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Examining the use of Simarouba glauca Seed Oil as a Feedstock for the Production of Biodiesel using a Small Scale Model Developed in India

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FLORIDA INTERNATIONAL UNIVERSITY

Miami, Florida

EXAMINING THE USE OF *SIMAROUBA GLAUCA* SEED OIL AS A FEEDSTOCK
FOR THE PRODUCTION OF BIODISEL USING A SMALL SCALE MODEL
DEVELOPED IN INDIA

A thesis submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE

in

ENVIRONMENTAL STUDIES

by

Andrew Aaron Jungman

2012

To: Dean Kenneth Furton
College of Arts and Sciences

This thesis, written by Andrew Aaron Jungman, and entitled Examining the use of *Simarouba glauca* Seed Oil as a Feedstock for the Production of Biodiesel using a Small Scale Model Developed in India, having been approved in respect to style and intellectual content, is referred to you for judgment.

We have read this thesis and recommend that it be approved.

Eric von Wettberg

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Date of Defense: November 6, 2012

The thesis of Andrew Aaron Jungman is approved.

Dean Kenneth G. Furton
College of Arts and Sciences

Dean Lakshmi N. Reddi
University Graduate School

Florida International University, 2012

DEDICATION

I dedicate this thesis to my mother because without her unconditional love, support, and encouragement I could have never made it through this journey.

Mom, you've always been there for me and I couldn't imagine a world without you,
thank you!

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I would like to thank my major advisors, Dr. Krish Jayachandran and Dr. Mahadev Bhat, for their mentorship not only as a graduate student, but as an undergraduate student as well. Their guidance has been fundamental in the process of completing this thesis. Dr. Jayachandran and Dr. Bhat have provided me with countless opportunities to grow in and outside of academia. I would also like to thank Dr. Eric von Wettberg for being part of my committee. His outside support and perspectives have been very beneficial and influential in the process of completing this thesis. I cannot forget to thank the multiple people who helped me while I was in India with particular attention to Dr. Balakrishna Gowda and Dr. K.T. Prasanna. Also, very importantly I need to thank the United States Department of Agriculture (USDA-HSI Grant # 2010-38422-21261 and 2008-51160-04356) because without their funding this manuscript would not have been possible. I'd like to thank all my friends that have been supportive throughout the last few years. Especially, my lab buddies Thelma Velez, Stephany Alvarez-Ventura, and Braian Tome without them this journey would have been a lot harder and less enjoyable. Finally, I would like to thank my father for watching over me and providing for me even in death.

ABSTRACT OF THE THESIS

EXAMINING THE USE OF *SIMAROUNBA GLAUCA* SEED OIL AS A FEEDSTOCK

FOR THE PRODUCTION OF BIODIESEL USING A SMALL SCALE MODEL

DEVELOPED IN INDIA

by

Andrew Aaron Jungman

Florida International University, 2011

Miami, Florida

Professor Mahadev Bhat, Co-Major Professor

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Simarouba glauca, a non-edible oilseed crop native to South Florida, is gaining popularity as a feedstock for the production of biodiesel. The University of Agriculture Sciences in Bangalore, India has developed a biodiesel production model based on the principles of decentralization, small scales, and multiple fuel sources. Success of such a program depends on conversion efficiencies at multiple stages. The conversion efficiency of the field-level, decentralized production model was compared with the in-laboratory conversion efficiency benchmark. The study indicated that the field-level model conversion efficiency was less than that of the lab-scale set up. The fuel qualities and characteristics of the *Simarouba glauca* biodiesel were tested and found to be the standards required for fuel designation. However, this research suggests that for *Simarouba glauca* to be widely accepted as a biodiesel feedstock further investigation is still required.

