# Production of Polyhydroxyalkanoate (PHA) from Plastic Waste for use in the Production of Class I Medical Devices

## Senior Design M&T Final Report

M&T Student: Seth Thayumanavan
Teammates: Rosangelica Mancini-Lander and Richa Patel
Advisor: Professor Daeyon Lee

# Executive Summary

Plastic pollution is one of the biggest issues facing our environment today. It is estimated that between 2.4 and 10.8 billion pounds of microplastics reside in the top foot of the ocean, not to mention the additional 11 trillion pounds in landfills (as of 2015). These plastics can take anywhere from 100-450 years to degrade, so this waste will only continue to grow. Plastic littering disrupts natural marine environments and pose physical and toxicological risks to organisms living in those environments. Additionally, most plastics are produced from petroleum, a rapidly depleted, nonrenewable resource, that is expected to run out in the next few decades, possibly before 2060. However, plastic remains one of the most important materials in our day to day lives, with the average American consumer using over 270 pounds of plastic per year, and plastic production continues to accelerate, with an estimated 489 million tons of plastic produced last year. Thus, we are faced with a three-pronged challenge: 1) find a sustainable source of plastics to avoid further depleting the world's supply of petroleum, 2) reduce the amount of plastic waste in landfills, and 3) prevent further waste accumulation in landfills.

Our project seeks to solve all three of these problems at once, by producing polyhydroxyalkanoates (PHA), a class of biodegradable plastic with similar physical properties to popular synthetic plastics, from mixed plastic waste. In particular, our process generates poly-(R)-3-hydroxybutyrate (PH3B), a type of PHA which degrades completely in 1.5 to 3.5 years in marine environments (compared with roughly 500 years for polystyrene). We designed a chemical process capable of processing 11,000 tons of mixed plastic waste per year, made up of polystyrene (PS), high density polyethylene (HDPE), and Polyethylene terephthalate (PET), and producing 324.5 tons of PHA. This is roughly equivalent to the amount of plastic waste produced by the Delaware Valley annually, and the goal of our project is to create a chemical plant capable of servicing any major metropolitan area, using Philadelphia as a proof of concept.

Our technology functions by milling the waste into small particles, dissolving it in acetic acid, and reacting it to break down the plastic polymers into organic acids. The acids are then reacted with *Pseudomonas putida,* a bacterium that digests the acids and converts them to PH3B. Finally, the polymer is separated from the bacteria, purified, and formed into pellets for sale.

Our business proposal is to act as a plastic supplier to manufacturers of class I medical devices. This includes products such as disposal bandages, diapers, and menstrual pads. In the short run, we are primarily targeting the diaper market. We chose to enter this market originally for 3 reasons: 1) Low regulatory barrier to entry – since the products above are low-risk, non-invasive devices, we can sell to manufacturers without FDA approval, which is expensive and time consuming. Once we gain a foothold in the medical device market, we can pursue FDA approval and sell to a broader range of manufacturers. 2) Clear Market need - the diaper industry creates roughly 3.5 million tons of non-degradable waste per year (Kesherim, 2023). This amounts to roughly 60,000 tons of polypropylene. The menstrual pad industry contributes an additional 200,000 tons of plastic waste. 3) Less crowded market – biodegradable plastic producers are primarily targeting the food packaging industry, leaving the medical device industry more open.

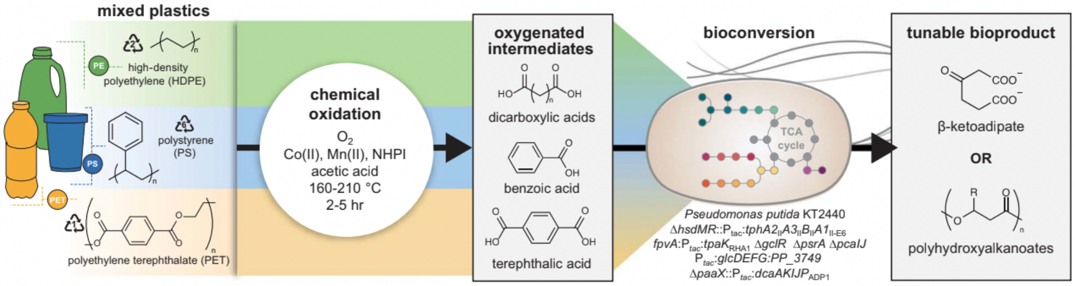


**Figure 1. Reaction overview.** Mixed plastic waste containing HDPE, PS, and PET is oxidized to form organic acids, which are fed into a bioreactor containing engineered *P. putida* cells capable of producing PH3B (The *P. putida* cells can also be engineered to produce β-ketoadipate, but we chose to produce only PH3B. (Sullivan et al., 2022)

# Process Design

Our process converts 11,000 tons of mixed plastic waste per year (1,400 kg/hr) into 324.5 tons of PH3B, via two reactions: a chemical oxidation, which breaks down the long chain plastic polymers into organic acids, and a bioreaction, in which genetically engineered *P. putida* cells digest the acids and generate PH3B (as shown in figure 1). As such, our process has two main subprocesses, centered around each reaction.

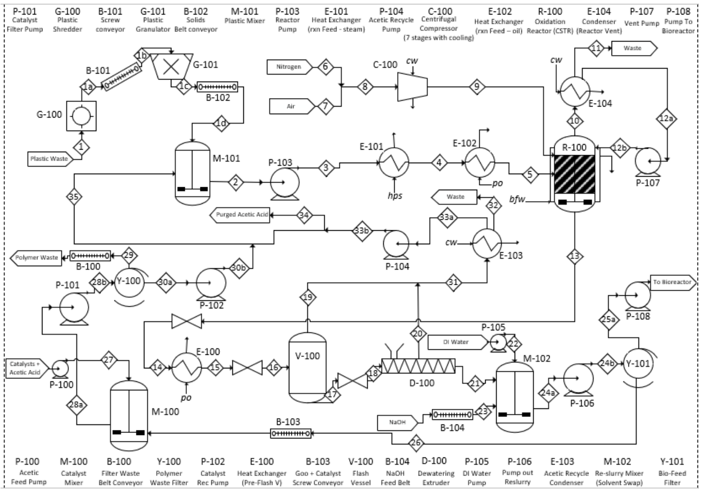


**Figure 2. Oxidation subprocess.** In the first half of the process, mixed plastic waste is crushed and milled (G-100 and G-101), dissolved in acetic acid, then reacted to form organic acids. After the reaction, the acetic acid is removed and recycled, and the acids are redissolved in highly basic water, and the catalysts and any impurities are removed. The products are then stored to be fed into the bioreaction subprocess.

Figure 2 contains a detailed description of the oxidation subprocess, including all the necessary equipment to produce the oxygenated intermediates. Figure 3 contains a simplified block flow diagram of the process, to make it easier to understand.

