Integrating Freshmen into Exploring the Multi-faceted World of Engineering and Sustainability through Biofuels Synthesis from Waste Cooking Oil

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1. Objectives:

Villanova University's (VU) College of Engineering has taken a fresh toll on how freshmen can be more integrated into exploring the various disciplines in engineering through engagement in hands-on – or what we call experiential - engineering projects. The two-semester program is structured to provide freshmen with the basic fundamentals in engineering while incorporating micro-projects outside the classroom followed by two multidisciplinary engineering projects, also known as freshman mini projects. This paper highlights one of the freshman mini projects that involves biodiesel synthesis from waste cooking oil produced by VU's dining services. Without ignoring the ever-growing importance of sustainability, freshmen are challenged to maximize by-product use through soap making. Coupled with experimental data and design principles, freshmen are then challenged to expand their scope through scale-up of laboratory work to a biodiesel processing plant while incorporating whole systems thinking of sustainability.

2. Introduction:

Well-designed first year experience courses are mainstays in the curriculum for freshman engineering students, as well as for freshmen in other fields. First year courses are building blocks in helping freshmen navigate through and discover a new major. It is imperative for freshmen to be exposed to different engineering disciplines to experience first-hand the expectations and variations among them. Many high school students considering engineering as a major have been equipped with experience in robotics and various software packages. Previously, students transition right into the classroom and are grinded with mathematics and engineering fundamentals at a university. However, newer students do not work that way. They need a reason and motivation to buy into an engineering education, thus an inviting and creative approach is needed early on. Rather than telling students to have faith and wait patiently for their sophomore year, VU's engineering program engages them in their first semester.

VU Engineering has strategized this teaching opportunity through a series of freshman mini projects designed by different engineering majors. The curriculum begins with a seven-week core course that incorporates engineering fundamentals with hands-on group micro-projects that bring classroom lessons to life. Following the core course, the students are presented to select two of six interdisciplinary, hands-on mini projects. These projects expose them to a minimum of two major disciplines, each throughout the second half of the fall and the first half of the spring semester. Mini projects offered include:

- Application of Acoustic Technologies for Predicting Structural Failure
- Biofuels Process and Sustainability: Biodiesel Synthesis from Waste Cooking Oil
- Electric Car Design
- Robotics and MATLAB Programming
- The Load/Deflection Character of a SMARTBEAM
- Adsorption – Drinking Water Treatment Process

By the mid-second semester, students select their intended major discipline and spend the remaining seven-weeks in the chosen disciplinary field.

3. Project Description:

The Biofuels Process and Sustainability mini project, which started in the Fall 2011 semester, was developed with the idea of exposing young freshmen to the latest changes in society. In response to our reliance on non-renewable fossil fuels that have rapidly depleted and caused negative impacts on our environment, our society is slowly transitioning into an era of bioeconomy. In bioeconomy, we attain vital sources of carbon and energy from biorenewable materials, such as biomass. Until our transportation systems are no longer energized by liquid fuels, we will continue to be dependent on carbon-based resources. Thus, it is crucial that the future generation, namely students embrace this transformation. For this to happen, our students first need to learn about the various aspects of bioeconomy.

This mini project has exposed Villanova freshman engineering students to two very important aspects of bioeconomy, namely how transportation liquid fuels can be produced from biorenewable materials and the sustainability issues related to how biofuels are produced and utilized. Specifically, the goal of this project is for students to use basic engineering and chemistry principles to synthesize and characterize biodiesel from a renewable resource, i.e. waste cooking oil from VU's dining services, use the experimental data to design a biodiesel processing plant and finally assess the sustainability of the process.

The 7-week freshman mini project was presented as a combination of lectures and in-class group exercises on various aspects on biofuel production and sustainability. Hands-on laboratory experiments on biodiesel synthesis and characterization, analysis on energy usage and heat transfer of the synthesis process, and the synthesis of soap from glycerin by-product were performed in the weeks following the lectures. Students perform the elementary transesterification of waste cooking oil (WCO) into biodiesel while producing a by-product of glycerin.