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I. Introduction

Over a hundred years ago Rudolf Diesel, the inventor of the famous engines that still bear his name, demonstrated at a World Fair that agriculturally produced seed oil (peanut oil) could be used as a fuel [1]. The use of these agriculturally derived oils as a fuel was phased out by petroleum-based diesel fuels that became more widely available because they had a cheaper price resulting from government subsidies in the 1920's [1]. Presently, with the depletion of the petroleum-based diesel, which replaced agriculturally produced oil in engines, the demand for alternatives to petroleum-based fuels continues to increase [2]. The increase in the popularity of these alternative biofuels is not only because of the depletion of fossil fuels, but also because these bio-energy resources have lower emissions than conventional fuels and are mostly made from renewable resources [2]. Biofuels refer to any kind of fuel generated that is made mostly from biomass or biological material collected from living or recently living resources [3-11]. Transportation sectors have shown particular interest in biofuels because of the potential for rural development, the availability of the feedstock, plus if done right they can be renewable and sustainable [12, 13].

Biodiesel production and use has been gaining popularity in the last two decades [14]. Biodiesel is considered a secondary first generation biofuel because of its feedstock and form of processing. Biodiesel can be made from many different natural renewable resources [15, 16]. The materials used can vary from raw, processed, or waste resources and can be harvested from a variety of renewable resources such as plant and animal stocks [16, 17]. The feedstock oils that are most frequently used for production of

biodiesel today are soybean, sunflower, palm, rapeseed, cottonseed, and *Jatropha curcas* [15]. The most common process used to produce biodiesel is a chemical process known as transesterification. The oil extracted is further broken down into its derivatives. The components that have similar properties to conventional diesel fuel are separated from the rest of the oil [18]. The reason why these oils have to go through transesterification process is that they have high viscosity and low volatility and cause problems in engines [18, 19, 20].

The focus of my thesis was to examine the use of *Simarouba glauca* as a feedstock for the production of biodiesel using a small scale production system developed at an agriculture university in India. There are several reasons for choosing or selecting *Simarouba glauca* for my study. First, *Simarouba glauca* has an oil composition that is similar to popular oil feedstock such as *Jatropha curcas* that are being used for the production of biodiesel. *Simarouba glauca* is not produced on a large scale for food production, pharmaceuticals, or industry like other oil borne crops such as soybean or rapeseed. [21]. *Simarouba glauca* grows in semi-arid regions and has potential to grow on lands where other crops of economic value cannot be grown [22]. Finally, *Simarouba glauca* is a native to South Florida, South America, and Central America, and any significant outcomes of my thesis research in India can inform ongoing and future research and development on this feedstock in these regions.

The University of Agriculture Sciences in Bangalore (UAS), India is part of the Karnataka State Biofuel Development Board (KSBDB). The KSBDB is a political entity that was developed in response for a need in oversight on the implementation of biofuels and to promote all aspects of their development in the Indian State of Karnataka [85]. The

program has been commended for taking a multi-species and farmer centered approach in order to take advantages of different synergistic potential in the production of biofuels. The small scale or farmer centered production of biofuels has been reported to have the potential to improve agriculture markets, enhance agriculture productivity, and reduce atmospheric pollution in rural areas [23, 24]. However, the success of a decentralized, small scale production models heavily depends on conversion efficiencies at multiple stages: from oilseed to oil, oil to biodiesel, and biodiesel to energy throughput [14].

As part of the KSBDB, UAS is one of various research institutions responsible for identifying suitable candidates, plant improvements, value addition, and technology developments. In particular, UAS is advocating the use of *Simarouba glauca* as a non-edible oilseed crop for the small scale production of biodiesel. However, limited research has been conducted to verify if the technical performances (i.e., conversion efficiency) at various stages of this proposed small scale model, using *Simarouba glauca*, meet theoretical standards. The objectives of this thesis were to:

1. Determine the efficiency of the production process of Simarouba biodiesel at UAS, Bangalore.
  - a. Determine the processes involved in the UAS biodiesel production system.
  - b. Investigate the efficiency of each process of the production system.
2. Explore how *Simarouba glauca* oil compares to conventional fuels.
  - a. Determine the following fuel properties of Simarouba oil and its Biodiesel: viscosity, density, acid value, calorific value, flash point, pour point, and cloud point.

