Novel design of simultaneous biodiesel production and lutein extraction from *Chlorella Vulgaris* in raceway ponds

Socio-political challenges of transitioning from a fossil-fuel to a biofuel dependent society

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By

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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

The global energy transition is gaining speed, and the use of fossil fuels is slowly being phased out. The need for more sustainable energy sources is ever growing and one of the possible sources is biodiesel. Biodiesel is primarily produced from biomass with high lipid (oil) content and one such biomass source is algae. The production of biodiesel in 2007 was primarily sourced from plants such as canola and Jatropha according to Borowitzka et al., but the subsequent failure of Jatropha as a viable oil producing crop in arid regions resulted in a transition to crops such as soybeans, sugar cane, corn, and palm oil. Terrestrial crops, however, are very land intensive and about 22% of terrestrial net primary production would be needed to completely replace fossil fuels (Borowitzka et al., 2013).

The problem we are addressing for our capstone project is the sustainable production of biodiesel from algae biomass instead of terrestrial plants. This decreases the land use required for production of biofuels while also using a biomass source that has a high oil content of ~28-53% for *Chlorella* (Udayan et al., 2022). However, our project also addresses the previous technological and economical limitations of biodiesel production from algae by incorporating novel separation techniques and co-producing lutein as a nutritional supplement to subsidize the cost of processing and separation of algae water. In addition, the challenge that algae production faces with regards to water sources is addressed by using municipal wastewater supplemented by manure for additional carbon and nitrogen.

In addition to technological challenges, I will investigate the socio-political challenges that biofuels face. I am specifically interested in how interest in biofuels peaked in the late 2000s before nearly completely collapsing after the global financial crisis in 2008 and some of the challenges biofuels have faced since. According to Eggert et al. (2011), even with high petroleum prices and no carbon taxation, most US and EU producers of first-generation biofuels are not price competitive and would not be able to operate without government subsidies. However, Brazil is able to produce competitive biofuels and is a world leading example because they have invested in producing biofuels since 1920 (Selfa et al., 2015). Brazil has been very successful at producing competitive ethanol-based biofuel since the 70s, but countries without this established infrastructure and land for crop growth find other sustainable energy sources much more attractive. The problem that I will address is how financial considerations have inhibited the continuation of government funded projects due to a drop in public opinion, improvements in electric vehicles, and advancements in hydrogen fuel production.

The technological limitations of biodiesel production are very closely related to the sociological and political challenges that biofuels face because economic viability depends on the cost of production and unviability impacts public opinion and political legislation. With new advances in technology, it is important to investigate whether biofuels face intrinsic challenges or if they could become a viable form of sustainable energy for the transportation sector. With algae as the biomass source, environmental factors like land-use and avoiding algal blooms in rivers might aid with improving public opinion and converting algae-based biodiesel into a popular, viable, and domestic source of fuel.

Novel design of simultaneous biodiesel production and lutein extraction from *Chlorella Vulgaris* in raceway ponds

In response to climate change and other environmental imperatives, our society has begun to actively seek sustainable alternatives to many contemporary, petrochemical-fueled technologies. Thus far, long-distance travel has resisted shifts to electrification, making the adoption of greener fuels a necessity (Gross, Oct. 2020). Algae-based biodiesel has emerged as a promising tool to help fight the global climate crisis. Algae-based methods can be more advantageous than first and second generation biofuel sources due to high energy content, rapid growth times, and reduced land and water requirements. However, industrial-scale algal biodiesel production remains constrained by its limited commercial feasibility (Prommuak et al., 2013). This capstone project aims to address these economic deficits.

The objective of our technical capstone project is to design a novel method of producing microalgal biodiesel by optimizing previous process strategies while subsidizing costs through the co-production of lutein as a high value byproduct to improve economic viability. Lutein, a carotenoid with anti-inflammatory properties, is widely recognized for its benefits in promoting eye health, particularly in preventing age-related macular degeneration. Additionally, research suggests potential positive effects in various clinical areas, including cognitive function, cancer risk reduction, and cardiovascular health improvement (Buscemi et al., 2018). The overall pathway is outlined in Figure 1.

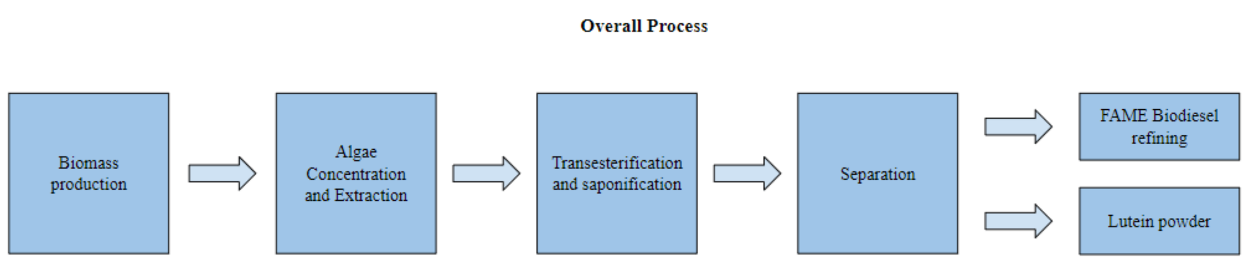

Figure 1. Overall process for FAME biodiesel and lutein.

