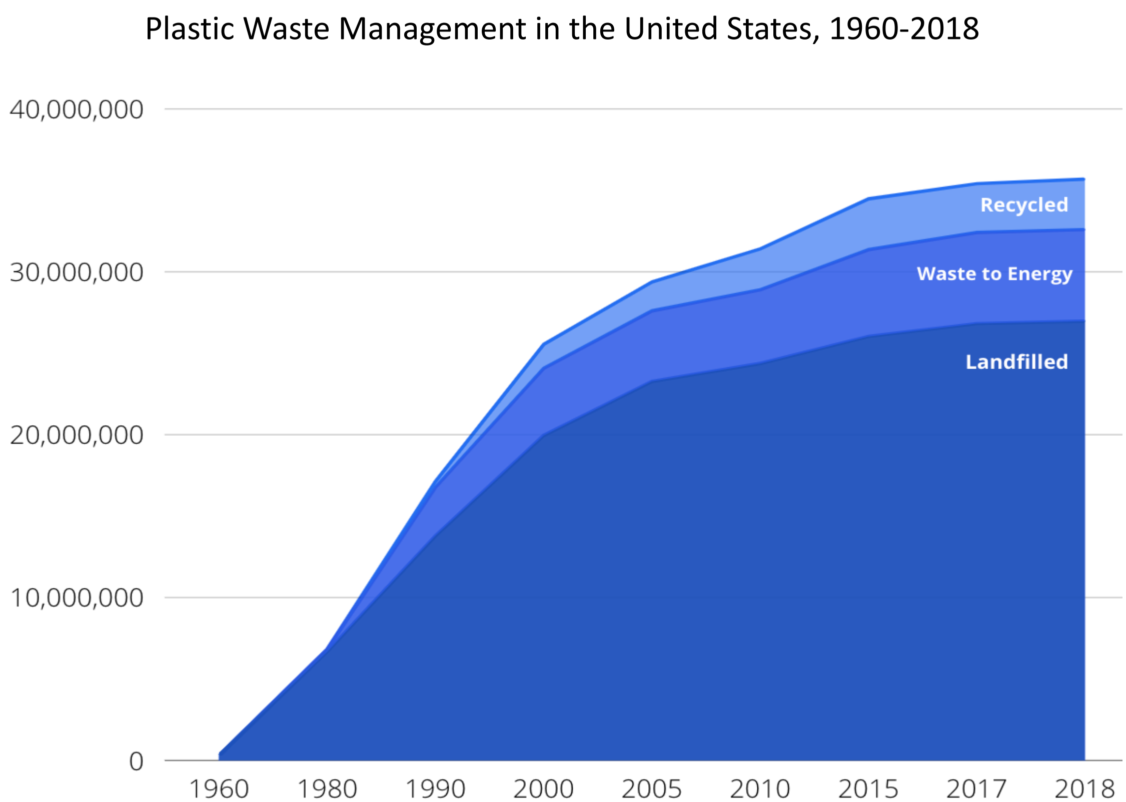

Figure 2. Plastic waste management in the United States, 1960-2018. Historically, the vast majority of plastic waste has been landfilled (dark blue) followed by waste-to-energy (medium blue) and recycling (light blue). Data from the United States Environmental Protection Agency (EPA), representing all plastic used in the United States.

More studies are needed to quantify the environmental impacts of disposing agricultural plastics, but it is worth noting their potential long-term costs, as landfilling agricultural plastics is not sustainable in the long run. Adopting better waste management strategies will likely result in lower life cycle impacts. This paper will explore the environmental tradeoffs of these strategies.

Preliminary Review of Solutions

To pinpoint strategies to reduce the impacts of agricultural plastics, we considered the following pollution prevention strategies:

- **Dematerialization**: Solutions that lead to a reduction in the amount of material used in berry agriculture.
- **Substitution:** Solutions that involve substituting agricultural plastics for other materials that are less harmful to the environment.
- **Reuse:** Solutions that result in multiple uses of a plastic, whether it be for the original or a different purpose.
- **End-of-Life Management:** Solutions that focus on how to manage plastic *waste.* Landfill, recycling, and waste-to-energy fall under this category.

Figure 3 provides a representation of our solution space, which included both high-level strategies and specific initiatives within each category:

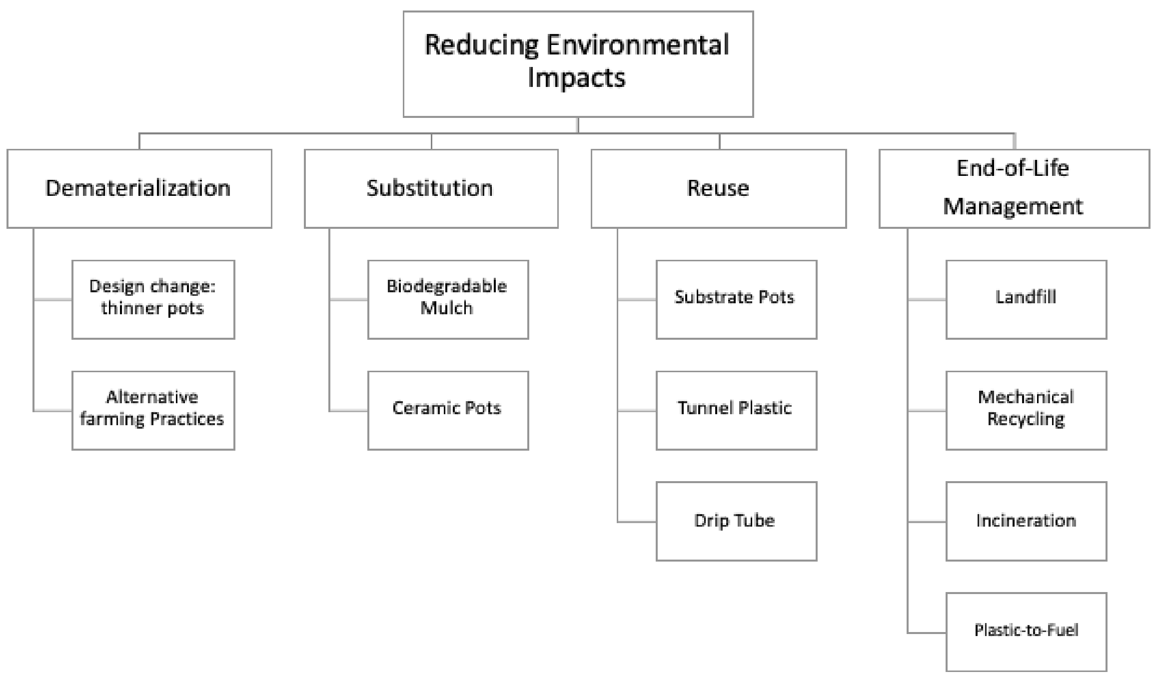

Figure 3. Preliminary solutions for reducing the environmental impacts of agricultural plastics. After a thorough literature review, we grouped potential solutions for reducing the environmental impacts of agricultural plastics by solution category. Categories included dematerialization, substitution, reuse, and end-of-life management. While we conducted a thorough and broad literature review of these different options there is still potential for further research to be done regarding impacts associated with additional substitution methods (e.g., biodegradable mulches or ceramic pots).

Dematerialization

Researchers have explored agricultural plastic reduction, but there is concern over losing the benefits of increased yields and resource efficiency described previously. Adopting regenerative agricultural techniques like no-till, cover cropping, and animal integration have been shown to increase soil health and thus improve crop yields in commodity systems, which could offset losses (Rhodes, 2017). However, some practices, like no-till, are challenging in annual fruit and vegetable production systems and can result in substantial yield declines. Furthermore, animal integration raises food safety concerns and the possibility of recall. Even if these new techniques could improve yields over time, the transition would take years and have not yet been shown effective in annual fruit and vegetable production systems.

Substitution

While Driscoll's cannot reduce its plastic use altogether, another commonly suggested option is to substitute traditional plastics with biodegradable plastics. Biodegradable mulch can be tilled into the soil or composted at the end of the season, which negates the monetary costs associated with labor and landfill tipping fees. This can reduce life cycle impacts of acidification, eutrophication, photochemical oxidation, global warming, non renewable energy resources, and abiotic depletion by as much at 80% (Goldberger et al., 2013; Razza et al. 2017; Fernando et al., 2002). That said, farmers need to consider many material properties including porosity, cost, and decomposition rates (Rosetto et al., 2019). Biodegradable mulches generally have higher up front costs and may decompose before the end of the growing season, which negatively impacts yields (Goldberger et al., 2013). The use of biodegradable mulch also negates the environmental benefit that comes from the useful end product of some end-of-life strategies. Furthermore, USDA certified organic growers cannot use biodegradable mulch products due to the certification's regulations (Goldberger et al., 2013).

Biodegradable container production, particularly ones made from coconut coir fiber and rice hull, have relatively good postproduction strength, but cost 10-40% more than their plastic counterparts (Nambuthiri et al., 2015). Currently, biodegradable plastics and natural fiber pots are gaining community interest and support; however, there are drawbacks when considering longevity, cost, and large scale availability. Additional research needs to be done (such as a life cycle assessment of these materials) to accurately compare the impacts from the single use nature of biodegradable containers to the multiple uses possible with plastic containers, and to find economically and technically feasible substitutes. The production of biodegradable containers is in early stages and they are not yet currently available for large scale use in the field. However, these plastics are gaining popularity and may provide a viable alternative with future technological developments.

Reuse

Studies have shown that reusing plastic mulch is technically feasible and may not negatively impact yields under certain conditions (Nyoike et al., 2014). That said, collecting and re-applying thin mulch films without damaging them would likely be cost-prohibitive. container production, on the other hand, are much thicker and sturdier than films which give them a greater potential for reuse (Lopez-Medina et al., 2004). Driscoll's already encourages its farmers to reuse these pots to reduce the environmental impacts of pot production and disposal. However, the environmental benefits of such behavior change can only go so far due to limits of the useful life of each material.

Our discussions with Driscoll's revealed that a farmer is typically able to use a pot for multiple growing cycles, for up to 6-8 years. After that, pots eventually degrade and crack due to prolonged sun exposure (Zweifel et al., 2009). Adding UV stabilizers can delay photo-oxidation, but pesticides can decrease their efficacy (Markarian, 2005). There may be potential to modify material composition and form of a pot to extend its lifetime. Driscoll's can work with pot manufacturers to encourage new designs, but it is a technical and economic solution that will require additional product research and development.

