RESEARCH

A SUSTAINABLE LOW COST PROCESS FOR THE PRODUCTION OF BIODIESEL SUITABLE FOR UNDERDEVELOPED REGIONS

Wesley Whipple, Bradley Butler, Christopher Sterrie, and Jeffrey Seay, PhD, PE[1]

ABSTRACT

Access to fuels for transportation and electric power for buildings is a critical component for prosperity. Reliable sources of energy are often difficult to access in rural or underdeveloped regions. Although developing countries in tropical regions are often rich in biological resources, such as biomass and oil seeds, however, extreme poverty, lack of an educated populace and an absence of a reliable manufacturing infrastructure mean that these resources go largely untapped. This contribution will describe the design of a promising prototype for an appropriate technology for the sustainable, low-cost production of biodiesel and its required raw materials from locally available materials and feed stocks.

The biodiesel processor will be fuelled by wood or charcoal, consist of no moving parts and utilize passive temperature control. This novel process will be safe, easy to operate and suitable for individual or community scale production. The project described herein has been developed in collaboration with the African Centre for Renewable Energy and Sustainable Technology (ACREST), an NGO in Cameroon. Further, the implementation of this process by a student team in Bangang Village, Cameroon in sub-Saharan Africa will be described. This project is part of a student led People, Prosperity and the Planet design project, sponsored by the U.S. Environmental Protection Agency.

KEYWORDS

Biofuel, Cameroon, sub-Saharan Africa, Appropriate Technology, Palm Oil

IMPLICATIONS

Access to energy for transportation and electric power for home and commercial use is vital for community development and improved standards of living. In underdeveloped countries extreme poverty and the lack of a manufacturing infrastructure means that reliable and affordable energy is often unavailable in rural communities. This can lead to a lower quality of life for people in rural or remote regions. Since the predominant liquid fuel used in sub-Saharan Africa is diesel, a renewable liquid fuel like biodiesel can be a viable option. This project can improve the availability of biofuel processing in the developing world, improve community wellbeing and minimize the environmental impacts of the use of liquid fuels.

[1]College of Engineering, University of Kentucky, Paducah, Kentucky, 42002, jseay@engr.uky.edu.

INTRODUCTION

Energy from Biodiesel in Underdeveloped Regions

In developing regions, particularly in remote or rural communities, the lack of access to reliable energy can actually increase the strain on the environment (Khavul and Brunton, 2012). For example, currently, 60% of the energy needs in Africa are met with wood, the availability of which is threatened by deforestation (Webersik and Wilson, 2009). Previous studies have concluded that so called "off-the grid" technologies for producing energy are growing in sub-Saharan Africa (Khavul and Bruton, 2012). However, technologies like car batteries are expensive and unsustainable and advanced technologies like solar panels are often too complex to be practical (Khavul and Bruton, 2012). Fortunately, there is another option. Due to the availability of agricultural resources in regions like sub-Saharan Africa, biofuels like biodiesel can be a viable alternative for providing fuel for power and energy. In areas with no or unreliable access to electricity, the availability of sustainable liquid fuels like biodiesel can make generators a viable means of producing electric power, and provide mobility through use as a transportation fuel. Unfortunately, in areas with unreliable or expensive electricity, the production of biodiesel is complicated due to the typically used traditional manufacturing processes which rely on vigorous mixing and precise temperature control. Additionally, in countries like Cameroon, the average per capita income is about $2,300 per year and 42% of the population lives below the local poverty line (CIA, 2012). The poorest one-third of the population of Cameroon lives on less than $1.25 per day (CIA, 2012), making access to certain types of energy impractical, in particular liquid fuels. This economic situation is typical for sub-Saharan Africa. Therefore a safe, rugged, simple, replicable, efficient and affordable processor for making biodiesel that can be built from locally available materials is needed. Biodiesel is an attractive fuel source in developing regions due to the prevalence of diesel powered generators and vehicles. Other locally produced energy sources like biogas are simply not practical for fuelling vehicles for transportation or generators for building power. Furthermore, the chemistry for producing biodiesel is well understood, the process is fairly flexible and the product is a reliable, sustainable fuel source. The vegetable oil used as the primary raw material for the production of biodiesel can be obtained at minimal cost in sub-Saharan countries like Cameroon—particularly if wild growing oil seeds like jatropha or castor are used. Although biodiesel can be produced in considerable quantities with available resources, in order to be appropriate for the region, the methods of construction and operation of the processor used to make the biodiesel needs to be simple and easily replicated due to the lack of infrastructure and the minimal technical training available for the biodiesel process operators. In addition the biodiesel reactor must be constructed of materials that are easily obtained at low cost.

In the United States, home processing of biodiesel on an individual scale is becoming quite popular. Open source designs such as the Appleseed processor are commonly used by small scale producers (Alovert, 2004). Using this design, small scale manufacturers can produce biodiesel from vegetable oil in a well-mixed batch reactor with a controlled temperature of 50–60°C. This is accomplished using electric heating, a circulation pump to mix the reactants, and an insulated reaction vessel. Due to the unreliable nature of the electricity in underdeveloped regions and the limited availability of construction materials, this method of producing biodiesel is impractical and economically prohibitive. To address this challenge, a novel prototype biodiesel processor where the heating requirements are met with wood or charcoal instead of electricity, passive temperature control is used and no moving parts are required has been proposed. Additionally, in order to be practical, the processor must be made from locally attainable materials such as used steel drums, junkyard car parts, and locally available plumbing supplies.