From the experiments, students prepared laboratory reports; one on the chemistry and mass balance aspects of biofuels synthesis and the other on the energy and heat transfer aspects of the biofuel synthesis. The report preparation involves conducting technical literature searches, performing data collection, and using spreadsheets to analyze data and perform numerical analysis. In addition to the chemistry and heat transfer aspects of biodiesel production; the element of entrepreneurship is also incorporated in the soap production via glycerol by-product. Students are also exposed to the scale-up of lab synthesis to a commercial level of a biodiesel production facility.

4. Technical Skills involved:

- Mathematics i.e. understanding the use of mathematical equations to explain engineering concepts
- Concept of mass and energy balances
- Concept of sustainability
- Problem solving
- Data collection and analysis
- Introduction to report writing
- Introduction to technical drawing
- Technical report writing
- Scholarly research:
  - Searching technical journal articles
  - Reading and analyzing technical articles

5. Non-technical skills involved:

- Teamwork – conflict resolution, communication, delegating responsibilities
- Project & time management
- Leadership
- People skills
- Ethics
- Oral presentation skills

6. Schedule:

The schedule of learning activities and gained skills from each activity are described in the table below.

Table 1: Schedule of learning activities coupled with gained skills from each lesson week.

Week	Learning Activities	Learned Skills
1	- Introduction to processes of biofuels production and concept of sustainability - Sustainability and carbon footprint: How much CO_2 does my household emit per year? Develop carbon footprint calculator	Concepts on biofuels production and sustainability, carbon footprint, programming using MATLAB, ethics, basic organic chemistry
2	Introduction to mass & energy balances and heat transfer phenomena	Concepts of mass & energy balances and heat transfer phenomena, problem solving & mathematics
3	*Laboratory work*: Synthesizing biofuels and collecting experimental data	Laboratory skills, collecting data, teamwork, time management
4	*Laboratory work*: Characterizing biofuels and collecting experimental data	Laboratory skills, collecting data, teamwork, time management
5	*Laboratory work:* - Analyzing data and using data to prepare a report on energy and heat transfer - Utilizing byproduct: Soap making	Data analysis, math, team work, computation skills, time management, laboratory skills, report writing
6	- Analyzing data and using data to prepare report on chemistry and mass balance - Lecture and in class activity: Concept of entrepreneurship.	Data analysis, math, teamwork, computation, time management, report writing. Concept of entrepreneurship, brainstorming, oral presentation
7	Final presentation: poster and final report	Oral presentation, teamwork, time management, poster preparation, executive summary writing

7. Identification and Description of Multidisciplinary Content:

This freshman mini project focuses on many basic skills necessary for all engineers regardless of their engineering discipline. Understanding the use of mathematical equations in explaining engineering concepts, collecting, analyzing and reporting experimental data and performing scholarly research, including preparing technical reports are important skills all engineers should know and master. Sustainability is a new interdisciplinary (not only within engineering) concept that every future engineer should understand, learn to appreciate as well as apply in his/her area of expertise. The engineering process design of biofuels production from renewable materials involves engineers from various engineering disciplines: chemical, mechanical, civil/environmental, and even electrical.

8. Fundamental Concepts in Biodiesel Synthesis from Waste Cooking Oil

The overall structure of the laboratory work evolves around 4 basic fundamentals. These concepts include:

I. Chemistry behind biodiesel synthesis from Waste Cooking Oil (WCO)
II. Mass and energy balance of biodiesel synthesis
III. Heat transfer phenomena: conduction & convection heat transfer during transient & steady state
IV. Sustainability & entrepreneurship: optimizing use of glycerin by-product and designing a marketing strategy for the soap production in terms of aesthetics, public appeal and consumer preference

With any reaction setup, conditions can no where be ideal. Therefore, freshmen are challenged to incorporate simplifying assumptions for a more holistic and complete analysis of engineering design and reactor setup.