End-of-Life Management

The final set of solutions explores impact reduction through end-of-life management strategies. Of the various disposal methods, landfilling is the most common due to the high soil residue levels of agricultural plastics. Landfills present a convenient and cost-effective disposal option, but plastics never fully break down and instead remain as microplastics for potentially hundreds or even thousands of years (Piehl et al., 2018). Furthermore, landfills are nearing capacity, and are generally unpopular among local community members (Mukherjee et al., 2020).

Other options for disposing of plastic waste include mechanical recycling, incineration, and plastic-to-fuel technologies, similar to pyrolysis or plastic reformation. Mechanical recycling converts plastic waste into plastic pellets through washing, grinding and extrusion (Briassoulis et al., 2013). Incineration combusts plastic, converting the heat into electricity (Al-Salem et al., 2009). Finally, plastic-to-fuel uses thermal decomposition, sometimes in the presence of a chemical catalyst, to convert the plastic waste into oil-based fuels like diesel (Mukherjee et al., 2020; Belgiorno et al., 2003; M. Pohjakallio and T. Vuorinen, 2020).

Comparative LCA studies suggest that these three options are environmentally preferable to landfill (Michaud et al., 2010). This is largely because of their potential to displace virgin material or energy production. In other words, these three processes produce useful outputs that may replace the primary production of those products. However, the aforementioned comparative LCA studies do not focus on agricultural plastics, whose high soil residue levels influence the amount of offset materials and energy. Still, they show environmental potential, and while these solutions do not address production or use-phase impacts, they avoid the yield issues that other solutions run into, and are therefore more likely to be economically feasible for Driscoll's growers. Table 4 describes the pros and cons of each alternative.

Table 4. Considerations for end-of-life scenarios. Mechanical recycling, incineration, and plastic-to-fuel are potential alternatives to landfilling of agricultural plastics, but each has its unique pros and cons.

Alternative End-Of-Life Scenarios		
End-of-Life Scenario	**Pros**	**Cons**
Landfill	Simplest and often cheapest	Not sustainable in the long term
Mechanical Recycling	Can displace virgin plastic production; avoids landfill	Uncertain and limited end markets; lack of available infrastructure; difficult for recyclers to deal with soil residue due to increased costs
Incineration	Can displace electricity production; avoids landfill	High emissions; Pure plastic not desirable for municipal solid waste incineration units
Plastic-to-Fuel	Can displace fuel production; avoids landfill	Commercially available, but uncommon; not currently applied to soil-contact plastics

Determining Project Scope

To determine where to focus our efforts, we characterized each solution not only by its potential to reduce environmental impacts, but on its technical, political, and economic feasibility. This involved reviewing the literature and Driscoll's data on current plastic use and recycling rates by plastic type to identify which plastics contributed the most environmental impacts and which had the best reduction potential. We also considered the importance of these plastics in maintaining in-field functionality and yield rates. Throughout this process, we discussed various solutions with the Driscoll's team to get feedback on which solutions they had already explored and why a solution may or may not have worked.

After discussions with Driscoll's about implementation feasibility, we decided to focus our research on end-of-life management solutions. Driscoll's team requested more support in identifying solutions for waste management in order to support a more environmentally friendly disposal method for their growers' agricultural plastic waste (APW). In addition, dematerialization, substitution, and reuse solutions can all negatively impact yields, which has a negative environmental impact by reducing production efficiency per unit of land. Keeping in mind business constraints and implementation potential, we determined that an end-of-life management comparison of LDPE film would be the most appropriate analysis to address our research question.

Our research focused particularly on LDPE films, or bed mulch and fumigation, because that is where we believed we could have the largest impact. Tunnels are already being reused and recycled at high rates and container production are made of recycled content and reused and recycled when possible. Soil contact LDPE films, however, represent a considerable portion of Driscoll's plastic use, yet have one of the lowest recycling rates due to high soil residue levels. Our next step was to determine the appropriate analysis for measuring and comparing the environmental impacts of different end-of-life scenarios.

Life Cycle Assessment Overview

To evaluate the total environmental impacts of our four end-of-life strategies, we chose to conduct life cycle assessments, or LCAs, according to the methodology provided in ISO 14044, which is an internationally recognized environmental management standard developed by the International Organization for Standardization (ISO). ISO 14044 provides a comprehensive guide for LCA methodology, which involves mapping out a system's relevant steps and aggregating their environmental impacts (International Organization for Standardization, 2006). A typical LCA involves the following steps:

1. Goal and Scope Definition: I*dentify the functional unit, reference flow, impact indicators, and system boundary.*

A *functional unit* is defined as the necessary function a product system performs and the *reference flow* is the amount of output required to fulfill the functional unit. The functional unit and reference flow allow us to understand the purpose of a product system and the material required to fulfil that purpose. *Impact indicators* are high level categories of environmental impact, comparable to key performance indicators. An example is global warming potential. Finally, the system boundary determines which processes in a product's life cycle are included in and which are excluded from the evaluation.

2. Inventory Analysis. *Map out the unit processes, elementary flows, and intermediate flows associated with the product system.*

A system's relevant steps are called *unit processes*, and each process's inputs and outputs are called flows. *Intermediate flows* flow between processes, or remain within the system boundaries, while *elementary flows* flow from or to the environment. They are associated with direct environmental impacts like natural resource consumption, emissions, and waste.

3. Impact Assessment: *Evaluate the environmental impacts of the system's elementary flows.*

Elementary flows come in many different forms, and therefore have many different units even if they impact the environment in similar ways. In this step, elementary flows are characterized and sorted into their relevant impact indicators and converted into the associated units. The now-comparable flows within each indicator are added up to get total impacts per indicator.

4. Interpretation. *Analyze and discuss the results.*

Scope

We identified landfill as the baseline disposal scenario, as this is the standard option for mixed and contaminated plastic wastes. We then selected three disposal processes to measure and compare against landfill and one another – mechanical recycling, incineration, and plastic-to-fuel. We reviewed the literature on available technology and collaborated with Driscoll's to choose these four scenarios, and limited our analyses to U.S. operations due to the availability of data.

Functional Unit and Reference Flow

To accurately compare results between different end-of-life scenarios, we standardized the amount of waste processed by each system by determining the functional unit and reference flow. Because we are focused solely on end-of-life management, we defined our functional unit as the disposal of one metric ton (t) of plastic waste. Therefore, our reference flow is also one metric ton of plastic waste, exclusive of soil residue. For example, 1t of plastic waste with 30% soil residue by weight would be made up of 1000kg of plastic plus 428kg of soil and organic waste for a total of 1428kg of waste. In this way, we can compare a consistent mass of plastic waste between our scenarios and with different amounts of soil residue. As Driscoll's measures plastic waste in tonnes, this reference flow will help visualize the results and compare them to their total waste streams.

Impact Indicators

As discussed, the many elementary flows associated with disposing 1t of plastic waste impact the environment in different ways. We group the elementary flows together by impact type, called impact indicators. We will use midpoint indicators, which quantify the *potential* to create damage. For example, human health is a midpoint indicator measured in kilograms of PM2.5, as opposed to the number of life years lost to respiratory disease. While using endpoint or damage indicators may help us better relate to the impacts of a process, they are much less reliable, as damages can be caused by numerous confounding variables (Bare et al., 2000). To avoid this uncertainty and to evaluate a wide range of environmental impacts, we used the EPA's Impact Assessment tool, TRACI 2.1, which groups impacts into the following midpoint indicators (Bare et al., 2012):

- **Acidification**: Acidification is defined as "the increasing concentration of hydrogen ions (H+) within a local environment." Plants, animals, and materials often rely on specific acidity levels, so acidification can lead to significant damages to both the natural and built environment. TRACI 2.1 measures acidification potential in kilograms of sulfur dioxide equivalent.
- **Ecotoxicity:** Ecotoxicity represents a broad range of impacts that can damage or stress an ecosystem. The EPA created a tool combining impacts from over 3,000 substances and exposure pathways (air, soil, drinking water, etc.) to understand how these substances can damage the natural environment. TRACI 2.1 measures ecotoxicity potential in CTUe, or Comparative Toxic Unit equivalent.
- **Eutrophication:** Eutrophication is the "enrichment of an aquatic ecosystem with nutrients (nitrates, phosphates) that accelerate biological productivity (growth of algae and weeds) and an undesirable accumulation of algal biomass." Eutrophication can alter nutrient and oxygen availability in water bodies, negatively impacting aquatic ecosystems. TRACI 2.1 measures eutrophication potential in kilograms of nitrogen equivalent.
- **Global Warming:** Global warming is an increase in Earth's average temperature, caused by the accumulation of heat-trapping greenhouse gases in the atmosphere. Global warming can alter

climate systems, damage ecosystems, and harm human health. TRACI 2.1 measures global warming potential in kilograms of carbon dioxide equivalent.

- **Human Health:** The human health indicator deals with particulate matter, which is "a collection of small particles in the ambient air which have the ability to cause negative human health effects including respiratory illness and death." TRACI 2.1 measures human health impacts in kilograms of PM2.5 equivalent. PM 2.5 refers to particulate matter that is smaller than 2.5 micrometers in diameter.
- **Human Toxicity (cancer + non cancer):** TRACI 2.1's human toxicity indicator is very similar to Ecotoxicity, but for substances and pathways that impact humans. TRACI 2.1 measures human toxicity potential in CTUh, or Comparative Toxic Unit for humans.
- **Smog Formation:** Smog is ground-level ozone created by the reaction between nitrogen oxides, volatile organic compounds, and sunlight. Smog can cause respiratory illnesses in humans and can damage crops and other natural ecosystems. TRACI 2.1 measures the potential for smog formation in kilograms of ozone equivalent.

System Boundaries

Next, we established the system boundaries to determine which unit processes to include in our models. LDPE film's total life cycle begins well before it reaches a farm, but this study is concerned with waste management solutions, which have no effect on anything that occurs before the film waste is collected from the fields. More so, the production and use phases of LDPE films are identical regardless of the chosen end-of-life scenario, so including them in our models would not change the outcome of our comparative analysis. Therefore, each model begins with plastic waste collection from the field.

Following plastic waste collection, each model includes the transportation of the plastic waste to its respective waste processing facility and the reprocessing or waste management process itself – either landfill, mechanical recycling, incineration, or plastic-to-fuel. If we were to end our models there, we would find that each scenario generates significant environmental impacts from reprocessing the waste material. However, every process but landfill results in a useful end product – mechanical recycling creates recycled plastic pellets, incineration creates electricity, and plastic-to-fuel technologies create various fuels. So, the benefits of these alternative end-of-life processes come not only from avoiding landfill but from their potential to displace the virgin production of their useful end products.

