Development of a Biomass Waste Circular Economy

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Abstract

This masters project, in collaboration with community partner Pashon Murray, developed case studies and resources to further the development of a biomass waste circular economy. The goal of this project was to address the growing waste crisis and establish solutions that are beneficial to both communities and the environment. Biomass waste has the potential to act as a feedstock for a variety of products including compost and bioenergy, as well as the input for products that utilize waste-exchange. A circular bioeconomy will open doors to new products and market segmentation, where stakeholders can utilize biomass throughout the value chain, from product design to waste management. The market segmentation allowed the team to identify the gaps in a circular bio-economy that can be filled with the development of by-products and allow communities to connect companies and businesses to keep revenue and products local. The two case studies completed examine the impacts of different feedstocks and the potential environmental and economic benefits of developing by-products locally. Our deliverable resources expand on growing research that aims to keep by-products local - this includes all stages of biomass waste, from crop development to compost and the development of organic fertilizers and biofuels. The creation of deliverable fact sheets divides biomass by major sector and provides big data points and take-aways associated with opportunities and challenges of each sector. Our work emphasizes the need for systemic changes in how waste is approached and highlights the positive potential outcomes achievable through the effective utilization of biomass waste as a resource.

List of Acronyms

AD	Anaerobic Digestion
ASTM	American Society for Testing and Materials
EIA	Energy Information Administration
EPA	U.S. Environmental Protection Agency
FT	Fischer-Tropsch
GHG	Greenhouse Gas
HEFA	Hydroprocessed esters and fatty acids
IRA	Inflation Reduction Act
IRP	United Nations International Resource Panel
LCA	Life Cycle Assessment
MFSP	Minimum fuel selling price
MMgge	Million gallons of gasoline equivalent
NREL	National Renewable Energy Laboratory
PANYNJ	Port Authority of New York and New Jersey
READ	Renewable Energy Anaerobic Digester
RES	Renewable Energy Sources
RPS	Renewable Portfolio Standards
SAF	Sustainable Aviation Fuel
TEA	Techno-economic analysis
USDA	United States Department of Agriculture

Overview of the Project

The Development of a Biomass Waste Circular Economy is a collaboration between a master's project team in the School for the Environment and Sustainability and community partner Pashon Murray, co-founder of Detroit Dirt. Detroit Dirt is a compost and waste collection company that diverts landfill waste by collecting biomass waste from various local organizations. Pashon has a focus on reducing biomass waste sent to landfills by circulating waste by-products for the Detroit community and decreasing Detroit's carbon footprint. The driving force behind this initiative is the critical imperative to tackle the escalating waste crisis while simultaneously devising solutions that benefit communities and the environment nationwide.

Central to the project is the intentional use of biomass waste, which can be a flexible raw material for various applications. The deliverables aim to find new ways for economic growth and environmental care through tasks like composting, bioenergy production, and waste exchange. A key aspect of the project involves using case studies to demonstrate the real benefits of using biomass waste in different industries. For instance, the two case studies examine Michigan Athletics and sustainable aviation fuel (SAF), highlighting the transformative potential of repurposing biomass waste to mitigate carbon emissions associated with athletic facilities and commercial travel, respectively.

The project offers detailed Quick Fact Sheets covering significant sectors like animal products, cereal crops, anaerobic digestion, pyrolysis, yard waste, wood/forestry, and restaurants. These fact sheets serve as invaluable resources, providing insights into the myriad opportunities for biomass waste utilization and sustainable waste management practices. Essentially, the Development of a Biomass Waste Circular Economy project seeks to change waste management practices significantly, fostering innovation, sustainability, and resilience in communities nationwide. By adopting circular bioeconomy principles, stakeholders can work together towards a future focused on efficient resource use, environmental preservation, and social fairness.

Researcher Profiles

Claire O'Dea is from Pennsylvania and graduated with a bachelor's degree in Secondary Education from The Pennsylvania State University in 2020. After graduating, she worked as a middle school science teacher in Providence, Rhode Island. She is a certified teacher in General Science and Earth and Space Science in both Pennsylvania and Rhode Island. Claire is currently pursuing an MS in Sustainable Systems with the hope to work with the broad scope of sustainability in urban settings.

Angie F. Sillah was born in the city of Monrovia in Liberia and graduated from the University of Liberia in 2018 with a bachelor's in Civil Engineering. Her most recent work was serving as a civil engineer supervisor at WAPCOS Limited/Mac –Africa Consultants, INC and a Construction and Maintenance Supervisor at the Gboni Enterprise, INC. She is an international student at the University of Michigan pursuing a master's of science degree in Sustainability and Development.

Brianna Fogal is from Templeton, Massachusetts and graduated from Worcester Polytechnic Institute in 2017 with a bachelor's in Mechanical Engineering. She worked as a manufacturing engineer in large gas turbine manufacturing with GE Power and then in aviation manufacturing with Williams International. She is currently pursuing a MS in Sustainable Systems and a MSE in Mechanical Engineering and hopes to work in a circular economy-focused role.

Dr. Sara Soderstrom completed her PhD at the Kellogg School of Management, Northwestern University and was a Post Doctoral Fellow at the Erb Institute at the University of Michigan. As of 2023, she is the Director of Program in the Environment (PitE) at University of Michigan. She is interested in how corporations engage in societal sustainability challenges. She studies how individuals within organizations mobilize others, develop coalitions, and access key decision makers when they are trying to implement sustainability initiatives.

Section 1: Introduction

1.1 The current state of waste in the U.S.

Waste is a major challenge facing much of the world, both in emerging and industrialized economies. To combat this continually growing challenge, the U.S. Environmental Protection Agency (EPA) created a waste management hierarchy (shown in Figure 1) for communities and industries as a guideline to ensure successful and proper management [1]. As demonstrated in the hierarchy, the most preferred method of waste management is source reduction. To reduce the source of waste, consumer behavior will be required to change. Changing consumer behavior is an incredibly difficult task that will require changes across the entire supply chain. As this is currently a challenging and slow-moving solution to the growing waste concern, changing consumer behavior is not a primary goal in the United States. Instead, individual companies and industries are tasked with reducing their waste (which occurs at varying stages of the product's lifecycle) for both economic and environmental benefits.

Figure 1. U.S. EPA Waste Management Hierarchy Diagram [1]

The rate of Municipal Solid Waste (MSW) generation has been increasing in the United States since 1960 with per capita waste generation steadily increasing alongside. In 2018, the U.S. EPA reported total municipal solid waste generation was 292.4 million tons which is equivalent to 4.9 pounds of waste per person per day [1]. Shown in Figure 2, as of 2018, food waste was the largest component category to end of life in landfills at 24.14% (with yard trimmings, wood, and paper included biomass waste accounts for about 50%) [1]. As demonstrated, with the increasing rate of total waste generated in the U.S. and food comprising the largest percentage of waste in landfills, there is potential to change the way the nation approaches waste and in-turn significantly decrease the amount ending in landfills. This would equate to approximately 58 million tons of diverted waste for alternative use.

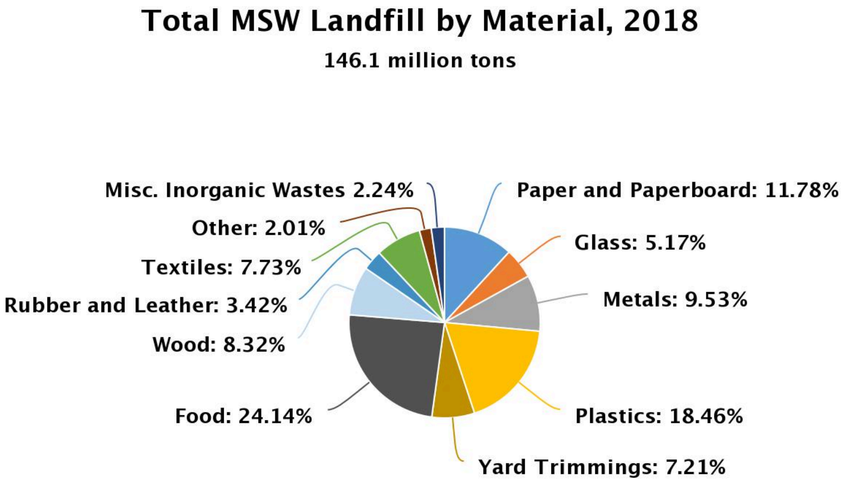


Figure 2. Total Municipal Solid Waste in Landfills by Material break-down in 2018 [1]

1.2 Biomass waste

The U.S. Energy Information Administration (EIA) defines biomass as renewable, organic material that comes from plants or animals [2]. Biomass waste primarily derives from municipal waste and wet waste – wet waste includes, but is not limited to, crop waste, forest residues, purpose-grown grasses, industrial wastes, urban wood waste, and food waste [3]. Biomass involves many different industries and includes numerous products in the current U.S. market. With its broad uses, biomass waste has incredible potential in the development of a circular economy in the United States; a practice that the U.S. has not commercialized, but has been a way of life for indigenous people for centuries [4]. Biomass waste can be used to develop by-products such as organic fertilizer or a fuel alternative to traditional fossil fuels [5]. The development of a biomass circular economy will have multifunctional benefits that include reduction of municipal solid waste entering landfills, reduction of greenhouse gas emissions, reduction of consumption of virgin materials, and reduction of reliance on fossil fuels. In turn, it can boost the national economy by keeping by-products and biomass fuels within the United States or by exporting to countries reliant on imports of fuels [5].

1.3 Market segmentation

Market segmentation generally refers to sectioning the economic market into components with similar interests to appeal to the largest percent of consumers [6]. This type of segmentation helps industries break down their target consumers and allows for planning to communicate and market their products to the appropriate audience [6]. The market can be segmented by interests of the consumers, demographics of the consumers, and/or beliefs of consumers. Market segmentation has been successful for many CEOs to better market their products and reach their target audiences.

In the case of waste, market segmentation can be applied to determine which industries produce waste that can be used as a by-product in other industries. In terms of biomass waste, there is a current lack of a by-product market in the United States, which is evident by the amount of biomass waste that ends in landfills every year. Without the knowledge and connections of who can use the waste produced, each company is adding to the growing waste crisis. The development of a market – outlined by a market segmentation – would aid in solving the waste crisis, while simultaneously adding other multifunctional benefits to each community and beyond.

1.4 Waste Circularity

When discussing potential solutions for reducing consumption of resources and limiting waste sent to landfills, circularity is a popular concept that is gaining traction in the sustainability realm. The U.S. EPA defines circular economy as reduction of materials used in manufacturing, redesigning of products and services to require less materials at all phases and to recapture waste to use in-place of virgin, extracted materials and resources [7]. A common term used to describe circularity of a product is cradle-to-cradle. Cradle-to-cradle is used to describe products that are intentionally designed for their next use and are actively circulated through the market [8]. In contrast, cradle-to-grave is a common term used to describe products that are sent to landfills or end their lives after the usefulness phase. The goal of a circular economy is to create products that are able to participate in cradle-to-cradle through different industries. This language originates from life cycle assessments (LCAs); a cradle-to-cradle LCA only considers environmental impact factors from a product's use-phase [9]. Creating a cradle-to-cradle product means we want this product to stay in its use-phase and not transition to an end-of-life phase (or cradle-to-grave).