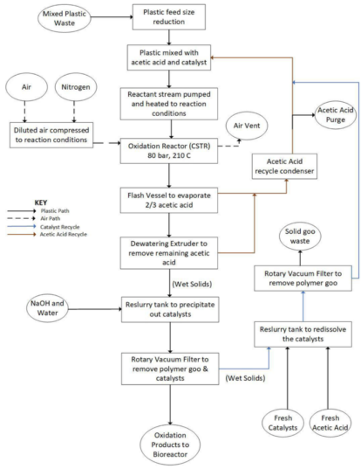


**Figure 3. Simplified diagram of oxidation subprocess**

The dissolved plastic will then be fed into a reactor operating at 210 °C and 80 bar, along with catalyst made up of cobalt, manganese, and zirconium, as well as an N-hydroxyphthalimide (NHPI) initiator. This will cause ~60% of the plastic to be converted to organic acids. After the reaction, the 97% of the acetic acid will be removed via flash distillation and a dewatering extruder, and the higher molecular weight acids will be redissolved in basic water, with a pH of 12. This will cause the catalyst and other impurities to precipitate out of the solution, and the solution will be filtered and stored for feed into the bioreaction subprocess. This process is operated continuously, with 1400 kg/hr of mixed plastic waste being fed 24 hours a day into the system, but the second subprocess can only be operated in batches every 8 hours, so storing the product is necessary. The acetic acid solvent and catalyst are recycled throughout this process. The remaining plastic forms an unknown side product under these reaction conditions. This side product is removed and disposed of safely.

The second half of the process is shown in figure 4. 12 hours' worth of oxidation product will be mixed with hydrochloric acid to restore a pH of 8, and then be placed in a bioreactor containing *P. putida*, which has been genetically engineered to produce PH3B. Genetically engineered *P. putida* will be purchased, and the process of engineering the cells to produce PH3B is beyond the scope of our project. As shown in figure 1, *P. putida* cells can also be engineered to form β-ketoadipate, a precursor to nylon, but our process will produce only PH3B, as nylon is not biodegradable, and has a much lower sales price. Over the course of 24 hours, the cells will digest the acids and produce PH3B (since each reactor holds only 12 hours of oxidation product, two bioreactors will be operating simultaneously, with a third available). After the reaction is completed, the cells will be mixed with sodium dodecyl sulfate (SDS), and the pH increased to 10, to lyse the cells and release the PH3B into solution. Then the solution will be centrifuged and filtered purified via dissolved air flotation to separate the PH3B from the cell debris. The dissolved air flotation operation uses SDS as a surfactant, and therefore does not require an additional surfactant to be fed. This achieves 99.75% purity of the final product. Finally, The PH3B, which comes out of the dissolved air flotation as a powder, will be extruded and pelletized to form a product for sale to downstream manufacturers.

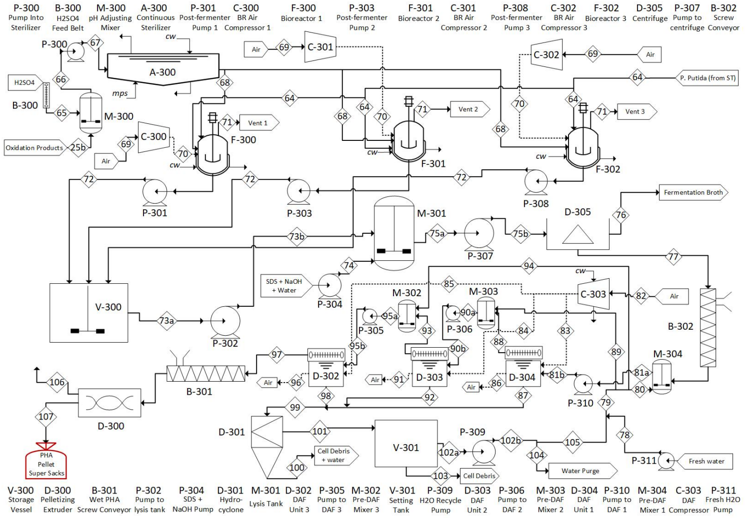


**Figure 4. Bioreaction subprocess.** In the second half of the process, organic acids are digested by *P. putida* cells to produce PH3B. The cells are then lysed to release the PH3B, and the cell debris is separated out. The PH3B is then purified and formed into pellets.

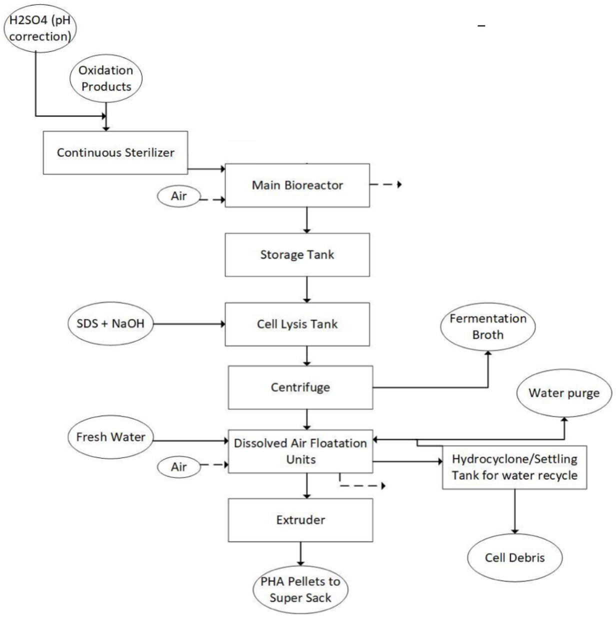


**Figure 5. Simplified block flow diagram of bioreaction subprocess.**

## Value Proposition

Our process supplies value to the world in three ways: it reduces the world's reliance on petroleum, actively eliminates pre-existing plastic waste by using it as feedstock and prevents future buildup of plastic waste by creating a rapidly degrading product. Our proposed customer segment is class I medical device manufacturers. We create value to our customers in three main ways: marketability to consumers - consumers are becoming increasingly environmentally conscious. It is estimated that 68% of American consumers are willing to pay a premium for more environmentally sustainable products. Using our product will enable consumer goods manufacturers to charge more for their products, improving their bottom line. 2) Overcoming expected regulatory changes - several countries, including Spain, Italy and the UK have implemented a plastic tax, and US federal lawmakers have recently proposed the REDUCE act, which would tax use of virgin plastic, with the tax increasing over the next three years. 3) Reduced dependence on oil - since most plastic currently on the market in sourced from petroleum, the cost of production is highly dependent on the cost of oil. In fact, 2021 was one of the only years in which aggregate plastic production declined, likely due in part to skyrocketing oil prices. By not using petroleum, our product will stabilize costs.

## Market Opportunity and Customer Segments

Our immediate target customer segment will be manufacturers in the diaper industry. Diaper manufacturers consume roughly 60,000 tons of polypropylene per year. The diaper market has three major players, Proctor & Gamble, Kimberly Clark, and Unicharm, but the market is relatively fragmented, with over 2/3 of the market share belonging to other, smaller manufacturers. However, since these three companies are all major consumer goods manufacturers, creating strategic partnerships with them could be beneficial as we scale, as it would allow us to supply plastic for a greater range of products. Additionally, this makes these companies good potential buyers if we seek to eventually be acquired.

After we can gain a foothold as a plastic supplier to the diaper industry, we plan to expand to all class I medical devices, such as disposal bandages and menstrual pads. Since none of these products require FDA approval, expanding into these markets will be achievable once we can get proof-of-concept by selling to diaper manufacturers and access to major consumer goods manufacturers. Once we have stable revenues from class I medical device manufacturers, we can use the cash flows to seek FDA approval and expand our sales to manufacturers of class II medical device manufacturers, such as syringes and tampons, and beyond.