Sustainability and Appropriate Technology

The development of this biodiesel process will rely on the application of appropriate technology. Appropriate technology (AT) is a decades old movement based on adapting technologies on a small scale to improve the standards of living in rural, impoverished or underdeveloped communities. In recent years, AT has been seen as a way of achieving the societal benefits of sustainability. In areas where large scale deployment of a power distribution infrastructure are impractical—due to remote location or lack of financial resources—renewable energy technology based on the principles of AT fill the gap. The principles of AT will be applied to the production of biodiesel for use as a liquid fuel for power generation or transportation. This means that the process design will be constrained to locally available construction materials and feed stocks, simple construction techniques, and low tech operation. In many cases, this will mean sacrificing efficiency for reduced cost and simpler operation, but the benefits will be an affordable technology that is appropriate for underdeveloped communities—particularly in sub-Saharan Africa.

Sustainabile Community Development

In its 1987 report titled *Our Common Future*, the U.N. World Commission on Environment and Development, also commonly called the Bruntland Commission, defined sustainable development as follows:

> "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (Brundtland, 1987)

This definition has been broadened to encompass development that is environmentally benign, economically viable and socially equitable. In developed economies, however, it can sometimes be difficult to illustrate the benefits of switching to a sustainable source of energy on a community. When energy for transportation and buildings is easily accessible, and the potential benefits of switching to renewable sources of energy are in the future, making the case for switching away from fossil fuels is a challenge. In other words, in developed economies, it is difficult to make the case that the basic standard of living in a community will be improved through the use of sustainable fuels. In underdeveloped regions however, the community benefits of renewable energy are immediately apparent. In places like rural sub-Saharan Africa, a modern infrastructure for delivering energy does not exist. Even in areas where an electrical grid does exist, 20–25 percent of the population still doesn't have electricity (Khavul and Bruton, 2012). Furthermore, large scale projects to build or expand fossil fuel based power plants are simply impractical. Because of this, approaches that have been used successfully in fully developed countries, like LEED building standards and solar power, simply are impractical in rural, underdeveloped regions. Therefore, a focus on small scale renewable energy projects based on applications of appropriate technology can have an immediate impact on improving the quality of life for individuals in underserved communities. According to the World Bank, better access to energy improves all aspects of life, from education, access to information and security (World Bank, 2008). Providing this energy to underdeveloped communities in a way that is simple, low cost and sustainable is key challenge. Therefore, the primary broader impact of research is the development of small scale and affordable processes for generating liquid fuels that will have an immediate impact on communities.

Finally, biodiesel has a positive impact on the global environment due to a reduction in greenhouse gas emissions versus petroleum diesel. Research on the use of biodiesel as a transportation fuel in India by the U.S. National Renewable Energy Lab has shown that using a blend of 20% biodiesel with petroleum diesel can reduce greenhouse gas emissions by 12% (Whittaker and Heath, 2009). Biodiesel also has negligible sulfur content, so SO_X emissions are also reduced versus petroleum diesel. This is particularly important for regions with no or lax regulations on sulfur emissions.

RESEARCH OBJECTIVE

The primary objective of this project is to develop low-cost, environmentally benign technology for producing biodiesel suitable for use in developing regions without using electricity or electronic controls. The process equipment for producing biodiesel must include a biodiesel processor designed on a scale to serve individuals or small communities. Due to the lack of reliable electricity and a manufacturing infrastructure, the process must be developed in such a way as to not require electricity or moving parts. The equipment must also be easy to construct, rugged, replicable, efficient, and affordable. The overall cost to construct the biodiesel processing unit must be low (typically less than 100 USD), construction materials must be readily available and construction methods must be simple and easily explained to people without formal technical training. The purpose behind this economic constraint is to give accessibility to even the poorest one-third of the population of developing countries like Cameroon.

These characteristics are critical to the design due to the constrained conditions by which the processor will be produced and operated. The development of the biodiesel processor was initiated by the African Centre for Renewable Energy and Sustainable Technology (ACREST), in Cameroon in Africa to fulfil their need for a low cost, locally available fuel source. The development of a prototype biodiesel processor has been carried out in collaboration with ACREST. The processor is intended to be produced by technicians at the ACREST facilities in Bangang Village in Cameroon, so it must be easily fabricated and utilize locally available materials. Lastly, the process is intended for operation by individuals with limited technical training, so it must be simple and safe. The proposed process described in the following sections has been developed and validated with a series of laboratory experiments and a prototype processor has been field tested in Cameroon.

BIODIESEL BACKGROUND

Biodiesel Chemistry

While vegetable oils such as soy, jatropha, palm and castor, or animal fats can be used as a fuel, the viscosity of pure vegetable oil is about 11–17 times higher than diesel fuel (Meher, *et al.*, 2006). This can affect the flow properties of the fuel, such as spray atomization, consequent vaporization, and air-fuel mixing in the combustion chamber. These operating conditions lead to adverse effects on the combustion process (Ranadhas, *et al.*, 2005). The results of this are excessive engine deposits and thickening of lubricating oil (Silvio, *et al.*, 2002).

Biodiesel, which is a chemically altered vegetable oil, can be used in a diesel combustion engine with little to no modification to the engine or the fuel injection system. Normally, biodiesel is produced by a chemical process called transesterification, illustrated in chemical equation 1. Chemically, vegetable oil is a mixture of triglycerides.

$$\text{Triglyceride} + 3\,[\text{R-OH}] \leftrightarrow \text{Glycerol} + R_1\text{-COOCH}_3 + R_2\text{-COOCH}_3 + R_3\text{-COOCH}_3 \qquad (1)$$

This process utilizes naturally occurring triglycerides, the primary components in vegetable oils or animal fats, an alcohol (R-OH), usually methanol or ethanol and a base catalyst, usually sodium hydroxide or potassium hydroxide. The stoichiometric reaction requires one mole of triglyceride to three moles of alcohol in order to form three moles of biodiesel (R_1-$COOCH_3$, R_1-$COOCH_3$, R_1-$COOCH_3$), chemically a fatty acid methyl ester (FAME), and one mole of glycerol in the presence of a strong base or acid catalyst (Muniyappa, *et al.*, 1996). This reaction consists of a sequence of consecutive reversible reactions where triglycerides are converted to fatty acid methyl esters (FAME), diglycerides, monoglycerides and finally to glycerol. The chemical reaction results in the production of crude biodiesel because soap is also formed as a side product. This soap has to be removed from the final product by water washing before the biodiesel is suitable for use as a motor fuel. The unreacted methanol can be recovered from the glycerol and the resulting methanol-free glycerol can serve as a valuable co-product, such as in the production of soap, by traditional methods (Lewis, 1993), or as a binder in the production of charcoal briquettes.