Beyond the benefits to the waste crisis, a circular economy addresses multiple climate change problems communities are facing. The United Nations International Resource Panel (IRP) determined around half of global greenhouse gas (GHG) emissions are the result of material and resource extractions [7]. Developing a circular economy in all sectors will not only be beneficial for the reduction of global waste, but also work to decrease global GHG emissions which will benefit all types of communities.

1.5 Supply Chain

Developing a sustainable biomass supply chain also helps divert biomass waste from traditional disposal methods. Utilizing biomass involves identifying suitable sources, implementing sustainable harvesting practices, establishing efficient collection and sorting systems, optimizing transportation logistics, and diversifying utilization pathways. Sustainable harvesting techniques are essential for minimizing ecological disruption and ensuring the long-term replenishment of resources [10]. Efficient collection systems streamline the gathering of biomass from various sources, and transportation logistics further reduce energy consumption and emissions. Diversifying biomass utilization pathways not only enhances economic viability but also maximizes environmental benefits. Thorough LCAs are crucial for pinpointing environmental hotspots and identifying opportunities for improvement. The involvement of stakeholders in collaboration and engagement is crucial for the successful development and implementation of sustainable biomass supply chains. Policy support and market incentives, including renewable energy mandates and carbon pricing mechanisms, play a pivotal role in stimulating investment in sustainable biomass supply chains [11].

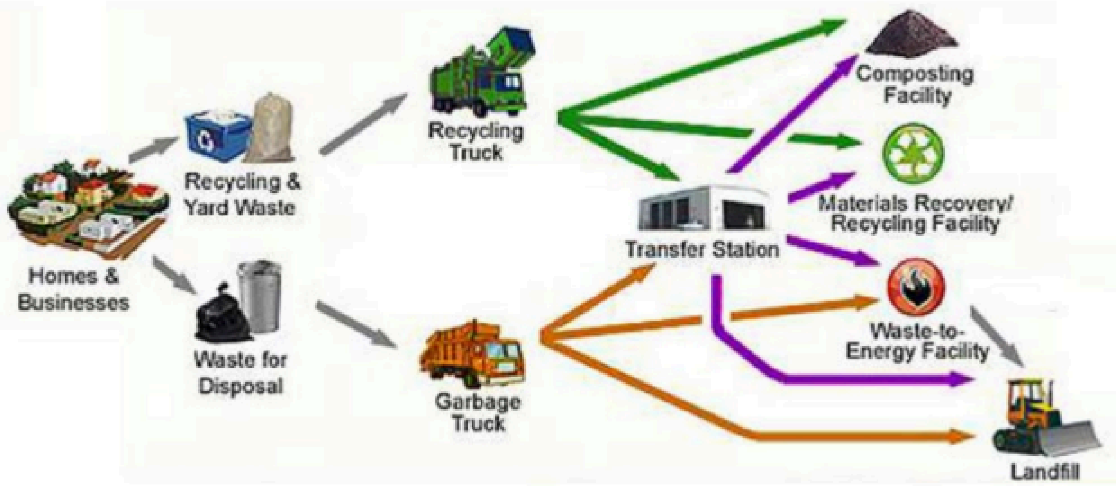


Figure 3. Waste Destinations between Generation and Disposal [12]

Section 2: Business Case

To understand the importance of diverting biomass waste from landfills to be reused and repurposed, we need to understand what is considered biomass. Biomass, as defined by the EIA, is renewable organic material that comes from plants and animals [2]. Using this definition, we can interpret biomass waste as waste produced from the organic material that comes from plants and animals. Examples of biomass waste include wood/urban wood, yard scraps (leaves and branches), leftover restaurant food and oils, and agriculture crops; all of which are examined more closely throughout this report. To achieve net zero emissions by 2050 as set by the White House through the Long-Term Strategy plan, reduction of emissions from landfills needs to be a priority [13]. One pathway to significant reductions in landfill emissions is to reduce the amount of biomass waste entering landfills.

Given biomass sector statistics of waste generated, just under half of all municipal solid waste in landfills is biomass waste [14]. According to the EPA [15], MSW landfills accounted for roughly 14.3% of methane emissions in the United States in 2021 (or 5.2% of U.S. economy-wide CO_2 emissions in 2022 [16]). Considering the amount of biomass waste that currently ends its life in landfills, there is a clear environmental benefit of diverting biomass waste through the development of a circular economy. In addition to emissions, the amount of waste produced each year is alarming. Looking more closely at the restaurant industry for emphasis on waste produced, 30-40% of food served to customers never gets consumed [17]. This is highly concerning when globally there are communities without access to nutritious food. In American restaurants, nearly 85% of food wasted is thrown into the trash and enters landfills [18].

Additionally, biomass is one of the few renewable energy sources (RES) whose availability does not depend on weather conditions, seasonal or diurnal variations, and can be stored for use on demand. Bioenergy is highly predictable and can be used to supplement current base load fossil fuel energy sources. The predictability gives bioenergy an advantage over other renewable energy sources [19]. Bioenergy is not intermittent or variable, unlike other renewable energy sources like solar and wind: the sun isn't always shining, and the wind isn't always blowing. The addition of storage technology is important for solar and wind energy to be able to deploy during intermittent or variable phases, unlike bioenergy. In comparison, while the availability of some biomass resources may be susceptible to seasonality, biomass energy plants can always turn on to provide power, regardless of the weather conditions outside [20]. It is important to recognize that bioenergy has numerous benefits, but the use of bioenergy still produces some GHG emissions. To minimize bioenergy’s environmental impact, prioritizing crop residues and biomass that would otherwise be sent to the landfill is preferable over land-use for the sole purpose of bioenergy feedstocks [20]. Bioenergy, when paired with a carbon capture and storage system, has the potential to have a negative global warming potential and should therefore be utilized as a transition away from fossil fuels [21].

Beyond environmental considerations, there are economic incentives for reducing biomass waste. The food service industry accounts for ~5.5% of the United States GDP [22]. This demonstrates the importance of food in all stages of the national economy. To dive more deeply into the cost of food waste, the USDA estimates the restaurant industry loses $162 billion annually as a result of wasted food [23]. To put this number into more relatable terms, the average American family of four spends $1,500 a year on food that goes uneaten [24]. Comparing this amount to the 2022 average American household income of $74,580, the cost of wasted food is roughly 2% of a family's annual income [25]. This may not seem like a significant percentage of annual income, but to many families the extra savings from wasted food could be used towards household priorities such as energy or water bills. Looking more closely at the economic benefits of transitioning to renewable energy sourced from biogas, the cost-benefit has the potential to be significant. Two tax credits, both state and federal, are available for the adoption of anaerobic digesters [26]. In addition, the transition to renewable energy from biogas can support statewide Renewable Portfolio Standards (RPS).

It is important to discuss the social impacts of biomass waste and the potential benefits of diversion strategies. Before diving into potential social benefits of biomass waste diversion, it is important to understand any social norms or behaviors associated with the production of biomass waste. The cultural norms and unclear information in the United States have contributed to the current waste crisis. One clear example of a cultural norm contribution is the thought process of taking leftover food home from a restaurant. One study found that if a restaurant server offered to box or wrap uneaten food, restaurant patrons would be more likely to take food home instead of the restaurant disposing of it [27]. The same study found if a restaurant patron was having a meal with friends or acquaintances compared to someone with little interaction they were more likely to take leftover food home. An example of the importance of clear information around food waste is associated with dates found on grocery items ("sell-by, use-by, and best-by"). The common confusion of these three dates in the United States often leads to consumers disposing of food on the date labeled even if the food is still edible and nutritious past this date. The United Kingdom recently switched over the one common date method on grocery items which resulted in the reduction of food waste [28].

Section 3: Methodology

3.1 Reflection of Methodology

The methods that have been used to complete this project have ebbed and flowed in accordance with the deliverables. We began by developing a deep understanding of the current biomass waste space both nationally and internationally. We aimed for research to cover both breadth and depth of biomass waste. Initially, we divided the research by sector to conduct a market segmentation, as that seemed most logical in terms of available feedstock and technology utilized. Our sectors included agriculture, restaurants, yard waste, forestry services/wood waste, residential, and current bioenergy technologies. Individually, we conducted research using google scholar to find peer reviewed articles discussing the challenges and successes of each sector respectively. The focus was on obtaining as much information, both qualitative and quantitative, and collecting that information in a usable format for future reference. Through our research, we found ourselves diving deep into industry and country level biomass waste success stories. Agriculture, technology, and restaurant sectors had information and case studies more easily accessible to use as a reference. Forestry/wood waste and yard waste relied mainly on articles from local news sources or small business websites.

With the initial goal of developing a market-based toolkit that explains pathways biomass waste could reenter the economy, our research transitioned towards a businesses and regional/community scale focus. The team created an excel document as a way to input quantitative data in a more uniform manner that was constantly updated with new information and client feedback. The biomass waste market is broad and can have entry points anywhere along the product's life cycle. For this reason, the team made another transition to take steps back and examine the entire market from cradle-to-grave with the hope of determining entry barriers for cradle-to-cradle. This was informed by the qualitative and quantitative research the team had conducted up to this point, along with the numerous conversations with our client, and virtual interviews with actors in this space. The developed product took the form of a flow chart that is displayed in Appendix C. The flow chart tells the story of biomass waste entering as a feedstock from a sector (such as agriculture) and follows the different pathways the waste can take until end of life as either reuse or waste-exchange. It is important to consider different policies and geographic considerations that may influence the flow of biomass waste; this is clearly labeled to the far left of the flow chart.

3.2 Final Deliverable Methodology

The methodology to achieve the final deliverables for our client are explicitly described in the following section. The final deliverables include two case studies (which are described in Section 4), quick fact sheets about each sector researched (Appendix A), and updates to client slide decks for presentations to different stakeholders.

3.2.1 Case Studies

The goal of the case studies was to demonstrate the use of the quantitative and qualitative information collected thus far in two separate industries, with the aspiration of influencing different stakeholders about the opportunities of partaking in a biomass waste market. The two case study topics were decided based on areas of interest from our client and growing biomass industries.