## Total Addressable Market

As a biodegradable plastic, the PHA generated by this process has the potential to address demand in three total markets: the US market for PHA in particular, which will be considered the short term target market, the US market for all biodegradable plastics, which will be considered the serviceable market, and the US market for all plastic, including petrochemical plastic, which will be considered the total addressable market.

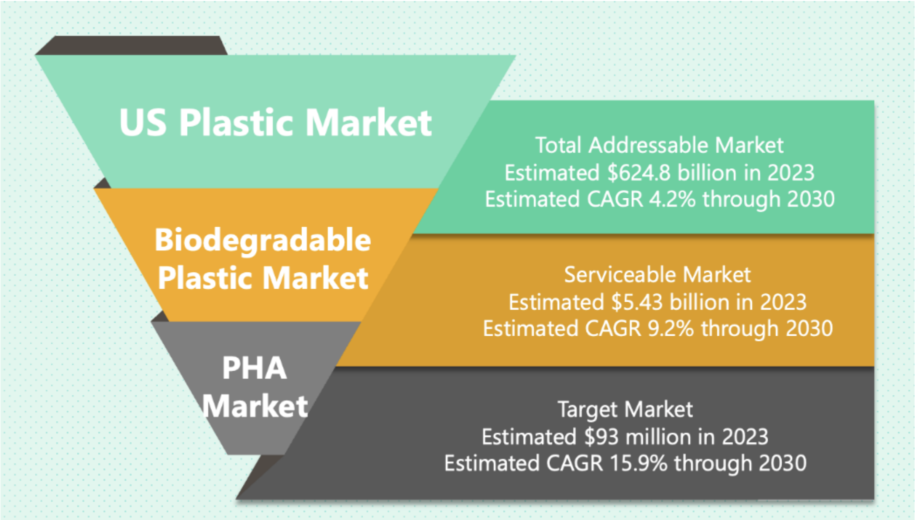


**Figure 6. Addressable Market Funnel for PHA (data from 2023)**

In 2023, the US plastic market was estimated to be $624.8 billion, with a projected CAGR of 4.2% through 2030. Most of this plastic was made up of polypropylene, polyethylene, and polyurethane, with market shares of 24%, 20%, and 17% respectively. Biodegradable plastic holds virtually no market share in the total plastic market, with all biodegradable plastic making up only 0.87% of the total plastic market. However, it is growing over twice as fast as the plastic market, with a market size of $5.43 billion in 2023 and a projected CAGR of 9.2%. Among biodegradable plastic products, the majority is starch-based plastics, with a 41% market share.

However, despite only a 1.7% market share in the biodegradable plastic market (and by extension 0.015% of the total plastic market), PHA is by far the fastest growing biodegradable plastic, with a CAGR of 15.9%. Its main uses include agriculture products, such as foil, film, and irrigation nozzles, consumer packaging, medical devices, and pharmaceutical drug encapsulation. Since our product is high purity (99.75% pure), targeting the medical device market makes the most sense, as agriculture products and consumer packaging are more crowded markets, and use lower quality PHA. We are not seeking sale in the pharmaceutical market, as it would require extensive regulatory approval. Given the high purity of our product, we may be able to enter the pharmaceutical market later down the road, as this would give us access to a customer base with a much higher willingness to pay.

In 2022, the diaper industry used approximately 60,000 tons of polypropylene. At a market price of $1326 per ton, this represents a roughly $80 million market, with a CAGR of 6.71%. The biodegradable diaper market made up less than 2.4% of the total diaper market and is growing only slightly faster than the overall diaper market, with a CAGR of 7.6%.

## Competition

*Non-degradable competitors (substitutes)*

The biggest source of competition is from incumbent plastic producers, who are making petroleum based plastic products. This mostly consists of large oil and chemical companies, such as Exxon Mobil, LG Chem, and Saudi Basic Industries Corporation. These competitors are too large and established to overcome in the short run. However, as the biodegradable plastic market increases and petroleum-based plastic becomes more costly to produce, it is possible that their market power will decrease. It is costly and high risk for these large companies to invest in R&D to develop processes for biodegradable plastic, so they may look to acquire us as our product becomes more popular.

*Biodegradable plastic manufacturers*

There are several manufacturers selling biodegradable plastics, such as Biome Bioplastics, a UK company that sells PLA, founded in 2002, and NatureWorks LLC, a Minnesota company that also sells PLA and other bioplastics, founded in 1989. The PHA market is much more fragmented, with several smaller players. PHA is a superior product to PLA, as it has a tougher filament than PLA and is substantially less brittle. It also more closely replicates the qualities of polyethylene, which makes up a large portion of the existing plastic market. The primary concern with these manufacturers is achieving lower costs, which can translate to lower prices to customers.

*Competitive advantage*

Our competitive advantage primarily relies on being able to protect the IP surrounding our process. Incumbents may be able to quickly replicate our process once we have proof of concept, with access to much greater capital. Luckily, our process can be protected by a product by process claim, which would protect our specific process design. We may appear more eco-friendly to end consumers, since we are not only preventing an increase in plastic waste by creating a biodegradable option but are actually actively reducing the amount of plastic waste already present in the world, resulting in a net negative effect.

From a cost perspective, our main source of value comes from the very low cost of our feedstock. The estimated cost for the mixed plastic waste feedstock is $0.1008 per kg. Petrochemical plastic producers must use fossil fuels as their feedstock, which are volatile in price, and are rapidly depleting as a resource, possibly running out entirely as soon as 2060. While our feedstock is more expensive in the short term, it may become cheaper due to these pressures. In addition, the feedstock is cheaper than the majority of current feedstocks used to produce PHA, which largely includes plant-based feedstocks such as vegetable oils, sugars, and starches. Ultimately, a sustainable competitive advantage will rely on two things: consumer perception of our product and achieving a lower price point than competitors. As it currently stands, our product is poised for tremendously positive consumer perception, but the cost to produce is higher than petrochemical producers.

## Revenue and Cost Model

Based on our current estimates, we believe that we will require a total permanent investment of roughly $108 million in capital expenditure to build the process. This includes purchasing land in Iowa (where our pilot plant will be launched), and the cost of materials to build the unit operations that make up our process. Beyond that, we expect to incur electricity costs to operate our pumps, compressors, centrifuges and reactors, as well as costs of steam and cooling water to adjust the temperature of our streams. These costs will total $5.23 per pound PHA produced, or $3.39 million annually.

In addition, we expect to incur raw material expenses associated with purchasing compressed nitrogen, bacterial stock solution, bacterial media, SDS, and sodium hydroxide and hydrochloric acid (for pH balance), as well as cleaning solution for our bioreactors, as well as our plastic waste feed, all of which are consumed during the process. We will also lose a small amount of acetic acid and catalyst each time we recycle it, due to imperfect separation, and loss during the reaction, where the catalysts may react to form side products. These costs total $26.275 per lb of PHA, or $17M annually. In addition, we expect to incur a royalty equal to 1% of sales, to the scientists who developed the genetically engineered bacteria, as well as a $409K expense to dispose of waste annually. We expect the plant will require $8.6M annually in wages, and $760K in SG&A. This brings our annual costs to roughly $31M.