Transesterification is a slow reaction, but it can be accelerated by the presence of an acid or base catalyst. The base catalysed reaction is much faster and is less corrosive than acid catalysis, and is the most commonly used in commercial processes (Ma and Hanna, 1999). Suitable alcohols used in this reaction include methanol, ethanol, propanol, butanol, and amyl alcohol. The most commonly used alcohol is methanol (MeOH), due to its low cost and its physical and chemical advantages (Ma and Hanna, 1999). Although MeOH is not readily available in Cameroon, it can be recovered by collecting and distilling the wood gases released during the production of charcoal by traditional methods. The most commonly used base catalysts are sodium hydroxide (NaOH) and potassium hydroxide (KOH) (Van Gerpen, 2005). However other easily obtained bases that can be used as a catalyst include, but are not limited to slaked lime, $Ca(OH)_2$, and potash (K_2CO_3) which are readily available in countries like Cameroon where they are used in traditional cooking.

Traditional Manufacturing Process

In typical biodiesel production processes, the reaction ingredients are heated to 55°C and vigorously mixed in a batch reactor. The heating increases the rate of reaction and the mixing improves the contact between the oil and alcohol phases in the mass transfer limited reaction. The 55°C requirement is based on the fact that the methanol will boil off at higher temperatures. The oil and alcohol used are immiscible and mixing improves contact between the phases, thus increasing the rate of reaction. The operating requirements present challenges for the production of biodiesel in rural settings in the developing world. First, mixing the reaction batch requires either the addition of an internal mixing mechanism or the use of an external circulating pump. Either option requires cost prohibitive additional equipment such as an agitator or pump that typically requires electricity to operate. Second, for operation in underdeveloped communities, equipment and instrumentation required to maintain a temperature of 55°C is prohibitively expensive. These complicating factors require a rethinking of the process for adaptation in places like Cameroon.

A Simplified Process Based on Appropriate Technology

Because of the many technical challenges involved in producing biodiesel, a new operating regime is proposed: increasing the reaction temperature to 100°C and carrying out the reaction in an unmixed, insulated, batch reaction vessel. The 100°C temperature requirement will be achieved by using a "double boiler" reactor design whereby the sealed batch reaction vessel is submerged in a larger vessel filled with boiling water, which has a normal boiling point of 100°C. The larger vessel will be heated in an insulated wood or charcoal fuelled oven. The elevated temperature (above 55°C) will cause the alcohol in the vessel to boil off. To address this problem, the reaction vessel will be fitted with an air cooled reflux condenser to return the vaporized methanol to the reaction vessel. As described, this design has no moving parts, eliminates the need for electronic temperature control, and does not require electricity. This novel, simplified production method has been validated with a set of controlled laboratory experiments as well as proof-of-concept field trials in Bangang Village, Cameroon, which are described in the following sections.

MATERIALS AND METHODS

A laboratory procedure has been developed to validate the proposed operating conditions for the low-cost, simplified biodiesel process. Reagents and solvents required for the laboratory validation experiments included:

- Virgin food grade soy bean oil purchased from a bulk supplier
- Fisher brand biotech grade methanol
- Fisher brand HPLC grade n-heptane
- Red Devil brand Potassium Hydroxide (90% purity)

The experiments were conducted in the laboratory facilities at the Department of Chemical Engineering, University of Kentucky, Paducah Extended Campus.

In the production of biodiesel by base-catalysed transesterification, MeOH was chosen because it can be made alongside the biodiesel by low-tech methods such as through the collection of wood gases from charcoal making by traditional methods. KOH was chosen because it can be easily made by running water through the ashes of hard woods. Villagers in Cameroon have extensive experience with this process due to its widespread practice in traditional cooking. Base catalysed transesterification was chosen over acid catalysed esterification due to the increase in reaction speed.

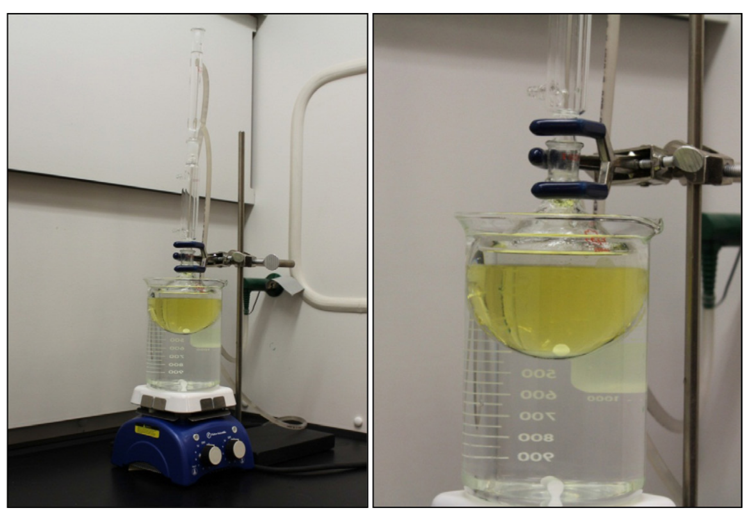
The main factors affecting the transesterification process are the concentrations of MeOH and KOH and the reaction time. In order to find the optimal ratios of reactants and reaction time, experiments were conducted with varying MeOH-to-oil and KOH-to-oil ratios. Each of these experiments was sampled at 15 minute intervals over a total reaction time of 45 minutes.

