Scale-Up of Laboratory-Verified Degradable Biopolymer Synthesis

(Technical Paper)

Consumer Spending Decisions and Potential for Adoption of Renewable Plastics

(STS Paper)

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Introduction

Our society is defined by plastics that we interact with every day. Often, these are used once and end up in landfills. As of 2017, there were 4.9 billion tons of plastic in landfills; this is projected to double by 2050 (Dengler, 2017). Traditionally, these plastics are made from byproducts from the oil and gas industry (Day, 2018) which contributes to pollution both through their processes and the products that they produce. Commonplace plastics can take up to 1000 years to decompose (LeBlanc, 2019) which leads to accumulation of these products post-consumer use. These make up around 10% of the mass of disposed waste, but a larger percentage of the volume (Thompson, 2009, n.p.). Governments know that landfill space will become exhausted and choose to send their plastic waste to developing countries. Some of these do not have the waste infrastructure to manage large quantities of plastic waste (Day, 2018), which leads to dumping into the environment and the oceans where it will impact marine life. Consumers may not be willing to pay more for a renewably sourced material if they are not properly educated by the businesses producing these.

Continual use of non-renewable plastics will cause the problems outlined above to persist. Some estimates suggest that plastic pollution results in around 100 million marine mammals killed every year (Henn, 2019 n.p.). Continual plastic pollution will have a long-lasting impact on the environment. Movement towards renewable plastics, both through cultural choice and industrial production, will help to reduce this impact. The technical project described here will involve research into the production of the bioplastic poly(dihydroferulic acid) (PHFA) from a lignin derived vanillin feedstock to make a product which mimics the mechanical properties of poly(ethylene terephthalate) (PET), one of the most commonly used plastics today. This would result in availability of an alternative to traditional plastics for companies and/or consumers to use. The STS research will focus on consumer values and actions relating to the adoption and use of renewable alternatives as plastic demands continue to increase.

Technical Topic – *Scale-Up of Laboratory-Verified Degradable Biopolymer Synthesis*

Current State of Biopolymer Research and Development

As national media sources intensify the spotlight on plastic pollution and the general public's distaste for non-sustainable materials heightens, the scientific community is expanding its efforts to innovate biologically-based, functionalized materials for polymerization. The search for useful and environmentally-friendly polymers has proven difficult for researchers, even those in groups that prioritize that field of study. Holmberg et al. (2016) summarize the primary issues: "Practical bio-based materials that can compete with petroleum-based plastics in both cost and performance are of growing interest yet are challenging to design due to trade-offs between cost, feedstock sustainability, and macromolecular properties" (p. 1286). Kristufek, Wacker, Tsao, Su, and Wooley (2016), researchers from the chemistry and chemical engineering departments at Texas A&M University, contended that recent advances in natural product synthesis and isolation bolster the development of scalable reaction schemes for bio-derived polymeric materials (2016, p. 433).

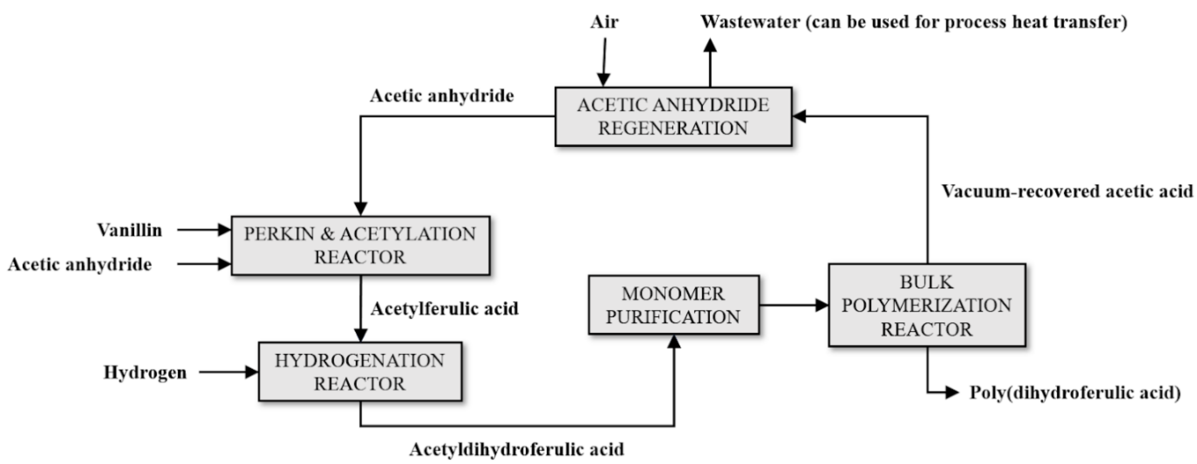
A myriad of review articles, exemplified by University of Florida chemist Stephen Miller's 2013 publication, extol the benefits of sustainable polymers supported by laboratory-scale research on the production and degradation of the materials. One such reaction that is gaining particular interest from researchers involves the depolymerization of lignin to obtain aromatic compounds for continued processing (Nicastro, Kloxin, & Epps, 2018, p. 14812; Ganewatta, Lokupitiya & Tang, 2019). Lignin is a natural polymer representing 30% of the world’s biomass and is generated as waste in the pulp and paper industry on the scale of millions of tons annually (Ganewatta et al., 2019, p. 2).