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Concept #1: Chemistry behind Biodiesel Synthesis from Waste Cooking Oil (WCO)

The goal of this experiment is to transesterify waste cooking oil (WCO) obtained from VU's dining services into biodiesel (also known as a Fatty Acid Methyl Ester – FAME) with the help of sodium hydroxide (NaOH) catalyst. While some groups transesterify waste cooking oil, others will transesterify pure canola oil. This is so that at the end of the reaction, the groups will be able to discuss the observation differences in color, layers of separation, heating value, quality of biodiesel, etc.

The reaction takes place in a reactor in the form of an Erlenmeyer flask at 65°C. With the help of the catalyst, NaOH in Methanol (MeOH), this transesterification reaction of waste cooking oil (made from canola oil) / pure canola oil into biodiesel is shortened to an hour. Without the catalyst, the reaction can take up to a couple of days.

In transesterification, NaOH and methanol are mixed to create sodium methoxide (Na^+ CH_3O^-). When mixed in with the WCO, this strong polar-bonded chemical breaks the transfatty acid into glycerine and also ester chains (biodiesel), along with some soap if one is not too careful. The esters become methyl esters. They would be ethyl esters if the WCO is reacted with ethanol instead of methanol. Figures 1-3 show these two reactions. The zigzag lines in the triglyceride diagram (Figure 1) are shorthand for carbon chains. At both ends of each line segment is a carbon atom.

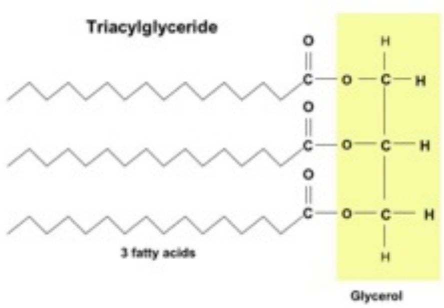

Figure 1: Triglyceride molecule consists of 3 fatty acids and a glycerol. *In Figures 2 & 3, the 'zigzags' in Figure 1 are shorthanded as R_1, R_2 & R_3.

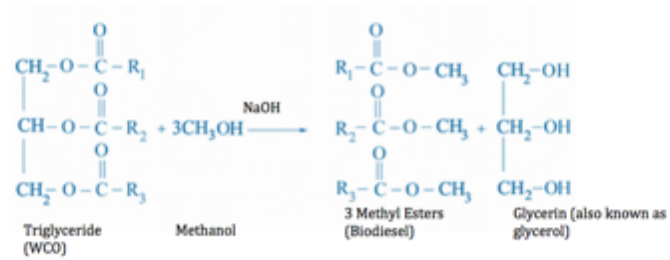

Figure 2a: Transeserification: Reaction of triglycerides (3 fatty acids & a glycerol molecule) with methanol to form methyl esters (biodiesel) and glycerin by-product.

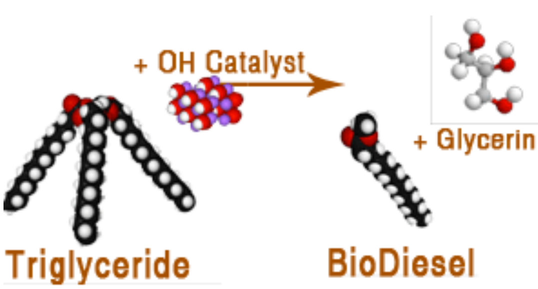

Figure 2b: Pictorial represenation of transesterification reaction of WCO (triglyceride) into biodiesel.

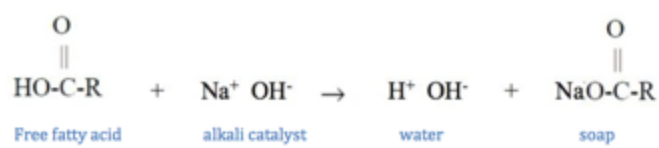

Figure 3: Saponification reaction - reaction of free fatty acid with alkali (NaOH) to form soap.

