The Feasibility of Existing Infrastructure for Recycling for the Transition to Bioplastics

A Research Paper submitted to the Department of Engineering and Society

Presented to the Faculty of the School of Engineering and Applied Science
University of Virginia

In Partial Fulfillment of the Requirements for the Degree Bachelor of Science,
School of Engineering

Xin Yin Chen

Spring 2022

On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

____ Date 06 May 2022
Xin Yin Chen

____ Date 05 May 2022
Advisor: Richard 'Doc' Jacques, Ph.D., Department of Engineering and Society

Introduction:

With the mass production of plastic polymers and the loose control on plastic disposal, it has led to an uncontrollable amount of plastic that has entered the water and land. Plastic has polluted many bodies of water and habitats by altering species distribution, entangling organisms, and increasing death in organisms that lead to ingestion (Welden, 2020) . There are more than 480 billion plastic bottles sold in 2016 worldwide and just a decade ago that number was 180 billion. About 269,000 US tons of plastic waste that goes into the ocean are from takeout orders (*Fact Sheet*, 2018). Sadly, bioplastic only composes one percent of about 360 million tons of plastic that is produced annually (EUBIO_Admin, n.d.). With COVID-19, there is even more problem with increased consumption of single use plastic masks, gloves, and other protective wears. The pandemic has halted the research programs there for plastic pollution. This personal protective equipment can be found everywhere (Ammendolia & Walker, 2022).

There has been a slight turn in the usage of bio-based plastic in order to help alleviate the amount of plastic being adding to the environment. Bio-based plastics are plastics based off of or at least partly based off of biological matter and will reduce the dependence on fossil fuels. There is also a biodegradable component to bioplastics where the plastic can actually be degraded by microbes in a reasonable amount of time (“Are Bioplastics Better for the Environment than Conventional Plastics?,” n.d.). However, these biodegradable plastics need proper composting and recycling facilities in order to degrade and break down the biodegradable plastics in a reasonable amount of time. The biodegradable plastic is broken down into carbon dioxide and water (Chinaglia et al., 2018). The major point of contention centers on the responsible choice of choosing carbon-rich raw materials as bioplastic feedstocks, public misconceptions, and lack of management in recycling and composting infrastructure. A common method for bioplastic production is cultivating starch-based feedstocks but that competes with land available for food production and adding on to the global food crisis. Additionally, this adds on to the carbon footprint from agricultural emissions (McCloy et al., 1999). With this in mind, I focused my research on investigating whether there is existing infrastructure for recycling and evaluating the feasibility of transitioning to bioplastics with the current resources available.

Technical Project:

My capstone team and I approached the problem by designing a protocol and procedure that maximize acetyl CoA production with the expectation to maximize PHB production. We are working with Transform, a startup company based in Charlottesville. I had the honor to join Transform in August 2021. Their main research goal is instead of using agro-industrial sources as the main carbon source for E.coli, use another waste. This the waste that they were focusing their research and product on is styrene which is another non-biodegradable waste. The styrene (sty) and Polyhydroxyalkanoate (pha) plasmid in E.coli is responsible for breaking styrene monomers into paa (Velasco et al., 1998). Then, E.coli will use paa as its sole carbon source in order to produce Polyhydroxybutyrate (PHB). PHB is produced through the paa pathway which is responsible for converting paa to acetyl CoA (Getachew & Woldesenbet, 2016). Therefore, maximizing the production of acetyl- CoA is crucial to maximizing PHB production. Our team   compared our control acetyl-CoA concentration data of just the wild-type E.coli strain K-12 MG1655 to the genetically modified E.coli through CRISPR-Cas9 in combination with lambda red. The genetically modified E.coli will include the proposed gene edits of the acetyl-CoA kinase (ackA) and phosphate acetyltransferase (pta), also known as the Acka-Pta pathway in order to inhibit the conversion of acetyl-CoA into acetate thereby increasing intracellular concentrations of acetyl-CoA available for PHB production (Ku et al., 2020). Our team also compared the acetyl-CoA concentrations between the wild and modified bacteria using a fluorometric acetyl-CoA assay in a regularly spaced time interval to determine if there is a significant increase in acetyl-CoA concentrations.