Since we plan to sell our product wholesale to manufacturers, our revenue will simply be based on our annual production and market prices. The market price of polylactic acid, another biodegradable plastic, is $12 per lb, so we originally assumed this as a benchmark price for our product. Unfortunately, this would result in a steeply negative income, as our variable costs alone are over $30 per lb. This would result in a net income of -$33.9M in the first year, and a 15-year NPV of -$178.2M, assuming a 15% cost of capital.

However, the sales price of PHA ranges significantly, going from anywhere between $10 per pound for agriculture products to $43,500/lb for medical grade PHA. Naturally, we cannot sell our product for such high prices if we do not plan to enter the pharmaceutical industry, but given the high purity of our product, we can expect to achieve a higher price point than the lower quality PHA used for agricultural products. The break-even cost for our plant in the first year is $140.65 per lb of PHA, which may be unrealistically high. To achieve a $0 15-year NPV, our sales price would need to be $98.68 per lb. Clearly, alternative measures are needed to find a path to profitability.

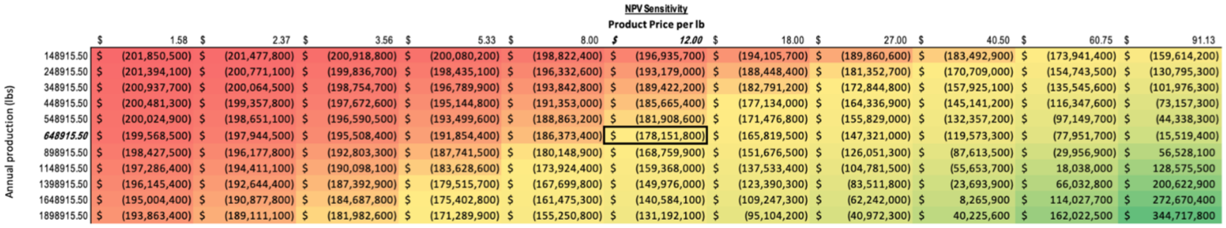
## Path to Profitability

Unfortunately, the fundamental issue with our business, as it currently stands, is the unit economics. Variable costs associated with producing our product makes up 2/3 of the total cost of operating the plant, suggesting that simply growing our plant will not achieve profitability. There are four key levers that can be used to drive down unit costs in the long run – achieving higher conversion of oxygenated intermediates, increasing selling price, reducing recycle loss of catalysts and acetic acid, and achieving a lower price point for raw materials.

As it currently stands, the most inefficient part of the process is the bioreaction. Currently, we assume that 0.058 grams of PHA are produced per gram of oxygenated monomer fed – a roughly 6% conversion. This is uncommonly low, and by optimizing our bioreactor, we may be able to significantly improve output. This would have a negligible effect on variable costs, as the majority of costs depend on the magnitude of our feedstock, not our output. It was found that a positive NPV could be achieved if the sales price is increased to $40.50/lb, and production is increased to 1.65M lbs, or a conversion of 0.15 g PHA/g oxygenated monomer is achieved. This would achieve a 15-year NPV of $8.3M. This seems to be a more realistic price point than $98.68/lb (as discussed previously), and this conversion is achievable by improving the bioreactor conditions. However, making this improvement would require extensive scientific research.

Our acetic acid and catalyst costs currently make up roughly half of our raw materials cost. It will be impossible to eliminate loss of catalysts and solvent, but reducing loss could improve cost structure significantly. Finally, it may be possible to reduce prices of raw materials via negotiations with suppliers. Apart from our catalyst and acetic acid costs, our greatest cost is the cost of our bacterial media, which costs $9 per lb of PHA produced, despite costing half a cent per liter of media, as so much of it is used. We chose to run sensitivity analysis on the cost of media to see how it affected our cost structure (shown in figures 7 and 8).

Right now, plastic waste is an urgent challenge that needs to be faced before we irreparably damage our world, making our technology both timely and impactful. We believe that by optimizing our reaction through further research to achieve higher production, achieving a higher selling price, and reducing our recycling capacity, we can find a path to profitability. Furthermore, we believe regulatory changes and changing consumer perception will push further demand for our product, making growth a viable strategy despite a small current target market. The potential of our product to reduce current landfill waste and prevent further accumulation of waste, all without a reliance on petroleum, should not be ignored, and we believe that this technology has the potential to create long-term positive change in both plastic production and plastic waste management.

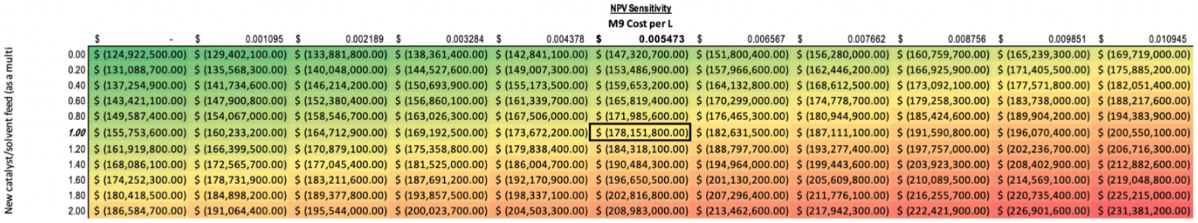


NPV Sensitivity

Product Price per lb

| Annual production (lbs) | $ 1.58 | $ 2.37 | $ 3.56 | $ 5.33 | $ 8.00 | *$ 12.00* | $ 18.00 | $ 27.00 | $ 40.50 | $ 60.75 | $ 91.13 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 148915.50 | $ (201,850,500) | $ (201,477,800) | $ (200,918,800) | $ (200,080,200) | $ (198,822,400) | $ (196,935,700) | $ (194,105,700) | $ (189,860,600) | $ (183,492,900) | $ (173,941,400) | $ (159,614,200) |
| 248915.50 | $ (201,394,100) | $ (200,771,100) | $ (199,836,700) | $ (198,435,100) | $ (196,332,600) | $ (193,179,000) | $ (188,448,400) | $ (181,352,700) | $ (170,709,000) | $ (154,743,500) | $ (130,795,300) |
| 348915.50 | $ (200,937,700) | $ (200,064,500) | $ (198,754,700) | $ (196,789,900) | $ (193,842,800) | $ (189,422,200) | $ (182,791,200) | $ (172,844,800) | $ (157,925,100) | $ (135,545,600) | $ (101,976,300) |
| 448915.50 | $ (200,481,300) | $ (199,357,800) | $ (197,672,600) | $ (195,144,800) | $ (191,353,000) | $ (185,665,400) | $ (177,134,000) | $ (164,336,900) | $ (145,141,200) | $ (116,347,600) | $ (73,157,300) |
| 548915.50 | $ (200,024,900) | $ (198,651,100) | $ (196,590,500) | $ (193,499,600) | $ (188,863,200) | $ (181,908,600) | $ (171,476,800) | $ (155,829,000) | $ (132,357,200) | $ (97,149,700) | $ (44,338,300) |
| *648915.50* | $ (199,568,500) | $ (197,944,500) | $ (195,508,400) | $ (191,854,400) | $ (186,373,400) | $ (178,151,800) | $ (165,819,500) | $ (147,321,000) | $ (119,573,300) | $ (77,951,700) | $ (15,519,400) |
| 898915.50 | $ (198,427,500) | $ (196,177,800) | $ (192,803,300) | $ (187,741,500) | $ (180,148,900) | $ (168,759,900) | $ (151,676,500) | $ (126,051,300) | $ (87,613,500) | $ (29,956,900) | $ 56,528,100 |
| 1148915.50 | $ (197,286,400) | $ (194,411,100) | $ (190,098,100) | $ (183,628,600) | $ (173,924,400) | $ (159,368,000) | $ (137,533,400) | $ (104,781,500) | $ (55,653,700) | $ 18,038,000 | $ 128,575,500 |
| 1398915.50 | $ (196,145,400) | $ (192,644,400) | $ (187,392,900) | $ (179,515,700) | $ (167,699,800) | $ (149,976,000) | $ (123,390,300) | $ (83,511,800) | $ (23,693,900) | $ 66,032,800 | $ 200,622,900 |
| 1648915.50 | $ (195,004,400) | $ (190,877,800) | $ (184,687,800) | $ (175,402,800) | $ (161,475,300) | $ (140,584,100) | $ (109,247,300) | $ (62,242,000) | $ 8,265,900 | $ 114,027,700 | $ 272,670,400 |
| 1898915.50 | $ (193,863,400) | $ (189,111,100) | $ (181,982,600) | $ (171,289,900) | $ (155,250,800) | $ (131,192,100) | $ (95,104,200) | $ (40,972,300) | $ 40,225,600 | $ 162,022,500 | $ 344,717,800 |