Laboratory Research Basis for Process Design

Mialon et al, researchers at the George and Josephine Butler Laboratory for Polymer Research at the University of Florida, reported a novel, biodegradable, and lignin-derived thermoplastic replacement for polyethylene terephthalate (PET) in 2010. The final product of their reported reaction, poly(dihydroferulic acid) (PHFA), exhibits thermal and mechanical properties comparable to those of PET, the third most common synthetic polymer, accounting for nearly twenty percent of global plastic production (Mialon et al., 2010, p. 1704). The monomer, dihydroferulic acid, is a modified form of vanillin, which is a product of wood-derived lignin depolymerization. The other reagent, acetic anhydride, can also be extracted from wood, resulting in a fully wood-sourced material (Mialon et al., 2010, p. 1704). A patent and trademark (Gatoresin™) for the product followed its discovery, indicating its perceived viability (Mialon & Miller, 2015; Florida Institute for Commercialization of Public Research, 2014). The technology then led to the founding of US Bioplastics, with Miller as the CTO. The company received initial funding, but never acquired the resources to build a pilot facility for the production of the material (Wayback Machine, 2019). Given the promise of the bioplastic itself, and the recent increase in demand for bioplastics, it is worth considering the development of a new design for industrial scale production of this sustainable material.

Thesis Project Objectives and Methods

The objective of the technical project is to design a fully-operational plant to mass-produce a bioplastic using the vanillin synthetic scheme described by Mialon et al., and the corresponding patent of Mialon and Miller (2010; 2015). A high-level block flow diagram for the proposed process is shown in Figure 1. By transitioning the synthesis from a batch to the continuous process portrayed below and by addressing issues of energy efficiency, operational safety, and waste abatement, the design will allow for profitable production of the bioplastic in quantities required for commercial applications. In addition to producing a sustainable product, it is crucial that the process design itself is sustainable to ensure that the environmental good of the PHFA polymer is not diminished in the production phase.



The Aspen Plus software suite will be used to simulate the unit operations required of the process (AspenTech, 2019). Other computer programs, including MATLAB, will supplement the modeling done in Aspen Plus (MathWorks, 2019). Specifically, since Aspen Plus excels in thermodynamic calculations but lacks in its reaction kinetics modeling, MATLAB will be used to design the reactors essential to the process.

The technical project will last the entirety of fourth year, in a two-semester senior design sequence directed by Professor Eric W. Anderson. The design group is comprised of fourth-year chemical engineering students Christopher Brodie, Ethan Bush, Jillian Dane, Gavin Restifo, and Rebecca Richardson. By the end of the fall semester, the initial plans for a plant will be detailed in a design basis memorandum. This document will include a description of feedstocks and final products and a high-level overview of the material and energy balances and purification techniques relevant to the process. Additionally, an economic appraisal will be included as a proof-of-concept for financial feasibility. At the end of the spring semester, a technical report will be authored, fully defining the bioplastic production process.