The first case study examined the potential impact Michigan Athletics could have on the reduction of carbon emissions and the cost benefit of composting year-round at the two largest athletic facilities using a campus purchased anaerobic digester. Using a collaboration with the Michigan Office of Campus Sustainability, we obtained data on waste produced from the Purdue vs. Michigan football game on 11/04/2023. The data was separated into both cubic yards and tons for categories including landfill, compost, recycling, and food donations. Using these numbers and assuming the 2023 football season was a typical schedule of home and away games (7 home games), we calculated the amount of compost waste that would be produced in a single season of only Michigan football. The detailed calculations can be found in the Appendix B and further description and justification can be found in Section 4 of this report. Comparing the amount of compost waste in tons produced in a single season and the current anaerobic digester fact sheet on Chomp's website [29], we concluded that Michigan football would not produce enough compost waste to run Chomp's Mini AD for a season. With this information, we looked beyond Michigan football and considered Michigan's Crisler Center in combination with the football stadium. To estimate the amount of organic waste produced by Crisler Center required many assumptions and a round-about method of collecting information. The combination of organic waste produced from Michigan Stadium in a single academic year was calculated using the single game statistics as an average and scaled up to account for roughly seven home games a season. Calculating the organic waste produced in a single academic year at Crisler Center required a bit more calculations and assumed the same average organic waste per person would be produced at Crisler Center as was in Michigan Stadium. This per person average was applied to an estimate of the attendance for all Crisler Center athletic events over the total 55 events held throughout one academic year. These two calculations were totaled to determine the potential organic waste produced from both Michigan Stadium and Crisler Center and the associated Anaerobic Digester scale that would be both environmentally and financially beneficial for the University to invest in. Specific processes and steps are described in the following sections.

The second case study examined a pilot program for potential sustainable aviation fuel production by using locally sourced feedstocks such as cherries and soybeans for the Detroit Wayne County Airport and considered both economic and environmental impacts. Detroit Wayne County Airport represents a bold step towards decarbonizing the aviation industry while supporting local agriculture and economic development. The techno-economic analysis, which compared the economics of a new, local production facility with various feedstocks, served as the basis for estimating the ranges for the minimum selling price (MSP) of SAF. The economic analysis followed the method outlined by the port authority of New York and New Jersey, with evaluation and comparison conducted by the NREL for a new, local production facility using multiple feedstocks.

3.2.2 Quick Fact Sheets

One-page fact sheets were developed with the intention to be a quick reference for important statistics and information in each researched sector. The process of completing these fact sheets was relatively quick considering the extensive research the team had conducted at the start of this project. Using the combined excel document and individual research notes, the team pieced together fact sheets for each sector by including general information (such as opportunities and by-product development) relevant to each sector. The addition of *Major Facts* as a category was added at the request of our client to pull big data points for use in consulting work. The majority of the additional research was finding these statistics by using internet searches for government related data or literature reviews. The team made adjustments to each sector such that the data found is uniform and under broad categories, while also being relevant to that specific topic. The U.S. EPA was a source for the majority of these major facts because it was important to the team to use reputable and highly cited sources. The culmination of research throughout the entire length of this project was used to inform the development of these one-page fact sheets. These quick fact sheets can be found in Appendix A of this document.

3.2.3 Presentation Materials

In addition to the two case studies and the quick fact sheets, the final deliverable came in the form of adjustments and additions to currently existing presentation materials from our client. The presentation materials are existing slide decks. The adjustments and additions to these materials were made using the research described throughout the length of this project. Using the quick fact sheets and the case studies, we added updated data that will be utilized for future meetings and events where our client will present the case for further development in a biomass waste market.

Section 4: Case Studies

4.1 Michigan Athletics

The following case study, described in Section 4.1.1 and 4.1.2, evaluates the potential university and community benefits to diverting athletic event food waste from the landfill via anaerobic digestion (AD). The two scenarios described below use food waste input from first the Michigan Stadium and second Michigan Stadium and the Crisler Center. In these scenarios we use anaerobic digestion as the process to turn food waste into biogas and liquid digestate. The EPA defines anaerobic digestion as the process through which bacteria breaks down organic matter in the absence of oxygen [30]. Typically this process takes place in a sealed vessel, like Chomp's mini AD used for this case study, containing complex microbial communities to produce the biogas and digestate by-products. These vessels allow for co-digestion, meaning we can put different types of feedstocks (yard waste, manure, food waste, cooking grease, etc) into the digester together to output biogas and digestate. The quantities of both by-products vary depending on the feedstocks used, as well as the nutrient value of the liquid digestate (or N-P-K ratio for fertilizer use) [30]. Due to this varying nature, the following calculations use approximate by-product quantities based on articles and Chomp's fact sheet. For more information, see the Anaerobic Digestion Fact Sheet in Appendix A.

4.1.1 Michigan Stadium

The goal of this case study was to determine if Michigan Stadium alone produces enough organic waste to financially justify an anaerobic digester and identify possible benefits of waste diversion. In collaboration with the Office of Campus Sustainability, we obtained stadium waste data from one game during the 2023-2024 football season. To complete the calculations needed for a single season, we made the assumption Michigan Stadium will produce waste from seven home football games during one academic year. This number was taken from the 2023-2024 football schedule and was assumed to be the same each season, excluding any non-regular season game such as any post-season game.

To complete the Michigan Stadium case study, assumptions were made due to the limited data available. We calculated a cost-benefit analysis of utilizing organic food waste as a feedstock for an anaerobic digester. As seen in Table 1, the costs and potential financial benefits are displayed and are analyzed in the following paragraphs.

Table 1. Cost-Benefit Analysis for Michigan Stadium Anaerobic Digester

	Category	**Cost/Value per Item**	**Quantity**	**USD ($)**	**Total Cost/Benefit**
Costs	Anaerobic Digester Capital Investment	$209,000[1]	1	$209,000 (one time)	$209,000 (initial) + $21,000 (yearly)
	Yearly Maintenance & Operation	$21,000[2]	1	$21,000/yr	

Benefits	Energy Offset	0.1368 $/kWh[3]	23,152 kWh/yr[1]	$3,167.19/yr	Fertilizer Sale: $58,765.19 (yearly) Fertilizer Use: $5,579.19 (yearly)
	Dumpster Offset	$95/dumpster /month[4]	6 dumpsters[5]	$1,710/yr	
	Organic Fertilizer Sale	$3.96/liter[2]	13,608 liters[6]	$53,888/yr	
	Organic Fertilizer Use	$260/acre[7]	2.7 acres[8,9,10]	$702/yr	

Notes: 1: Chomp [29]; 2: WWU [31]; 3: UMich Facilities [32]; 4: Waste Management [33]; 5: Office of Campus Sustainability [34]; 6: UC Davis [35]; 7: MSU [36]; 8: AASHE [37]; 9: GreenView [38]; 10: Song et al. [39]

The upfront cost of an anaerobic digester was determined by utilizing Chomp's Fact Sheet for their anaerobic digesters. Chomp was chosen as the reference source for organic waste input and digester size because the team had the opportunity to interview a member of the Chomp team to learn more about their products during the summer of 2023. It is important to also consider the yearly maintenance costs of anaerobic digesters. They will need to be maintained to ensure proper functioning and continued success. The Inflation Reduction Act (IRA) can provide a 30-40% tax benefit for the University by utilizing organic waste [40]. Though these tax benefits were not included in our analysis, it is important to note this will provide further incentives for the University to invest in an AD.

The first benefit that was researched calculated the energy offset per year from the biogas produced from AD. Based on the typical energy output range listed for Chomp's mini AD on their product fact sheet [29], the lowest end of the range at 79 MMBTU/year was chosen due to the low quantity of feedstock Michigan stadium could provide. After converting this to 23,152.61 kWh/year, it was multiplied with the average cost ($0.13/kWh) University of Michigan pays to DTE in 2020 [32]. This results in an annual benefit of $3,168.81 and covers approximately 8.5% of the stadium's total electricity use [32]. Though it is important to note this average electricity cost is much lower than the average Washtenaw county resident ($0.19/kWh) and depending on the allocation of electricity, this could have a higher annual economic impact [41].

Under the assumption Michigan Stadium organic waste is manually separated from Municipal Solid Waste after entering a dumpster, the potential financial savings from dumpster uses in the transition to an anaerobic digester for a single season are roughly $570. To come to this conclusion, the team assumed each dumpster in Michigan Stadium will hold 8 yards of waste. Using the total waste reported from the Office of Campus Sustainability [34], the stadium will need 13 dumpsters for the totality of a three-month season when not separating organic waste from MSW. The total landfill waste in cubic yards was provided by the Office of Campus Sustainability data sheet [35]. After subtracting the total waste in cubic yards and the MSW in cubic yards excluding organic waste, the total number or dumpsters needed for a single season was determined under the assumption all organic waste will be sent to an anaerobic digester. The total number of dumpsters needed would be 7 for a single season, assuming MSW stays relatively constant. Utilizing the cost of one dumpster per month for rent and trash removal from Waste Management [33], the cost savings from the reduction of dumpsters was calculated to be $1,710 for one academic year with removal for three months (roughly the length of a football season). It is important to note that this is not a substantial amount of money for the university, but the extra savings could be used to support the maintenance of an anaerobic digester.

The third and fourth benefit listed in Table 1 present two pathways for the liquid digestate by-product: sell the digestate to local businesses or use the digestate to fertilize green spaces around campus. To calculate the potential benefit from organic fertilizer sale by the University of Michigan, the University of California Davis report was utilized to find statistics for their Renewable Energy Anaerobic Digester (READ). UC Davis is one of the few universities converting campus food waste directly into energy and fertilizer, who also provide public access to input and output data. The UC Davis report that was referenced for this case study provided the typical organic food waste each year and the associated amount of fertilizer output per year. Scaling these numbers to fit the Michigan Stadium game and associated season, the total potential fertilizer output was calculated at 13,608 liters. To find the potential cost benefit of selling this fertilizer, the average cost of $15/gallon, from a WWU study on anaerobic digestion [31], was converted to reach the cost per liter. Multiplying the cost per liter and the total liters produced, the possible revenue from fertilizer sale was estimated to be $53,887 for one football season worth of food waste input into an anaerobic digester.

The fertilizer use pathway is more complicated to calculate as the nitrogen, phosphorus, and potassium levels of the biomass waste input is important to estimate their levels after the digestion process. Understandably, without knowing the exact ratios of the inputs, this benefit pathway calculation has the most uncertainty. For the purposes of this case study, we assumed the digestate retains 90% of its nitrogen content based on Song et al.'s food waste anaerobic digestate as a fertilizer study [39] and digestate nitrogen levels remain at 0.6%. With a goal of 2 lbs/sqft of nitrogen for grass [38], or 87.12 lbs/acre, we calculated approximately 50 liters/acre of digestate are needed for Michigan green space use. According to AASHE's Sustainability Tracking, Assessment, and Rating System (STARS), the University of Michigan has 1,030 acres of managed green space. With a digestate output of 13,608 liters, the anaerobic digester would be able to provide fertilizer for 2.72 acres, or 0.26% of campus. In terms of economic benefit for using digestate, based on a cost of $260/acre from Michigan State University's Agriculture Product Center [36], we calculate a potential annual benefit of $702. A complete set of calculations can be seen in Appendix B.