- b. Find out how the overall fuel efficiency of Simarouba biodiesel compare to that of conventional diesel when mixed with conventional diesel at varying percentages.

In order to determine the conversion efficiency of the small scale production model and examine if *Simarouba glauca* is a good candidate for the production of biodiesel, an amount of 200kg of *Simarouba glauca* seeds were converted to biodiesel using UAS production model methods. The conversion efficiency of the field scale model was then compared to the efficiency of a smaller accurate model performed in the UAS labs. The properties of the oil and the biodiesel produced were tested according using UAS lab methods and compared to American Society of Testing and Materials (ASTM) standards and European standards to determine quality of the biodiesel. The *Simarouba glauca* biodiesel was then blended with conventional diesel and tested in a diesel test engine. The performance results for four different blends plus, conventional diesel were analyzed.

The rest of the thesis is organized in the following way: After the introduction there is a literature review on the use of vegetable oil as a fuel and how the use of biodiesel evolved. The section that follows the literature review is the methods of the thesis, after the methods of the thesis are the results of all the investigations performed. The subsequent section is the discussion of the results and lastly followed by the conclusion of the thesis.

II. Literature Review

The purpose of this chapter is to review literature on the development of biodiesel from vegetable oil. The chapter includes literature reviews on the basic chemical properties of biodiesel, chemical methods of biodiesel conversion, potential of *Simarouba glauca*, a cautionary case of *Jatropha curcas* (an alternative biodiesel feedstock that is similar to *Simarouba glauca* and is used for many comparisons in the results), and the production of biodiesel on small scales.

The use of vegetable oil as an alternative to conventional diesel fuel

There has been a consensus among many researchers for several years that vegetable oils could serve as an alternative to conventional fuels in diesel engines [25, 26]. Many articles have been published showing that vegetable oil could be used to fuel a diesel-powered engine under normal conditions. For example, one researcher ran a tractor on sunflower seed oil for 1000 hours with an 8% power loss [27], and another researcher demonstrated that rapeseed oil had similar energy output to diesel [28]. However, further researcher documented that there are problems associated with the use of vegetable oil such as heavy wax and gum deposits in diesel engines and carbon build up in the combustion chamber with sunflower oil [29, 30]. Plus, engines run on rapeseed oil reportedly had some difficulties on account of carbon deposits on piston rings, valves and injectors after 100 hours [28].

A more promising study in the support of using vegetable oil evaluated several chemical and physical properties of a variety of oils and found that the carbon deposits

were reduced when the oil was heated prior to combustion, and that the carbon deposits were a function of oil composition such as high viscosity [31]. Research has demonstrated that blending vegetable oil with conventional diesel fuel at different proportions can minimize deposits and extend the life of the engine [32, 33]. Researchers typically blended diesel with variety of oils like peanut, cottonseed, sunflower, rapeseed, and palm oil and the mixing ratio could reach to 50:50. [33-42]. They observed that one could run the engines on the blend of vegetable oils/diesel with no immediate adverse effects and long term lifecycle effects that were similar to those found on engines that have been operated with pure diesel. However, the percent of vegetable oil in the blends was a large variable in many of the studies; blends with higher ratio of vegetable oil to diesel caused increased carbon deposits. The studies on blending vegetable oil with conventional diesel fuel also suggested that the increase in carbon deposits could be a result of the different atomization and injection characteristics that are likely because of high viscosity and low volatility of the vegetable oils [43, 44].

