Producing Bioplastic from Biodiesel Waste: Polyhydroxybutyrate Using Crude Glycerol
(Technical Prospectus)

Biopolymers Ahead of Their Time: The Failure of the Metabolix-ADM PHA Venture
(STS Prospectus)

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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.

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Introduction

Plastic waste is one of several pressing environmental challenges facing humanity today. Despite efforts to recycle, only three million of the 35.7 million tons of generated plastic were recycled in the United States in 2018, a recycling rate of 8.7% (Environmental Protection Agency, 2022). Most plastics are derived from petroleum and take hundreds of years to break down. Even newly manufactured plastic, in the form of pellets called "nurdles," ends up polluting the environment following spills or leaks (Jiang *et al.*, 2021). Regardless of when in its lifecycle plastic enters the environment, it will slowly break down into microplastics, which cause a multitude of health and environmental problems. Developed countries produce millions of tons of plastic waste each year, and often, marginalized groups and communities who are not even responsible for the bulk of the waste are disproportionately affected by plastic pollution (UNEP, 2021).

I, along with my capstone design team, will work towards a technical solution to the problem of plastic waste by designing a biopolymer plant using a crude glycerol waste stream as a carbon source to feed microorganisms that produce the biodegradable polymer polyhydroxybutyrate (PHB). PHB is non-toxic, biodegrades in an ambient environment in a matter of weeks and shares many material properties with common polyolefins, providing an attractive alternative to traditionally-produced plastics. I will also employ actor-network theory to examine the role that social and conceptual factors, including absence of demand for PHB due to lack of information made available to consumers, played in the failure of a joint venture between Metabolix and Archer Daniels Midland (ADM). The two companies started a largescale plant in Clinton, Iowa for producing PHAs, a group of polyesters including PHB, which failed only a few years later.

The challenge of plastic waste is one that is sociotechnical in nature, and hence we must tend to both the technical and social facets. Neglecting the social factors of the issue will leave it only partially resolved at best; we may develop the technology to produce more sustainable materials, but this is meaningless if there is no conscious effort to shift consumption or waste disposal habits. It is equally important that an economically feasible, environmentally sustainable process is designed as it is that the social factors at play are addressed. In what follows, I will elaborate a technical project concerning an industrial-scale process that starts with the purification of crude glycerol and ends with the production of the sustainable bioplastic PHB and an STS project that examines the social factors at play in the failure of the Metabolix-ADM PHA plant.

Technical Project Proposal

We intend to produce polyhydroxybutyrate (PHB) using the crude glycerol co-product from a biodiesel plant. PHB is a biodegradable polymer that is produced by microorganisms (Akhlaq et al., 2022). Posada et al. describes a process for the production of PHB in Colombia that