Concept #2: Mass and Energy Balance of Biodiesel Synthesis

Mass Balance

Mass balances (also known as material balances) are based on the fundamental Law of Conservation of Mass. This law states that the mass of an isolated system will remain constant over time. In other words the mass of the reactants must equal the mass of the products. The setup for the mass balance looks like the following:

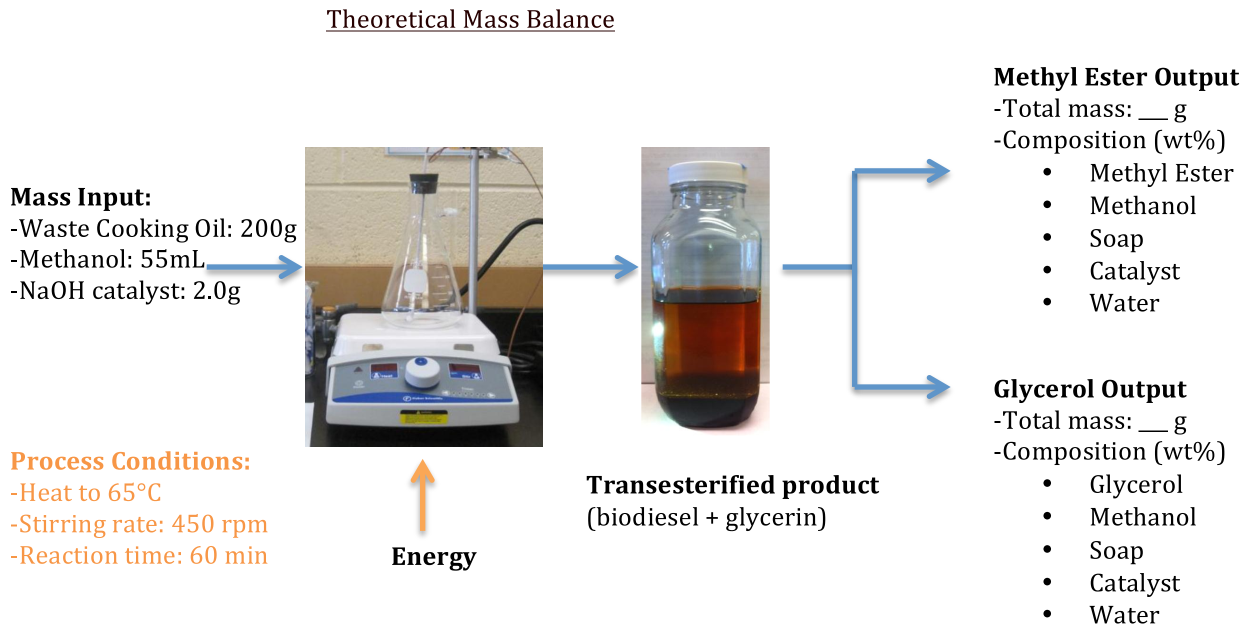

Figure 4: Mass balance scenario of biodiesel production from waste cooking oil.

All vegetable oil are not created equal in which physical and chemical properties are dependent on the fatty acid constituents in the oil. By knowing the percentage of fatty acid in the oil and the molecular weight of triglycerides formed from each type of fatty acid, the average molecular weight of the oil can then be estimated. Then, based on reaction stoichiometry, students can determine the amounts of alcohol and catalyst needed for converting WCO into biodiesel (methyl ester).

Energy Balance

Synonymous to the first law of thermodynamics is Law of Conservation of Energy. This law states that energy can neither be created nor destroyed. Therefore, the sum of all the energies in a system is a constant.

During the biodiesel synthesis process, the electrical power usage and reaction temperature will be recorded manually using a watt meter and infrared thermometer. The data collected will be used to determine the efficiency of the process, both during transient and steady state periods.