The development of biodiesel from vegetable oil

Vegetable oil has potential to be considered as an alternative diesel fuel, but it has short comings like high viscosity, low volatility, poor cold flow properties, and the carbon buildup in engines [45, 46]. The drawbacks have directed the investigation to search for various derivatives of the fuel of which biodiesel seem to be the most popular one. The term biodiesel was introduced to the U.S. mainstream in 1992 by the National Soy Diesel Development Board presently known as the National Biodiesel Board, which has been a pioneer in commercialization of biodiesel in the United States [14]. The

chemical definition of biodiesel is the mono alkyl esters of long chain fatty acid that comes from a renewable resource or lipid [14]. Lipids or oils are water insoluble, hydrophobic substances that consist of one mole of glycerol and three moles of fatty acid, and are usually referred to as triglycerides [47]. The composition of oils consists of 90-98% triglycerides. Oils and fats derived or collected from different sources have diverse fatty acid compositions [47]. Fatty acid compositions differ in their carbon chain length and in the number of bonds they contain. The most common fatty acids in vegetable oil are stearic, palmitic, oleic, linoleic and linolenic [48, 49, 50]. Some common saturated fatty acids are stearic, palmitic, dihydroxystearic, and some common unsaturated fats are oleic, linoleic, ricinoleic, palmitoleic, and linolenic [51].

The fatty acid composition of the feedstock oil greatly affects the properties of biodiesel [51]. Therefore, an important factor in the selection of vegetable oils for production of biodiesel is their fatty acid profile. Vegetable oils containing particular fatty acids have said to produce a biodiesel with more similar characteristics to conventional fuel [52, 53]. For example, it is important to know the ratio of unsaturated fatty acids to saturated fatty acids because if the oil has more saturated fatty acids than unsaturated fatty acids it is usually more viscous [16, 54]. In contrast, oils with higher unsaturated fatty acids tend to be less viscous and have higher cloud point and pour points (properties that deal with low temperatures where the fuel can no longer be used in engines) [52,55]. Duration of storage is another factor that can be influenced by the fatty acid composition of the feedstock oil, for example unsaturated fatty compounds have been shown to have a strong affect on the long term oxidative stability of biodiesel [56].

Transesterification

There are three popular forms of biodiesel production: pyrolysis, micro-emulsification and transesterification [20]. However, transesterification has been proven to be the easiest and most efficient process for production of biodiesel. In transesterification, the free fatty acids and triglycerides are reduced to fatty acid esters and glycerin [20, 57]. The transesterification process for biodiesel is the reversible consecutive stepwise organic reaction of a triglyceride with an alcohol to create glycerol and esters, where excess in alcohol pushes the reaction towards the formation of esters because of its reversible nature [58]. In other words in the transesterification process triglycerides are converted from diglycerides, to monoglyceride, and then glycerol, releasing or freeing a mole of ester at each step [59, 60]. Figure 1 has the general equation for transesterification.

Figure 1. Transesterification of triglycerides with alcohol and catalyst where R is the alkyl group

A catalyst is commonly added to increase the yield and improve the rate of reaction [61]. In transesterification there are a few options for catalyst. The most

common method is alkali catalyzed transesterification [62]. In this reaction the anion of the alcohol and the catalyst attacks the carbonyl carbon atom of the triglyceride molecule forming a tetrahedral intermediate that reacts with the alcohol to regenerate the ion of the alcohol and catalyst. The rearrangement of the tetrahedral intermediate results in the formation of a fatty acid ester and a diglyceride [63]. The process is repeated freeing two more esters from diglyceride to monoglyceride and then monoglyceride to glycerol. For this type of transesterification, the glycerides and alcohol must be anhydrous state because the presence of water turns the reaction into saponification [63].

Edible oil feedstock transition into non-edible oil feedstock

Recently, there have been debates over the negative impacts of biodiesel production. Environmentalists point out that biodiesel production through agricultural feedstock is causing deforestation and destruction of ecosystems while economists argue that the line between food and fuel economies is being blurred as both sectors compete for the same oil resources [51]. While there is a continuous increase in the production of vegetable oil worldwide, there has been a decline in the amount of vegetable oil stocks. The decline of vegetable ending stock has been primarily related to the production of biodiesel [51].