The reactor design for this project is novel in that no mechanical mixing is used during the reaction, and that a boiling water bath is used for temperature control. In Cameroon, wood or charcoal can be used as a heat source in order to boil water. The reaction vessel in turn is simply placed in the water to maintain a constant reaction temperature of 100°C. The 100°C reaction temperature will cause the MeOH to vaporize. It will then be condensed using a knock back condenser. The velocity of the MeOH as it re-enters the reaction vessel allows it to penetrate the interfacial barrier created by the phase separation between the oil and MeOH. In addition as FAME is produced along the interfacial boundary, glycerol is also produced. The glycerol, along with dissolved MeOH will then sink to the bottom of the reaction vessel. As the glycerol sinks, the MeOH contained in the mixture vaporizes due to the reaction temperature, causing MeOH vapor bubbles to rise through the oil phase. The vaporized MeOH has increased surface area in which to react with the oil to make more FAME, further propagating the reaction and facilitating mixing. Eventually the two phase solution will achieve an equilibrium that allows the mixture to become a single bulk phase without the addition of mechanical mixing.

The experimental setup was constructed using laboratory glassware. A 150 mL round bottom flask was filled with 50 ml of oil and placed in a boiling water bath. The boiling water ensures an operating temperature of 100°C and closely models the pilot scale reactor that will be used in the field. Before beginning the reaction, the required amounts of catalyst and MEOH were mixed and dissolved completely. The oil was warmed in the water bath prior to the introduction of the MeOH catalyst mixture. A sample of the oil/FAME phase was taken from the reaction vessel at fifteen minute intervals. Once the oil reached operating temperature the catalyst and MeOH mixture was added. A water cooled knock back condenser was used to ensure that as the MeOH vaporized it was reintroduced to the system. As the reaction moved towards completion, the boundary between the two-phase mixture would begin to become less defined. Eventually the two phase mixture would reach a critical point and become completely mixed in a bulk solution. A photo of the experimental apparatus is shown in Figure 1.

Samples from the reactor apparatus were analysed using gas chromatographic analysis performed on a Hewlett Packard 5890 Series II GC equipped with a Phenomenex Zebron ZB-5HT column (15m × 0.32 mm × 0.10µm) with a 2 m × 0.53 mm spliced guard column and a flame ionization detector. The analytical method used included an injector temperature of 200°C, a detector temperature of 380°C and a split ratio of 100 : 1. The temperature profile recommended by the column manufacturer was utilized for the GC oven (Nguyen, *et al.*, 2008). The temperature profile is as follows: 50°C for 1 min to 180°C @ 15 °C/min to 230°C @ 7°C/min to 380°C @ 30°C/min for 10 min. Ultra high purity helium was used as the carrier gas and the hydrogen required for the Flame Ionization Detector (FID) was generated on site using a Parker Balston H2 1200 Hydrogen Generator.

FIGURE 1. Photo of laboratory apparatus for biodiesel experiments.



Analysis was performed by diluting the biodiesel sample in n-heptane at a 1:10 ratio and injecting 1 μl of this solution mixture into the gas chromatograph. The analytical grade n-heptane solvent was used as an internal standard for the analysis of the integrated results. The chromatogram peak areas were calculated using a Hewlett Packard 3396 Series II Integrator. The actual percentage of FAME and unreacted oil was calculated using the actual sample to n-heptane dilution ratio as a correction factor.

$$C = \frac{A}{\frac{\sum A}{A_T} / \frac{m_B}{m_T}} \quad (2)$$

Where: C = Corrected FAME content (%w/w)
$\sum A$ = total FAME peak area from chromatogram
A_T = total area from all peaks
A = Area under the curve of the peak of interest
m_T = total mass of the prepared sample
m_B = mass of biodiesel in prepared sample

The experimental results were then analysed using Response Surface Methodology (RSM), which can be applied in the research of complex variable processes (Meyers and Montgomery, 2002). Multiple regression and correlation analysis have been shown to be useful tools in determining the effects of two or more independent factors on the dependent variables of a process, particularly in the production of biodiesel (Boonmee, *et al.*, 2010). The use of a factorial design can be applied to reduce the number of experimental runs needed to produce statistically significant results. RSM has been applied to optimize the alkali-catalysed transesterification of soy bean oil to produce FAME as a function of three factors:

- Factor 1—MeOH to oil ratio
- Factor 2—Catalyst concentration
- Factor 3—Reaction time

A three factorial design of experiments was employed in this study resulting in nine experiments; samples were drawn at 3 time intervals. The results were statistically analysed using the Minitab (Minitab, 2011) software program in order to produce response surfaces. The independent variables of time, catalyst concentration, and methanol-to-oil ratio were selected to optimize the conditions for yield and selectivity for FAME production of KOH catalysed transesterification. Two replications were carried out for all experimental design conditions and the average results reported, minimizing the chance for experimental error. The central values chosen for the experimental design were a MeOH-to-oil ratio of 1:5 by volume, a 0.275 g/ml catalyst concentration, and a 30 min reaction time. Experimental conditions are listed in Table 1.

EXPERIMENTAL RESULTS AND DISCUSSION

The results from these proof of concept experiments indicated that a high reaction yield can be achieved using the process described above. The mass transfer limitations due the immiscibility of the alcohol phase and the oil phase are counteracted by the increased temperature. These results indicate that the process will be suitable for biodiesel production under the conditions described in Cameroon.

TABLE 1. Experimental Design and Results.