The following is a schematic setup of the process:

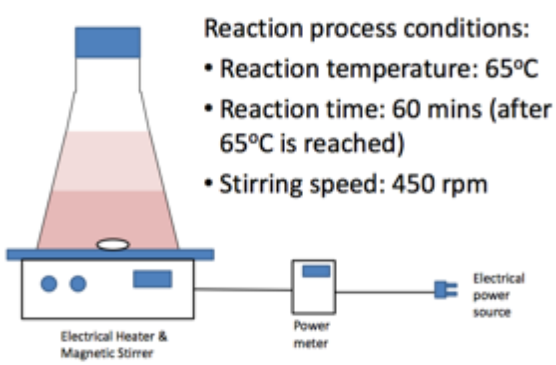

Figure 5: Schematic diagram of reaction setup.

Energy efficiency (%):

$$\eta = \frac{Energy\ required\ by\ process}{Energy\ supplied\ for\ process} \times 100\%$$

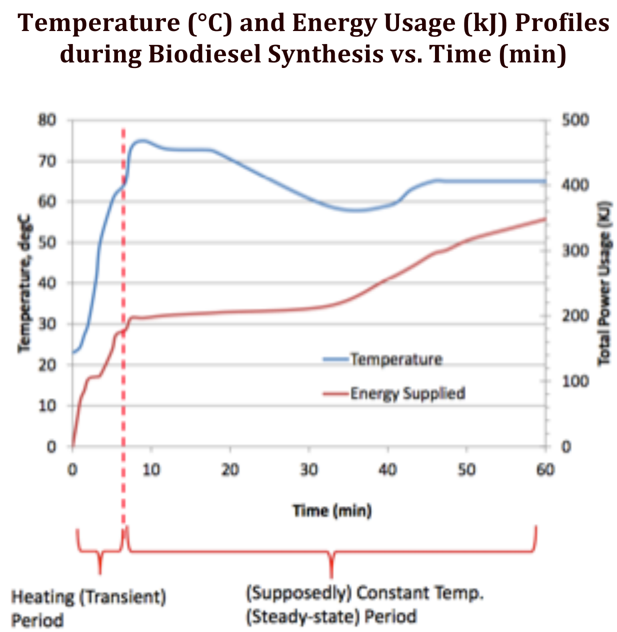

Figure 6: Temperature & Energy Profile of Biodiesel Synthesis over a period of 1 hour (total reaction time)

Concept #3: Heat Transfer Phenomena: Conduction & Convection during Transient & Steady State

Heat is the amount of energy transferred between two objects or substances of varying temperature. Heat only flow is a temperature gradient is present in which one material is warmer than the other or vice versa. Generally, when heat is transferred to a material, the motion of the particles speed up and its temperature increases.

In this section, students are introduced to the three methods of heat transfer, namely, radiation, conduction and convection. Students are challenged to consider the heat transfer events taking place during biodiesel synthesis period through the different methods of heat transfer. Heat transfer will be analyzed at two reaction time periods: (a) Transient state period (heating period) (b) Steady state period (period at constant reaction temperature).

Transient state analysis:

This calculation involves the energy needed to bring reactor to the desired reaction temperature of 65°C.

Basic equation introduced: $Q = m \cdot C_p \cdot \Delta T$

where:

- Q Heat required in Joules
- m Mass in grams
- C_p Specific heat in Joules/gram°C
- ΔT Final temperature – initial temperature in °C

During the biodiesel synthesis time, at transient and steady state periods, heat is released via convection from the surfaces of the reactor and hot plate exposed to the environment (air surrounding the system). Additional energy needs to be supplied to replace the energy loss in order to maintain the system at desired conditions, 65°C. Students are asked to consider experiment/ design modifications to eliminate or reduce energy losses (i.e. insulation).

Heat Losses by Convection
The basic equation introduced is: $Q_{convection} = h \cdot A \cdot \Delta T$
where:

Q	Heat loss in Joules
h	Heat transfer coefficient $\left(\frac{J}{S \cdot m^2 \cdot °C}\right)$ or $\left(\frac{W}{m^2 \cdot K}\right)$
A	Surface area of heat being transferred
ΔT	Surface temperature – environment temperature in °C

Again, students are asked to consider simplifying assumptions to reduce the complexity of the system and also calculations.