After calculating the organic waste produced in a single football season, the total amount falls slightly short of the input needed for even a mini anaerobic digester with total organic waste produced being 18.144 tons and a minimum of 25 tons needed, respectively. The complete breakdown of calculations can be found in Appendix B with a link to our excel document. With the lower amount of organic waste input, to complete a cost-benefit analysis we made the generalization that the total tons of organic waste match the lower end organic waste input needed to run Chomp's mini anaerobic digester. This number was taken from the current Chomp AD Fact Sheet [29]. If the university were to choose the liquid digestate sale benefit pathway, this option would become economically beneficial after 6 years with total costs at $335,000 and total benefits at $352,591. If the university were to choose the liquid digestate use benefit pathway, this option would not become economically beneficial in the near future with the total cost at $293,000 after only four years.

The GHG emission savings were also calculated as another potential source of encouragement for the university to transition away from fossil fuels and utilize the waste produced on campus to reach targets for a carbon neutral complex around scope 1 and 2 emissions as laid out in the carbon neutrality goals by the Office of the President. The total greenhouse gas emission savings from one football season would equal 10.995 MT CO_2e. This number was calculated under the assumption the MSW and organic waste from one game is equivalent to the average for a single season and was applied to all seven home games at the Big House. Organic waste sent to landfills makes up a majority of MSW and contributes to emissions from landfills. The emission savings were calculated under the premise that organic waste not entering landfills will reduce landfill emissions associated with university's waste.

4.1.2 Michigan Stadium & Crisler Center

After determining the stadium will likely not provide enough yearly organic waste for a mini anaerobic digester from Chomp, we decided to transition the case study to examine the impact of including waste from both Michigan Stadium and Crisler Center. However, this was challenging due to a lack of data on food waste generated by the center. We are unsure if Athletics does not track any of this data or if this is considered proprietary and not available to the general public. To determine a rough amount of organic waste produced in Crisler Center we relied on assumptions of all sports played in Crisler Center for a single academic year [42]. We also relied on the assumption organic waste is currently separated from municipal waste, which is unlikely.

To begin determining the quantity of organic waste produced at Crisler Center, we calculated the tons of organic waste per person produced at Michigan Stadium during the 11/04/2023 football game. This number gave us a rough estimate of the amount of organic waste that could be produced per person at an event in Crisler Center. Using the only data available, we obtained the seat capacity for Crisler Center to be 13,609 [42]. To find the number of sporting events held in Crisler Center for one academic year, we had to get creative with our methods of obtaining information. There are no general sources of information for Crisler Center as a whole; instead we found each sport that is housed in the center and counted the number of home games in a single season for each sport (refer to Appendix B). For the academic year 2023-2024, there are a total of 55 home sporting events held in Crisler Center excluding any event that is post-regular season. We took this number to be the average for all of these sports each year. Knowing football draws the largest crowd of all sports at the University of Michigan, we assumed an average seat capacity of 65% for all 55 events held at Crisler Center. This gave us an average attendance of 8,846 people per event. Using the calculated tons of organic waste per person from Michigan Stadium and applying that to Crisler Center, we concluded that in one academic year, Crisler Center will produce 11.433 tons of organic waste.

Table 2. Cost-Benefit Analysis for Michigan Stadium & Crisler Center Anaerobic Digester

	Category	**Cost/Value per Item**	**Quantity**	**USD ($)**	**Total Cost/Benefit**
Costs	Anaerobic Digester Capital Investment	$222,257[1]	1	$222,257 (one time)	$222,257 (initial) + $21,000 (yearly)
	Yearly Maintenance & Operation	$21,000[2]	1	$21,000/yr	
Benefits	Energy Offset	0.1368 $/kWh[3]	27,382 kWh/yr[1]	$3,745.93/yr	Fertilizer Sale: $95,009.62 (yearly) Fertilizer Use: $8,605.31 (yearly)
	Dumpster Offset	$95/dumpster/month[4]	3 dumpsters[5]	$3,420.00/yr	
	Organic Fertilizer Sale	$3.96/liter[2]	22,182 liters[6]	$87,843.69/yr	
	Organic Fertilizer Use	$260/acre[7]	4.44 acres[8,9,10]	$1,154.38/yr	

Notes: 1: Chomp [29]; 2: WWU [31]; 3: UMich Facilities [32]; 4: Waste Management [33]; 5: Office of Campus Sustainability [34]; 6: UC Davis [35]; 7: MSU [36]; 8: AASHE [37]; 9: GreenView [38]; 10: Song et al. [39]

Each stadium and complex individually does not have the feedstock input to successfully run a mini anaerobic digester. However, the combination of both Michigan Stadium and Crisler Center would produce 29.577 tons of organic waste in one academic year which is an appropriate amount to run Chomp's mini anaerobic digester. To determine the yearly costs and benefits shown in Table 2, we scaled all previous calculations used for Table 1 to reflect the new biomass waste input quantity. The only calculation difference is for calculating how many dumpsters we can remove. In this scenario we assumed the dumpsters are active year round, whereas in the previous scenario we assumed the dumpsters were only active for the 3 month football season and therefore the university would only pay for dumpster pickup for the season. Despite these differences, the timeline to reach economic feasibility is similar. If the university were to choose the liquid digestate sale benefit pathway, this option would become economically beneficial after 4 years with total costs at $306,257 and total benefits at $380,038.48. If the university were to choose the liquid digestate use benefit pathway, this option would not become economically beneficial in the near future.

We believe university athletics has the potential to scale this number up for all athletic events on campus and could economically benefit from utilizing an anaerobic digester for organic food waste on campus. This case study can also be scaled for professional sporting complexes (such as major league baseball) where there are a substantial amount of home games in a single season. It is important to note the limitations of this study include the ability to access only data from a single football game for the 2023-2024 academic year. There were many assumptions made to come to these conclusions and updates should be made when more information is available.

4.2 Sustainable Aviation Fuel (SAF)

Sustainable aviation fuel (SAF) is a liquid fuel that is being used by aviation and can be produced from biomass feedstocks. It has the potential to significantly lower the carbon footprint of the aviation industry and help combat climate change. SAF can be blended at different levels with limits between 10% and 50%, depending on the feedstock and how the fuel is produced. Worldwide, aviation accounts for 2% of all carbon dioxide (CO_2) emissions and 12% of all CO_2 emissions from transportation [43].

Detroit, a key transportation hub, faces the challenge of reducing carbon emissions from aviation while fostering regional economic development. Aircraft movements assumingly account for 739,961 metric tons, which is 92% of DTW CO2 emissions, and SAF represents an opportunity to reduce aircraft emissions [44]. The Wayne County Airport Authority (WCAA) has a sustainability program with the goal of achieving zero emissions by 2050, focusing on initiatives such as waste reduction and GHG emissions reduction. This case study explores the potential impact of a pilot program at the Detroit Wayne County Airport for sustainable aviation fuel derived from cherries and soybeans. The aim is to align with the WCAA roadmap's emission reduction targets, specifically focusing on Action 14 of Investigating SAF/Future Aviation Trends.

This section provides an in-depth analysis of feedstock quantities and evaluates the feasibility of producing SAF from cherries and soybeans in Michigan. Additionally, the analysis aims to evaluate the environmental impact and benefits of using SAF compared to traditional aviation fuel. Cherries and soybeans were selected as feedstocks for SAF production due to their classification as high-producing energy sources in Michigan and their categorization under lipid feedstocks, aligning well with American Society for Testing and Materials (ASTM) approved pathways for SAF production.

4.2.1 Existing Fuel Production Facilities

LanzaJet has opened its Freedom Pines Fuels facility in Soperton, Georgia, marking a historic milestone in sustainable fuels technology. The facility uses ethanol-based technology, the world's first viable next-generation sustainable fuels (SAF) technology, to produce 10 million gallons of SAF and renewable diesel annually. The technology is expected to meet the White House's SAF Grand Challenge, which calls for a supply of at least 3 billion gallons of SAF annually by 2030 to reduce aviation emissions [45].

Neste is the world's leading SAF producer, offering SAF made from sustainably sourced renewable waste and residues such as used cooking oil and animal fat waste [46]. Gevo’s SAF is a renewable drop-in jet fuel produced from a broad range of non-petroleum biomass sources using the alcohol to jet (ATJ) conversion processes. ASTM has qualified this alternative jet fuel production pathway to produce fuels that are comparable with conventional jet fuel in terms of materials, safety, and composition. A drop-in fuel does not require adaptation of the fuel distribution network or the engine fuel systems. The specifications for alternative jet fuels are defined in ASTM Standard

D7566, and specific annexes to the Standard apply to individual processes for producing alternative jet fuels [47].

Shell Aviation is working throughout the value chain to help the aviation sector reach net zero. Shell is investing in SAF production and developing new technologies to provide SAF safely and securely to clients, as well as ensuring all supply chain aspects, from sustainable feedstock to blending facilities, are in place. Shell Aviation currently sells SAF to North America, Europe, and Asia Pacific clients, including some of the world's main airport hubs. [48].

4.2.2 Feedstock Availability Assessment

Feedstocks need to be available at a scale, quantity, cost, carbon footprint, and with a sustainability profile that enable large-scale production of SAF. We considered feedstock availability and conversion efficiency to determine the specific quantities of cherries and soybeans needed for SAF production in Michigan. We identified cherries and soybeans as energy feedstocks within Michigan, conversion technology pathways, and their associated costs, and obtained data on annual yields per acre for cherries and soybeans from local agricultural extension offices and farming cooperatives. In the quest for sustainable feedstocks, cherries, and soybeans have garnered attention for their potential as viable sources for SAF production. Cherries and Soybeans offer unique characteristics and advantages as feedstocks for sustainable aviation fuel production. Their abundance, regional availability, high sugar or oil content, and compatibility with existing processing infrastructure make them promising candidates for advancing the sustainability goals of the aviation industry in Michigan. According to Michigan agriculture facts, soybeans are also Michigan’s top agricultural commodity export. In 2022, $236 million of Michigan soybeans were exported around the world. Lenawee, Sanilac, and Saginaw counties are Michigan’s top soybean producers. Michigan's soybean industry plays a significant role in the state's economy, contributing to both domestic and international markets [49]. The success of Michigan soybean producers highlights the state's agricultural diversity and global competitiveness in crop production.

Michigan grows 74 percent of tart cherries in the United States. In 2022, Michigan produced 180 million pounds of tart cherries with a value of $36.5 million [49]. Michigan's agricultural industry extends beyond soybeans, with tart cherries being a significant crop contributing to the state's economy and reputation. The National Cherry Festival in Traverse City celebrates Michigan's status as the largest producer of Montmorency tart cherries globally.

Cherries have an annual yield of 5 tons per acre, with 1,000 acres available for cultivation, resulting in a potential feedstock supply of 120,500,000 lbs per year [50]. Soybeans, on the other hand, have an annual yield of 46 bushels per acre, with 2,030,000 acres harvested, leading to a potential feedstock supply of 93,380,000 bushels per year [49]. Chemical analyses confirm the suitability of these feedstocks for SAF production, considering their lipid and carbohydrate content. These feedstocks can contribute significantly to the production of sustainable aviation fuel (SAF) due to their high lipid and carbohydrate content.