Experimental Design				Variable Values			Results	
Experiment Number	Factor 1	Factor 2	Factor 3	Methanol to Oil Ratio	Catalyst Mass (grams)	Time (minutes)	FAME %	STDEV
1	1	1	–1	30%	0.3625	15	89.67%	9.51%
2	1	1	0	30%	0.3625	30	94.35%	2.45%
3	1	1	1	30%	0.3625	45	95.04%	1.13%
4	1	0	–1	30%	0.2750	15	83.76%	4.48%
5	1	0	0	30%	0.2750	30	93.85%	1.61%
6	1	0	1	30%	0.2750	45	93.15%	1.72%
7	1	–1	–1	30%	0.1875	15	84.50%	3.75%
8	1	–1	0	30%	0.1875	30	89.06%	4.22%
9	1	–1	1	30%	0.1875	45	89.36%	3.47%
10	0	1	–1	20%	0.3625	15	96.96%	1.73%
11	0	1	0	20%	0.3625	30	98.09%	0.88%
12	0	1	1	20%	0.3625	45	95.38%	1.27%
13	0	0	–1	20%	0.2750	15	88.85%	4.01%
14	0	0	0	20%	0.2750	30	93.52%	1.89%
15	0	0	1	20%	0.2750	45	94.36%	1.35%
16	0	–1	–1	20%	0.1875	15	91.46%	3.11%
17	0	–1	0	20%	0.1875	30	93.70%	1.61%
18	0	–1	1	20%	0.1875	45	94.39%	0.78%
19	–1	1	–1	10%	0.3625	15	91.63%	3.04%
20	–1	1	0	10%	0.3625	30	91.13%	3.42%
21	–1	1	1	10%	0.3625	45	90.46%	3.29%
22	–1	0	–1	10%	0.2750	15	91.43%	2.30%
23	–1	0	0	10%	0.2750	30	91.94%	2.98%
24	–1	0	1	10%	0.2750	45	90.45%	2.22%
25	–1	–1	–1	10%	0.1875	15	89.78%	1.65%
26	–1	–1	0	10%	0.1875	30	90.56%	2.44%
27	–1	–1	1	10%	0.1875	45	91.14%	3.08%

The reactions were carried out by varying the methanol to oil ratio in the reaction vessel, the mass of catalyst added and the reaction time. All the reactions were conducted at 100°C, the boiling point of water. Experimental results are given in Table 1. It was observed that the alkali-catalysed transesterification was able to convert quickly and that nearly complete reactions could occur within 15 minutes, however even greater conversion was achieved as time was increased, but with diminishing returns. Contour plots of the experimental results showing the interactions among the experimental variable are illustrated in Figures 2, 3 and 4. Additionally, results show that a methanol concentration of 20% by volume, which is about double the stoichiometric quantity, is optimal, and the reaction is essentially complete after 35 minutes of reaction time.

FIGURE 2. Contour plot showing Reaction Percent Conversion as a function of methanol concentration (%) versus Time (min).

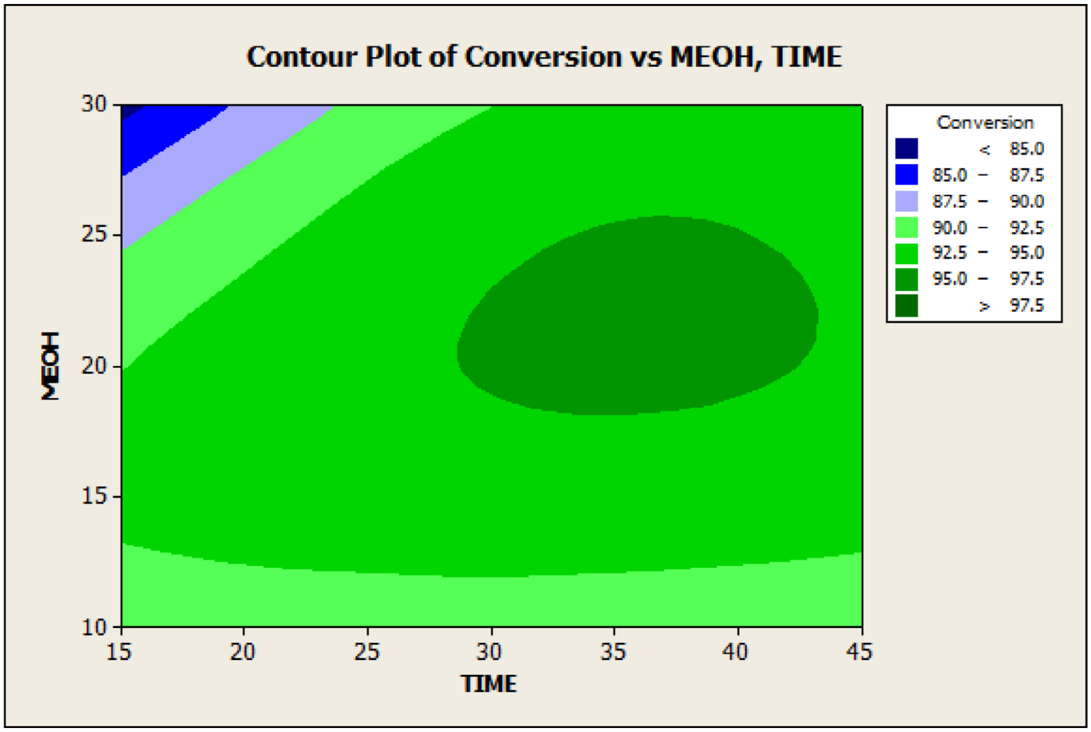


FIGURE 3. Contour plot showing Reaction Percent Conversion as a function of Catalyst Concentration (g/50 mL) versus Time (min).