**Figure 7.** Sensitivity Analysis of NPV to Product Price and Production Volume

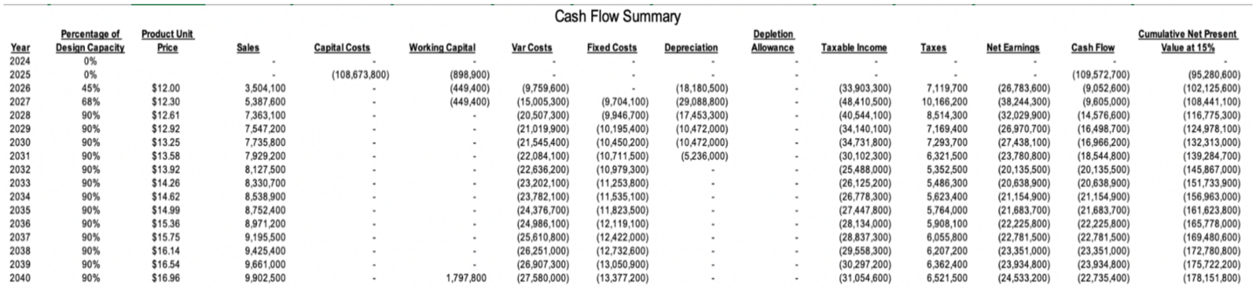


NPV Sensitivity

M9 Cost per L

| New catalyst/solvent feed (as a multi | $ - | $ 0.001095 | $ 0.002189 | $ 0.003284 | $ 0.004378 | **$ 0.005473** | $ 0.006567 | $ 0.007662 | $ 0.008756 | $ 0.009851 | $ 0.010945 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.00 | $ (124,922,500.00) | $ (129,402,100.00) | $ (133,881,800.00) | $ (138,361,400.00) | $ (142,841,100.00) | $ (147,320,700.00) | $ (151,800,400.00) | $ (156,280,000.00) | $ (160,759,700.00) | $ (165,239,300.00) | $ (169,719,000.00) |
| 0.20 | $ (131,088,700.00) | $ (135,568,300.00) | $ (140,048,000.00) | $ (144,527,600.00) | $ (149,007,300.00) | $ (153,486,900.00) | $ (157,966,600.00) | $ (162,446,200.00) | $ (166,925,900.00) | $ (171,405,500.00) | $ (175,885,200.00) |
| 0.40 | $ (137,254,900.00) | $ (141,734,600.00) | $ (146,214,200.00) | $ (150,693,900.00) | $ (155,173,500.00) | $ (159,653,200.00) | $ (164,132,800.00) | $ (168,612,500.00) | $ (173,092,100.00) | $ (177,571,800.00) | $ (182,051,400.00) |
| 0.60 | $ (143,421,100.00) | $ (147,900,800.00) | $ (152,380,400.00) | $ (156,860,100.00) | $ (161,339,700.00) | $ (165,819,400.00) | $ (170,299,000.00) | $ (174,778,700.00) | $ (179,258,300.00) | $ (183,738,000.00) | $ (188,217,600.00) |
| 0.80 | $ (149,587,400.00) | $ (154,067,000.00) | $ (158,546,700.00) | $ (163,026,300.00) | $ (167,506,000.00) | $ (171,985,600.00) | $ (176,465,300.00) | $ (180,944,900.00) | $ (185,424,600.00) | $ (189,904,200.00) | $ (194,383,900.00) |
| *1.00* | $ (155,753,600.00) | $ (160,233,200.00) | $ (164,712,900.00) | $ (169,192,500.00) | $ (173,672,200.00) | $ (178,151,800.00) | $ (182,631,500.00) | $ (187,111,100.00) | $ (191,590,800.00) | $ (196,070,400.00) | $ (200,550,100.00) |
| 1.20 | $ (161,919,800.00) | $ (166,399,500.00) | $ (170,879,100.00) | $ (175,358,800.00) | $ (179,838,400.00) | $ (184,318,100.00) | $ (188,797,700.00) | $ (193,277,400.00) | $ (197,757,000.00) | $ (202,236,700.00) | $ (206,716,300.00) |
| 1.40 | $ (168,086,100.00) | $ (172,565,700.00) | $ (177,045,400.00) | $ (181,525,000.00) | $ (186,004,700.00) | $ (190,484,300.00) | $ (194,964,000.00) | $ (199,443,600.00) | $ (203,923,300.00) | $ (208,402,900.00) | $ (212,882,600.00) |
| 1.60 | $ (174,252,300.00) | $ (178,731,900.00) | $ (183,211,600.00) | $ (187,691,200.00) | $ (192,170,900.00) | $ (196,650,500.00) | $ (201,130,200.00) | $ (205,609,800.00) | $ (210,089,500.00) | $ (214,569,100.00) | $ (219,048,800.00) |
| 1.80 | $ (180,418,500.00) | $ (184,898,200.00) | $ (189,377,800.00) | $ (193,857,500.00) | $ (198,337,100.00) | $ (202,816,800.00) | $ (207,296,400.00) | $ (211,776,100.00) | $ (216,255,700.00) | $ (220,735,400.00) | $ (225,215,000.00) |
| 2.00 | $ (186,584,700.00) | $ (191,064,400.00) | $ (195,544,000.00) | $ (200,023,700.00) | $ (204,503,300.00) | $ (208,983,000.00) | $ (213,462,600.00) | $ (217,942,300.00) | $ (222,421,900.00) | $ (226,901,600.00) | $ (231,381,200.00) |