4.2.3 Conversion Pathways

ASTM approves seven alternate jet fuel routes [51]. Two feedstock-based conversion processes were chosen: hydroprocessed esters and fatty acids (HEFA) and Fischer-Tropsch with a 50% mixing restriction. Because cherries and soybeans are good SAF feedstocks, HEFA and FT synthesis function well. HEFA methods employ soybean oil, whereas FT synthesis uses cherry lignocellulosic biomass. This illustrates that these methods work with many feedstocks. Cherry and soybean properties, along with HEFA and FT technologies, may help the aviation sector become sustainable, renewable, and compatible with existing processing infrastructure, making them promising candidates for advancing the sustainability goals of the aviation industry in Detroit and beyond.

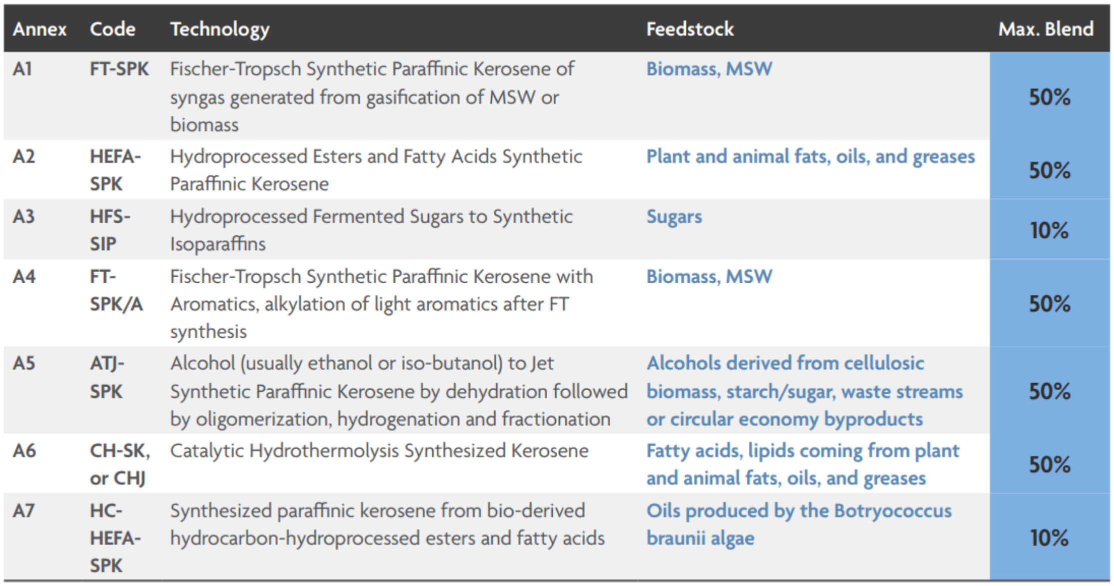
4.2.4 Hydrotreated Esters and Fatty Acids (HEFA)

HEFA hydrogenates vegetable oils, waste oils, and fats into SAF. The HEFA process begins with hydrodeoxygenation. Next, straight paraffinic molecules are fractured and isomerized to jet fuel chain length. HEFA is comparable to hydrotreated renewable diesel generation, except it cracks longer-chain carbon molecules more severely. The maximum mix ratio is 50% [51], [52].

4.2.5 Fischer-Tropsch

FT breaks down carbon-containing materials into gaseous building units. FT synthesis turns these building components into SAF and other fuels. ASTM has recognized two FT processes: one that generates straight paraffinic jet fuel (SPK) and one that creates aromatic chemicals. According to the standard, both procedures may employ any carbon-containing starting material. The maximum mix ratio for both options is 50% based on ASTM standard D7566 Annex 1 and 4 for SPK and SAK, respectively (shown in Figure 4) [51], [52].

The capital costs and equipment requirements vary among the pathway and feedstock combinations. These differences partially result from differences in initial feedstock chemistries which dictate the number of steps required to convert the material into a hydrocarbon. In short, all biological feedstocks contain oxygen. Those with the greatest amount of oxygen and the most diverse set of constituent compounds tend to require more operations resulting in higher capital costs to convert.



Annex	Code	Technology	Feedstock	Max. Blend
A1	FT-SPK	Fischer-Tropsch Synthetic Paraffinic Kerosene of syngas generated from gasification of MSW or biomass	Biomass, MSW	50%
A2	HEFA-SPK	Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene	Plant and animal fats, oils, and greases	50%
A3	HFS-SIP	Hydroprocessed Fermented Sugars to Synthetic Isoparaffins	Sugars	10%
A4	FT-SPK/A	Fischer-Tropsch Synthetic Paraffinic Kerosene with Aromatics, alkylation of light aromatics after FT synthesis	Biomass, MSW	50%
A5	ATJ-SPK	Alcohol (usually ethanol or iso-butanol) to Jet Synthetic Paraffinic Kerosene by dehydration followed by oligomerization, hydrogenation and fractionation	Alcohols derived from cellulosic biomass, starch/sugar, waste streams or circular economy byproducts	50%
A6	CH-SK, or CHJ	Catalytic Hydrothermolysis Synthesized Kerosene	Fatty acids, lipids coming from plant and animal fats, oils, and greases	50%
A7	HC-HEFA-SPK	Synthesized paraffinic kerosene from bio-derived hydrocarbon-hydroprocessed esters and fatty acids	Oils produced by the Botryococcus braunii algae	10%

Figure 4: Overview of Pathways Incorporated as Annexes of ASTM D7566 [51]

4.2.6 Economic Methodology

Many studies have evaluated the feasibility of sustainable aviation fuel production by conducting techno-economic analysis (TEA) of various conversion technologies. The techno-economic analysis, which compared the economics of a new, local production facility with various feedstocks, served as the basis for estimating the ranges for the minimum selling price (MSP) of SAF. The economic analysis was completed using the method outlined by the port authority of New York and New Jersey, where the NREL evaluated and compared the economics of a new, local production facility using multiple feedstocks. NREL performed a TEA using data from regional feedstock availability based on the resources of interest, including organic wet wastes (e.g., grease and fats, manure, food waste, and sludge), oil crops, woody biomass, and crop residues. NREL plays a crucial role in developing and maintaining TEA models that intricately describe the process and production economics of conceptual biochemical conversion pathways to biofuels and bioproducts, showcasing their expertise in the field. NREL generated the data via Aspen Plus process simulation using a set of conversion parameters, material and energy balances, and flow rates. The report used Aspen Plus process simulation to generate data that was used to determine the size and cost of process equipment, compute raw material costs, and determine other operating costs. The study employed a discounted cash flow rate of return to calculate the minimum selling price of fuel necessary to achieve a net present value of zero, considering an internal rate of return of 10% and the annual fuel capital investment (TCI), crucial for assessing the project's financial feasibility. It stated that the TEA outputs carry some uncertainty related to the assumptions made for capital and raw material costs [53]. The minimum jet fuel selling price (MFSP) was estimated to be \$3.74/gge (Soybeans Oil) and \$5.39/gge (cherries) for HEFA. The production cost for FT and HEFA was estimated to range between \$5.2 and \$12.1/gge, respectively. Which is much higher as compared to the cost of production of the market price of jet fuel \$1.93/gal [53].

To determine the total amount of feedstocks needed for processing, the total amount of soybeans grown in bushels was multiplied by 10.7 (lbs/soybean bushel) to get the number of pounds needed to make one pound of crude soy oil needed to process through the pathways. Cherries grown in pounds were multiplied by 0.15 to get the number of cherries needed for SAF production. The oilseeds were then converted to SAF from the pathway calculation of the SAF input ratio provided in the port authority report. Using the SAF input ratio and the total pounds of oilseed input, we calculated the SAF output ratio and converted the SAF to gallons. After finding the total SAF from the feedstock, the cost of production was evaluated by multiplying the TCI ($12.1 and $5.2/g) by the total SAF in a million gallons. The cost analysis also factored in other variables, such as transportation costs and processing fees, to determine the overall profitability of producing SAF from soybean oil and cherry oil seen in Table 3 below.

Table 3. Profitability of Producing SAF

Feedstock Type	**Feedstock Input (lbs)**	**SAF Production Output (MGGe)**	**Total Capital Investment (TCI)**	**Minimum Fuel Selling Price (MFSP)**	**Cost of Production**
Soybeans Crude Oil	10 million lbs	212 million gallons	$5.2/gge	$3.74/gallon	$1 billion
Cherries Oil	1.5 million lbs	9.5 million gallons	$12.1/gge	$5.39/gallon	$115 million

4.2.7 Role of Airlines and Airport Owners in SAF Production

Many airlines have entered into off-take agreements with SAF producers as shown below. Delta and Neste, the leading SAF producer, started their 1M gallons from 2021/2022 partnership, including a trial with Neste and Colonial Pipeline to test how to transport SAF through existing pipeline systems. In the trial, SAF was delivered from Texas to New York’s LaGuardia airport over nearly 1,500 miles and across 11 states through the Colonial and Buckeye pipeline systems [46].

Delta and Gevo, signed a “take-or-pay” agreement, which will supply 75 million gallons of sustainable aviation fuel (SAF) per year for seven years. Long-term investments such as the agreement between the two companies are critical to Delta’s goal to lower its carbon footprint while planning for a more sustainable future [54]. Delta will purchase up to 10 million gallons of neat SAF from Shell Aviation over a two-year period for use at its hub at Los Angeles International Airport (LAX). This agreement will bring Delta's SAF commitments to nearly 200 million gallons, more than halfway to its 2030 objective of 10% of fuel usage being SAF, and well on its way to 35% SAF use by 2035. Delta’s ambitions complement those of Shell which aims to be a net-zero emissions energy business by 2050 [55].

Airports do not purchase jet fuel, but many are eager to use SAF to satisfy greenhouse gas reduction objectives, support state climate targets, and benefit local airport communities. Airport owners may collaborate with airlines, fuel suppliers, fixed-based operators that oversee airport refueling infrastructure, and others to find the optimum SAF mix delivery options. The local supply chain is trained to accept, mix, and dispense SAF/Jet A blends at airports by the port authority research and others by Port of Seattle (owner of Seattle-Tacoma International Airport) and San Francisco International Airport. Two Port of Seattle papers examined regional SAF production and financing options for their airport to reduce expenses without purchasing SAF. See Figure 5 for the Worldwide SAF Production Projection.