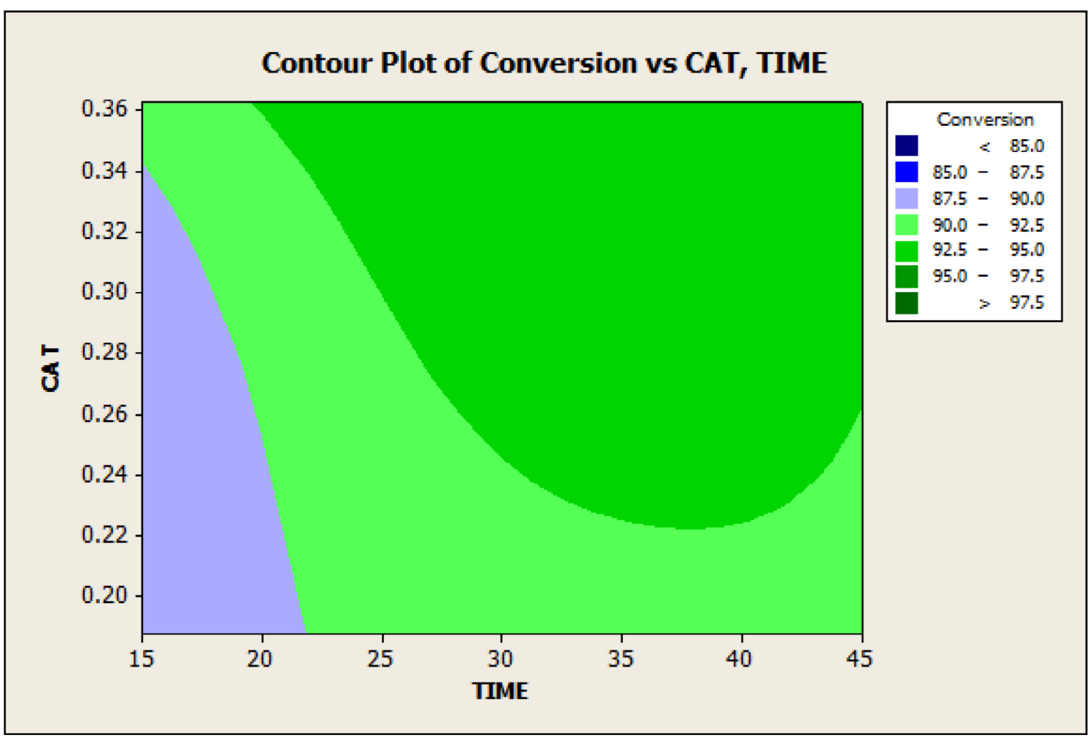
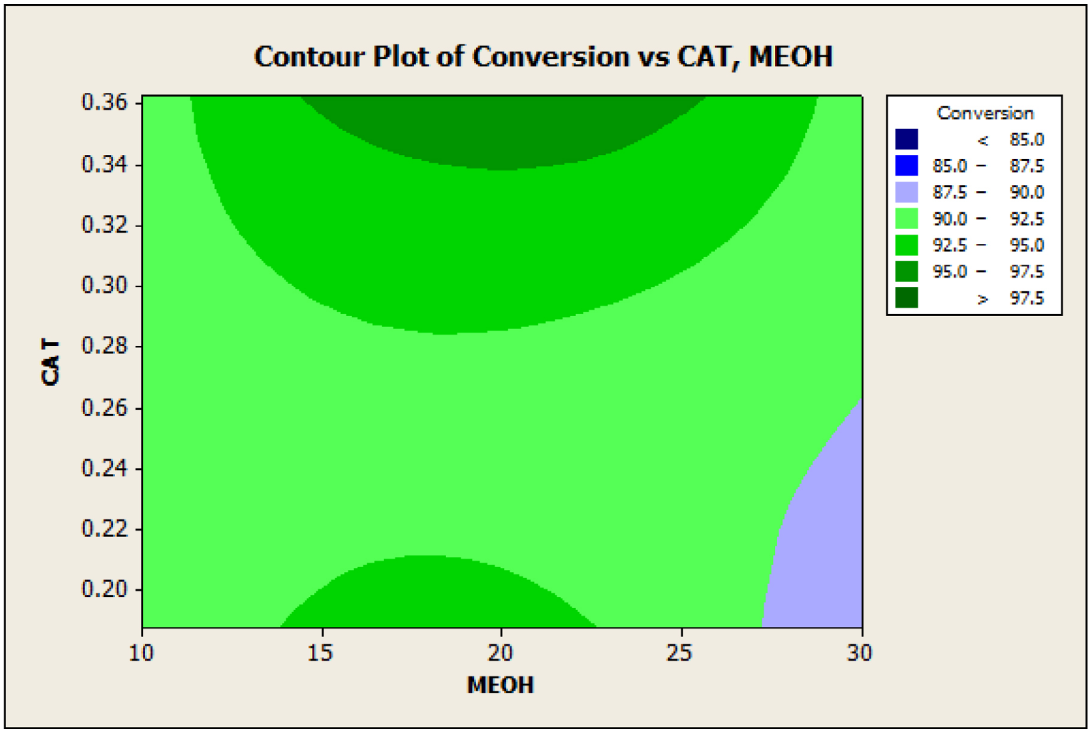


FIGURE 4. Contour plot showing Reaction Percent Conversion as a function of Catalyst Concentration (g/50 mL) versus Methanol Concentration (%).



The experimental results indicate a significant improvement in reaction time over previous studies (Boonmee, *et al.*, 2010). Conversions over 95% are possible within 30 minutes of reaction time. Optimal reaction results are achieved under the following conditions:

- Catalyst concentrations of 7.25 grams/liter
- Methanol concentration of 20% by volume, which is approximately equivalent to 2 times the stoichiometric ratio.