The most common types of feedstock vegetable oil for biodiesel production throughout the world are currently soybean, sunflower, palm, rapeseed, canola, cotton seed, and *Jatropha* [14]. Most of these oils are recognized as edible. In particular, the common biodiesel feedstock in the U.S. is soybean oil, whereas rapeseed oil is the most common in Europe, and Palm oil in tropical countries. So, it is safe to say that the most

popular biodiesel feedstock are of edible nature. Unlike the U.S. and Europe, India is not self sufficient in edible oil production, it has been a major edible oil importer since 1965 when demand for edible started exceeding the production of oilseed and oils in the country [22, 84]. Two key components for the selection of a feedstock are low production cost and large production scale [14]. Hence, feedstock for the production of biodiesel should also not compete with other applications such as food or pharmaceutical production that would raising the price of raw material for all, which is one of the main problems with current feedstock oils [14].

One type of feedstock showing promise because of low production cost and it creates little to no competition between food and energy are non-edible oilseed crops [14]. Non-edible vegetable oils have similar oil composition to edible oils, but have certain qualities that are toxic or have a taste that is not palatable. As stated above oil composition is one of the most important factors when selecting feedstock oil for the production of biodiesel [51]. The biodiesel discussed in this review refers to the mix of fatty acid methyl esters (FAME) produced from *Simarouba glauca* [64]. *Simarouba glauca*, is commonly referred to by many names as paradise tree, bitter-wood and aceituno. It is a tree borne oilseed that belongs to the family *Simaroubaceae* [65]. Very importantly *Simarouba glauca* oil has not been recognized as edible oil by local populations in India and is not currently used by any industrial process [22].

Simarouba glauca

Simarouba glauca is grown widely across South America, Central America, and India. The most economically important part of the plant is the seed oil. The *Simarouba*

seed contain between 55-65% oil content. Figure 2 shows a comparison of an India's one rupee coin with seed husk and the seed kernel that was removed. The oil has many industrial uses, including its ability to be turned in to fat or margarine [66]. The fruits have a semi-sweet pulp that is suitable for eating or use in the beverage industry [67]. The leaf litter and seed cake are good sources of manure [66]. Lastly, the bark and leaves have been known to have medicinal qualities and have at least one patent has been applied for using *Simarouba glauca* [66]. It is popular because all the parts of the tree can be used in different processes [67]. Figure 3 shows a young *Simarouba glauca* plant to show an example the leaf structure and the plant.

Figure 2. Size comparison of a *Simarouba glauca* seed husk with the seed removed, and seeds with husk still intact in relation to an Indian one rupee coin.

Figure 3. Young *Simarouba glauca* plants.

In one hectare of land about 200 trees can be grown. The trees usually begin to produce seeds at four to six years of age, while the tree begins to fruit at an early age some plantations have not seen the full potential of about 20kg-50kg of seed until approximately the tenth year [21]. Estimations are that a one hectare plantation of *Simarouba glauca* can yield about 6000kg of seeds that would provide over a ton of oil [22]. The estimated yield compares well to the yield of current feedstock with exception to Oil Palm that produces about 5 tons per hectare [51]. Table 1 gives a good comparison of *S. glauca* with other popular feedstock used for the production of biodiesel.

Table 1. Comparison of oil yields between common oilseed crops

Type of oil	Oil Yield (kg oil/ha)	Oil Yield (wt%)
Simarouba glauca [21]	>1000	55-65 (seed kernel)
Jatropha curcas [51]	1590	50-60 (seed kernel)
Soybean [51]	375	20
Oil Palm [51]	5000	20

Simarouba glauca was introduced to India from El Salvador in 1961 and has subsequently has been planted across the country. It has shown a very wide adaptability to diverse soil and climate conditions; it also has to its credit other desirable traits such as drought tolerance, non-browsing by animals, and quick recovery from shock [22]. Plus, researchers have reported that the fatty acid composition does not significantly differ from seeds of one country to another [21]. The major fatty acid composition for

Simarouba glauca is: between 52-54% oleic acid, 27-33% stearic acid, and 11-12% palmitic acid, a composition that is very similar to that of several feedstock already being used like *Jatropha curcas* and soybean [21,51]. Table 2 shows a comparison of popular feedstock fatty acid composition and the fatty acid composition of *Simarouba glauca*.