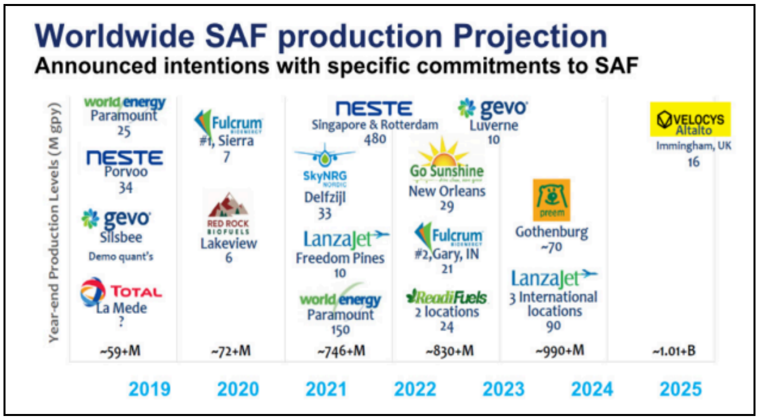


Figure 5: Worldwide SAF Production Projection [56]

4.2.8 SAF Supply Chain

The method of moving fuels throughout the country depends on the location of production, fuel type, and volume. The modes of transport for fuels include barge, ship, pipeline, rail, and truck. Biofuels are typically moved by rail, truck, and barge, whereas Jet A travels primarily by pipeline. A blend of SAF and Jet A could move by pipeline [53].

There are approximately 37 fuel terminals in Michigan and six in Detroit that could supply jet fuel via pipeline to the Detroit airport [57]. Buckeye Pipeline and Swissport Fuel Services are two possible existing petroleum pipeline systems that currently handle jet fuel and can receive fuel by all modes of transport, allowing for flexibility in receiving domestic and imported SAF. These terminals have the infrastructure and capacity to blend SAF with conventional jet fuel, making them a cost-effective and efficient option for distribution. By utilizing existing pipeline systems, the transportation of SAF to airports can be streamlined and reduce overall emissions from aviation fuel. See Figure 6 below.

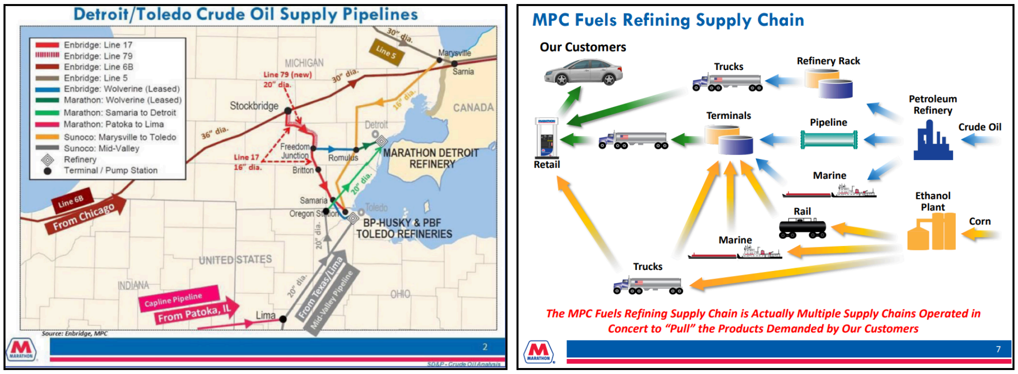


Figure 6: Detroit/Toledo Crude Oil Supply Pipelines (left) & MPC Fuels Refining Supply Chain (right) [58]

4.2.9 Key Findings

The amount of SAF that can be produced from the available regional feedstock of soybeans and cherries are summarized in Table 3. The combination will potentially produce 222 million gallons of SAF, which is equivalent to approximately 93 days of fuel for DTW [59], although the price per gallon for pioneer facilities starts at nearly three times the cost of conventional jet fuel. It should be emphasized that the TEA outputs carry some uncertainty related to the assumptions made for capital and raw material costs by the NREL. A new facility could have different capital and input costs that would impact the overall costs and economics.

The feedstock assessment and techno-economic analysis revealed an abundant supply of feedstocks in Michigan, including corn, forestry, yard waste, animal waste, used cooking oil, grease, MSW, etc., which, when combined, can potentially yield a significant annual amount of SAF. Collaborating with refineries such as Zeeland Farm Service and partnering with renewable fuel companies can significantly lower production costs.

As part of the supply chain for SAF production, no matter where it is produced, it must be blended before aircraft use. NREL suggests blending at terminals due to their infrastructure and capability to verify the SAF/Jet A mix according to ASTM D1655 before reaching airports. SAF from neighboring facilities is expected to be transported by trucks to a terminal. Remote domestic plants may transport SAF to a port using rail, barge, or pipeline for the SAF/Jet A mix, whereas imported SAF will arrive via ship. Future federal code amendments may allow unblended SAF to be transported via pipelines.

Section 5: Recommendations

5.1 Using Guide

This report provides valuable information on the current status of biomass waste and the potential diversion pathways to reduce landfill waste. This report can be used by numerous stakeholders with vastly different goals and agendas. The business case is broken down into the environmental, economic, and social benefits of developing a biomass waste circular economy. Clearly stating the importance of this work and the recognition of the growing waste problem globally will lay the foundation for the rest of this report. We encourage organizations and businesses who want to learn more about biomass waste to read through the entirety of this report. In the hope to increase the utilization of biomass waste as a by-product, we encourage readers to take apart the key components relevant to your industry to further the development of technology and convince stakeholders of the potential for biomass waste by-products in the face of climate change mitigation efforts.

The case studies provide detailed examples of analyses that can be completed to encourage the diversion of organic waste to become an economic resource. Each case study can be scaled up or down depending on the organization or industry that will benefit from these results. In the paragraphs that follow, a detailed description of our recommended use of each case study is provided.

The Michigan Athletics case study can be used to encourage the university or similar institutions to value organic waste as a resource instead of as an unusable endpoint. The university should further collaborate with the Office of Sustainability to collect more data on organic waste from other athletic complexes. More support will be needed to expand this case study to the entire campus which could have immense benefits for the environmental footprint and economic prosperity of the university. In the event of other similar institutions referencing the Michigan Athletics case study, we recommend collaboration with the athletic offices and university grounds or maintenance departments.

Sustainable Aviation Fuel (SAF) is growing in demand as a potential replacement for fossil fuels. We recommend using this case study to make informed decisions about the potential environmental benefits of transitioning to SAF as a fuel source in the aviation industry. Additionally, prioritizing the exploration and implementation of sustainable transportation methods for SAF could significantly reduce carbon emissions associated with its distribution. Considering the various transportation options available for SAF, it is crucial to minimize environmental impact and promote sustainability in the aviation sector by choosing the most environmentally friendly and efficient methods. Diversifying transportation methods, such as using electric vehicles and sustainable shipping options, can significantly reduce the industry's carbon footprint and contribute to a more sustainable future. Implementing efficient and sustainable distribution methods for SAF can also help lower costs and increase accessibility, making it a more viable option for airlines looking to reduce their carbon footprint. Furthermore, collaboration between industry stakeholders and policymakers is crucial not only in developing comprehensive strategies but also in fostering innovation and investment to support the widespread adoption of SAF in aviation.

The quick fact sheets found in Appendix A should be utilized for businesses or organizations that want a convenient source for critical information related to a specific biomass sector. These fact sheets can be used as a “business” case to provide support for the need to transition away from biomass waste sent to landfills and towards diversion pathways. Depending on the business goal, the fact sheets can also provide quick but thorough details about any opportunities and challenges associated with biomass waste in a particular sector. Developing an overview of critical information on a topic is often needed before any discussions towards business endeavors can begin.

The flow chart found in Appendix C is included to provide an overview of the flow of biomass throughout a products life cycle. Although not included in this document, a flow chart with the inclusion of an arrow in reverse was developed to demonstrate cradle-cradle potential. The team recommends using the flow chart as a basis for understanding where an organization might enter the life cycle and opportunities for communication and collaboration on either side of the entry point. The flow chart will hopefully provide some insight into waste diversion pathways that can be used in conjunction with the case studies and the business case.

5.2 Updating Guide

The inclusion of our methodology is for the purpose of updating and replicating this report. To update the Michigan Athletics case study, we recommend collaborating with Athletics management to obtain more concrete data about capacity and attendance of all sporting events. The process used to separate organic waste from MSW at each venue was unclear, if it is even sorted at athletic facilities beyond Michigan Stadium. The case study calculations found in Appendix B are included for the purpose of updating the case study once more data becomes available in the future or for replication use. The thought process behind each calculation and the flow of data are clearly displayed in the appendix. We would recommend going one step further and examining community wide benefits for the diversion of compost to an anaerobic digester. Community benefits can include expected public health outcomes, social improvements, environmental justice, and so on. The time constraint did not allow us to dive deeper into these subcategories, but it should be noted that social considerations and benefits are equally as important as financial and environmental.

Updating the Sustainable Aviation Fuel case study can include evaluating other available feedstocks through different pathways in Michigan for the increment of annual SAF production. Additionally, exploring partnerships with local universities and research institutions can help accelerate advancements in SAF production technology. This collaborative approach can also attract funding opportunities for scaling up production facilities in the state. Furthermore, engaging with key stakeholders, such as government agencies and industry associations, can help create a supportive regulatory environment for SAF production. By building a strong network of partners, Michigan can position itself as a leader in sustainable aviation fuel production and contribute to reducing carbon emissions in the aviation sector.

The Fact Sheets in the appendix of this report will require regular updating to ensure the information is accurate with the current biomass space. The addition of new regulations and bills (such as the implementation of the Farm Bill) will add a new layer of complexity and reinforce the need to reduce waste entering landfills. With these considerations, we recommend updating the Fact Sheets yearly to obtain a thorough understanding of both global and national biomass waste resources and diversion pathways.

Section 6: Conclusion

Organic Waste is a global problem and by-product development can simultaneously reduce carbon emissions and limit waste entering landfills. For the U.S., the DOE released the 2023 Billion-Ton Report which estimates approximately 217 million tons of biomass MSW per year could be reallocated for by-product development [60]. This amount of waste could be used to produce about 25% of the total SAF needed to support U.S. aviation fuel demand - a by-product option this report presents. In this example alone, using biomass MSW for biofuel, could cut not only landfill emissions, but aviation emissions as well.

Opportunities for by-product creation currently exist and are easy to implement without changes in consumer behavior. Reducing consumption is the best way to reduce GHG emissions and our impact on the environment; however, it is often seen as a more difficult option to change consumer behavior. Many of the pathways for by-product development our team researched require little to zero change in consumer behavior. Specifically, industries entering the biomass circular economy at an agriculture, manufacturing (food processing or cotton clothing manufacturer), or product selling (restaurant or grocery store) stage have the ability to change their waste management processes, reducing waste before the product reaches the consumer phase entirely.

Many of these technologies are commercially available now, but have historically had limited financial support and incentive. However, Michigan Athletics alone can support an anaerobic digester and, depending on the liquid digestate use case, can economically benefit from this investment in just four years. Athletic stadiums across the country can not only support their financial investment in anaerobic digestion, they can also support local urban farms and community green spaces, divert tons of MSW, support additional jobs for AD operation, and decrease their carbon footprint. With more federal and private investment, broader education, and further research - a biomass circular economy will have significant economic, social, and environmental benefits for communities globally.