STS Research Paper:

Though advancing to bioplastics allows for a very promising future and better for our environment, there are still factors that are hindering the growth of that field. Specifically, the lack of infrastructure available for recycling and enforcement of the regulations. There is also lack of consumer education of how to properly dispose of wastes that hinders the transition to bioplastic. There needs to be enough recyclable goods in order to actually go to the facility in order to justify turning those goods into new recycled products. With this mentioned, this STS research paper focuses on investigation of existing infrastructure for recycling and evaluation of the feasibility of transitioning to bioplastics. This paper looks at case studies in order to look into the feasibility of these infrastructures, consumer education, and class disparities. Through a constructive sustainability assessment framework along with some principles of life cycle analysis, I assessed and analyzed the case studies to evaluate the feasibility. Taking into consideration the different hindering factors and trying to tackle them, understanding the roots of them is an important part in the transition of bioplastics and the research process of the STS study to truly investigate the social-technical dimension. This also allows for a better understanding and decision making in policies in government regarding recycling and composting infrastructures for the transition to bioplastics.

Literature review:

One of main hindrances of a complete and ideal circular plastic economy is trying to actually get used packaging and materials from the consumer back to the recycling facility (*Engaging Consumers to Reduce and Recycle*, n.d.). Without proper consumer education it makes it difficut to make the cycle circular and put it back into the supply chain. Having circularity is crucial to keep the long term sustainability of plastic. Without having enough recycled goods to actually go to the facility it is nearly imposible to justify turning those goods into new recycled products. Therefore, consumer participation in dividing the waste properly is extremely crucial (*Engaging Consumers to Reduce and Recycle*, n.d.). The lack of consumer participation comes from a lack of consumer education and public awareness. This can also be traced back to lack of enforcement in separation of waste. It is enormously difficult to change the behaviors of consumers from intention to action. Consumers may have the intention of wanting to properly dispose of plastic or waste but the lack of education of knowing what can actually be recycled hinders the action. Often, when the wrong material is entered in the wrong waste that leads to loss to the economy. Many manufacturers and retailers change their packaging or material without informing their consumers how to dispose of it properly and along with growing consumer distrust in the plastic recycling system, this may further lead to consumers being disappointed with businesses' effort (o'neill, 2021). It is impossible to cut plastics completely out of our lives but there is still a chance in solving this plastic challenge. This would require scaled-up business action and the effort of consumers, businesses, and government to work together (*Engaging Consumers to Reduce and Recycle*, n.d.). Together, we may be able to step closer and reshape the future of plastic and bioplastics.

Governments are essential in playing the role of an effective collection infrastructure and enforcing regulatory and policy landscapes in the plastic industry (Ebner & Iacovidou, 2021). Compostable plastic packaging is possible but it currently lacks an effective collection and composting infrastructure (*Engaging Consumers to Reduce and Recycle*, n.d.). The United States has 633 materials recycling facilities currently. These facilities are responsible for cleaning, sorting, and baling a total of 100,000 tons of recyclables a day. Materials recycling facilities operators had to toss out about half of what comes to them due to contamination (O'neill & Conversation, n.d.; *Plastic Recycling - an Overview | ScienceDirect Topics*, n.d.) . In order to upgrade materials recycling facilities and grow the domestic market for plastics will require a large-scale investment. It is found that it may be decades before the postconsumer plastic even reaches the recyclers' facility (Merrington, 2011).

Some states require a deposit to be made on drink containers and these deposits will be returned once the container is returned to recycling. The consumer and business are set as unpaid separation facilities for the PET recycling industry that allows a homogenous post-consumer recycling stream. The PET from these streams can be reused in producing new bottles, clothes, and carpet(Merrington, 2011).

There are currently over 85 facilities that accept compostable plastic and some that accept on a case-by-case basis. Proper composting facilities are required in order to break down fully biodegradable plastics in reasonable time. They need to be composted in commercial composting facilities with proper equipment to break down and compost materials. However, a limitation to composting plastic currently is that biodegradable plastics are not accepted at many commercial composting facilities (*Compostable Plastics*, n.d.). If bioplastics were subsidized and politically supported like biofuels then global growth could reach 10-20%. PLA and like some other plastics lack adequate recycling options. PLA recycling can be improved if there is increased demand and recycling-oriented regulations along with improved biodegradation facilities. The U.S government currently has made an effort to attempt more environment and climate focused policies. The “Break Free from Plastic Pollution Act” introduced in February of 2020 aims to limit single use items and non-recyclables in the market after 2022. This is to be carried out by taxing carry-out bags and making plastic producers responsible for collecting and recycling their products (Rosenboom et al., 2022).