Table 2. The major fatty acid composition of simarouba and popular feedstock

Feedstock				
Fatty Acid	<i>Simarouba glauca</i> [21]	<i>Jatropha curcas</i> [51]	Soybean [51]	Oil Palm [51]
Oleic	52-54%	43.10%	23.00%	40.00%
Linoleic	-	34.30%	51.00%	10.00%
Palmitic	11-12%	14.20%	10.00%	45.00%
Stearic	27-33%	6.90%	4.00%	5.00%

Cautionary case of *Jatropha curcas*

In the early 1990's there was a big movement to grow *Jatropha curcas* because like *Simarouba glauca* it was a non-edible oil borne seed that had a large potential for producing energy from marginal land without too many inputs [68]. However, many of these plantations are now abandoned because of low productivity and/or higher labor cost than expected [68]. That in turn spurred a scientific movement to increase the knowledge of *Jatropha curcas* potential yield under sub-optimal and marginal conditions plus, the research of other beneficial properties that *Jatropha curcas* may contain [69]. The case of *Jatropha curcas* serves as a cautionary tale for the production of biodiesel from any new feedstock.

Some of the misconceptions associated with the *Jatropha curcas* boom are as follows: the amount of water and nutrients needed to produce a high yield of seeds and oil use, root space needed for adequate growth, and yield of plantations developed on marginal lands. Studies show that while *Jatropha curcas* has good drought tolerance mechanisms, given the chance it would use large amounts of water for growth and there are limited studies that show *Jatropha curcas* could produce a good oil yield under drought conditions [70]. Unfortunately most successful applications are usually found in areas that are the most similar to its natural environment of semiarid and arid conditions [69]. Furthermore, given the right amount of amendments favorable characteristics of *Jatropha curcas* can be enhanced and small-scale cultivation in rural areas shows promise [68, 71, 72]. Therefore, like with *Jatropha curcas* there is still a lot of information to be determined before *Simarouba glauca* can be suggested as a feedstock for the production of biodiesel without a doubt that it will not be successful.

Small scale production systems

Literature suggests that large scale biodiesel production can successfully produce more energy than its input into the system and that large scale commercialization is mostly impeded by its cost competitiveness [73]. There is a limited amount of research conducted on small scale biodiesel production systems in the U.S., with the exception of Fore et al. [73]. The main conclusion of this study is that small scale systems have many on-farm benefits and have potential for community development. However, it is cautioned that the economic viability of small scale biodiesel production is heavily reliant on the price of petroleum diesel and protein livestock meal just as large scale systems are

[73]. Furthermore, small scale biofuel production models have been particularly appropriate in places where petroleum fuels are expensive and hard to find such as developing countries [74].

These production models have the potential to increase sustainable development and reduce poverty by providing energy in areas that could not otherwise afford to have it [74]. Small scale production of biofuel has been reported to have the potential to strengthen agriculture markets, enhance agriculture productivity, and reduce the emission of harmful pollutants being released into the atmosphere in developing countries [74]. If done correctly on-farm production of biofuels takes advantage of the synergistic potential of several aspects of agriculture in a manner that can improve the ecological integrity of the system. Farms can take advantage of the synergistic potential through the cycling of nutrients and energy using crops grown on farm to meet on farm demands [75].

There are many challenges associated with the small scale production of biodiesel. First, it is expensive to certify and without certification producers assume the potential risk of any mechanical damage to their diesel engines [76]. Then, despite the size of scale many economic analyses suggest that there are too many volatile factors that have an impact on profitability, the main one being the price of the feedstock [77-80]. Lastly from an environmental view point the absence of methanol reclamation equipment allows methane to be released into the atmosphere during the course of production, which offsets the reduction of emissions resulting from the biodiesel burning cleaner than conventional petroleum based diesel fuel [81-83].