To account for this, we included in our scope the traditional production process for each scenario's useful end product. To summarize, each of our models will begin with field collection, continue with waste management, and end with displaced production to get a full picture of end-of-life impacts.

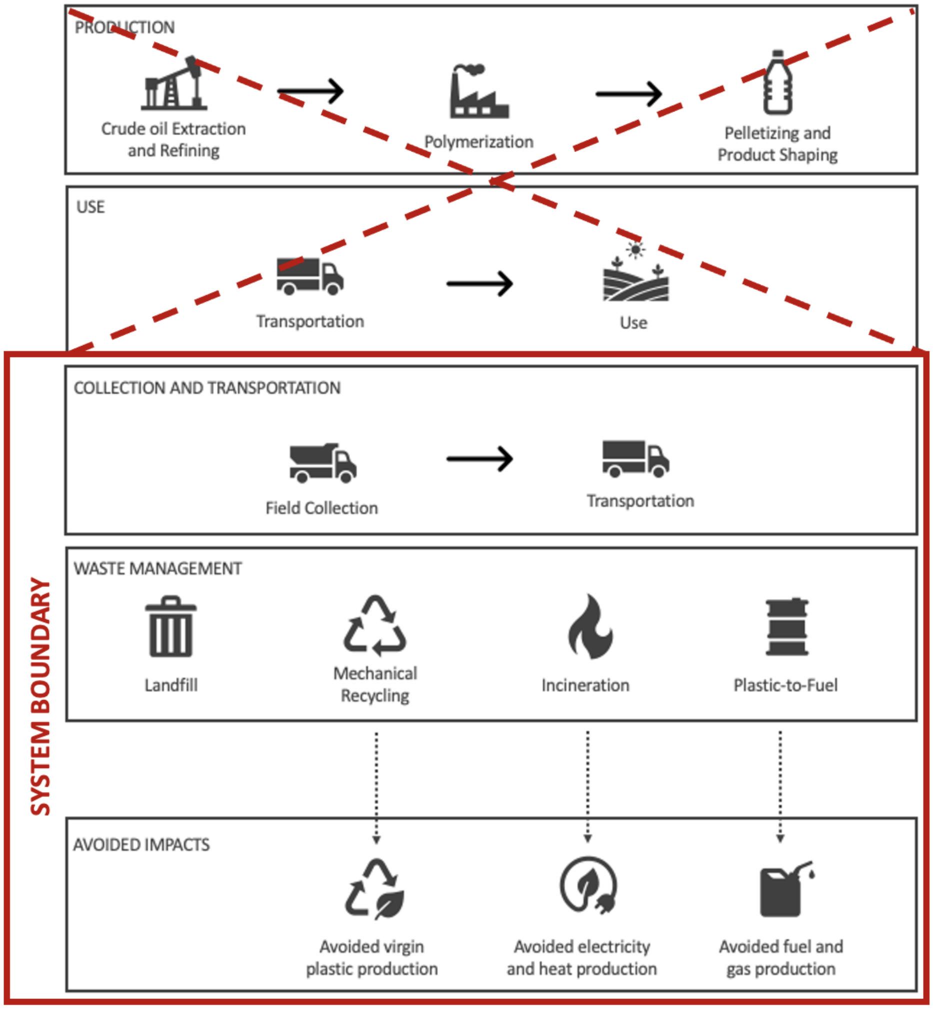

Figure 4. System boundaries for LCA models of end-of-life scenarios. Each system begins with field collection and transportation, continues with waste management or reprocessing, and ends with displaced production. The initial production and use phases are left out due to our focus on end-of-life management.

In addition to the production and use stages, we omitted the following processes from each LCA:

- Manufacturing of machinery and equipment used in processes (trucks, combustion chambers, mechanical shredders, etc.)
- General maintenance, lighting, and heating of end-of-life facilities
- Packaging and transportation of end products to their secondary markets

Per ISO 14044 standards, we left out these processes because their expected cumulative contributions to any given environmental impact category is anticipated to be negligible compared to total impacts. We also made the decision to omit transportation to most secondary markets. Because we will model the avoided impacts up to the point of virgin fuel or plastic production, we will not analyze processes that occur after the production of recycled content or recovered fuel.

Waste Management Models

Data Sources

Upon determining the appropriate system boundaries for our models, we began the process of collecting data for each relevant unit process. For each process, we collected primary data wherever possible. Driscoll's provided collection and transportation data in the form of miles driven and vehicle specifications. For reprocessing, we established partnerships with one company from each scenario, except for landfill. While this means our results will be company-specific, Driscoll's could work with these particular companies depending on the results of our analysis. We sent each company preliminary process flow diagrams along with questions and interactive spreadsheets to collect comprehensive input and output data, which included electricity and water consumption, waste products, useful outputs, transportation distances, and more.

We used this primary data to create mass balance sheets in Excel to ensure we could accurately track a unit of plastic waste through the entire system. We then modeled collection, transportation, and reprocessing with the LCA software GaBi and supplemented our models with background processes from the GaBi ThinkStep and EcoInvent databases. Primary production of each process's end products were also modeled using existing process inventories already in GaBi. The following sections will discuss each end-of-life model in greater detail.

Landfill

As discussed, landfilling is the most common destination for soil-contact APW due to the large amount of soil residue. The landfilling process, based on our literature review, is shown in the following diagram:

Figure 5. Landfill process diagram. Plastic waste is collected from the field and transported to a landfill.

The landfill model includes plastic collection from the field, transportation to the landfill, and the landfilling process itself, which will likely have few impacts aside from general landfill operations, as plastic and soil are assumed to be inert materials. The inputs into our model include diesel and plastic waste, both of which go into a truck for transportation. As this is a landfill, there are no useful outputs. The model uses existing process inventories from the GaBi Professional database for the transportation and landfill processes. We used primary data from Driscoll's to reflect the specifics of the collection and transportation steps. Finally, we modeled the landfill process with 45% soil residue levels, as this represents an average amount of soil content for hand-pulled plastics. Because we assume soil and plastic to be inert, residue levels will have minimal impacts aside from the weight of material that must be transported to the landfill.

Mechanical Recycling

Unlike landfill, mechanical recycling of plastic waste has the potential to displace virgin plastic production. We worked with a national agricultural plastics recycler to gather primary data on agricultural plastics recycling. We built the following diagram based on our communications:

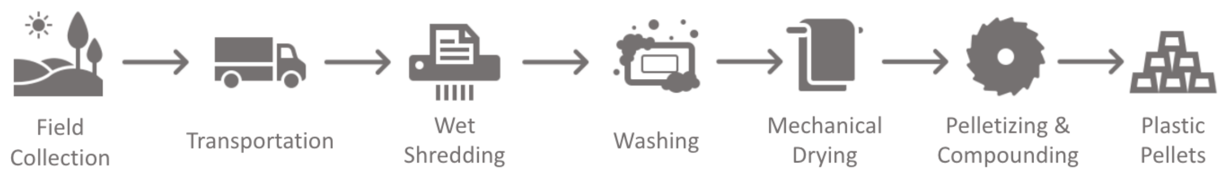

Figure 6. Mechanical recycling process diagram. After field collection, the soil-contact APW is transported to a recycling facility, where it undergoes wet shredding, washing, drying, and extrusion to be transformed into recycled plastic pellets.

Our mechanical recycling process begins with field collection, in which a diesel-powered mechanical removal machine collects and shakes the soil-contact films to remove as much soil as possible. After transportation to the recycling facility, the homogenous APW is then shredded in a machine with rotating blades and washed with water to remove impurities. Because soil-contact agricultural plastics bring with them large volumes of soil, the washing stage must be comprehensive to avoid leftover soil and pesticide residue that could lead to low-quality products or health concerns (Briassoulis et al., 2012). The clean plastic flakes are then dried, melted, cooled in water, and transformed into pellets through a process called extrusion. The pellets are then packaged and shipped to a secondary market.

The wet shredding, washing, and drying phases all result in soil sludge and unrecyclable plastic waste. The soil sludge is left to dry and the remaining dirt is transported offsite to a land application site. The unrecyclable plastic waste is transported to a local landfill. Inputs into the process include diesel for transportation, electricity for all reprocessing steps, and water for washing and extrusion. For our baseline recycling model, we assumed California operations, so we used the California electricity grid mix and modeled transportation using the average distance between Driscoll's farms and the client's mechanical recycling facility. We supplemented our primary data with GaBi database processes.

Finally, we used a baseline of 30% soil residue by weight, with the assumption that these plastics are pulled mechanically. We input the associated amount of recycled output pellets into GaBi's Virgin LDPE Pellet Production process to model the avoided impacts of producing that same mass of pellets in a traditional way.

Incineration

Agricultural plastics have a high heating value (or calorific value [CV]), ranging from 30-40 MJ/kg, compared to 48.6 MJ/kg of fuel oil and 27.3 MJ/kg of coal (Lawrence, 2017). In circumstances that prevent recycling of plastic waste due to technical and/or economic limitations, incineration with energy recovery provides a means to recover part of their calorific value (Wasilewski, 2013). Additionally, the volume of plastic waste is reduced by 90-99% through incineration, which may be especially important as landfills near their capacities (Al-Salem et al., 2009).

Energy recovery involves direct combustion of waste in order to produce energy in the form of heat, steam and electricity (Al-Salem et al., 2009). Energy recovery of plastic solid waste (PSW) is generally done by incorporating PSW with municipal solid waste (MSW) for incineration or by using as a substitute solid fuel (Wasilewski, 2013). All incineration units utilize a high temperature between 750°C and 1000°C to achieve a combustion reaction (Al-Salem, 2019a). All of the unit types also allow for flue gas scrubbers to remove hazardous chemicals, while filters can be used to remove particulate matter (Al- Salem, 2019).

California has two mass burn incineration facilities with a combined total capacity of 2180 tons of MSW per day and an electrical capacity of 58.4 MW. We worked with the company that operates these facilities in order to develop our model of APW incineration, depicted in the following diagram:

Figure 7. Incineration process diagram. After field collection and transportation, APW is mixed with MSW and combusted. The resulting heat is collected and converted to electricity.

Initial transportation was modeled using the average distance from each growing region to the incineration facility. This process utilizes MSW from surrounding areas to generate electricity which it then sells to the local grid. While there are two incineration facilities in California, we developed our model based on data for the facility located in Stanislaus County.