It can be seen that though there have been efforts made in trying to improve the plastic industry, there are many hindrances. In Addition to lack of public education on plastic disposal and lack of business in educating their consumer to their product, there is lack of recycling and composting facilities for plastic (Rosenboom et al., 2022). Of those 633 recycling facilities previously mentioned, about 200 are actually plastic recycling facilities (*Plastic Recycling Plants In United States - ENF Recycling Directory*, n.d.). Out of the 200 plastic recycling facilities, most of the facilities are located in more populated cities and are not located throughout the states. This lack of facilities available everywhere is a factor in the hindrance of advancing recycling because a lack of facilities available makes the transition to bioplastics infeasible.

This STS research is a novel approach in combining both life-cycle assessment (LSA) and constructive sustainability assessment (CSA) to analyze the feasibility of the transition to bioplastic given the existing resources. Through the lenses of both LSA and CSA this can further emphasize the need to have a proper recycling and composting facility. I hypothesize that after reviewing the combination of the two lenses, existing recycling and composting facilities are inefficient to allow the transition to bioplastics.

Relating this to our technical research, the novelty of our technical project is to aim to help the problem with high cost that is hindering bioplastic production. Currently PHB is16 times the price of polypropylene (PE) (Hankermeyer & Tjeerdema, 1999). This is economically not favorable, and consumers would definitely choose the less expensive option. Our aim is to maximize the acetyl-CoA concentration in order to maximize PHB production to decrease the overall PHB production cost. Our technical project provides direction that will close the gap on the economic barrier to the bioplastic industry.

The methodology:

In order to evaluate whether with our current facility available is feasible for transitioning of bioplastic, the constructive sustainability assessment (CSA) will be used. CSA builds and reflects on both theory and practice that enables the application of sustainability assessments of the technologies emerging. The CSA incorporates four design-principles that are proposed for evaluating the sustainability of emerging technologies. The four design principles include: transdisciplinary, exploring uncertainty and anticipation. Additionally, a concise but flexible three-step methodology to demonstrate practical implementation of the framework. This part includes formulating the sustainability assessment in collaboration with stakeholders, evaluating potential sustainability implications using life-cycle assessment (LCA) , and interpreting and exploring the results of the deliberative process (Matthews et al., 2019). The framework will allow a transdisciplinary response to allow the governance of technologies emerging in regard to sustainability. Through using this framework, engineers, scientists, and policymakers in the field of emerging technologies relating to sustainability will be in their interest.

Along with CSA, the LCA will also be used to further determine and assess the impact of the current existing recycling and composting infrastructures. The most widely used and comprehensive method used on assessing sustainability that focuses on environmental sustainability is LCA. The LCA involves expanding perspectives when evaluating products and processes where the flows and impacts are being considered in a cradle to grave life cycle. This will allow a more holistic view and consideration of potential impacts of a product in order to stay away from the geographic burden of shifting and the impacts that are unexpected. With this in mind, the combination of CSA and LCA will be used with the expectation to achieve more sustainable patterns of consumption and production. The life-cycle impact assessment (LCIA) which is a branch of LCA incorporates improving the understanding of pollutant pathways, ecosystem, and human health impact mechanisms (Matthews et al., 2019). With the use of CSA and LCA analysis will be utilized to evaluate the existing recycling and composting infrastructure to determine its feasibility to transitioning to bioplastics. This review aims to help decision makers with future waste management strategies in regard to greenhouse gas emission to help the transition to bioplastics ("Using Life Cycle Analysis to Measure GHG Emissions from Composting," 2020).

Results

The following three plastic recycling facilities chosen to be investigated and evaluated in order to accurately determine the efficiency of plastic recycling facilities from different parts of the states: Accel Polymer, B&B Plastics Inc, and Cipherwaste. These three were chosen because they are located in different geographic areas in the United states and are two out of the 198 plastics recycling facilities (*Plastic Recycling Plants In United States - ENF Recycling Directory*, n.d.).