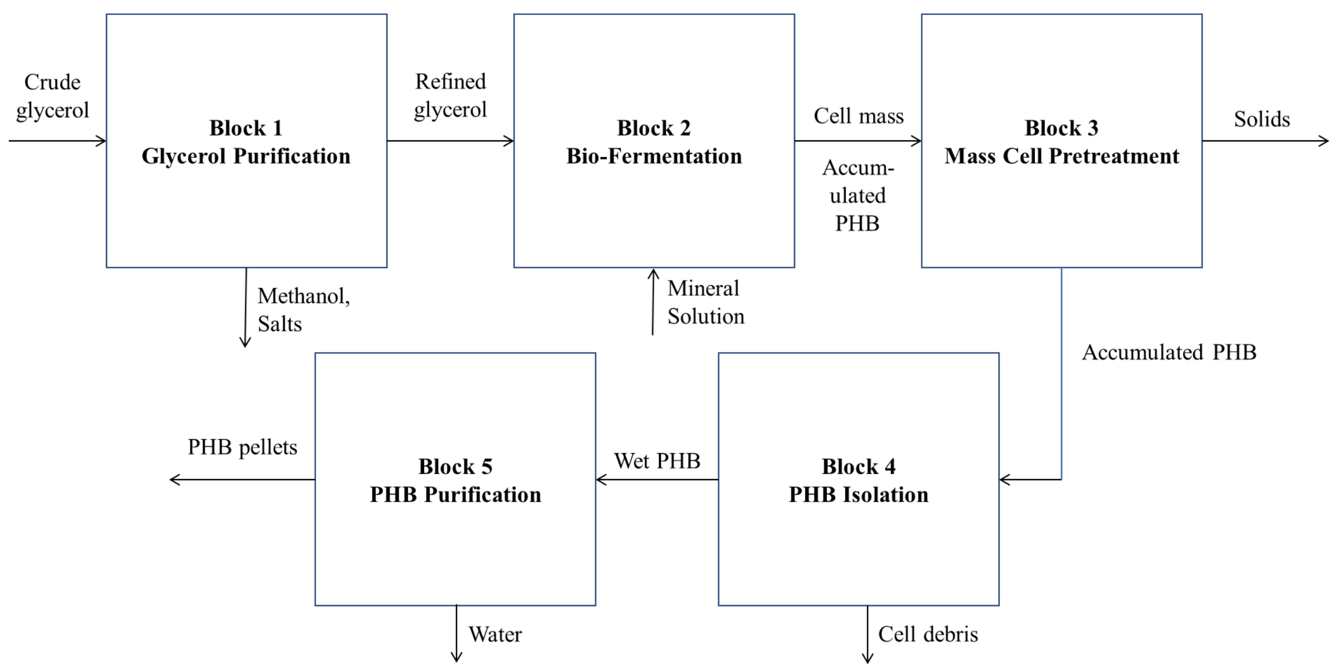

Figure 1. Block Flow Diagram of Overall Process for PHB Production

we will adapt to fit the specifications of glycerol waste stream from a biodiesel plant in Iowa. The general block flow diagram begins with purification of the crude glycerol using a distillation column to prepare it for the fermentation process (Figure 1).

In the fermentation process, a growth fermenter and an accumulation fermenter will be used to cultivate mass cell growth and promote PHB synthesis, respectively. In the growth fermenter, glycerol will serve as the carbon source for the cultivation of the microorganism *Cupriavidus necator*. The fermentation is a fed batch process, and the first fermenter will be at optimum nutritional conditions to achieve high cell density. Restricting nitrogen in the accumulation fermenter will then promote PHB synthesis. During the second fermentation stage, cell density remains constant while PHB concentration increases. After the fermentation process, the PHB is extracted from the microorganisms and purified. Cells are pretreated in a high-pressure homogenizer and centrifuged to extract excess water. Following pretreatment, the product stream undergoes solvent extraction. Once isolated, the PHB stream is treated to reach 99.9% product purity. For commercial sale, the PHB stream is extruded to form pellets.

Biodiesel is a growing commodity as the transportation sector transitions to low carbon fuel sources (Hejna et al., 2016). Glycerol is the main byproduct (10 wt%) of biodiesel production, and there is currently an untapped market for turning this waste into a profitable end-product (Posada et al., 2011). Glycerol is mostly produced synthetically and is used in many consumer products. It can also be used as a carbon source to produce PHB, a biodegradable plastic. Transitioning to the use of biodegradable plastics will decrease the amount of waste in landfills and will avoid the release of harmful substances into the environment from the breakdown of plastic (Mostafa et al., 2020). Currently, the total capacity for PHB production is 30 kilotons per annum (ktpa) and is produced by Monsanto through the genetic modification of plants (Koller &

Mukherjee, 2022). Our proposed method is more sustainable and uses a lower price material as a feedstock, making it price competitive with Monsanto's process (Koller & Mukherjee, 2022). The PHB plant would be located in Iowa, where US biodiesel production is concentrated, to maximize access to waste glycerol and limit transport costs. To produce 0.130 ktpa of PHB, we would need 12 ktpa of crude glycerol feedstock. REG is one of the major biodiesel producers in Iowa with a total glycerol production capacity of about 30 thousand tons per annum (ktpa). REG operates 3 plants within 150 miles of each other and we would buy waste glycerol from one or more of their biorefineries (Table 1).

Table 1. Feedstock Sources for PHB Plant in Iowa (" The Latest News and Data About Biodiesel Production," n.d.)

	Location in Iowa	**Biodiesel Annual Capacity (ktpa)**	**Glycerol Annual Capacity (ktpa)**
REG Ralston LLC	Ralston	99.55	9.95
REG Newton LLC	Newton	99.55	9.95
REG Mason City LLC	Mason City	99.55	9.95
		Total Supply	29.86
		Maximum PHB Production Capacity	1.856

We will execute the technical project as a team over the course of two semesters. Aspen, a unit operations modeling software, will be utilized to model the different unit operations such as the fermenter and distillation column for purification. Along with modeling, material stream analysis will be done in Aspen. Excel will be used to perform further analysis on the process data (purity, stream flow rates, compositions) and for economic analysis of the entire process. A Design Basis Memorandum, including a description of the starting materials, products, scale and process as well as a brief economic appraisal, will be completed in the fall semester. The remainder of the research and complete design of all equipment, plant specifications, and full economic analysis will be developed in the Spring semester. The design data will be derived from multiple journal articles that detail process steps and parameters.