Because we are concerned with incineration of pure LDPE plastic waste, we used a database process that uses attributional life cycle inventory in order to produce impact assessment results for PE in an incineration unit that utilizes MSW feedstock. The database process was adjusted according to the net efficiency of the facility in Stanislaus, which was provided by the company. The outputs of this database process include steam and electricity, however the facility we modeled does not utilize the waste steam for heating or other purposes. Therefore, the only output of interest is the electricity production, which we then compared to the impacts of the California grid mix. The California grid mix was modeled separately according to 2019 data on in-state generation by fuel type published by the California Energy Commission and utilizing 'US average' electricity production processes from the ThinkStep database.

Our baseline incineration model also assumes 30% soil residue, mechanically-pulled plastic waste. We modeled the plastic waste's soil content according to its calorific value. Uncontaminated plastic waste (LDPE) has a calorific value of 43.5 MJ/kg, or 4350 MJ/tonne. For plastic waste with soil residue, the calorific value of 1t of waste was modeled proportionately to its soil residue levels. For example, for plastic waste with 30% residue levels, 1t of soil-contact APW was assumed to have 70% of the calorific value of 1t of uncontaminated APW. We thus relied on the assumption that soil residue has zero calorific value and would only result in greater amounts of bottom ash. The amount of electricity generated from 1t of APW with soil residue would be proportionately less than the amount of electricity generated from pure APW. To account for this, the displaced impacts from electricity production by the California grid mix were subtracted from the impacts of incineration according to the amount of electricity produced with various amounts of soil residue.

Plastic-to-Fuel

Plastic-to-fuel technologies are processes by which heat and pressure are applied to waste (typically plastic) in the absence of oxygen to create valuable end products and a waste residue (e.g., valuable products like diesel and petrol fuels; waste residue including coke, solid char, etc.) (Mukherjee et al., 2020; Belgiorno et al., 2003; M. Pohjakallio and T. Vuorinen, 2020). At temperatures ranging from 350 – 900 degrees Celsius, plastic-to-fuel technologies effectively vaporize plastic waste into pyrolytic gases which are then condensed into liquid products with or without the help of a catalyst (M. Pohjakallio and T. Vuorinen, 2020; Antelava et al., 2019).

Plastic-to-fuel is typically divided into two main types: thermal and catalytic (Antelava et al., 2019). Thermal plastic-to-fuel technology uses moderate temperatures to create end products that have low octane values and high residue contents (Antelava et al., 2019; Seth and Sarkar, 2004). These end products require further refining to be used as fuels. Catalytic plastic-to-fuel technology allows the process to be conducted at lower temperatures with faster reaction times. Catalytic plastic-to-fuel produces hydrocarbons with high calorific content such as fuel oil (Antelava et al., 2019; Almeida and Marques, 2016).

To model the plastic-to-fuel process, we collaborated with an external client, whose thermochemical treatment process of plastic waste is represented in the following diagram:

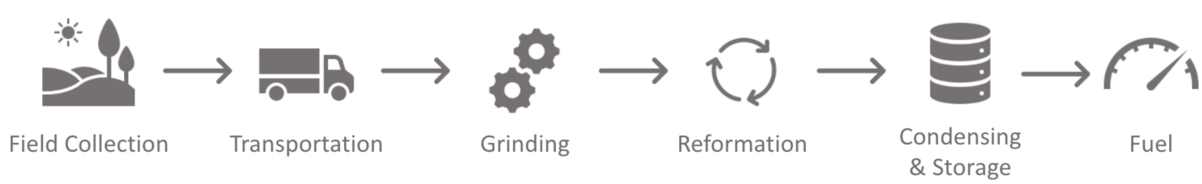

Figure 8. Plastic-to-fuel process diagram. From the field, the soil-contact agricultural plastic waste is transported to a reformation site where it undergoes grinding, reformation, and condensing, which results in the output of various useful oil-based fuels.

In this process, heat is applied to the plastic waste in a controlled environment where it breaks down and then condenses into valuable fuel products. In order to minimize the amount of soil residue carried with the plastic waste input, this process utilizes mechanical pullers to shake dirt off and collect the plastic from the field, which is then transported to the facility via truck. Once at the facility, we modeled each subprocess using primary data provided by the company, utilizing the California grid mix as the electricity input where necessary. Processes include mechanical pulling to collect field plastic, transportation to facility, grinding of the waste plastic, reformation, and then condensing to co-products.

The co-products of this process include various marketable fuels, as well as ash. Aside from the ash, which is landfilled, these products are sold to a local distributor. To understand the potential environmental impacts and/or benefits associated with the process, we separately modeled the avoided primary production of each of the valuable products. Our baseline model also uses mechanically-pulled APW with 30% soil residue by weight. We modeled soil content levels by altering the amount of waste ash produced by the process.

We assume the reformation process initially requires purchased natural gas or propane to run, but following the initial batch, a portion of the mixed gas co-product from the reforming process is used to run the reformer, with the rest being sold to a distributor. Given this, we modeled reformation just using the recycled mixed gas as an input.

The data provided by the plastic-to-fuel company is based on a pilot plant and although they anticipate results will be reflective of a fully commercialized process, results in this report are not intended to be utilized as such. Comparison data and data for any gaps in the received primary data were filled through secondary research and through proxies where necessary.

Results Evaluation

Upon building our GaBi models, the software characterized and aggregated all elementary flows into the TRACI 2.1 impact categories. To understand which scenario is the most environmentally friendly, we utilize the following equation to calculate and evaluate the net environmental impacts of each end-of-life strategy:

$$E^{i}_{\text{Net}} = \underbrace{E^{i}_{\text{Coll}} + E^{i}_{\text{Trans}} + E^{i}_{\text{Rep}}}_{E^{i}_{\text{Direct}}} - E^{i}_{\text{Virgin}} - E_{\text{Land}}$$

where i = respective end-of-life scenario

If $E_{\text{Net}} < 0$, process i is preferable to landfill*

E_{Net}	Net Environmental Impacts
E_{Coll}	Impacts from Collection
E_{Trans}	Impacts from Transportation
E_{Rep}	Impacts from Reprocessing
E_{Virgin}	Impacts from Virgin Product Production
E_{Land}	Impacts from Landfill
E_{Direct}	Direct Impacts from End-of-Life Management

Figure 9. End-of-life scenario net impact equation. This equation is used to calculate the net environmental impacts of each end-of-life process. Net impacts are the sum of direct impacts minus (avoided) impacts from landfill and virgin product production.

The *direct* impact from each scenario is the sum of impacts from collection, transportation, and end-of-life reprocessing, or E_{Direct}. But we account for useful end products by subtracting the environmental impacts of virgin product production. Finally, we subtract impacts from the landfill scenario (E_{Land}, or E^{L}_{Direct}) as another avoided burden, because plastic waste would end up in a landfill if not for an alternative scenario. We are left with E_{Net}, which represents the net environmental impacts of a given process compared to landfill.

If E_{Net} is negative, we can infer that that process is a net environmental benefit compared to landfill. With that logic, the most negative E_{Net} is the most environmentally friendly process. However, it's not quite that simple. Our models will provide us with quantitative results for each impact category, but we cannot simply add them together because they have incompatible units. For example, we cannot combine global warming potential with eutrophication potential because the former is measured in carbon dioxide equivalent (CO_2-eq) while the latter is measured in nitrogen equivalent (N-eq). There will likely be tradeoffs between indicators. Therefore, we can make a claim about which process is least impactful for certain indicators, but we may not be able to claim that one process is the best overall. By presenting Driscoll's with categorized impact results, we will give them the tools to select the end-of-life option(s) that most align with their environmental priorities.

Assumptions and Limitations

As with any model, we made certain assumptions to perform our analyses. We recognize that because our models use primary data from specific companies, the results do not necessarily apply beyond these companies' operations. They may not be as accurate for Driscoll's growers' operations outside of California or the United States. Conversely, when we were unable to use primary data, we were limited to filling in any gaps with processes available in GaBi's databases, which may at times generalize processes at too high a level. For details on our specific process assumptions, please refer to Appendix B.

We also recognize that an end-of-life approach does not address impacts that occur during agricultural plastic's production or use phase. With our approach, we can only address impacts associated with plastic waste and avoided production. Further research is needed to explore strategies that address production or use-phase impacts without negatively impacting yields.

Results

The following tables present the results from each of our GaBi models. Our baseline models are built with the most likely scenario for each end-of-life method. We assume that plastic sent to landfill is pulled by hand, resulting in approximately 45% soil residue. For the purposes of our baseline comparison, we assume that plastic collected for the other three scenarios is pulled with mechanical removal mechanisms, resulting in 30% soil residue. We used California operations for all scenarios. These baseline scenarios yielded the following *direct* impacts:

Table 5. Direct environmental impacts from each end-of-life scenario. Direct impacts include the environmental impacts of each end-of-life process with no consideration of avoided burden.

Comparative LCA Results: Direct Impacts (E_{Direct})				
Indicator	**Landfill**	**Mechanical Recycling**	**Incineration**	**Plastic-to-Fuel**
Acidification (kg SO_2 eq.)	0.18	0.69	0.42	0.55
Ecotoxicity (CTU eq.)	2.20	10.20	5.40	9.93
Eutrophication (kg N eq.)	0.01	0.03	0.03	0.03
Global Warming (kg CO_2 eq.)	29.20	178.00	3,160.90	95.80
Human Health (kg PM2.5 eq.)	0.02	0.03	0.03	0.05
Human Toxicity (CTUh)	0.00	0.00	0.00	0.00
Smog Formation (kg O_3 eq.)	3.31	11.60	7.85	14.44

Key Findings

In considering only the direct impacts of each scenario, landfill is the preferable option for all indicators except for human toxicity, in which incineration is preferable. However, we need to consider the environmental benefits from avoiding virgin production and landfill.

Our baseline scenario models yielded the following *net impacts:*

Table 6. Net environmental impacts from each end-of-life scenario. Net impacts include the avoided burden generated when the secondary products from each end-of-life process displace equivalent primary products.

Comparative LCA Results: Net Impacts (E_{Net})				
Indicator	**Landfill**	**Mechanical Recycling**	**Incineration**	**Plastic-to-Fuel**
Acidification (kg SO_2 eq.)	—	-3.41	-0.76	-0.74
Ecotoxicity (CTU eq.)	—	-855.00	-8.40	-330.28
Eutrophication (kg N eq.)	—	-3.10	-0.01	-0.41
Global Warming (kg CO_2 eq.)	—	-1,521.20	2,809.70	-287.20
Human Health (kg PM2.5 eq.)	—	-0.43	-0.02	-0.07
Human Toxicity (CTUh)	—	0.00	0.00	0.00
Smog Formation (kg O_3 eq.)	—	-77.61	-2.48	-10.68

Key findings
When we calculate overall net impacts (direct impacts minus avoided impacts from landfill and primary production), we find that each scenario is a net environmental benefit compared to landfill, with the exception of incineration for global warming potential. Incineration had a much higher global warming potential than landfill, even after subtracting avoided electricity production. Mechanical recycling is the least impactful end-of-life option for all environmental indicators, followed by plastic-to-fuel, incineration, and then landfill.