Accel Polymer is located in St.Charles, Missouri. They have worked directly with plastic manufacturers for over 30 years. They are a full-service plastics recycler that specializes in the development of unique recycling processes. Their recycling service aims to positively impact raw material cost and carbon footprint and convert waste stream into a clean renewable feedstock to maximize profitability. They provide processes such as: pelletizing, shredding/grinding, reprocessing resins, and recycling the scraps. In terms of LCA, this plastic recycling facility fits in with the cradle-to-grave criteria as its mission statement agrees with the circulating process. Its mission is to take existing material and aim to return that back to our system in order to reduce carbon footprint and maximize profitability. Their process returns the value of these materials fully back to the manufacturer for significant cost savings and allowing high-end application. Additionally, they aim to help its customers create a closed loop recycling process (“About Us,” n.d.-a). They satisfy the perspective of seeking a holistic consideration of a product’s impacts to avoid unexpected impacts. After viewing through the lens of CSA, Accel demonstrates some of the best design principles. They have clear goals and criteria along with integration of analytical knowledge on sustainability which are listed on their website which demonstrates transdisciplinary criteria. Additionally, they satisfy the criteria of design 2by engaging with a range of different stakeholders. They mentioned that they have built relationships with major distributors and producers over the past 30 years (“About Us,” n.d.-a). It is hard to evaluate whether or not Accel actually fulfills principle three, therefore inconclusive. Accel satisfies principle 4 of anticipation of futures by their emphasis on trying to be sustainable so as to positively impact raw material and carbon footprint.

B&B Plastics INC is a recycling business that started in 1997 and ranked number one in California and fourth in the United States. They have a full-service custom compounder of thermoplastics and a major source of supply positions from many major plastic producers. Their mission is to reduce carbon footprint and to increase the longevity of natural resources and environment. Additionally, they try to set plastic recycling as their priority and alleviate local landfills to reduce greenhouse gas (*B & B Plastics Inc.* | *Industry Leader in Plastic Recycling*, n.d.). In terms of LCA it is hard to evaluate exactly if they fit the cradle- to- grave criteria. It does emphasize on trying to increase resource longevity. They both sell and purchase plastic resin. Therefore, it is respomsive in terms of LCA in satisfying that criteria (*B & B Plastics Inc.* | *Industry Leader in Plastic Recycling*, n.d.). After viewing it through the lens of CSA, B&B satisfies all four principles. They have multiple stakeholders from different countries, and they emphasize trying to reduce their carbon footprint. They are hoping their service can lead to a brighter future for the plastic industry.

Cipher Waste is a plastic recycling facility located in Houston, Texas for 30 years and is familiar with pioneering complex recycling projects. They aim is to minimize impacts that may result from the processes and waste by promoting continuous improvement and practicing sustainable growth. In their ethics and values statement, their drive of taking account of the environment and demonstrating environmental and social responsibilities ("About Us," n.d.-b).Their mission statementdoes not really check the cradle -to- grave idea of a circulating cycle in LSA. However, they are more of a commercial company where their main purpose is selling plastic polymers and resins. After viewing through the lens of CSA, Cipher Waste does not fulfill any of the design principles. They seem to emphasize more on selling and buying parts rather than the environmental impact. They have heavy emphasis on cost but not really much about trying to keep a circular loop to reduce harm on the environment.

In order to further evaluate the three companies using LCA, a few other factors have to be put into consideration. The LCA definition from ISO 14040 evaluates the inputs, outputs, and the potential environmental impacts of the system through its whole cycle. However, the inputs, outputs, and other potential impacts each of these facilities generate is hard to measure given the limited time and resources. Therefore, LCA was measured based on the information about the recycling facilities available and compared to the criteria of LCA. Therefore, CSA will utilize the analysis to evaluate the feasibilities of the chosen three companies. Additional research placed on investigating the locations of the other 195 recycling facilities to further evaluate the current feasibility to switch to bioplastic. Additionally, there are 185 total full operating compost facilities in the states from a total of 37 states. The top three numbers of facilities were located in CA, NY, and WA (*Food Waste Composting Infrastructure In The U.S.*, 2019). The recycling facilities were spreadout but larger and more populated states had more recycling facilities. Ohio had the most , 24 and CA had 20. As big as NY is, it only has 7 recycling facilities (*Plastic Recycling Plants In United States - ENF Recycling Directory*, n.d.). There were only 31 states with recycling facilities leaving 19 states with no recycling facilities which was quite shocking to find. We would think with the ongoing plastic crisis and attention paid to recycling that every state would at least have one recycling facility.