We are drawing upon the insights presented by Tabernero et al. as inspiration for the development of our overall process. The first stage begins with the cultivation of *Chlorella vulgaris* in raceway ponds. Raceways offer an affordable and low maintenance method for growing algae (Griffiths et al., 2021). Agricultural waste will provide an inexpensive source of carbon and nitrogen. Paddles and spargers will be utilized to ensure complete mixing of nutrients and adequate aeration, therefore promoting a high rate of algae growth. Algae harvested at the end of the raceway will undergo a dewatering process to increase its concentration for further processing. This will involve a combination of mechanical centrifugation and a flocculation process assisted by nano magnetites described by Patel et al. to increase efficiency.

The downstream steps are modeled after the methodology outlined by Prommuak et al. but will be augmented to accommodate industrial scale production. Triglycerides and lutein fatty acid ester, crude forms of the desired products, will be removed from harvested algae via cell disruption. A scaled-up version of a Soxhlet extraction employs methanol and chloroform as solvents (Wang et al., 2023) to extract the lipids and dissolved lutein from the algal biomass. The remaining algae residue will be recycled back into the raceway as an additional carbon source. The chloroform and methanol will subsequently be removed to isolate the crude lipids, where they will then be converted to biodiesel and lutein through a coupled transesterification and saponification process. This process as well as subsequent separations needed to derive the final biodiesel and lutein powder products will be inspired by the flow diagram in Figure 2. Further refining of the biodiesel with a fractional distillation column may be able to achieve higher purity and thus increase the value of this product. The ultimate goal following the process design is to perform an economic analysis to determine the viability of microalgae biodiesel production alongside lutein co-production.

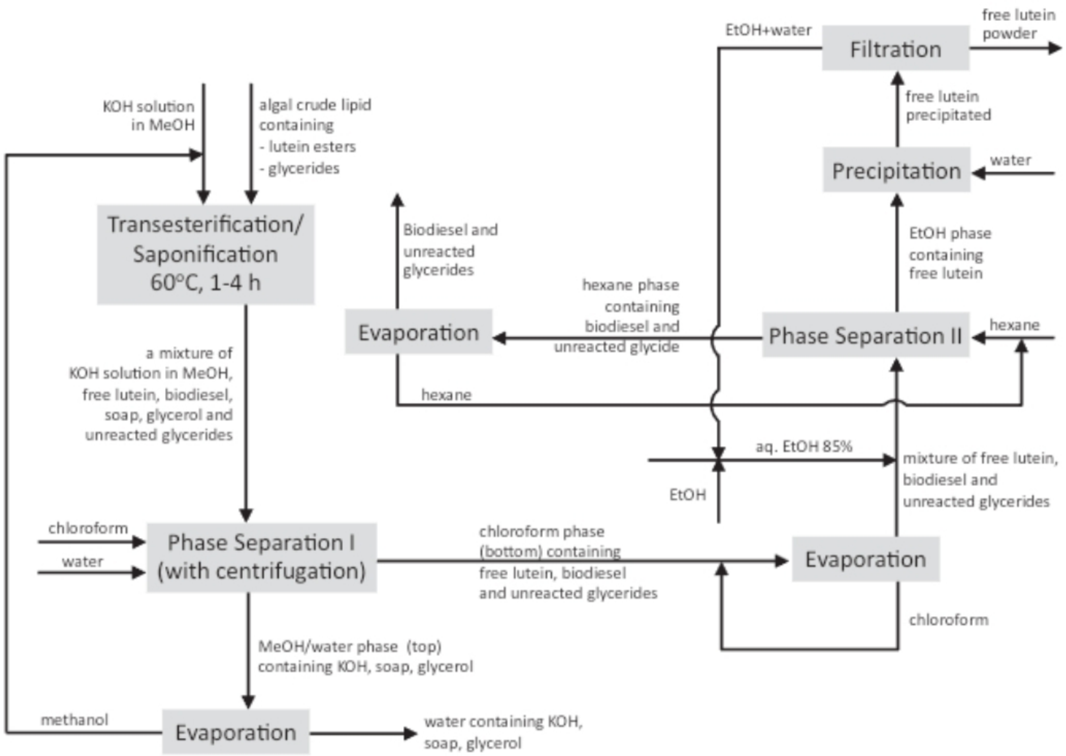

Figure 2: Reaction and separation to produce lutein and FAME biodiesel as presented by Prommuak et al. The final design will incorporate further separations for solvents used in reactions to improve overall functionality.