Role of Deliverable in the Future of Sustainable Materials

This project will contribute to the progress of the chemical industries since biomass-derived plastic is valuable not only for its lower environmental impact compared to fossil-fuel-derived equivalents but also as an element of cross-industry sustainability. As the transition to renewable resources is driven by the rapid consumption of nonrenewable oil and gas, future material feedstocks could be made in biorefineries that utilize biologically-generated molecules in real time, rather than millions of years after the fact. Lignin would be one component of this system. The authors of Biofuels from Algae, which details the algal component of a biorefinery vision, point out, “[E]conomic analyses have consistently indicated that algal-based biofuel feasibility hinges on the possibility of production coproducts with a market value from the spent biomass” (Guedes, Amaro, Sousa-Pinto, & Malcata, 2014, p. 206). In this context, failing to scale bioplastic production will not only result in continued issues with conventional plastics, but will obstruct the future of sustainability in all other chemical industries currently based on fossil fuel inputs.

STS Topic – *Consumer Spending Decisions and Potential for Adoption of Renewable Plastics*

Many plastics are used a limited number of times by typical consumers and many are single use. With this large consumption of plastics and their low degradability, plastic waste will continue to accumulate. The costs for commodity plastic packaging materials are often negligible compared to the product that they are used with, and some consumers may not be willing to pay a premium for a product that implements expensive plastics. Possessing a "green" viewpoint, one that values environmentally friendly behavior, is insufficient in creating any environmental change through spending on sustainable materials. Studies have shown that people with this viewpoint do not necessarily exhibit pro-environmental behavior (Rynarzewska, 2019). This paper discusses the reasoning for this, specifically how customers may be wary of the motivation of for-profit companies, may have taken in misinformation, or may lack the proper knowledge that they need to make environmentally conscious decisions. Bridging this gap between values and actions of consumers is a difficult task given to businesses and organizations (White, 2019) that must be combatted through clear business motivations and proper customer education.

Microplastics, small plastic particles produced from modern plastic degradation, result from both consumer and industrial plastic use and impact marine life once they travel into rivers and oceans. These particles may be at a similar size of plankton, resulting in uptake by predators (Ogunola, 2018, in.p.) Naturally, these microplastics will make their way throughout the food chain of the ocean. The health impacts of microplastics are seen from small fish and crustaceans to seals and whales. Various sources of microplastics and their pathways that lead to ocean uptake are shown in the Figure 2.