Discussion

Since this evaluation was viewed through a limited lens of LCA due to lack of resources and limited to achieve the calculations of emission of each recycling facility, this evaluation is limited to only giving a small portion of the recycling facilities in existence.. The results show that with investigating three recycling facilities, only one satisfied all four design principles. It can be seen that different companies' mission and ethical statement provided were generally similar in trying to recycle as much as they can. However, some companies put more emphasis on profit. Additionally, some emphasized more on sustainability and aiming to have a closed loop plastic cycle. From the data found on the number of existing composting facilities, it can be seen again that only the largest cities/states have composting facilities. This brings up the discussion mentioned earlier in the paper regarding that only more funded and populated states or cities have the right to recycling/composting facilities. If smaller and less fortunate areas do not have these facilities available to them, does that mean those areas do not even have the option of being sustainable?

Conclusion

In conclusion, the existing recycling and composting facilities are not really feasible for a transition to bioplastic. A major reason for this is the lack of recycling and composting facilities. Additionally, there is not even one of each facility in each state. The recycling and composting facilities are concentrated in larger and more populated states. This makes it difficult for the smaller, less populated, and less fortunate areas to make the transition to bioplastics. Our economy and society are heavily reliant on petroleum based plastic and the reliance on this has created some challenges. Most importantly, due to shortage of organic compounds from decreasing supply of oil/gas resources along with increasing oil/gas prices. There are also concerns with degradation, incineration, global warming, cross contamination, and consumer toxicity risks. Therefore, several companies have tried to switch to bioplastics (Nagalakshmaiah et al., 2019). However, with current resources it is nearly impossible for a transition to occur. The current facilities are heavily focused on the purpose of producing profits instead of truly trying to reduce the carbon footprint. Additionally, there is a lack of customer education of knowing how to separate rather than something going into recycling or composting. There is definitely   enormous workto be undertaken in order to achieve the goal of a complete bioplastic industry.

References:

About Us. (n.d.-a). *Accel Polymers*. Retrieved April 14, 2022, from https://accelpolymers.com/about-us/

About Us. (n.d.-b). *CipherWaste Polymers LP*. Retrieved April 14, 2022, from https://cipherwaste.com/about/

Ammendolia, J., & Walker, T. R. (2022). Citizen science: A way forward in tackling the plastic pollution crisis during and beyond the COVID-19 pandemic. *Science of The Total Environment*, *805*, 149957. https://doi.org/10.1016/j.scitotenv.2021.149957

B & B Plastics Inc. | Industry Leader in Plastic Recycling. (n.d.). B & B Plastics Inc. Retrieved April 14, 2022, from https://bbplasticsinc.com/

Chinaglia, S., Tosin, M., & Degli-Innocenti, F. (2018). Biodegradation rate of biodegradable plastics at molecular level. *Polymer Degradation and Stability*, *147*, 237–244. https://doi.org/10.1016/j.polymdegradstab.2017.12.011

Compostable Plastics: The Next Generation Of Plastics. (n.d.). World Centric. Retrieved April 14, 2022, from https://www.worldcentric.com/journal/compostable-plastics-the-next-generation-of-plastics

Ebner, N., & Iacovidou, E. (2021). The challenges of Covid-19 pandemic on improving plastic waste recycling rates. *Sustainable Production and Consumption*, *28*, 726–735. https://doi.org/10.1016/j.spc.2021.07.001

Engaging Consumers to Reduce and Recycle. (n.d.). ERM. Retrieved April 13, 2022, from https://www.sustainability.com/thinking/engaging-consumers-to-reduce-and-recycle/

Fact Sheet: How Much Disposable Plastic We Use. (2018, April 18). Earth Day. https://www.earthday.org/fact-sheet-how-much-disposable-plastic-we-use/