This project will be completed over the course of two semesters by our 5 person group. Certain aspects, including biodiesel refining and phase separation, will be modeled using the chemical process simulation software Aspen Plus. Since lutein and lipid production are well-established processes, we have access to an abundance of papers to reference and will utilize more specialized sources for each unit operation. To ensure an even distribution of work and timely completion of the project, we will assign team leaders to each process defined in Figure 1. Team leaders will oversee and delegate tasks like selection and calculations on specific operation units, ensuring a balanced workload and schedule flexibility. This approach ensures team members gain familiarity with all process aspects.

The final product of this design project will be a technical report containing material and energy balances, equipment designs, and an evaluation of the proposed process on economic, environmental, and safety grounds. This report will be produced in CHE 4476 in the spring of 2024. This project will align technology, innovation, and environmental responsibility in the pursuit of developing sustainable energy solutions.

Socio-political challenges of transitioning from a fossil-fuel to a biofuel dependent society

In my research during the spring, I will be investigating the socio-political challenges biofuels have faced primarily in the last 15 years. This is an important area of study because understanding the challenges biofuels have faced may facilitate the integration of biofuels as a competitive sustainable energy source in the modern world. Analysis of policy and relevant stakeholder interactions with consumers as well as federal bodies may shed some light as to why other forms of sustainable energy for transportation (primarily clean electricity) have an advantage over biofuels.

Prior to the global financial crisis of 2008, biofuel projects around the world had a great deal of interest and funding. However, the rapid shift in global economy caused much of this funding to be retracted and most projects were abandoned with little to no progress in developing sustainable and competitive methods of biofuel production. For example, Global Clean Energy Holdings Inc. (GCE) invested in cultivating Jatropha in Sucopo on the Yucatan peninsula of Mexico with promises of 15-30 years of cash infusion into the local economy through wages and social programs. However, after a mere five years of poor production and detrimental effects on the local ecosystem and agricultural harvest, GCE backed out of Sucopo and left the community with a lingering sense of disillusionment (Selfa et al., 2015).

Furthermore, post 2008 financial crisis government interest and public opinion of biofuels plummeted when it became clear that further technological advancements were required before biofuel production would be economically competitive with fossil fuels. Prior to 2008, there were numerous acts established in the United States to ramp-up biofuel production. For example, Title XV of the Energy Policy Act of 2005 included a Renewable Fuels Standard that required 4 billion gallons/year (bg/y) of ethanol to be blended into gasoline by 2006 and 7.5 bg/y by 2012 (Hoekman, 2009). Policy drivers such as this have been enormously influential for the production of primarily corn-based ethanol and other first-generation biofuels (biofuels derived from edible plants), but second and third-generation biofuels (ligno-cellulosic and algal based biofuels respectively) have not had the same support despite providing some benefits such as not using valuable edible feedstock and having a much lower arable land requirement than their first-generation counterparts (Lee et al., 2013). Reasons for this disparity in legislation and support stem from lack of infrastructure and technology for biomass processing and separation techniques, but also from geographical concerns specific to third-generation, algal derived fuels. Algae can only grow in warm conditions, and since much of North America experiences harsh winters that would significantly reduce the yearly viable operation period, third generation biofuels have not had the sufficient support to grow as an industry.

In my research, I will primarily take a historical perspective when it comes to analyzing the effect of the financial crisis of 2008 and federal legislation on the success of the biofuel industry in the United Staes. Success of the industry will not only be determined numerically by quantitative production values of biofuels since 2008, but also qualitatively from the changes in composition of the biofuel sector with regards to first, second, or third-generation biofuels.

Conclusion

The global clean energy transition is the foremost challenge that humanity faces in the 21st century. The purpose of this investigation and design proposal is to facilitate innovation in the development of a sustainable method to produce biodiesel from algae. In our technical design, we propose coproducing biodiesel with lutein extract in order to subsidize processing and purification costs. We also propose the novel addition of reusable nano magnetite flocculation in the processing of algal biomass to increase yield while also avoiding expensive chemical flocculants that cannot be retained. I will also conduct research into the socio-political challenges that biofuels have faced in the last 15 years focusing on the effects that the global financial crisis of 2008 had on the biofuel industry and relevant legislative progress. The goal is to develop a thorough understanding of what has limited the growth of the biofuel industry and how these challenges can be overcome so that biofuels can have a place in the more sustainable world of the future.

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