STS Project Proposal

In 2006, agricultural giant Archer Daniels Midland (ADM) announced a joint venture with bioscience startup Metabolix, Inc. to build the first commercial plant producing the natural biodegradable plastic polyhydroxyalkanoates (PHAs) marketed as "Mirel" in Clinton, Iowa (ADM, 2006). The $400 million plant was completed in early 2010, but was delayed in going fully commercial, which was defined as selling at least one million pounds of Mirel manufactured at the Clinton plant to third parties (Goldsberry, 2021). A year into its operation, the plant was receiving noise and smell complaints from its neighboring community, still working to streamline the purification process, and experiencing difficulty in finding customers due to its strict requirements (Schut, 2011). In 2012, ADM backed out of the partnership and closed the plant, citing rising costs and the slow market growth rate (Tullo, 2015). Metabolix retained its intellectual property and attempted to continue to produce PHA on its own for a few years, trying to create a market. However, Metabolix was spending far more than it could earn, and by 2016, had sold the technology to South Korean company CJ CheilJedang for $10 million.

By many accounts, the venture failed simply because Metabolix was unable to maintain its finances without ADM's resources, and as stated by ADM, there were "uncertain projected financial returns" in the venture (Goodwin Procter LLP, 2013). While this is true, this view overlooks the role played by social factors such as consumer habits and awareness, or lack thereof, of the significance of biodegradable plastics and the general public's misconceptions about them. For example, many consumers do not fully understand the meaning of "compostable" when it comes to plastics. Many so-called compostable plastics actually require an industrial facility to be broken down, and the likelihood that they make it to an industrial composter depends on consumers (Oakes, 2019). PHAs differ in that they will break down naturally, even in ambient environments such as the ocean (Tullo, 2019). If we solely attribute the Clinton plant's failure to lack of sales or financial uncertainty, we neglect the root issues that must be addressed for any future venture in biodegradable plastics to succeed. The technology for transitioning to biodegradable plastics exists, but several key social factors are inhibiting the development of the necessary infrastructure for this change to occur.

Drawing on Actor-Network theory, I will argue that it was the exit of ADM from the project, difficulty in developing a market, and challenges with the process in conjunction with consumer culture, lack of education, and absence of any regulatory or legislative motivations to invest in biodegradable plastics that contributed to the failure of the Clinton plant. Actor-Network theory, as described by science and technology studies scholars Bruno Latour and Michel Callon, seeks to characterize a network builder that identifies a problem and recruits the human and non-human actors needed to solve it. Callon (1986) describes the process of forming actor-networks, "translation," in four stages: problem and actor identification, actor recruitment, role assignment, and mobilization of the actors into action. Finally, the network functions as a stable entity, or black box. Using this framework, I will describe the dissolution of the Metabolix-ADM PHA plant network by identifying the actors and their relationships within the network. To support my argument, I will analyze evidence from news articles and press releases from throughout the lifetime and following the shutdown of the plant, interviews with involved parties, and data regarding plastic pollution.

Conclusion

The technical project will deliver the design of a PHB plant in Iowa that will meet growing demand for biodegradable plastics while simultaneously utilizing a waste stream from biodiesel production processes. Using a low-cost material as the feedstock will make this venture more attractive than existing processes. We will perform extensive modeling and economic analyses to ensure the feasibility of this process. The STS project will provide a comprehensive understanding of the social factors at play in the failure of the Metabolix-ADM Clinton plant, giving insight that will prevent the same mistakes from being repeated and ensure the demand for biodegradable plastics. Actor-Network theory serves as the framework for this study. The combined results of the technical and STS projects will contribute to addressing the global challenge of plastic waste by detailing the production of a sustainable, highly compostable polymer and by explaining how human and non-human actors will function in unison to facilitate a transition away from petroleum-derived plastics.