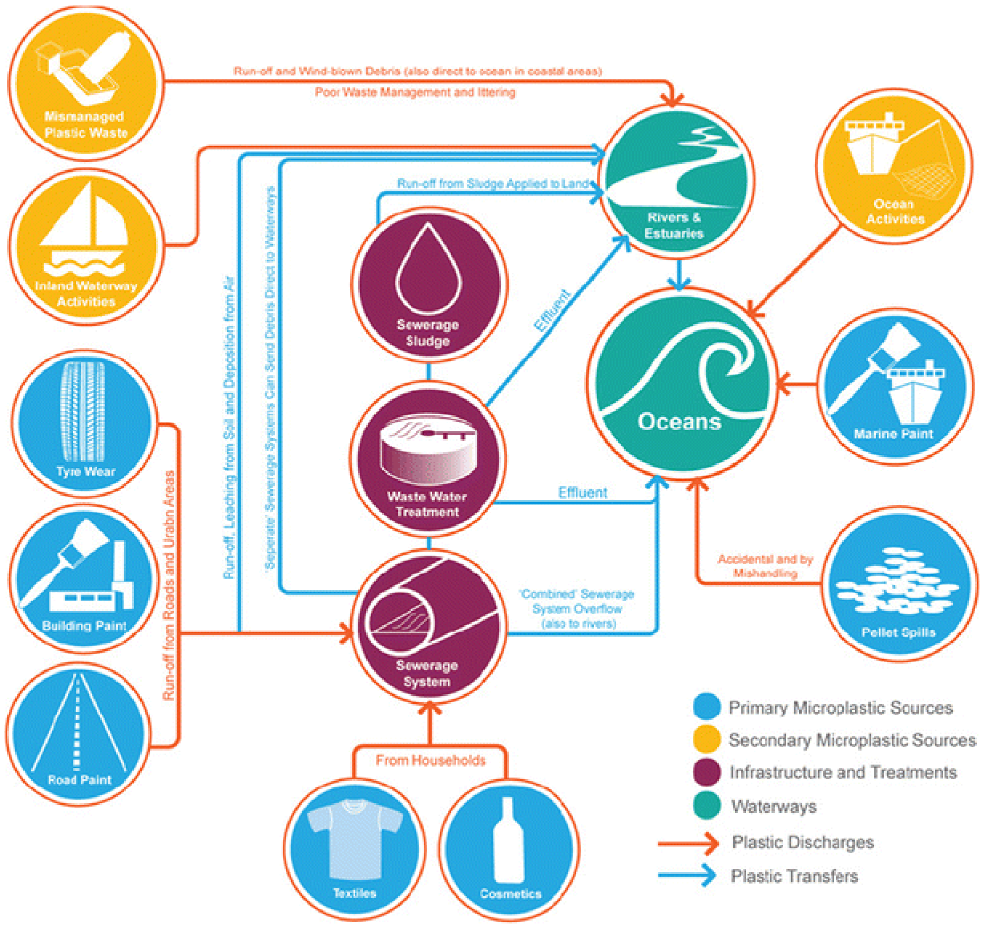


Figure 2. Major microplastic sources and their pathways into the environment. Notable sources are the household sources, textiles and cosmetics, as well as public managed waste, which consumers contribute to through waste disposal. Some household waste follows a very short pathway to oceans. (Ogunola, 2018, in.p.)

The average consumer contributes to the sources of microplastics from household waste but also from waste management facilities from disposing of single use plastics. The impact of these microplsatics can even reduce tourism if people are discouraged from visiting locations due to plastic debris (Ogunola, 2018, in.p.). While consumers continue to use non-renewable plastics, these problems will persist and worsen.

Renewable plastic alternatives are more expensive than currently used plastics, but consumers may be willing to spend more on products that are clearly sustainable in some way (Yue, 2010, p. 769). This allows motivated consumers to act on their values if these products are readily available. How these products are displayed and how they are produced dictated consumers' willingness to pay a premium for them. If they are designed and presented correctly, they can be priced in a way that makes their production sustainable and profitable while achieving adoption by the general public. Consumers must develop a habit for choosing sustainable options. Environmentally friendly habits can be developed when consumers are exposed to effective marketing and are motivated by societal norms, but lack of a tangible payoff for their actions may keep them from making 'green' decisions. This is described well by White (2019) as consumers are often present-focused individuals, and intangible results may appear uncertain or distant, and the payoff of pro-environmental decisions becomes less desirable. Studies show that consumers are ignorant of the impact that plastic waste has on the environment (Ogunola, 2018, in.p.). This article also discusses how a provision of incentives may motivate consumers to responsibly dispose of their plastic waste. Effective environmental education could address this by raising awareness and helping consumers understand their individual consumption patterns and the resulting environmental consequences. Proper awareness, education, and incentives may encourage consumers to change their behavior and develop environmentally friendly habits. The resulting community shift and adoption of renewable plastic resources will reduce the impact that we, as contributors to plastic pollution, will have on the environment and marine life.

Conclusion

Development of an economical production process for a renewable biopolymer provides an opportunity for society to move in a more environmentally friendly direction. This opportunity has potential to be culturally adopted when both consumers and producers push the market to become more sustainable. The technical project outlined above will culminate in a complete industrial design and economic analysis for the production process of the biopolymer

PHFA from a sustainably sourced vanillin feedstock. This creates an avenue for availability of alternative plastics in the consumer market. Potential for consumer adoption and the necessary conditions to cause this will be analyzed in my STS research, focusing on consumer spending, decision making, and education, as well as producer marketing and incentive implementation. If these deliverables are successfully completed, they will create both opportunities, from product availability, and incentive, from consumer willingness to pay, for both consumers and producers to become more sustainable in their use and production of plastic products.

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