Scenario Analyses

To accurately compare the environmental impacts across each end-of-life option, we built our initial models assuming California operations, 30% soil residue levels for all scenarios aside from landfill, and average farm-to-facility transportation distances. To understand the importance of these parameters in influencing our end results, we ran our models for alternative scenarios. The alternative scenarios were chosen based on numerous discussions with Driscoll's and the waste management companies to understand the bounds for each system's transportation, location, and soil residue parameters. The different scenarios are as follows:

Table 7. Alternative scenarios for each end-of-life method. To understand the sensitivity of our results to transportation, soil residue, and location parameters, we modeled multiple scenarios shown below based on the most realistic scenarios seen in the field.

Comparative LCAs: Sensitivity Analyses			
End-of-Life Method	**Baseline Scenario**	**Alternative Scenarios: Location of Reprocessing**	**Alternative Scenarios: Soil Residue Levels**
Landfill	National average facility; 45% soil residue	—	—
Mechanical Recycling	California facility; 30% soil residue	Southeast facility (grid mix and transportation changes)	15%, 45%, & 70% soil residue
Incineration	California facility; 30% soil residue	—	15%, 45%, & 70% soil residue
Plastic-to-Fuel	California facility; 30% soil residue	Maximum distance: field to plastic-to-fuel facility	15% soil residue

Landfill

Landfilling sites are abundant compared to the other three disposal options and are located close to Driscoll's growers' operations. Therefore, transportation distances and locations are well known and are unlikely to drastically change. Plastic intended for landfill would likely be hand-pulled and not mechanically-pulled, so we modeled the landfilling process assuming 45% soil residue levels. As plastic waste is an inert material and there is no reprocessing component, soil residue levels would have negligible impacts on final results. Therefore, we did not model any alternative scenarios for landfill.

Mechanical Recycling

While they plan to open operations in California soon, our mechanical recycling partner in this research project is currently only processing plastic waste at its Southeastern facilities, which would increase transportation distance from 112 to 2000 miles. More than that, moving operations over state lines means that the electricity used to reprocess the waste comes from a different grid mix. Therefore, we modeled an alternative Southeastern scenario that took into account both the increased transportation distance and a different grid mix.

We assume soil residue levels will impact our results, as they influence the amount of virgin production that will be displaced. Our baseline scenario assumes that plastic is removed from the fields with a mechanical remover resulting in 30% soil residue. However, some fields can reduce soil residue levels to as low as 15% and others that use hand-pulling can result in 45% soil residue levels. To account for this, we modeled alternative scenarios for both California and the Southeast in which the plastic waste is 15% and 45% soil residue, with the 45% scenario not including the diesel-powered mechanical remover. Finally, we modeled soil residue levels at 70%, as this represents the upper bound of hand-pulled waste that Driscoll's has measured.

Incineration

In order to provide a range of impact assessment results depending on proximity to the incineration facility, we calculated results for a maximum distance of 300 miles and a minimum distance of 85 miles in addition to our baseline average. Similar to mechanical recycling, soil residue levels influence the amount of valuable product produced. For greater soil residue levels, less electricity is generated due to lower total calorific value per tonne of waste. Our baseline scenario uses mechanically-pulled 30% soil residue plastic waste, and we modeled an alternative scenario with 15% soil residue mechanically-pulled waste and 45% and 70% hand-pulled waste.

Plastic-to-Fuel

Plastic-to-fuel is a relatively uncommon technology. However, we were able to model transportation distances based on a proposed facility in California. We tested our results' sensitivity to transportation distances by modelling an average distance of 116.5 miles and then a maximum of 265 miles to see if these different distances significantly influenced total environmental impacts. Finally, plastic-to-fuel's net impacts also rely on soil residue levels because they influence the amount of viable fuels created. In addition to our 30% soil residue baseline scenario, we modeled a scenario with 15% soil residue plastic waste. The plastic-to-fuel process in the pilot project is only technically feasible for waste with up to 30% soil residue levels, so we did not include scenarios with 45% and 70% soil residue for the plastic-to-fuel model.

Scenario Analysis Results

In all scenarios, mechanical recycling resulted in the lowest net environmental impacts. Transporting plastic to the Southeastern facility does slightly increase direct impacts because of greater transportation distances and a slightly dirtier grid mix, but because offset virgin plastic production is so intensive, mechanical recycling still has the lowest impacts of the four methods (Table D4, Appendix D). In addition, transportation accounts for 9% of total global warming impacts for mechanical recycling under the baseline scenario. Even if we transported the plastic coast-to-coast, the net global warming impacts would remain the lowest for mechanical recycling. These results also hold true regardless of transportation distance for plastic-to-fuel and incineration (Tables E4 & E3, Appendix E). Changes to soil residue levels followed this trend as well. Incineration in particular consistently resulted in the highest impacts, so we focused our comparative soil residue level assessment on mechanical recycling and plastic-to-fuel (Table 8):

Table 8. Net impacts of mechanical recycling and plastic-to-fuel at varying soil residue levels. To properly compare mechanical recycling and plastic-to-fuel, the most likely soil residue levels for each process are shown side by side.

Comparative LCA Results: Mechanical Recycling (CA) vs Plastic-to-Fuel						
Indicator	Mechanical Recycling (CA, 15%)	Mechanical Recycling (CA, 30%)	Mechanical Recycling (CA, 45%)	Mechanical Recycling (CA, 70%)	Plastic-to-Fuel (15%)	Plastic-to-Fuel (30%)
Acidification (kg SO_2 eq.)	-3.49	-3.41	-3.27	-3.09	-1.12	-0.74
Ecotoxicity (CTU eq.)	-868.65	-855.00	-831.90	-749.54	-404.34	-330.28
Eutrophication (kg N eq.)	-3.14	-3.10	-3.01	-2.73	-0.52	-0.41
Global Warming (kg CO_2 eq.)	-1,562.20	-1,521.20	-1,464.20	-1,282.50	-383.66	-287.20
Human Health (kg PM2.5 eq.)	-0.43	-0.43	-0.41	-0.40	-0.10	-0.07
Human Toxicity (CTUh)	0.00	0.00	0.00	0.00	0.00	0.00
Smog Formation (kg O_3 eq.)	-79.31	-77.61	-75.11	-76.61	-18.71	-10.68

Assessing each scenario at 15% and 30% soil residue levels did not change our end results. When we modeled mechanical recycling with lower soil residue, we offset an even larger amount of plastic pellets, further reducing net environmental impacts. Regardless of soil residue levels, mechanical recycling is less impactful than the plastic-to-fuel process. We repeated these results for mechanical recycling in the Southeast, and while recycling's net impacts increased slightly, it was still the most environmentally friendly option (Tables D1-D5, Appendix D).

Alternative Displacement Ratios

In each of our baseline models and alternative scenarios, we assumed a 1:1 displacement ratio. In other words, we have assumed that our useful outputs completely displace the same amount of virgin production. In reality, each unit of recycled or reprocessed product may not prevent the production of one unit of virgin product. After our results consistently showed mechanical recycling as the least impactful option, we tested different displacement ratios for recycled plastic pellets to determine a break-even displacement rate, the rate of displacement for mechanical recycling at which plastic-to-fuel (with 1:1 displacement) becomes the least impactful option with respect to global warming potential (Tables 9 & 10).

Table 9. Net impacts with varying displacement ratios - 30% soil residue.

Comparative LCA Results: Net Impacts with Different Displacement Ratios (30% Soil Residue)			
Indicator	**Mechanical Recycling (CA, 30% soil residue)**	**Mechanical Recycling (AR, 30% soil residue)**	**Plastic-to-Fuel (30% soil residue)**
	26% Displacement	**46.5% Displacement**	**100% Displacement**
Acidification (kg SO_2 eq.)	-0.50	-1.40	-0.74
Ecotoxicity (CTU eq.)	-216.38	-366.10	-330.28
Eutrophication (kg N eq.)	-0.79	-1.39	-0.41
Global Warming (kg CO_2 eq.)	-285.40	-285.75	-287.20
Human Health (kg PM2.5 eq.)	-0.10	-0.18	-0.07
Human Toxicity (CTUh)	-7.77	0.00	0.00
Smog Formation (kg O_3 eq.)	-14.04	-33.05	-10.68

Table 10. Net impacts with varying displacement ratios - 15% soil residue.

Comparative LCA Results: Net Impacts with Different Displacement Ratios (15% Soil Residue)			
Indicator	**Mechanical Recycling (CA; 15% soil residue)**	**Mechanical Recycling (AR; 15% soil residue)**	**Plastic-to-Fuel (15% soil residue)**
	30.5% Displacement	**49% Displacement**	**100% Displacement**
Acidification (kg SO_2 eq.)	-0.73	-1.36	-1.12
Ecotoxicity (CTU eq.)	-259.83	-397.14	-404.34
Eutrophication (kg N eq.)	-0.94	-1.48	-0.52
Global Warming (kg CO_2 eq.)	-380.70	-380.20	-383.66
Human Health (kg PM2.5 eq.)	-0.13	-0.18	-0.10
Human Toxicity (CTUh)	0.00	0.00	0.00
Smog Formation (kg O_3 eq.)	-18.64	-28.89	-18.71

At 30% soil residue levels, plastic-to-fuel would be the better option for global warming if recycled pellets offset no more than 26% or 46.5% of virgin material in California and the Southeast, respectively. At 15% soil residue levels, those percentages become 30.5% or 49% offset in California and the Southeast, respectively. These findings show that the displacement ratio for recycled pellets would have to be less than half, and in some cases about a fourth, the level of plastic-to-fuel displacement before the latter becomes the preferred solution, at least for global warming potential.

Discussion and Key Considerations

Analysis of Current and Future Outcomes

Our analysis reveals that all other end-of-life options for APW are environmentally preferable to landfill, with the sole exception of the GWP impacts caused by incineration. Other comparative LCA studies conducted on plastic waste have arrived at similar conclusions, where mechanical recycling has the lowest net impacts while incineration results in a net increase in GWP even after subtracting impacts of displaced electricity production (Eriksson & Finnveden, 2009; Lazarevic et. al, 2010). Incineration likely has such high global warming impacts because pure plastic waste is an inefficient fuel compared to alternative fuels like natural gas or fuel oil. In addition, the direct impacts associated with combustion are high because of the embedded carbon in plastic. Because plastic is made from crude oil, the combustion process releases the carbon previously sequestered in the polymers.