References

ADM. (2006, February 13). *ADM and Metabolix announce first commercial plant for PHA natural plastics* [Press Release]. Retrieved October 23, 2022, from https://www.adm.com/en-us/news/news-releases/2006/2/adm-and-metabolix-announce-first-commercial-plant-for-pha-natural-plastics/

Akhlaq, S., Singh, D., Mittal, N., Srivastava, G., Siddiqui, S., Faridi, S. A., & Siddiqui, M. H. (2022). Polyhydroxybutyrate biosynthesis from different waste materials, degradation, and analytic methods: a short review. *Polymer Bulletin 2022*, 1–33. https://doi.org/10.1007/S00289-022-04406-9

Callon, M. (1986) Some elements of a sociology of translation: The domestication of the scallops and the fishermen of St.Brieuc Bay. In Law, J. (Ed.), *Power, action & belief: A new sociology of knowledge?* London: Routledge & Kegan Paul.

Environmental Protection Agency. (2022, September 19). *Facts and figures about materials, waste and recycling - Plastics: material-specific data*. EPA. Retrieved October 26, 2022, from https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/plastics-material-specific-data

Goldsberry, C. (2021, April 26). *Investment management firm issues cautionary report on Danimer Scientific*. Plastics Today. Retrieved October 27, 2022, from https://www.plasticstoday.com/advanced-recycling/investment-management-firm-issues-cautionary-report-danimer-scientific

Goodwin Procter LLP. (2013, November 21). *Goodwin litigators win dismissal of class action for Metabolix* [Press Release]. Retrieved October 24, 2022, from https://www.goodwinlaw.com/news/2013/11/11_21_13_goodwin-litigators-win-dismissal-of-class-action-for-metabolix.

Hejna, A., Kosmela, P., Formela, K., Piszczyk, Ł., & Haponiuk, J. T. (2016). Potential applications of crude glycerol in polymer technology–Current state and perspectives. *Renewable and Sustainable Energy Reviews*, *66*, 449–475. https://doi.org/10.1016/J.RSER.2016.08.020

Jiang, X., Lu, K., Tunnell, J. W., & Liu, Z. (2021). The impacts of weathering on concentration and bioaccessibility of organic pollutants associated with plastic pellets (nurdles) in coastal environments. *Marine Pollution Bulletin*, *170*. https://doi.org/10.1016/j.marpolbul.2021.112592

Koller, M., & Mukherjee, A. (2022). A new wave of industrialization of PHA biopolyesters. *Bioengineering*, *9*(2). https://doi.org/10.3390/BIOENGINEERING9020074

Mostafa, Y. S., Alrumman, S. A., Alamri, S. A., Otaif, K. A., Mostafa, M. S., & Alfaify, A. M. (2020). Bioplastic (poly-3-hydroxybutyrate) production by the marine bacterium *Pseudodonghicola Xiamenensis* through date syrup valorization and structural assessment of the biopolymer. *Scientific Reports*, *10*(1). https://doi.org/10.1038/s41598-020-65858-5

Oakes, K. (2019, November 5). Why biodegradables won’t solve the plastic crisis. *BBC*. Retrieved October 24, 2022, from https://www.bbc.com/future/article/20191030-why-biodegradables-wont-solve-the-plastic-crisis.

Posada, J. A., Naranjo, J. M., López, J. A., Higuita, J. C., & Cardona, C. A. (2011). Design and analysis of poly-3-hydroxybutyrate production processes from crude glycerol. *Process Biochemistry*, *46*(1), 310–317. https://doi.org/10.1016/J.PROCBIO.2010.09.003

Schut, J. (2011, January 19). Where is Metabolix's PHA biopolymer? [web log]. Retrieved October 23, 2022, from https://plasticsengineering.wordpress.com/2011/01/19/where-is-metabolix%E2%80%99s-pha-biopolymer/.

The latest news and data about biodiesel production. (n.d.). *Biodiesel Magazine*. Retrieved October 16, 2022, from https://biodieselmagazine.com/plants/listplants/USA/page:1/sort:state/direction:asc

Tullo, A. H. (2015, May 25). The final hour for biobased plastics maker Metabolix. *Chemical & Engineering News*, *93*(21). Retrieved October 23, 2022, from https://cen.acs.org/articles/93/i21/Final-Hour-Biobased-Plastics-Maker.html#.

Tullo, A. H. (2019, September 9). PHA: A biopolymer whose time has finally come. *Chemical & Engineering News*, *97*(35). Retrieved October 23, 2022, from https://cen.acs.org/business/biobased-chemicals/PHA-biopolymer-whose-time-finally/97/i35.

UNEP. (2021, March 30). Plastic pollution is an environmental injustice to vulnerable communities – new report. *UN Environment Programme*. Retrieved October 23, 2022, from https://www.unep.org/news-and-stories/press-release/plastic-pollution-environmental-injustice-vulnerable-communities-new.