Conclusion of literature review

To summarize, many scientists agree that vegetable oil can be used as an alternative to conventional diesel engine fuels [14]. Research in recent times has been more concerned with the problems associated with using vegetable oil as a fuel for diesel engine and how can they be lessened, which has led to the development of fuel made from their derivatives such as biodiesel. Biodiesel by definition is the mono alkyl esters of long chain fatty acids made from a renewable resource [14]. The original oil composition of the feedstock plays a pivotal role in the quality of the biodiesel produced [16-20]. The most popular form of producing biodiesel is transesterification, where the free fatty acids and triglycerides are to fatty acid esters and glycerin by an alcohol and a catalyst [20].

Presently, biodiesel is most commonly made from edible feedstock [51]. The use of edible oils for the production of biodiesel has sparked many debates about diverting resources from the production of food to energy blurring the economies of both the sectors and creating fluctuation in price and demand of these feedstock [51]. Both the U.S. and European Union can afford to produce biodiesel from edible oils as they are net exporters. Some countries like India cannot as they currently do not meet the demand for edible oils and must import [22, 84]. As a result many non-edible oil borne crops are being investigated to determine their potential as feedstock for the production of biodiesel [14]. Non-edible oils have similar oil composition to edible feedstock and if grown on land where other cash crops are not viable then they have almost no competition with food [51].

One feedstock recently gaining popularity for biodiesel production in India is *Simarouba glauca* because it is not considered an edible crop by the local population. It has a similar oil composition to popular feedstock, many parts of the plant can be used, the oil yield for hectare are considered to be very high, and it has the potential to grow on degraded lands [22]. However, the case of *J. curcas* should serve as a cautionary tale. In the early 1990's, some experts suggested that *J. curcas* had great potential to produce energy from degraded lands. The assertion of great potential for *J. curcas* led to a boom in the development of *J. curcas* plantations worldwide, many of which are now abandoned because of low productivity and/ or higher labor cost than anticipated [68]. To avoid the same mistakes that occurred with *Jatropha curcas*, *Simarouba glauca* should be further studied before any recommendation on its potential as a feedstock for the production of biodiesel is made.

Finally, small scale biofuel production system are gaining popularity because they have many on-farm benefits and have shown some success in areas where petroleum fuels are particularly expensive or hard to get [73]. If orchestrated correctly small scale biofuels production can take advantage of the synergistic potential of using several components of crops grown on farm to meet on farm demands [75]. Nonetheless, there are a few barriers to the popularization of small scale biodiesel production systems. These are mainly economic barriers like the high price of certifying the fuel with the proper agency, competition with food markets, or the volatility of the feedstock price. There are also environmental problems like the lack of methanol reclamation equipment that

negates any of the benefits gained from shifting to burning a cleaner fuel from conventional petroleum based fuels [73].

III. Methods

My thesis research entailed three phases: determining the efficiency of the UAS model of producing biodiesel from *Simarouba glauca*, determining the fuel chemical properties of *Simarouba glauca* seed oil and its biodiesel, and lastly testing the *Simarouba glauca* biodiesel blended with conventional diesel in a test engine.

It was hypothesized that the UAS production model would show some efficient aspects and will have comparable outputs to those of the smaller lab scale model. The reason is that the UAS production model exhibits qualities such as being small scale and decentralized. The use of a farmer centered multi species approach serves to benefit the community in ways that a crop feedstock produced in larger scale does not. It was also hypothesized that the *Simarouba glauca* oil produced using the UAS model would have similar yield and composition to other studies conducted. Further, when the oil was converted to biodiesel it was hypothesized that the latter will have a composition and performance qualities that are more similar to conventional diesel fuel.

Figure 4. A map of the study area acquired from Google earth.

Description of the UAS study site and community level development of biofuels

The UAS is a member of the taskforce on biofuels, sponsored by the Government of Karnataka. According to the head of the special task force, Sir Y.B. Ramakrishna, the task force is a product of many interests from government, industry, academic, and corporate sectors without one wanting to take the lead [85]. On the taskforce there is a consensus that biofuels should not come from edible sources mainly because India is the largest producer and consumer of edible oil on the planet and still has to import oil. Therefore, UAS scientist wanted to incorporate a different model for the production of biodiesel in Karnataka, India [85].