We anticipate significant changes to the grid mix, both across the U.S. and especially in California, that may influence these results in the future. In 2018, California passed Senate Bill 100 (SB 100) which requires that 100% of electricity retail sales to end-use customers are sourced from renewable energy and zero-carbon resources by 2045 ("SB 100 Joint Agency Report", n.d.). A cleaner California grid mix would decrease the environmental impacts, particularly the GWP, of reprocessing and virgin production steps that rely on electricity. The changing grid's relative impacts to each unit process are unclear, causing net impacts to be ambiguous. Conversely, the net impacts of incineration will increase because the avoided burden of electricity production will decrease as more electricity is sourced from renewable and carbon-free sources. This supports our conclusion that mechanical recycling is and will continue to be the least impactful disposal option for global warming potential.

Direct Waste Management Costs

While mechanical recycling is consistently the best environmental option, we also should consider economic costs, starting with the direct costs to farmers. Due to the many factors that influence costs for each reprocessing facility and each farm, we cannot definitively measure and compare the costs within this report, rather provide a discussion of factors that contribute to the final costs of each end-of-life scenario.

Direct waste disposal costs consist of three main components: cost of soil residue reduction (e.g. by mechanical removal), transportation to the end-of-life facility, and tipping fees, or the cost paid to either the landfill or respective reprocessing facility. Regardless of disposal option, farmers need to pay for waste disposal, and thus a cost analysis should not be intended to show that farmers can make money through waste management. Rather, an analysis of cost should consider how costs may be impacted, either positively or negatively, when considering more environmentally friendly disposal options. To keep consistent with our environmental analyses, cost should be considered as a net difference from total landfill costs.

General Economic and Technical Feasibility

As mentioned, we calculated net environmental impacts by relying on the assumption that useful end products will perfectly displace the production of virgin materials or fuels. We are fairly confident that the electricity and fuels generated from incineration and plastic-to-fuel technologies have reliable end markets, but are less confident when it comes to recycled plastic pellets. Even if there are reliable end markets, we cannot be certain that supply and demand dynamics will shift perfectly so that one unit of recycled pellets sold will reduce virgin plastic production by one full unit. There is concern that recycled plastic simply creates a market for a new product altogether, which does not displace virgin production and only delays the landfill process instead of preventing it (Zink & Geyer 2019). Closed-loop recycling systems for agricultural plastics are extremely rare because the quality of the recycled pellets make the process technically and economically challenging (Garcia & Robertson, 2017; Katz, 2019; Briassoulis et al., 2013). While the mechanical recycling client can technically recycle berry mulch films, there are concerns over whether it is economically viable due to quality concerns (i.e., is the recycled film of high enough quality to displace virgin material).

Agricultural plastic waste has the advantage of being generated in high geographical concentrations relative to municipal plastic waste streams, which reduces costs associated with collection (Briassoulis et al., 2013). However, soil-contact plastics require advanced washing infrastructure to prepare them for recycling, increasing initial costs. This extra washing also requires recyclers to purchase and consume more water and energy during the washing stage. The soil and stones tumbling around in machines cause damage and wear down blades more frequently, requiring continual maintenance and increased recycling costs (Briassoulis et al., 2012). Additionally, demand for recycled plastic pellets falls when the price of oil, and therefore of virgin plastic, is low (Cho, 2020).

Because of high manufacturing prices, uncertain secondary markets, and complicated trade dynamics, many countries lack the infrastructure to recycle PE at a large scale. Recycling infrastructure in the United States is lagging because up until 2018, the United States sent a lot of plastic waste to China. In 2018, China banned the import of many types of plastic wastes, leaving countries, such as the United States, scrambling to develop their own recycling infrastructure (Katz, 2019). As of 2018, the United States recycles only about 8.5% of its plastic waste ("Advancing Sustainable Materials Management," 2020).

However, other countries like Mexico have successfully implemented large-scale recycling programs, at least for PET, which is different from the LDPE used to make soil-contact plastics. The Mexican government has introduced regulations requiring corporations to establish recycling programs, which is expanding the market and therefore encouraging new infrastructure ("Mexico's Plastics Recycling Industry"). This suggests that government directives are a very important instrument in combating climate change and resource depletion, and other countries, like the United States, might consider introducing regulations to encourage recycling.

This provides Driscoll's a unique opportunity to contribute to the narrative on waste management and to reduce the environmental impacts from APW disposal. Within the parameters of this study, Driscoll's gains insight into potential costs and benefits of the various APW disposal options to the environment.

Conclusion and Recommendations

Through this study, we found that Driscoll's can improve waste management practices to significantly decrease their environmental impacts. Considering net impacts and the many socioeconomic factors at play, we recommend that Driscoll's considers both plastic-to-fuel technologies and mechanical recycling as viable alternatives to landfill, with a preference for mechanical recycling when economically possible. Driscoll's plans to use these recommendations to inform their sustainable agriculture plastic strategy. While the development of new legislation and infrastructure for these solutions may require time and capital investments, the plastic problem is not going away anytime soon.

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Appendices

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Appendix A – GaBi Models

Figure A1. GaBi landfill model.

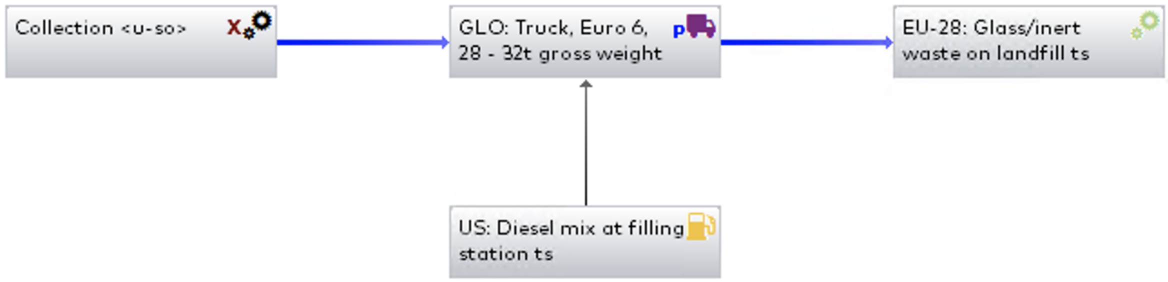


Figure A2. GaBi mechanical recycling model.

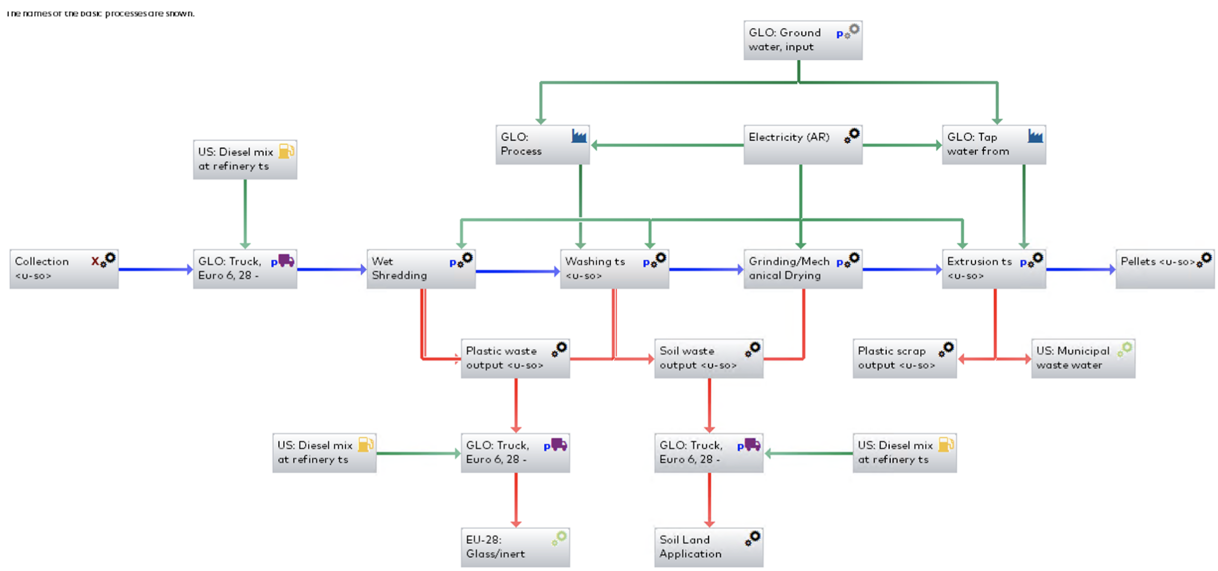


Figure A3. GaBi incineration model.