**Figure 8.** Sensitivity Analysis of NPV to M9 media price and new catalyst/acetic acid feed required.



Cash Flow Summary

| Year | Percentage of Design Capacity | Product Unit Price | Sales | Capital Costs | Working Capital | Var Costs | Fixed Costs | Depreciation | Depletion Allowance | Taxable Income | Taxes | Net Earnings | Cash Flow | Cumulative Net Present Value at 15% |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2024 | 0% | | - | - | - | - | - | - | - | - | - | - | - | - |
| 2025 | 0% | | - | (108,673,800) | (898,900) | - | - | - | - | - | - | - | (109,572,700) | (95,280,600) |
| 2026 | 45% | $12.00 | 3,504,100 | - | (449,400) | (9,759,600) | - | (18,180,500) | - | (33,903,300) | 7,119,700 | (26,783,600) | (9,052,600) | (102,125,600) |
| 2027 | 68% | $12.30 | 5,387,600 | - | (449,400) | (15,005,300) | (9,704,100) | (29,088,800) | - | (48,410,500) | 10,166,200 | (38,244,300) | (9,605,000) | (108,441,100) |
| 2028 | 90% | $12.61 | 7,363,100 | - | - | (20,507,300) | (9,946,700) | (17,453,300) | - | (40,544,100) | 8,514,300 | (32,029,900) | (14,576,600) | (116,775,300) |
| 2029 | 90% | $12.92 | 7,547,200 | - | - | (21,019,900) | (10,195,400) | (10,472,000) | - | (34,140,100) | 7,169,400 | (26,970,700) | (16,498,700) | (124,978,100) |
| 2030 | 90% | $13.25 | 7,735,800 | - | - | (21,545,400) | (10,450,200) | (10,472,000) | - | (34,731,800) | 7,293,700 | (27,438,100) | (16,966,200) | (132,313,000) |
| 2031 | 90% | $13.58 | 7,929,200 | - | - | (22,084,100) | (10,711,500) | (5,236,000) | - | (30,102,300) | 6,321,500 | (23,780,800) | (18,544,800) | (139,284,700) |
| 2032 | 90% | $13.92 | 8,127,500 | - | - | (22,636,200) | (10,979,300) | - | - | (25,488,000) | 5,352,500 | (20,135,500) | (20,135,500) | (145,867,000) |
| 2033 | 90% | $14.26 | 8,330,700 | - | - | (23,202,100) | (11,253,800) | - | - | (26,125,200) | 5,486,300 | (20,638,900) | (20,638,900) | (151,733,900) |
| 2034 | 90% | $14.62 | 8,538,900 | - | - | (23,782,100) | (11,535,100) | - | - | (26,778,300) | 5,623,400 | (21,154,900) | (21,154,900) | (156,963,000) |
| 2035 | 90% | $14.99 | 8,752,400 | - | - | (24,376,700) | (11,823,500) | - | - | (27,447,800) | 5,764,000 | (21,683,700) | (21,683,700) | (161,623,800) |
| 2036 | 90% | $15.36 | 8,971,200 | - | - | (24,986,100) | (12,119,100) | - | - | (28,134,000) | 5,908,100 | (22,225,800) | (22,225,800) | (165,778,000) |
| 2037 | 90% | $15.75 | 9,195,500 | - | - | (25,610,800) | (12,422,000) | - | - | (28,837,300) | 6,055,800 | (22,781,500) | (22,781,500) | (169,480,600) |
| 2038 | 90% | $16.14 | 9,425,400 | - | - | (26,251,000) | (12,732,600) | - | - | (29,558,300) | 6,207,200 | (23,351,000) | (23,351,000) | (172,780,800) |
| 2039 | 90% | $16.54 | 9,661,000 | - | - | (26,907,300) | (13,050,900) | - | - | (30,297,200) | 6,362,400 | (23,934,800) | (23,934,800) | (175,722,200) |
| 2040 | 90% | $16.96 | 9,902,500 | - | 1,797,800 | (27,580,000) | (13,377,200) | - | - | (31,054,600) | 6,521,500 | (24,533,200) | (22,735,400) | (178,151,800) |

**Figure 9.** Cash flow summary

# References

Alfa Laval. (2024). Alfa Laval ALDEC range of decanter centrifuges. https://www.alfalaval.com/globalassets/documents/products/separation/centrifugal-separa tors/decanters/alfa-laval-aldec-decanter-product-leaflet.pdf

Alfonso, E. E., & Castro-Mayorga, J. (2020). Evaluation of different methods of extracting polyhydroxyoctanoate (PHO) produced from Pseudomonas putida KT2440. Universidad de los Andes. https://repositorio.uniandes.edu.co/server/api/core/bitstreams/7ce70ce5-a695-4508-b666-dcfa027a3b49/content

Andriz Engineering. (2021). HIGH-CAPACITY VACUUM FILTRATION. https://www.andritz.com/resource/blob/13392/cf688eac900250897d0062f4b9df0407/se-y u-drum-filter-data.pdf

Beckham, G., Ellis, L. D., Sullivan, K. P., & Werner, A. J. Z. (2024). Upcycling mixed plastic waste through chemical depolymerization and biological funneling (U.S. Patent No. US20240018555A1). U.S. Patent and Trade-mark Office. https://patents.google.com/patent/US20240018555A1/en?oq=US20240018555

Bhattacharyya, A., Ellyn, G., & Walenga, J. T. (2015). Process for producing terephthalic acid (U.S. Patent No. US8933266B2). U.S. Patent and Trade-mark Office. https://patents.google.com/patent/US8933266B2/en?oq=US8933266B2

Brooks, M. C. et. al. (1999) Process for recovering polyhydroxyalkanoates using air classification. (E. P. Patent No. EP0763125B1). European Patent Office. https://patents.google.com/patent/EP0763125B1/en?oq=EP0763125B1

Burek, S. (2010, October). *When Will Fossil Fuels Finally Run Out and What Is the Technical Potential for Renewable Energy Resources?* EBSCO Information Services,. Retrieved April 22, 2024, from http://web.p.ebscohost.com/abstract?direct=true&profile=ehost&scope=site&authtype=cr awler&%20jrnl=13637681&AN=55830446&h=XyIj1Ug4zntvhfsys6fOg9iN%2fAk1atm 7xjAp6lXqxd%20yHdsw9t4fbZ%2bGEW%2bGAPE0cu8q9XeGHNyDCFz3IqHgqsA% 3d%3d&crl=c&resu%20ltNs=AdminWebAuth&re

Business AnalytIQ. (2024). *Acetic Acid price index - businessanalytiq*. BusinessAnalytiq. Retrieved April, 2024, from https://businessanalytiq.com/procurementanalytics/index/acetic-acid-price-index/ Business AnalytIQ. (2024). *Ammonium chloride price index - businessanalytiq*.