Concept #4: Sustainability & Entrepreneurship: Optimizing Glycerin By-product and Marketing Strategy for Soap Production
Every process that is sustainable strives to apply the different elements of eco-efficiency. Two among which include maximizing sustainable use of renewable resources and enhancing the recyclability of materials. In biodiesel production, waste minimization and management is a key issue to consider. Students will be exposed to alternative use of glycerin by-product in which soap can be made by the addition of more lye.

The process of making soap is called saponification. In saponification, fatty acids are combined with alkali (NaOH) to make soap. Since glycerol that is 'freed' from the WCO when producing biodiesel contains a mixture of glycerol, soap, methanol, and some saponifiable elements (monoglycerides, diglycerides & free fatty acids), the glycerol by-product layer can be made into soap. This only happens after methanol, which is toxic, has been removed via evaporation at its boiling point of 65°C.

The resulting glycerol by-product soap will contain much more glycerol than soap produced with traditional methods. A normal soap containes 10-15% glycerol whereas a glycerol by-product soap can contain from 40-80% glycerol. This extra glycerol leads to a sweaty and somewhat soft bar of soap. In most cases, the bar soap formed will have little latherability. Therefore, the element of entrepreneurship is introduced to make the glycerin bar soap more appealing to a consumer. Among some steps that are implemented to perfect the bar of soap in terms of hardness and latherability include adding saturated fats such as cocoa butter, vegetable shortening and coconut oil. Aesthetics play an equal part in the marketability of a product. As a result, different scents and coloring are added to mask the dark colored, 'french-fry' smelling bar of soap.

The following are some end products of bar soaps produced with the glycerin by-product:

Figure 7a: Different scented & colored glycerin by-product bar soaps made by students.

Figure 7b: Lavender scented glycerin by-product bar soaps wrapped in organic soy paper and recycled paper ribbon.

Figure 7c: Wrapped Orange Valencia & Moroccan Mint scented glycerin by-product bar soap with added button for 'Recycling' theme

Figure 7d: Key lime pie scented glycerin by-product soap.

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9. Recruiting platform for Student-run Villanova Biodiesel Program

The freshman engineering project on biofuels was also developed in conjunction with the on-going student-run Villanova Biodiesel program in the Department of Chemical Engineering. In the 2-year old biodiesel production program, students operate a biodiesel production facility located in the Department of Chemical Engineering's Unit Operations laboratory to convert waste cooking oil into biodiesel, which is now powering diesel-run lawn mowers on campus. The production facility has the capacity to process approximately 50% of the estimated 7000 gallons of waste cooking oil produced from VU dining services yearly. Currently, only about 10-15% of the waste cooking oil is processed for biodiesel production. In order to increase the capability of the facility to produce more biodiesel, increased student participation is needed. The next phase of the project is to provide fuel for other diesel vehicles on campus. VU also has received a permit from the state that will make biodiesel available for campus vehicles that use public roads. Thus, the proposed mini project can serve as a recruiting platform by introducing new freshman engineering students to various aspects involved in biodiesel production.

Figure 8: Nalgene hoppers used for biodiesel separation from glycerin by-product

Figure 9: Batch reactors used for transesterification of waste cooking oil (WCO) into biodiesel

10. Conclusion

All activities related to biofuels production and process plant design are not only constrained to chemical engineering, but extend to areas of other engineering disciplines as well. They include mechanical, civil, environmental and electrical engineering. The development of a chemical processing facility is a highly interdisciplinary engineering effort, which requires the expertise of all major engineering disciplines.

Overall, the freshman mini project is geared to motivate freshman engineers to consider and recognize engineering design and development in daily life. Apart from introducing students to a variety of engineering design and development tools, the mini projects have been a seed in helping students decide early on in their journey for a successful undergraduate career.

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