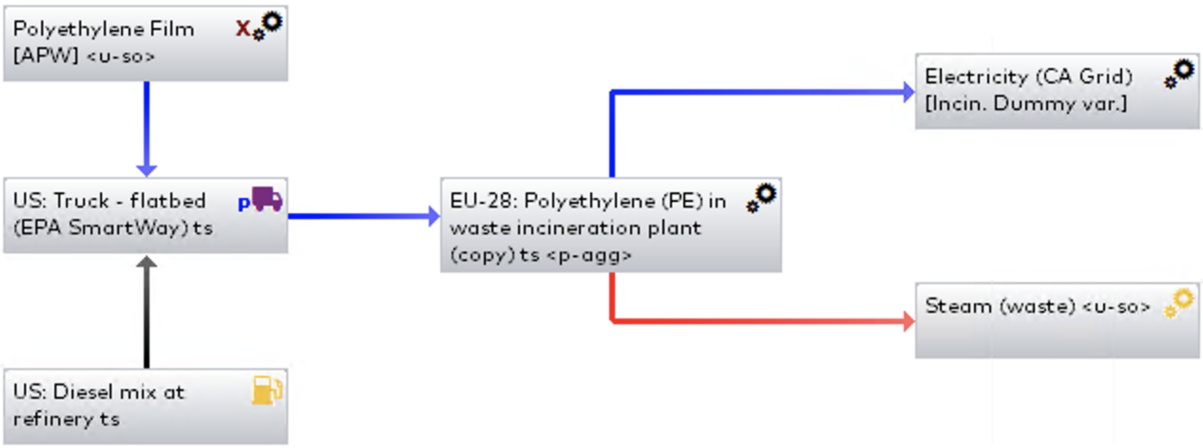
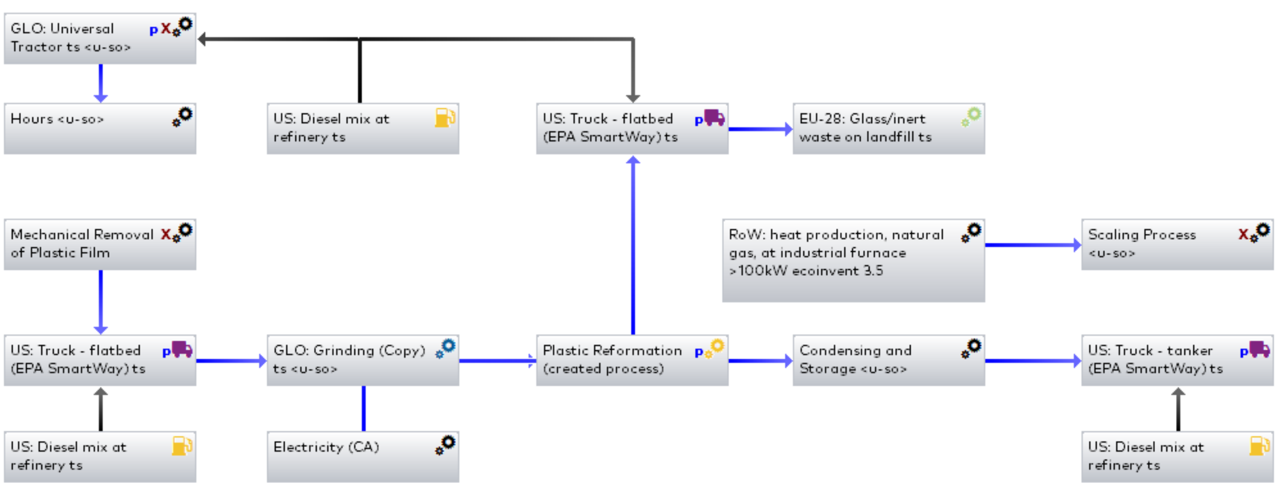


Figure A4. GaBi Plastic-to-fuel model.



Appendix B – GaBi Model Inputs, Outputs, & Unit Processes

Table B1. Comparative LCA inputs/outputs.

Comparative LCA Inputs/Outputs		
Input/Output	**Disposal Option(s)**	**Description**
Low density polyethylene	All	This input by PlasticsEurope represents the production mix of commercial polyethylene production from cradle to gate including slurry suspension polymerisation, solution polymerisation, and gas phase polymerisation.
Diesel	All	"US: Diesel mix at refinery ts" by Thinkstep, was used for diesel fuel into the transportation processes. This input includes the entire supply chain of refinery products and is specific to production in the United States.
Landfill	All	"EU-28: Glass/inert waste on landfill" by Thinkstep was used for disposal to landfill. This output includes leachate treatment and without collection, transport and pre-treatment with a 100 year deposit.
Groundwater	Mechanical Recycling	"Process water from groundwater (for regionalization)" by thinkstep, was used as it represents the treatment of groundwater with ion exchangers and allows for regionalization from the water source and electricity source. For the water source input into the "Process water from groundwater (for regionalization)", the "Ground water, input regionalization dummy" process was used for a high water scarcity region as we are considering this process for California and Mexico.
Tap water	Mechanical Recycling	"GLO: Tap water from groundwater (for regionalization) ts" by thinkstep was used to model tap water from groundwater as it models drinking water purification of groundwater.. For the water source input into the "GLO: Tap water from groundwater (for regionalization) ts", the "Ground water, input regionalization dummy" process was used for a high water scarcity region as we are considering this process for California and Mexico.
Electricity	Mechanical Recycling	The electricity grid mix was found for the respective states and the proportion of each electricity generating technology was modeled to get impacts from electricity specific to the state that was being analyzed.
Thermal Energy	Mechanical Recycling	"US: Thermal energy from natural gas ts" by thinkstep was used for thermal energy. This process includes all relevant process steps and technology along the supply chain for the production of thermal energy from natural gas. The process is specific to the United States natural gas production mix.

Municipal Wastewater Treatment	Mechanical Recycling	"US: Municipal waste water treatment (agricultural sludge application) ts" by thinkstep was used for treatment of waste water from sewage. This process includes all steps and technologies across the supply chain such as chemical and biological treatment of waste water and sludge. This process represents an end-of-life inventory and is region specific to the United States.
Plastic Waste	Mechanical Recycling	"Plastic waste output" was used as a dummy process to move plastic waste from their respective process to transportation.
Soil Waste	Mechanical Recycling	"Soil waste output" was used as a dummy process to move soil waste from their respective process to transportation.
Soil Land Application	Mechanical Recycling	"Soil Land Application" process was created as a dummy process to indicate that soil waste from mechanical recycling is placed on land at another location.
Plastic scrap	Mechanical Recycling	"Plastic scrap output" process was created as a dummy process to indicate that there is plastic scrap that does not become pellets. We did not model or offset virgin production for this plastic scrap because we are not convinced that this scrap is of high enough quality to have a viable end market comparable to virgin material.
Coke	Plastic Reformation	"Coke" represents an assumed inert waste that results from the reformation process and is sent to landfill.
Product (unspecified) [Valuable substances]	Plastic Reformation	This mix of co-products from the reformation process includes scaled combined outputs of diesel, gasoline, kerosene, mixed gas and paraffin. Not included in this number is the portion of mixed gas used to run the reformer. That was modeled in our industrial furnace process so as to represent impacts from combustion.

Table B2. Comparative LCA processes.

Comparative LCA Processes		
Process	**Disposal Option(s)**	**Description**
Collection	Mechanical Recycling	"Collection" is a dummy process created for collection of plastic prior to transportation to its respective process.
Transportation	Landfill	"GLO: Truck, Euro 0-6 mix, 28-32t gross weight / 22t payload capacity ts" by thinkstep was used for truck transportation of agricultural plastic. The particular truck size was based on the size of truck that Driscoll's currently uses to dispose of APW. An average of 15 miles with a payload of 22.5 tons was used based on the primary transportation data from Driscoll's.

Wet Shredding	Mechanical Recycling	“Wet Shredding” was created using primary data from the mechanical recycling client of what inputs and outputs are required. This process requires plastic and electricity as inputs and contaminated plastic shreds, plastic waste, and soil sludge as outputs.
Washing	Mechanical Recycling	“Washing” was created using primary data from the mechanical recycling client of what inputs and outputs are required. This process requires contaminated plastic, process water, and electricity as inputs and contaminated plastic shreds, plastic waste, and soil sludge as outputs.
Grinding/Mechanical Drying	Mechanical Recycling	“Grinding/Mechanical Drying” was created using primary data from the mechanical recycling client of what inputs and outputs are required. This process requires contaminated plastic shreds and electricity as inputs and clean plastic shreds, plastic waste, and soil sludge as outputs.
Extrusion	Mechanical Recycling	“Extrusion” was created using primary data from the mechanical recycling client of what inputs and outputs are required. This process requires Clean plastic shreds, water (tap water), and electricity as inputs and Plastic pellets, Plastic scrap, and wastewater as outputs.
Pellets	Mechanical Recycling	“Pellets” was created as a dummy process to indicate the final output from the mechanical recycling process from the mechanical recycling client.
Mechanical Removal of Plastic Film	Plastic Reformation	“GLO: Universal Tractor ts” was used to model mechanical removal of plastic film, as the mechanical removal mechanism is just an additional attachment to a regular diesel driven tractor. We updated the process to match the provided power rating (kW) and fuel consumption values of the mechanical removal tractor.
Hours	Plastic Reformation	“Hours” was created to model the output of the mechanical removal process (hours the tractor is being run). We created a time-related input process for modeling purposes. This process does not include environmental impacts.
Mechanical Removal of Plastic Film Output	Plastic Reformation	“Mechanical Removal of Plastic Film Output” was created to scale the entire process flow diagram. The process only contains an output of 1 kg of plastic, and the entire process is fixed to a scaling factor of 1000 to model our reference flow of 1000 kg of plastic waste.
Transportation: Farm to Facility, Facility to Landfill	Plastic Reformation	“US: Truck – flatbed (EPA SmartWay) ts” was used to model the collection of agricultural plastic waste from the field and also the collection of waste coke from the plastic reformation process (facility to landfill). For the field to facility plastic, adjusted settings of this process include the distance to match the associated distances from field to the client’s facility.
Grinding	Plastic Reformation	“GLO: Grinding (Copy) ts” was a modified grinding process used to model the grinding of the plastic waste at the plastic reformation

		facility. The process just includes the plastic input and output flow along with a California electricity input to run the grinder.
Reformation	Plastic Reformation	"Plastic Reformation (created process)" was created simply as a mechanism to distribute flows to their respective end stages. The plastic is input, and a coke product and valuable product are output going to landfill and condensing and storage, respectively. This process does not include environmental impacts; a separate process, "RoW: heat production, natural gas, at industrial furnace > 100kW ecoinvent 3.5" was used to model the expected combustion process for plastic reformation.
Condensing and Storage	Plastic Reformation	"Condensing and Storage" was a created process to model the condensing process of the facility, which includes an electricity input per batch, and then the valuable co-product flows from the plastic reformation process.
Landfill	Plastic Reformation	We used the "EU-28: Glass/inert waste on landfill ts" process to model the spent coke product. We assume that there are no usable carbon contents available in the coke, so its lifetime impacts at landfill will reflect those of similar inert materials. If our assumption proves wrong, we anticipate that the extra carbon content would then most likely be sold to a distributor instead of landfilled (reducing overall net environmental impacts due to the displacement of other coke production).
Reformation Combustion	Plastic Reformation	We used a proxy to model the reformation combustion process. This proxy was "RoW: heat production, natural gas, at industrial furnace > 100 kW ecoinvent 3.5". To model the combustion process for plastic reformation, we first had to compare the heat contents of the fuel input. The client gave us a heat content for their recycled mixed gas of 925 btu/scf. This most closely matched the heat content for natural gas (950-1050 btu/scf). Given this similarity we needed a simplistic combustion process to model the combustion of the recycled mixed gas, which we now call natural gas as a proxy. After comparing various combustion processes and their associated impacts in both ecoinvent and thinkstep, we settled on this process. An industrial furnace involves a similar simplistic combustion process and the power rating had negligible impacts on overall associated environmental impacts.
Scaling Process	Plastic Reformation	"Scaling Process" was a created process to simply scale the industrial furnace process to combust the relevant amount of natural gas (proxy) as reflected in a 1000kg batch.