Under these conditions, the highest levels of conversion are achieved between 30 and 45 minutes of reaction time. The authors conclude that the increased reaction temperature overcomes the mass transfer limitations caused by lack of vigorous mixing. Due to its simplicity, this process is appropriate for low cost processing in underdeveloped communities.

VALIDATION OF THE BIODIESEL PROCESS IN CAMEROON

The biodiesel production process described above has been field validated in Bangang Village in Cameroon, in sub-Saharan Africa at the request of, and in collaboration with the African Centre for Renewable Energy and Sustainable Technology (ACREST). ACREST is an NGO focused on developing and promoting renewable energy, sustainability and appropriate technology to combat poverty, deforestation and resource depletion. ACREST operates a technology and training centre in Bangang Village where skilled technicians design and build products that adhere to ACREST's stated goals. Additionally, the ACREST staff will train local villagers to safely operate the biodiesel processor. Producing biodiesel in a low-cost processor using locally available building materials and feedstocks is a project that fits well with ACREST's mission. In recent years, ACREST has partnered with U.S. universities to develop appropriate and sustainable technologies for people in the region. One of these projects includes the development of a diesel powered Basic Utility Vehicle (BUV), which was created in partnership with Purdue University (Purdue, 2011), (Lumkes, 2012). The BUV project has provided additional incentive for developing a low-cost process for producing fuel for the vehicle. Therefore, the challenge is to develop a biodiesel process that can not only provide a renewable biodiesel fuel for the vehicle using Cameroon's locally available natural resources, but is safe, reliable, easy to operate and low cost.

FIGURE 5. Building supplies for biodiesel processor in Cameroon.

The materials of construction for the prototype biodiesel processor built at the ACREST facility were limited to used steel drums, scrap metal, junk yard automobile parts and basic plumbing supplies. See Figure 5. Only basic welding and machining equipment is available at the ACREST facility, so all fabrication was kept as simple as possible. The basic design consists of an insulated wood or charcoal kiln, which is used for heating, a water bath for temperature control, the batch reaction vessel and a car radiator, which is used as the reflux condenser. A schematic sketch of the processor is illustrated in Figure 6. Photographs of the 20 liter prototype reactor built at the ACREST facility in Cameroon using the process described herein are shown in Figures 7 and 8. Although the chemistry required to convert vegetable oil to biodiesel is fairly flexible, the "recipe" was converted into a set of simple instruction to make it easier for local villagers to reproduce.

The vegetable oil used for testing the prototype at the ACREST facility in Cameroon was palm oil, which is abundant in the region. The freshly pressed palm oil does need to be filtered by running it through a cloth prior to use, but as long as fresh oil is used, no titration to determine the free fatty acid content is required. Calcium oxide solid dissolved in water was used as the base catalyst for the initial trials. KOH extracted from wood ashes was used for subsequent trials. Extracting KOH from wood ashes is a common practice in Cameroon as part of local cooking methods, and the local villagers have extensive experience with this process. A photo of the final biodiesel product is shown in Figure 9. Ethanol was used as the alcohol source, since it is easy to get in the region. Ultimately, the process will use methanol recovered from charcoal making operations (Willett and Seay, 2013). Additionally, once the methanol is recovered from the wood gas, the remaining liquid can be used as an organic pesticide (Willett and Seay, 2013). Finally, the process of making biodiesel from vegetable oil produces two side products: soap and glycerol. Some of the soap which is formed as the base catalyst is consumed