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Appendix A: Fact Sheets

Agriculture Animal Products Fact Sheet:

Major Facts of the Agriculture Animal Products Industry:

- Livestock farming for human consumption generates almost 15% of total global GHG emissions [61]
- Livestock farming uses approximately 70% of global agricultural land [61]
- If we stopped meat and dairy production globally, we could stop the increase of GHG emissions for the next 30 years [62]
- US Department of Agriculture estimates U.S. livestock farming generate 3x more raw waste than generated by Americans [63]

By-Product Overview: [63]

- Animal waste: Dairy - manure contaminated runoff, milking house waste, bedding, spilled feed, silage leachate, mortalities; Beef - manure, bedding, contaminated runoff, mortalities; Swine - manure, contaminated runoff, mortalities; Poultry - manure, mortalities, litter, wash-flush water, wasted feed
- Aerobic treatment lagoons (Co-mixing food waste with animal manure can increase methane production in anaerobic digestion methods)
- Biofuel - cattle manure, pig manure
- Biogas via anaerobic decomposition or thermochemical conversion - manure combined with potato peels (co-digestion) increases by 10% compared to their individual production
- Fish meal - cattle manure processed via anaerobic digestion
- Example: Dairy Doo - produces a wide range of vegetable garden compost, potting soils, and fertilizers primarily from cow manure and provides fertilizer to large agriculture businesses as well as households across Michigan and the midwest [64]

Opportunities and Considerations:

- Use reusable packaging for product delivering (e.g. using reusable glass cartons instead of single-use wax carton)
- Policy example: Rhode Island [65]
    - The following composting on agricultural units do **not** require registration: composting of tree stumps, brush, manure, agricultural by-products that were generated within the boundaries of the agricultural unit
    - The following materials in addition to agricultural by-products on agricultural units **do** require registration: non-agricultural sources of manures or animal bedding materials, and anything more than 10 tons per day of compostable material recovered from food or beverage industry, anything more than 1 ton per day of material recovered from restaurant or kitchen, and anything more than 0.5 ton per day of unprocessed meat or fish

Agriculture General Fact Sheet:

Major Facts of the Agriculture General Industry: [66]

- >2 Gt of crop residues are burned during an incineration process contributing to 18% of total global emissions of CO_2
- The major global crops (wheat, maize, rice, soybean, barley, rapeseed, sugarcane and sugar beet) in the selected countries/regions with large biomass potential (EU27, Pan Europe minus the EU27, United States of America, Canada, Brazil, Argentina, China and India) produce almost 3.3 Gt residue
- Agricultural intensification (producing more per unit of land) will increase crop residues- agricultural productivity in 2050 is projected to be 60% higher than 2005

By-Product Overview: [67]

- Fibers for textile industry - cellulosic fibers from plant residue (like corn husks, bagasse, banana, & bamboo)
- Flammable & water resistant materials - sugarcane fiber is found to be less flammable and more water-resistant than industrial textile materials
- Bio-bricks - form of carbon sequestration (322.2 gm of CO_2 per block) and can be used in combination with wood and metal to build low-cost housing [68]
- Absorbents to treat industrial wastewater - sugarcane, rice husk, sawdust, neem bark, oil palm shell, coconut husk to remove heavy metal and magnetic ions from wastewater
- Biofuel: from sugarcane bagasse, coffee, cotton, orange peel, rice bran, apple pomace, oil palm fruit, barley straw, rice straw, wheat straw, corn stover [69]
    - Bioethanol - maize and sugarcane (any sugar content of a starch)
    - Biohydrogen (by 2050 biohydrogen may be the preferred automotive fuel) - wheat bran/straw, corn stalks, and potato peels
    - Biobutanol/biodiesel to replace petrofuel - food industry waste, vegetable & fruit
- Energy: from straw, food processing waste, and farm yard waste

Opportunities and Considerations:

- Animal feed - many agricultural residues can be combined to create animal feed with minimal processing
- Minnesota: Agriculture sector is the state’s largest source of emissions, the majority of which comes from large scale concentrated animal feeding operations (CAFOs) for dairy, hogs, and beef and ethanol production (using nitrogen-based fertilizers). MN announced its Climate Action Framework (2022) which preserves land for natural carbon sequestration, promotes community based agriculture to reduce transportation and increase food access, and expands the use of cover crops and perennial crops that can better hold water and limit nitrogen pollution [70]

Agriculture Cereal Crops Fact Sheet:

Major Facts of the Agriculture Cereal Crops Industry:

- Cereal crops (wheat, maize, rice, barley, oats, rye, and sorghum) provide more food energy worldwide than any other type of crop [66]
- Globally, 66% of the residual plant biomass comes from cereal straw (stem, leaf and sheath material), with over 60% of these residues produced in low-income countries [66]
- 50% of the world’s population is dependent on cereal crops [71]

By-Product Overview: [66], [71]

- Energy via anaerobic digestion - from straw, food processing waste, and farm yard waste
- Biochar from Pyrolysis - recalcitrant source of carbon, can not only sequester carbon, but can improve water quality when applied to agricultural fields due to its high pollution absorption potential
- Paper & Pulp - bagasse, cereal straw, kenaf, cotton stalks, & rice straw are non-wood raw materials that can be used to make paper
- Mushroom growing medium - wheat straw, paddy straw, maize straw, soybean husk, sugarcane straw, bagasse, rice straw, and wheat bran help to grow temperate mushrooms
- Packing materials - milling process in cereal grain production creates by-products like bran & middlings that could be used for packaging
- Rice straw paper for food packaging - extracted fibers can be used to make paper for antibacterial food packaging
- On site composting
- Example: MTPAK Coffee make rice paper bags, paper labels, coffee bags, & custom packaging for customers [72]

Opportunities and Considerations:

- Surface mulch - adding rice straw and cereal crop residue helps preserve and maintain moisture levels (reduces crop water use by 3-11%) & low temperatures in the soil (which chili, potato, soybean, sugarcane, wheat, sunflower, and maize need to be grown)

Anaerobic Digestion Fact Sheet:

Major Facts of Anaerobic Digestion: [73], [74]

- The process through which bacteria break down organic matter—such as animal manure, wastewater biosolids, and food wastes—in the absence of oxygen
- It can reduce the bioload of the waste and simultaneously produce biogas, a mixture of methane (CH4) and carbon dioxide (CO2), which can be used as a renewable energy source
- Currently, there exist over 2000 facilities producing biogas in the United States; however, that number could climb to over 11,000 provided that proper support is afforded

  Anaerobic System Design and Technology:
    - **Feedstock Collection system**: Organic waste (e.g., food scraps, manure) is collected and sometimes pre-treated to optimize the digestion process
    - **Anaerobic Digester Designs**: Once the feedstock is collected and prepared, it is introduced to the anaerobic digester, which is sometimes referred to as an anaerobic reactor. Given the specific type of manure collection system, the digester is designed to provide the optimal conditions for converting the organic waste into biogas

By-Product Overview:

- **Biogas Utilization**: The produced biogas can be used directly for heating, upgraded to biomethane for injection into the gas grid used as vehicle fuel, or converted into electricity using a combined heat and power (CHP) unit
- **Digestate Processing**: The solid and liquid by-products (digestate) are rich in nutrients and can be used as a natural fertilizer or further processed into marketable products

Opportunities and Considerations:

- Renewable Energy and Digestate Production: Biogas can displace fossil fuels, reducing dependence on non-renewable energy sources and rich organic fertilizer that can improve soil structure and nutrient content
- Waste Reduction: Diverts organic waste from landfills, reducing leachate and methane emissions
- Capital and Operational Costs: High initial investment and maintenance costs can be barriers to adoption
- Feedstock Availability: Sufficient and consistent quantity and quality of feedstock are necessary for efficient operation

Pyrolysis Fact Sheet:

Major Facts of Pyrolysis: [75]

- Pyrolysis is a thermochemical decomposition process of organic material at elevated temperatures in the absence of oxygen
- It is an essential technology for converting various types of biomass and waste materials into valuable products such as biochar, pyrolysis oil, and syngas
  Pyrolysis System Design and Technology:
  - Feedstock Preparation: Biomass or waste materials are dried and sometimes shredded, to ensure consistent particle size and moisture content for optimal processing
  - Pyrolysis Reaction: The prepared feedstock is heated in a pyrolyzer at temperatures typically between 400°C and 800°C, leading to chemical changes that produce a mixture of solid, liquid, and gas phases

By-Product Overview:

- **Biochar (Solid)**: Carbon-rich residue with applications in agriculture as a soil amendment, and in industrial processes for carbon sequestration or as a precursor for activated carbon
- **Pyrolysis Oil (Liquid)**: Viscous liquid that can be used as a fuel (Sustainable Aviation fuel) or a chemical feedstock to produce chemicals and other materials
- **Syngas (Gas)**: A combination of hydrogen, carbon monoxide, and often some carbon dioxide and methane, which can be used for heat and electricity generation or as a chemical feedstock

Opportunities and Considerations:

- Waste Reduction: Converts various waste materials into reusable products, reducing landfilling
- Renewable Products: Provides a route for the generation of bio-based fuels and chemicals
- Carbon Sequestration: Through the production of biochar, pyrolysis can contribute to reducing atmospheric CO2 levels
- Energy Efficiency: The process can be energy self-sufficient with the energy recovery systems in place
- Technological Complexity: Requires careful control of process conditions and feedstock composition to optimize product yields and quality
- Environmental Impacts: Proper management of by-products and effluents is essential to minimize potential pollution
- Economic Viability: The feasibility often hinges on the market demand for pyrolysis products and the scale of the operation to achieve profitability

Yard Waste Fact Sheet:

Major Facts of the Yard Waste Industry: [76]

- According to the EPA, ~ 12.1% of MSW is composed of yard trimmings
- Nationally, ~63% of yard waste is composted each year or used as wood waste mulch
- In 2018, 2.6 million tons of yard trimmings were combusted
    - Represents 7.4% of all MSW combusted with energy recovery
- In 2018, landfills received ~10.5 million tons of yard trimmings
- The single largest components of MSW by weight but small by total volume [77]

By-Product Overview:

- Drop-off sites
    - Few states have implemented successful drop-off sites where you pay based on the weight of yard waste or size of truck bed
- Pick-up programs
    - Many cities off to pick up yard waste but only during the Fall season (“leaf season”)
- Most yard trimmings not sent to landfills are composted
- Only a small fraction are combusted with energy recovery
- Successful city-wide Example [78]
    - Ann Arbor, Michigan
    - Drop-off station that accepts yard waste (branches, leaves, etc) with an additional fee
    - Able to request assistance for people who need it
    - Entry fee depending on size of vehicle (car vs. large vehicle)
- Successful Statewide Example [79]
    - Massachusetts
    - Commercial yard waste locations accept drop-offs across the state - but public awareness is a challenge
    - Use of I.D. is required to confirm residence within the state
    - Only biodegradable bags can be left at the site - all else must taken back with residents

Opportunities and Considerations:

- Grasscycling and backwards composting where households leave leaves and yard trimmings on their lawns instead of removal practices

Wood and Forestry Fact Sheet:

Major Facts of the Wood and Forestry Industry: [80]

- In the United States, wood waste accounts for 17% of total waste received at MSW landfills
- ~29.6 million tons of urban wood waste is disposed of annually
    - Adds up to more than $1,124 million in annual disposal costs
- More than 1,350 acres of wood waste consume landfills each year
- World Bioenergy session in Sweden (2014) concluded the best source of unused biomass can be found in the stumps of trees

By-Product Overview:

- Landscapers interested in forestry scraps
    - Used to make particleboard and other composite products
- Woodchips, sawdust, and scraps of wood that are waste material for lumber mills are shipped to paper mills to make paper
    - Paper is the largest recycled product in the United States
- Pulp, paper mill sludge, and municipal waste - all liquids
    - Should be used for the anaerobic digestion of biogas
- Successful city-wide Example [81]
    - St. Paul, Minnesota
    - The largest district energy system in the US - utilizes urban wood waste to provide heating and cooling and electricity generation
    - Burns ~ 25,000 tons of wood waste
        - Machinery originally designed for coal burning to make steam
        - Easy conversion to utilize wood waste
    - Composition: urban tree trimmings, damaged tree removal, habitat restoration activities, and leftovers from forest management

Opportunities and Considerations:

- Organizations utilizing wood from fallen trees not sources for economic reasons
- Keeps carbon sequestered
- Financially beneficial to municipalities to not pay for disposal
- Successful Company Example [82]
    - Urban Ashes in Ann Arbor, Michigan

Restaurants Fact Sheet:

Major Facts of the Restaurant Industry:

- Food Service Industry earns ~4% of national GDP [83]
- Restaurant Industry loses ~ $162 billion annually due to food waste [23]
- 4-10% of food purchased by restaurants never gets to the customer [84]
- 30-40% of food served to customers never gets consumed [84]
- In American restaurants, 85% of food wasted is thrown in the trash [18]

By-Product Overview:

- Compost, biofuel, conversion into other food products
- Successful Restaurant Example [85]
  - Romania
  - A shopping center with multiple restaurants feeds one compost center on-site
  - Produces organic fertilizer that is used for green spaces around the shopping center
- Successful Small Business Example [86]
  - Sir Kensington’s Company
  - Takes aquafaba from hummus manufacturers in the state and produces vegan mayo
    - Aquafaba acts as an egg replacement

Opportunities and Considerations: - Food Donations:

- Donators are protected from liability of illness under the Bill Emerson Good Samaritan Food Donation Act [87]
- Potential tax benefits of donating food such as tax deductions depending on state
- Many food banks will pick up food donations
  - Limits the effort and time cost for restaurants
- Example Successful Organization [88]
  - City Harvest is located in New York, New York
  - Rescue and delivery of ~ 200,000lbs of food each day
  - In one year, City Harvest helped to avoid 26.5 kg of CO_2 from entering the atmosphere through landfills

Residential Sector Fact Sheet:

Major Facts of the Residential Sector:

- Household-level food waste accounts for ~40% of national food waste [89]
- According to the EPA, ⅓ of all food in the United States goes uneaten [24]
- ~96% of households food waste ends up in landfills, combustion facilities, or in the sewer system [24]
- The average family of four spends $1,500 on food that goes uneaten each year [24]
- Common confusion on the date label from purchased food (“best-by, sell-by, use-by”) [90]

By-Product Overview:

- Develop city or municipality-wide composting programs
- Food waste collection services
- Successful city-wide Example [91]
    - San Francisco, California
    - Highest national recycling and composting diversion rate of any major city
    - Ordinance requiring all residents to participate in a compost program
    - Collects ~650 tons of organic waste daily and converts into ~350 tons of finished compost daily
- Successful Country-Wide Example [92]
    - South Korea
    - Recycles 95% of food wasted throughout the country
    - Set economic fines if food waste is placed in trash and sent to landfills
        - Trash will not be collected if food waste is found
        - Designated food waste trash bags
    - Each household/organization/business manually separates waste (compost, MSW, recycle)
    - Important: community buy-in and behavior change
    - Liquid food waste is turned into biogas
    - Solid food waste is turned into compost or used for livestock feed

Appendix B: Case Study Calculations

Michigan Stadium Other Calculations

1. What is the amount of waste produced from a single game in a season?
    a. Purdue vs Michigan on 11/04/2023
    b. Total waste produced: 13.36 tons
        i. MSW: 3.42 tons
        ii. Recycling: 7.34 tons
        iii. Compost: 2.592 tons
        iv. Food Donation: 0.50 tons (*not included in total waste produced total)
2. What is the potential amount of waste sent to compost in a single season?
    a. ~7 home games in a season (*based on 2023 home football schedule)
    b. Assuming the same amount of waste is produced every game
    c. Total waste sent to compost in a year: **18.144 tons**
3. What are the potential emission savings in a season from composting organic waste?
    a. What were the emissions from MSW landfills in 2018 per ton?
        i. $\frac{88.6\ MMT\ CO2e\ MSW}{146.2\ x\ 10^{6}\ tons\ MSW}$ = 0.606 MT CO_2e/ton
    b. What emissions would have been emitted if ALL waste was sent to landfills?
        i. $\frac{0.606\ MT\ CO2e}{ton}$ x 13.36 tons = 8.09616 MT CO_2e
    c. What will be emitted from MSW sent to landfills?
        i. $\frac{0.606\ MT\ CO2e}{ton}$ x 3.42 tons = 2.07252 MT CO_2e
    d. What emissions are saved from waste sent to compost?
        i. $\frac{0.606\ MT\ CO2e}{ton}$ x 2.592 tons = 1.570752 MT CO_2e
    e. What potential emission can be saved from composting in one football season?
        i. 7 games x 1.570752 MT CO_2e = **10.995264 MT CO_2e**
4. Anaerobic Digester Analysis:
    a. If utilizing an anaerobic digester similar to Chomp, the amount of organic waste as input is not enough for even the mini system to function
        i. A mini Chomp AD requires 25-175 tons of organic waste input a year
        ii. The stadium would provide 18.144 tons of organic waste a football season (*one year)

5. What is the amount of waste produced from Crisler Center in one academic year?
    a. Michigan Stadium attendance of 110,254 on 11/04/2023
        i. Compost ton/person
            1. $\frac{2.592\ tons}{110{,}254\ people}$ = 2.35 x 10^{-5} tons/person
    b. Crisler Center seat capacity of 13,609
        i. Teams that compete at Crisler Center: Mens and Womens Basketball, Women's Gymnastics, Wrestling, and Volleyball
            1. Women's Basketball: 14 home games
            2. Men's Basketball: 15 home games
            3. Women's Gymnastics: 5 home meets
            4. Wrestling: 4 home meets
            5. Volleyball: 17 home games
        ii. Assume typical number of home athletic events in a single season based on 2023-2024 academic year schedules
        iii. Assume only regular season games and meets are held at Crisler Center (*no playoffs or post season games included)
        iv. Average capacity of Crisler Center
            1. No clear data on attendance of these events
                a. Assuming an average attendance of 65% capacity -> 8,846 people per game
                b. 55 University of Michigan Athletic events held in an academic year at Crisler Center
            2. $\frac{2.35\ x\ 10^{-5}\ tons}{person}$ x $\frac{8{,}846\ people}{game}$ = 0.208 tons/game
            3. $\frac{0.208\ tons}{game}$ x 55 games = **11.433 tons** of organic waste in a season
6. Combining Michigan Stadium and Crisler Center, the estimated organic waste total sent for composting for one academic year would be **29.577 tons.**

Case Study Table Calculations

1. Michigan Stadium Excel Calculations
2. SAF Excel Calculations

Appendix C: Flow Chart

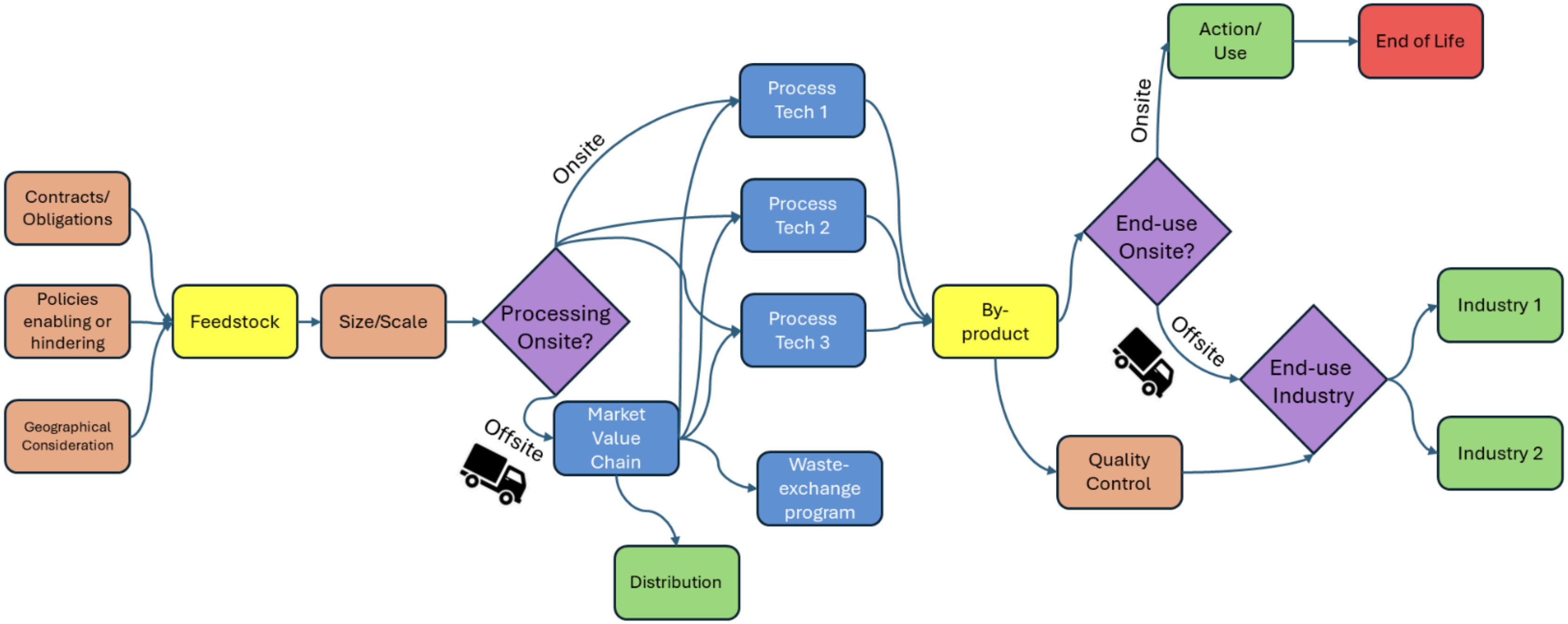

Figure 7: Flow chart of the general process and direction biomass waste flows through the system to development of a by-product. Attachment to the entire flow chart can be found using this link.