Appendix C – State Grid Mixes

To build the California and Southeastern grid mix processes in GaBi, we used energy data from the U.S. Energy Information Administration (EIA) and converted total energy generation per source to percentages. Those grid mixes are shown in the following tables:

Table C1. California grid mix.

California Grid Mix	
Energy Source	Percentage
Natural Gas	46.54%
Solar	13.99%
Hydro (Large & Small)	13.52%
Nuclear	9.38%
Wind	7.23%
Geothermal	5.92%
Biomass	3.03%
Other (Petroleum Coke/Waste Heat)	0.22%
Coal	0.15%
Oil	0.02%
Total	**100.00%**

Table C2. Southeastern grid mix.

Southeastern Grid Mix	
Energy Source	Percentage
Coal	36.18%
Petroleum Liquids	0.07%
Natural Gas	33.78%
Nuclear	21.07%
Hydroelectric	6.50%
Solar	0.33%
Biomass	2.07%
Total	**100%**

Figure C1. California grid mix GaBi process.

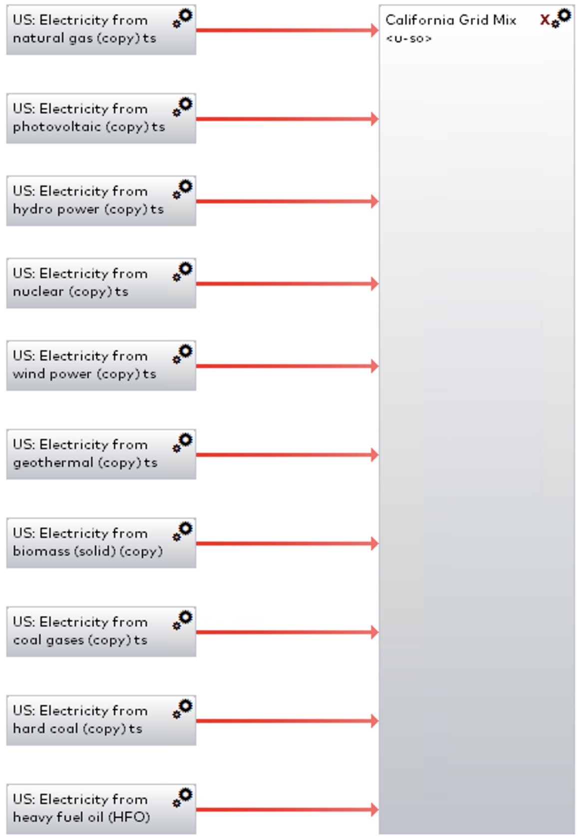
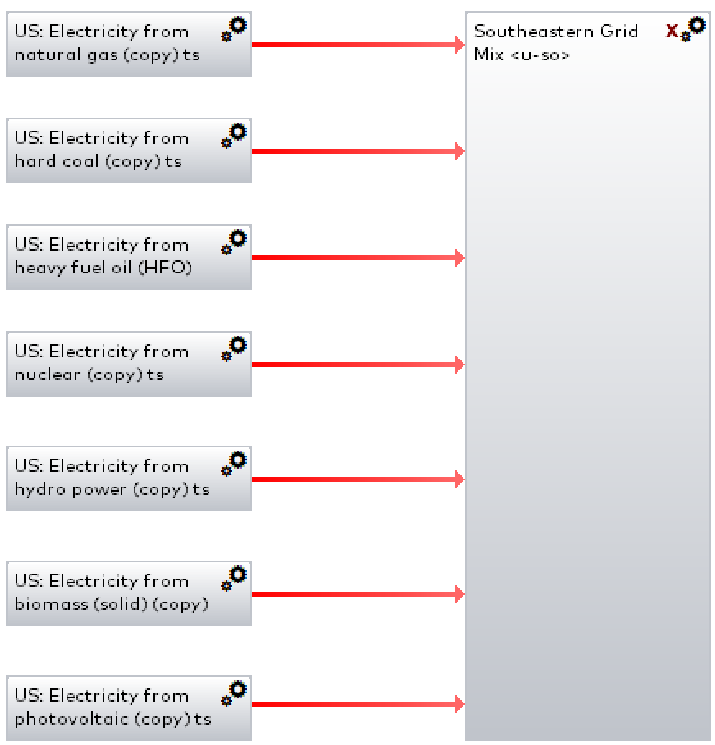


Figure C2. Southeastern grid mix GaBi process.



Appendix D – Scenario Analyses

Table D1. Comparative LCA results at 15% soil reside.

Comparative LCA Results: Sensitivity Analysis 15% Soil Residue					
Indicator	Landfill	Mechanical Recycling (CA)	Mechanical Recycling (AR)	Incineration	Plastic-to-Fuel
Acidification (kg SO_2 eq.)	—	-3.22	-3.12	-1.28	-1.12
Ecotoxicity (CTU eq.)	—	-775.96	-775.41	-15.32	-404.34
Eutrophication (kg N eq.)	—	-2.80	-2.77	-0.02	-0.52
Global Warming (kg CO_2 eq.)	—	-1.44E+03	-1.23E+03	2636	-383.66
Human Health (kg PM2.5 eq.)	—	0.00	-0.10	-0.03	-0.10
Human Toxicity (CTUh)	—	0.00	0.00	0.00	0.00
Smog Formation (kg O_3 eq.)	—	-6.15	-18.71	-6.15	-18.71

Key Findings

At 15% soil content by weight, mechanical recycling located in California has consistently positive environmental impacts due to avoided burden. This is followed by mechanical recycling at the Southeastern facility, plastic-to-fuel, and finally incineration (with the exception of acidification which yields lower impacts than plastic-to-fuel in this category).

Table D2. Comparative LCA results at 70% soil residue.

Comparative LCA Results: Sensitivity Analysis 70% Soil Residue				
Indicator	Landfill	Mechanical Recycling (CA)	Mechanical Recycling (AR)	Incineration
Acidification (kg SO_2 eq.)	—	-3.09	-2.73	-0.11
Ecotoxicity (CTU eq.)	—	-749.54	-679.94	-2.10
Eutrophication (kg N eq.)	—	-2.73	-2.63	0.02
Global Warming (kg CO_2 eq.)	—	-1,282.5	-568.5	2,991.90
Human Health (kg PM2.5 eq.)	—	-0.40	-0.35	0.01
Human Toxicity (CTUh)	—	0.00	0.00	0.00
Smog Formation (kg O_3 eq.)	—	-76.61	-63.28	5.26

Key Findings

At 70% soil content by weight, mechanical recycling at the California facility continues to have the highest environmental benefit followed by mechanical recycling at the Southeastern Facility, and then incineration. With the exception of incineration in the global warming impact category, each of these processes at 70% soil content are still a net benefit when compared to landfill.

Table D3. Plastic-to-fuel results with longer transportation distance.

Comparative LCA Results: Sensitivity Analysis Distance		
Indicator	**Landfill**	**Plastic-to-Fuel (longer transport, 15% Soil Content)**
Acidification (kg SO_2 eq.)	—	-1.00
Ecotoxicity (CTU eq.)	—	-401.85
Eutrophication (kg N eq.)	—	-0.51
Global Warming (kg CO_2 eq.)	—	-366.50
Human Health (kg PM2.5 eq.)	—	-0.10
Human Toxicity (CTUh)	—	0.00
Smog Formation (kg O_3 eq.)	—	-15.88

Key Findings

Even when shipping soil-contact plastic waste a longer transportation distance than the baseline - plastic-to-fuel results in a net benefit to the environment across impact indicators due to the fuel produced from the process.

Table D4. Mechanical recycling in CA and SE vs incineration and plastic-to-fuel.

Comparative LCA Results: Mechanical Recycling Location				
Indicator	Mechanical Recycling (Baseline)	Mechanical Recycling (30%, SE)	Incineration (30%)	Plastic-to-Fuel (30%)
Acidification (kg SO_2 eq.)	-3.41	-3.50	-1.04	-0.74
Ecotoxicity (CTU eq.)	-855.00	-827.80	-11.90	-330.28
Eutrophication (kg N eq.)	-3.10	-3.06	-0.01	-0.41
Global Warming (kg CO_2 eq.)	-1,521.20	-1,179.20	2,719.40	-287.20
Human Health (kg PM2.5 eq.)	-0.43	-0.41	-0.03	-0.07
Human Toxicity (CTUh)	0.00	0.00	0.00	0.00
Smog Formation (kg O_3 eq.)	-77.61	-79.01	-4.67	-10.68

Key Findings

The differences between the California and Southeastern facilities are mainly due to the higher transportation levels in shipping to the Southeast and the differences in grid mix between the two areas. Additionally, the inclusion of mechanical removal use to reach 15% soil content levels is included in the mechanical recycling model for this scenario. In terms of overall environmental impact from least to most the ranking is as follows: mechanical recycling CA, mechanical recycling SE, plastic-to-fuel, incineration. It is important to note that incineration is not a net benefit compared to landfill in the case of global warming.

Table D5. Mechanical recycling vs plastic-to-fuel across realistic levels of soil residue.

Comparative LCA Results: Mechanical Recycling (SE) vs Plastic-to-Fuel						
Indicator	Mechanical Recycling (SE, 15%)	Mechanical Recycling (SE, 30%)	Mechanical Recycling (SE, 45%)	Mechanical Recycling (SE, 70%)	Plastic-to-Fuel (15%)	Plastic-to-Fuel (30%)
Acidification (kg SO_2 eq.)	-3.39	-3.50	-3.32	-2.73	-1.12	-0.74
Ecotoxicity (CTU eq.)	-843.90	-827.80	-796.60	-679.94	-404.34	-330.28
Eutrophication (kg N eq.)	-3.09	-3.06	-2.10	-2.63	-0.52	-0.41
Global Warming (kg CO_2 eq.)	-1,247.20	-1,179.20	-1,050.20	-568.50	-383.66	-287.20
Human Health (kg PM2.5 eq.)	-0.40	-0.41	-0.40	-0.35	-0.10	-0.07
Human Toxicity (CTUh)	0.00	0.00	0.00	0.00	0.00	0.00
Smog Formation (kg O_3 eq.)	-73.41	-79.01	-75.21	-63.28	-18.71	-10.68

Key Findings

Mechanical recycling remains a higher net benefit to the environment than plastic-to-fuel in all cases. Mechanical recycling at 70% soil residue levels is a lower net benefit to the environment compared to plastic-to-fuel with 15% soil content. Mechanical recycling with 70% soil residue is an upper bound in terms of soil residue levels and quite rare to see in the field. In most cases, mechanical recycling is the preferable option to plastic-to-fuel in terms of environmental net benefit.