BusinessAnalytiq. Retrieved April, 2024, from https://businessanalytiq.com/procurementanalytics/index/ammonium-chloride-price-inde x/

Creative Mechanisms Staff. (2017, January 22). Everything You Need to Know About PHA. Creative Mechanisms. Retrieved February 8, 2023, from https://www.creativemechanisms.com/blog/everything-you-need-to-know-about-phapoly hydroxyalkanoates

CarlRoth. (2024). *Manganese(II) acetate tetrahydrate*. Carl Roth. Retrieved April, 2024, from https://www.carlroth.com/com/en/a-to-z/manganese%28ii%29-acetate-tetrahydrate/p/027 7.7

Carolina. (2024). *Pseudomonas Bacteria Cultures*. Carolina. Retrieved April, 2024, from https://www.carolina.com/bacteria/pseudomonas-aeruginosa-microkwik-culture-vial/155250A.pr?catId=&mCat=&sCat=

Demirci, A., & Ngadi, M. O. (Eds.). (2012). *Microbial Decontamination in the Food Industry: Novel Methods and Applications*. Elsevier Science.

EPA. (2016, February 21). *Resource Conservation | State Recycling Tax Incentives | US EPA*. EPA Archive. Retrieved April 22, 2024, from https://archive.epa.gov/wastes/conserve/tools/rmd/web/html/rec-tax.html

Evoqua. (2024). Dissolved Air Flotation (DAF) Systems. Evoqua Water Technologies. Retrieved April 22, 2024, from https://evoqua.com/en/evoqua/products--services/clarifiers--separators/dissolved-air-flotation-daf-systems/
Evoqua Water Technologies. (2022). VAFTM Hydrocyclone separators VHS series. https://www.evoqua.com/siteassets/documents/products/filtration/vaf-hydrocyclone-separator-ds.pdf
Fadzil, N. H., Rahim, M. H., & Maniam, G. P. (2014). A brief review of para-xylene oxidation to terephthalic acid as a model of primary C–H bond activation. Chinese Journal of Catalysts, 35(10), 1641-1652. https://www.sciencedirect.com/science/article/pii/S1872206714601935#cesec40

Garcia-Ochoa, F., Gomez, E., Santos, V. E., & Merchuk, J. C. (2010, May 15). Oxygen uptake rate in microbial processes: An overview. *Biochemical Engineering Journal*, *49*(3), 289-307. https://www.sciencedirect.com/science/article/abs/pii/S1369703X10000380

*Biodegradable Plastic Market Size, Share & Trends Analysis Report By Product (Starch Blends, Polylactic Acid, Poly(butylene adipate-co-terephthalate), PBS, PHA), By Application, By Re*. Wikipedia. Retrieved April 22, 2024, from https://www.grandviewresearch.com/industry-analysis/biodegradable-plastics-market?utm_source=google&utm_medium=paid_ad&utm_campaign=cmfe_latest&utm_term=biodegradable_plastic_market&gad_source=1&gclid=CjwKCAjwrIixBhBbEiwACEqDJcKCZacUxp9HZBe_t9KhfSSFCyqkJ6o

Grand View Research. (2023). *Plastic Market Size, Share, Trends & Growth Report, 2030*. Grand View Research. Retrieved April 22, 2024, from https://www.grandviewresearch.com/industry-analysis/global-plastics-market

Haihang Industry. (2024). *N-Hydroxyphthalimide*. Haihang Industry - Top chemical manufacturer & exporter. Retrieved April, 2024, from https://haihangchem.com/

Inframat Advanced Materials. (2024). *Cobalt Acetate Powder*. Infrastructure Nanomaterials. Retrieved April, 2024, from http://www.inframat.com/products/27C-AC-01.htm

Ishii, Y., & Sakaguchi, S. (2006). Recent progress in aerobic oxidation of hydrocarbons by N-hydroxyimides. Catalysis Toda, 117, 105-113. https://www.sciencedirect.com/science/article/pii/S092058610600246X

Jiang, Y., Mikova, G., Kleerebezem, R., van der Wielen, L. A., & Cuellar, M. C. (2015). Feasibility study of an alkaline-based chemical treatment for the purification of polyhydroxybutyrate produced by a mixed enriched culture. AMB Expres, 24(5). https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4305094/

Jiangsu Coroge Health Technology Co., Ltd. (2024). *Industrial Salt Prices*. Material Offers. Retrieved April, 2024, from https://www.materialoffers.com/supplier/jsklj

Kolata, G. (1999, March 24). A Study Finds Link Between Birth Defects And Solvents (Published 1999). *The New York Times*. https://www.nytimes.com/1999/03/24/us/a-study-finds-link-between-birth-defects-and-solvents.html

Kruẅger, G. (2023, October 11). How to Get FDA Approval for Medical Devices | Perforce. *Perforce Software*. https://www.perforce.com/blog/alm/how-get-fda-approval-medical-devices

Lakshman, K., & Ramachandriah Shamala, T. (2006, November 3). Extraction of polyhydroxyalkanoate from Sinorhizobium meliloti cells using Microbispora sp. culture and its enzymes. Enzyme and Microbial Technology, 39(7), 1471-1475. https://www.sciencedirect.com/science/article/pii/S0141022906001785

Levin, D. B. & Sharma, P. (2013). Microbial Production of polyhydroxyalkanoate. (U.S. Patent No. US20130288323A1). U.S. Patent and Trade-mark Office. https://patents.google.com/patent/US20130288323A1/en?oq=US20130288323A1

DS_3037012_US_EN.pdf
Ma'arif, S. (2019, March). Schematic diagram of the dewatering machine | Download Scientific

Diagram. ResearchGate. Retrieved April 22, 2024, from https://www.researchgate.net/figure/Schematic-diagram-of-the-dewatering-machine_fig2 _331970407

McCabe, M. (2023, September 20). Whitehouse, Doggett Reintroduce Bicameral Bill Act to Tackle Plastic Pollution Crisis and Hold Polluters Accountable. *Senator Sheldon Whitehouse*. https://www.whitehouse.senate.gov/news/release/whitehouse-doggett-reintroduce-bicame ral-bill-act-to-tackle-plastic-pollution-crisis-and-hold-polluters-accountable/

Milbrandt, A., Coney, K., Badgett, A., & Beckham, G. T. (2023). Quantification and evaluation of plastic waste in the United States. https://www.osti.gov/servlets/purl/1866379

Mordor Intelligence. (2023). *Polyhydroxyalkanoate (PHA) Companies - Top Company List*. Mordor Intelligence. Retrieved April 22, 2024, from https://www.mordorintelligence.com/industry-reports/polyhydroxyalkanoate-market/com panies

(n.d.). Cole-Parmer US, an Antylia Scientific company - Lab equipment and supplies for life sciences. Retrieved April 22, 2024, from https://www.coleparmer.com/

NIST Standard Reference Database Number 69. (2023). In *NIST Chemistry WebBook*. DOI: https://doi.org/10.18434/T4D303. https://webbook.nist.gov/chemistry/

NMEICT-MHRD (Govt. of India) Project on - Creation of e-Contents on Fermentation Technology [Image provided by Dr. J. Cohen]

O'Connor, K., Kenny, S., & Nikodinovic, J. (2009). Method for producing polyhydroxyalkanoate. (W.O. Patent No. WO2009124918A2). World Intellectual Property Organization. https://patents.google.com/patent/WO2009124918A2/en?oq=WO2009124918A2

O'Neill, A. (2024, February 7). *Monthly prices for sugar in the United States, Europe and worldwide from January 2014 to January 2024*. Statista. Retrieved April 18, 2024, from https://www.statista.com/statistics/673460/monthly-prices-for-sugar-in-the-united-states-e urope-and-worldwide/