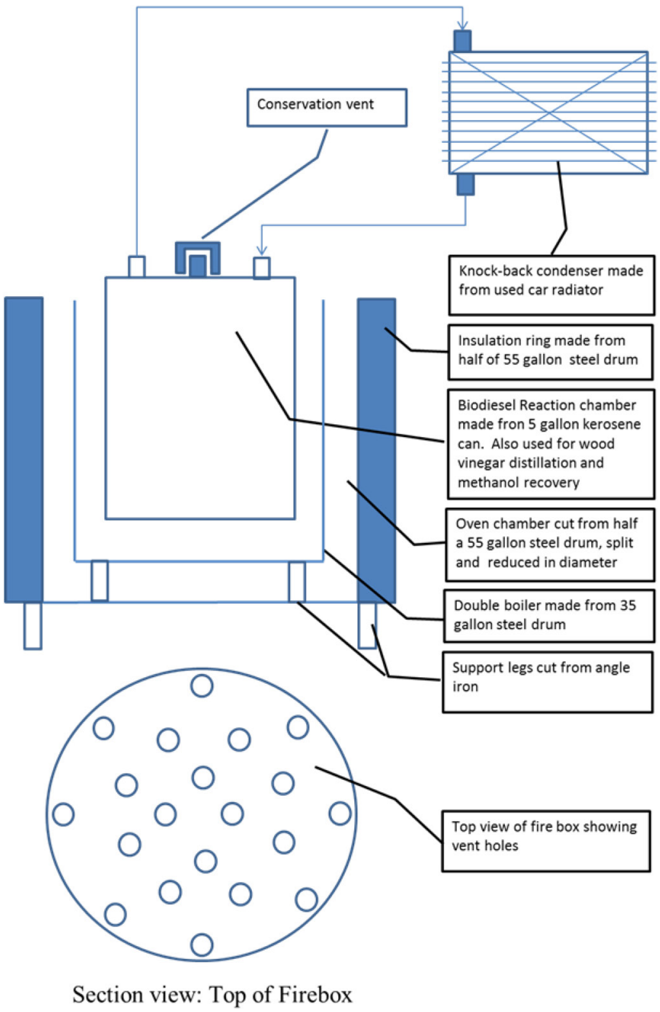


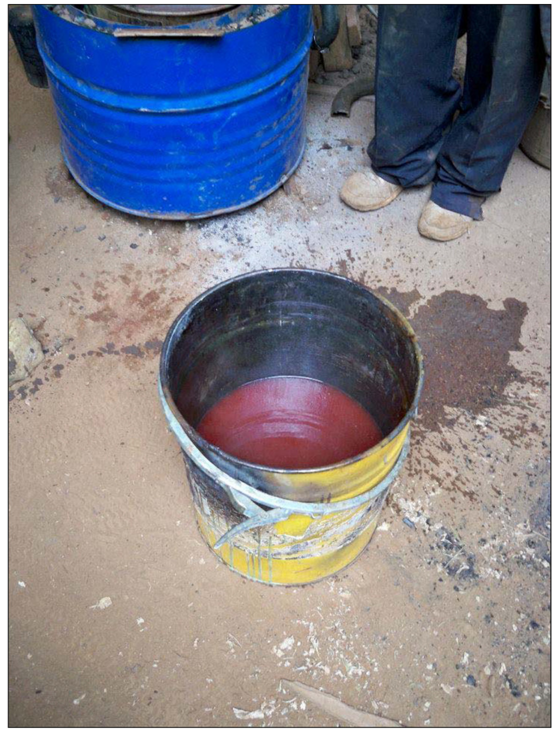
FIGURE 6. Schematic drawing of prototype processor.

FIGURE 7. A technician assembles the low cost biodiesel reactor at the ACREST facility in Cameroon.

FIGURE 8. Completed biodiesel processor built at the ACREST facility in Cameroon.

by the reaction remains in the biodiesel at the conclusion of the reaction and must be removed prior to use as a fuel. This can be accomplished simply by mixing the crude biodiesel product with water and allowing the soapy water to separate from the biodiesel by gravity. This process was also tried in Cameroon, although additional research to optimize the process is required (Croft and Seay, 2013). The second side product, glycerol, is heated to recover methanol and mixed with additional base catalyst to form a liquid soap product. The results of the proof of concept trials using the prototype processor indicated that it was indeed possible to make biodiesel using only locally produced materials and feed stocks in Cameroon, or other similar regions. A flowchart illustrating the interconnectivity of the process is illustrated in Figure 10. Based on this figure it can be seen that from only three feedstocks–wood, water and vegetable oil–biodiesel, charcoal, soap and an organic pesticide can be produced.

FIGURE 9. Final biodiesel product made the ACREST facility in Cameroon.



In terms of sustainability, palm oil is not the best choice as a feedstock for biodiesel in Cameroon. Palm oil is a staple of the local diet and using it for the production of fuel competes directly with the local food supply. Other oil sources like jatropha seeds or castor beans, which grow wild in the area, may be more sustainable choices from a societal aspect. It should be noted however, that castor beans contain a toxin, and can present health dangers to workers processing the beans to collect the oil (Maderia, *et al.*, 2011).

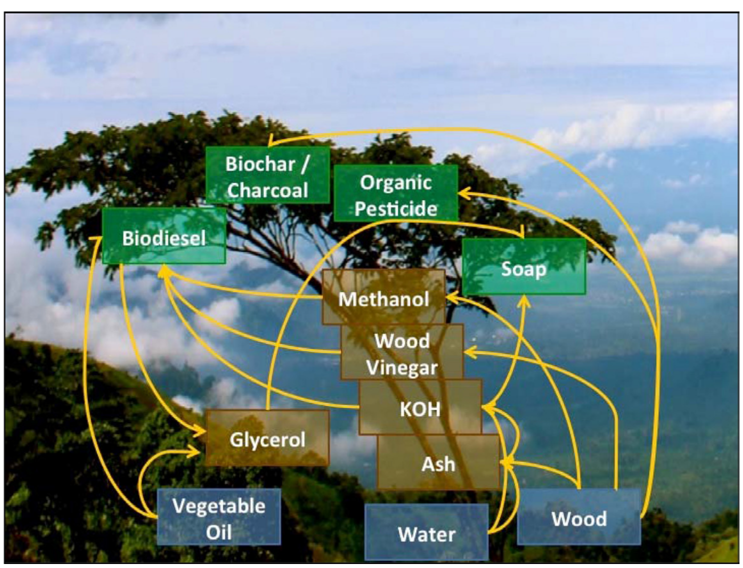


FIGURE 10. Interconnected process for producing biodiesel and associated products using Appropriate Technology.

CONCLUSIONS AND FUTURE WORK

In areas like sub-Saharan Africa environmental pressures like climate change, land and water degradation, desertification and biodiversity loss are undermining the quest for sustainable development (Weberstik and Wilson, 2009). Therefore, there is a pressing need for processes to generate energy on a local scale to provide transportation fuels and power for buildings. This study demonstrates that through the application of appropriate technology, biodiesel can be successfully and sustainably produced from vegetable oil by alkali-catalysed transesterification without the need for external mixing or sophisticated controls. The optimal conditions for the purposes of biodiesel manufacture in Cameroon can be achieved with short reaction times. Produced under the optimal conditions in the lab, greater than 95% conversion was achieved under the stated design and operational constraints. These results are consistent with other studies in terms of time and concentrations having a positive effect on conversion (Boonmee, *et al.*, 2010). The prototype reactor built in Cameroon achieved greater than 80% conversion under less than ideal conditions, indicating promise for the proposed design. The novel reactor design developed as a result of this project does trade efficiency for simplicity, but this study has shown that this trade off does not hamper the ability to produce biofuel.

Although the implementation of the project in Cameroon has shown promise, future work, including a complete mass and energy balance on the process, efficiency improvements, improving the biodiesel washing process and utilizing other, non-food, oils such as jatropha and castor will be explored in the laboratory. To conduct this future work, the original prototype processor has been reconstructed and experiments under laboratory conditions are on-going. Since palm oil is a staple of the local diet in Cameroon, other oils previously mentioned like jatropha and castor which grow wild in the region and are not eaten will improve the sustainability of the project.

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