Food Waste Composting Infrastructure In The U.S. (2019, January 4). BioCycle. https://www.biocycle.net/food-waste-composting-infrastructure-u-s/

Getachew, A., & Woldesenbet, F. (2016). Production of biodegradable plastic by polyhydroxybutyrate (PHB) accumulating bacteria using low cost agricultural waste material. *BMC Research Notes*, *9*, 509. https://doi.org/10.1186/s13104-016-2321-y

Hankermeyer, C. R., & Tjeerdema, R. S. (1999). Polyhydroxybutyrate: Plastic made and degraded by microorganisms. *Reviews of Environmental Contamination and Toxicology*, *159*, 1–24. https://doi.org/10.1007/978-1-4612-1496-0_1

Ku, J. T., Chen, A. Y., & Lan, E. I. (2020). Metabolic Engineering Design Strategies for Increasing Acetyl-CoA Flux. *Metabolites*, *10*(4), 166. https://doi.org/10.3390/metabo10040166

Matthews, N. E., Stamford, L., & Shapira, P. (2019). Aligning sustainability assessment with responsible research and innovation: Towards a framework for Constructive Sustainability Assessment. *Sustainable Production and Consumption*, *20*, 58–73. https://doi.org/10.1016/j.spc.2019.05.002

McCloy, K., Leung, S., Belden, J., Castenada, J., Erickson, V., Koch, K., Livingston, N., Moughrabis, S., & Gawlinski, A. (1999). Effects of injectate volume on thermodilution measurements of cardiac output in patients with low ventricular ejection fraction. *American Journal of Critical Care: An Official Publication, American Association of Critical-Care Nurses*, *8*(2), 86–92.

Merrington, A. (2011). 11—Recycling of Plastics. In M. Kutz (Ed.), *Applied Plastics Engineering Handbook* (pp. 177–192). William Andrew Publishing. https://doi.org/10.1016/B978-1-4377-3514-7.10011-X

Nagalakshmaiah, M., Afrin, S., Malladi, R. P., Elkoun, S., Robert, M., Ansari, M. A., Svedberg, A., & Karim, Z. (2019). Chapter 9 - Biocomposites: Present trends and challenges for the future. In G. Koronis & A. Silva (Eds.), *Green Composites for Automotive Applications* (pp. 197–215). Woodhead Publishing. https://doi.org/10.1016/B978-0-08-102177-4.00009-4 o’neill, jessica heiges and kate. (2021, September 11). *The simple way to make companies responsible for their waste? Make them pay for it*. Fast Company. https://www.fastcompany.com/90674483/the-simple-way-to-make-companies-responsible-for-their-waste-make-them-pay-for-it

O’neill, K., & Conversation, T. (n.d.). *The plastic waste crisis is an opportunity for the U.S. to get serious about recycling at home*. Retrieved April 14, 2022, from https://phys.org/news/2018-08-plastic-crisis-opportunity-recycling-home.html

Plastic Recycling Plants In United States—ENF Recycling Directory. (n.d.). Retrieved April 14, 2022, from https://www.enfrecycling.com/directory/plastic-plant/United-States

Plastic Recycling—An overview | ScienceDirect Topics. (n.d.). Retrieved April 14, 2022, from https://www.sciencedirect.com/topics/engineering/plastic-recycling

Rosenboom, J.-G., Langer, R., & Traverso, G. (2022). Bioplastics for a circular economy. *Nature Reviews Materials*, *7*(2), 117–137. https://doi.org/10.1038/s41578-021-00407-8

Using Life Cycle Analysis to Measure GHG Emissions from Composting. (2020, August 6). *Green Mountain Technologies*. https://www.compostingtechnology.com/using-life-cycle-analysis-to-measure-ghg-emissions-from-composting/

Velasco, A., Alonso, S., García, J. L., Perera, J., & Díaz, E. (1998). Genetic and Functional Analysis of the Styrene Catabolic Cluster of Pseudomonas sp. Strain Y2. *Journal of Bacteriology*, *180*(5), 1063–1071.

Welden, N. A. (2020). Chapter 8—The environmental impacts of plastic pollution. In T. M. Letcher (Ed.), *Plastic Waste and Recycling* (pp. 195–222). Academic Press. https://doi.org/10.1016/B978-0-12-817880-5.00008-6