Pagliano, G., Galletti, P., Samorì, C., Zaghini, A., & Torri, C. (2021, February 10). Recovery of Polyhydroxyalkanoates From Single and Mixed Microbial Cultures: A Review. *Frontiers in Bioengineering and Biotechnology*, *9*. https://doi.org/10.3389/fbioe.2021.624021

Partenheimer, W. (2005). Transformation of polymers to useful chemicals oxidation

(U.S. Patent No. US6958373B2). U.S. Patent and Trade-mark Office. https://patents.google.com/patent/US6958373B2/en?oq=US6958373B2
*Pearson - General Chemistry - Bond Energy Table*. (2024). Pearson. Retrieved April, 2024, from https://www.pearson.com/channels/general-chemistry/asset/c1dbda42/a-in-polyvinyl-chloride-shown-in-table-12-6-which-bonds-have-the-lowest-average-
Peltekis, K., Kumble, B., & Astill, C. (2018). Plant and process for pyrolysis of mixed plastic waste. (W.O. Patent No. WO2018000050A1). World Intellectual Property Organization. https://patents.google.com/patent/WO2018000050A1/en?oq=WO2018000050A1

*PLA*. (2014, December 13). MonoFilament DIRECT. Retrieved April 22, 2024, from https://www.monofilamentdirect.com/shop/pla/pla/

*Plastic Market Size, Share, Trends & Growth Report, 2030*. (n.d.). Grand View Research. Retrieved April 22, 2024, from https://www.grandviewresearch.com/industry-analysis/global-plastics-market

*Poly(3-hydroxybutyric acid) natural origin, average Mn ~500,000*. (n.d.). Sigma-Aldrich. Retrieved April 22, 2024, from https://www.sigmaaldrich.com/US/en/product/aldrich/915092

Rajaram, B., Onepe, M., & Ulrich, M. (2022, May 23). Material Analysis for Bioplastics Quality Assurance and Degradation. TA Instruments. Retrieved March 14, 2023, from https://www.tainstruments.com/material-analysis-for-bioplastics-quality-assurance-and-d egradation/

Rinde, M. (2022, July 12). *Philadelphia says it's no longer mixing recycling and trash, but residents have doubts about the process*. Billy Penn. Retrieved August 19, 2023, from https://billypenn.com/2022/07/12/philadelphia-recycling-trash-pickup-diversion-rates-sur vey/

Ritchie, H., Samborska, V., & Roser, M. (2023, November 10). *Plastic Pollution*. Our World in Data. Retrieved April 22, 2024, from https://ourworldindata.org/plastic-pollution?insight=only-a-small-share-of-plastic-gets-re cycled#key-insights

Sankhyan, S., Możejko-Ciesielska, J., & Ray, S. (2023, Nov 11). Recent Challenges and Trends

of Polyhydroxyalkanoate Production by Extremophilic Bacteria Using Renewable Feedstocks. Polymers (Basel), 15(22), 4385.
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC10674690/#:~:text=Few%20studies%20 have%20shown%20PHA,various%20industries%20(Table%201)

*Secondary Materials Pricing (SMP)*. (2024). RecyclingMarkets.net. Retrieved 2024, from https://recyclingmarkets.net/secondarymaterials/index.html

Seider, W. D., Lewin, D. R., Seader, J. D., Widagdo, S., Gani, R., & Ng, K. M. (2017). *Product and Process Design Principles: Synthesis, Analysis, and Evaluation*. John Wiley & Sons Incorporated.

Shouguang Bangze Chemical Co.,Ltd. (2024). *Sodium dodecyl sulfate price*. Shouguang Bangze Chemical Co.,Ltd. -- Industrial salts. Retrieved April, 2024, from http://www.sgbzchem.com/about_e/id/1.html

Sikkema, W. D., Cal, A. J., Hathwaik, U. I., Orts, W. J., & Lee, C. C. (2023, July). Polyhydroxyalkanoate production in Pseudomonas putida from alkanoic acids of varying lengths. *PLoS One*, *18*(7). https://www.ncbi.nlm.nih.gov/pmc/articles/PMC10358918/

Statista. (2023, November 10). *Zirconium import price U.S. 2022*. Statista. Retrieved April 18, 2024, from https://www.statista.com/statistics/1318970/average-price-of-zirconium/

Statista. (2024, February 6). *Salt prices U.S. by type 2023*. Statista. Retrieved April 18, 2024, from https://www.statista.com/statistics/916733/us-salt-prices-by-type/

Sullivan, K. P., Werner, A. Z., Ramirez, K. R., & Ellis, L. D. (2022, October 14). Mixed plastics waste valorization through tandem chemical oxidation and biological funneling. Science, 378, 207-211. 10.1126/science.abo4626 (a)

Sullivan, K. P., Werner, A. Z., Ramirez, K. R., & Ellis, L. D. (2022, October 14). Supplementary Materials for Mixed plastics waste valorization through tandem chemical oxidation and biological funneling. Science, 378, 207-211. 10.1126/science.abo4626 (b)

Surendran, A., Lakshmanan, M., Chee, J. Y., Thuoc, D. V., & Sudesh, K. (2020, March 17). Can Polyhydroxyalkanoates Be Produced Efficiently From Waste Plant and Animal Oils? Frontiers in Bioengineering and Biotechnology, 8. *https://www.creativemechanisms.com/blog/everything-you-needto-know-about-pha-polyhydroxyalkanoates*

TriStar. (2024). Rotary Vacuum Drum Filters from TriStar Ltd. TriStar LTD. Retrieved April 22, 2024, from https://www.tristarltd.com/rotary-vacuum-drum-filters-from-tristar-ltd..html Tullo, A. H. (2019, September 8). PHA: A biopolymer whose time has finally come. *C&EN*. https://cen.acs.org/business/biobased-chemicals/PHA-biopolymer-whose-time-fin ally/97/i35

van Hee, P., Elumbaring,, A. C. M. R., van der Lans, R. G.J.M., & Van der Wielen, L. A.M. (2006). Selective recovery of polyhydroxyalkanoate inclusion bodies from fermentation broth by dissolved-air flotation. Journal of Colloid and Interface Science, 297, 595–606. Science Direct. doi:10.1016/j.jcis.2005.11.019

Dunn, R. & Vrana, B. (2024). Equipment Costing Spreadsheet v7. [Correlations from Seider et. al., 2017].

Wang, Y., Horlamus, F., Henkel, M., Kovacic, F., Schläfle, S., Hausmann, R., Wittgens, A., & Rosenau, F. (2019, January). Growth of engineered Pseudomonas putida KT2440 on glucose, xylose, and arabinose: Hemicellulose hydrolysates and their major sugars as sustainable carbon sources. *Global Change Biology Bioenergy*, *11*(1), 249-259. https://onlinelibrary.wiley.com/doi/full/10.1111/gcbb.12590

Welding Engineers LTD. (2024). Dewatering extruder: SDU; Drying extruder: VCU; Turbulator. Welding Engineers Ltd. Retrieved April 22, 2024, from https://www.weldingengineers.com/Extruders.htm