The chief scientist at UAS, Dr. Balakrishna Gowda, said that the UAS exploring using non-agriculture land to grow a portfolio of feedstock. He said that the UAS is using farm centers that the government has established with villages to establish collection centers, using unemployment programs to train farmers to produce biofuels. Then they want use the commonly known milk collection cooperative system as an example [86]. The farmers grow the feedstock, prepare the seeds for oil expelling, and expell the oil from the seeds. The oil is then collected to be converted into biodiesel. Dr. Gowda explained that one of the main reasons for the decentralization models recent gain in popularity is that it allows all the by-products, such as seed cake to be used at the community level [86]. By educating farmers on how to dry and expel the oil from the seed feedstock the UAS model lets advantage of left over seed cake that is nutritious for plants and if detoxified can serve as animal feed meal [66].

The multiple by-products made during the production of biodiesel make it more economically secure and the decentralization limits the control on the market by big corporations [86]. The biodiesel production model of the UAS is novel in that it is primarily dependent on the principles of decentralization, small scales, and alternative fuel sources. By diverting many small areas that were not able to grow economically significant crops in different communities to the production of biofuels UAS can help displace a substantial amount of conventional diesel fuel. However, research points out the benefit of small scale biofuel production are contingent on the cost of the production and on the ability to maintain mechanical efficiency and durability during use [73]. Additionally, small scale production is reliant on the implementation of testing biofuels for quality control to protect equipment from mechanical detriment [73].

Determining the efficiency of the UAS biodiesel production model

Determining the efficiency of the UAS model was a unique approach. The aspects of the model were identified and observed by the process of converting the *Simarouba glauca* seeds into biodiesel. Then, the efficiency of each component was examined by data collection during the process of conversion from seed to biodiesel. All seeds were collected from campus plantations by UAS staff and the entire seed was sun dried for several days prior to storage. Seeds were stored for approximately three months prior to the experiment.

Seed Decortication

Decortication is the act of separating the seed husk or seed shell from the actual seed or kernel [87]. Decortication is an essential step prior to milling and extracting the oil from the kernel or seeds. While there is extensive research on the decortication of various edible feedstock there is still little research done on the decortication of alternative feedstock like *Jatropha curcas* and *Simarouba glauca* [87]. The decorticator used for the experiment was a mechanical model used for the decortication of ground nut that was adapted to process other varieties of seeds. During the time of the experiment the seed decorticator was being used by the UAS to process seeds of neem, *Jatropha curcas*, and *Simarouba glauca*.

For my research 200kg of the whole seeds of *Simarouba glauca* were input into the decorticator in (see Figure 5) in 10kg increments; the time it took to decorticate each increment was recorded along with the weight of seeds being separated and the shells. The seeds that failed to separate were weighed with the shells. The average recovery of seed kernels compared to shells or husk for each increment was calculated to determine the efficiency of the process. The following statistical regression was estimated to determine if the time the mechanical decorticator was run had any effect on the efficiency of the decortication process.

where D is the percent of kernels recovered from decortication; T is the duration of decortication; a and b are the regression coefficients; ϵ is the random error.

Figure 5. The seed decorticator that was used at UAS. The machine runs on a 10 HP electric motor.

Oil expelling and extraction

Expression refers to the process of pressing the liquid out of liquid containing solids mechanically where extraction refers to the process of separating a liquid-solid system [90]. Mechanical expression of seed oils using a screw press is said to be the oldest and most popular method of expelling oil from seeds in the world [89]. While solvent extraction has proved to be more efficient the simplicity and safety aspects of expelling have made it the more advantageous process [89]. Plus, solvent extraction adds chemicals contaminating the protein rich cake that can be used or sold to increase the efficiency of the production model [89].

Figure 6. The oil expeller used at UAS. The machine runs on a 10 HP motor as well

On the production scale oil was expelled using a mechanical screw press (Figure 6). The oil expeller was produced by Sardar Engineering Company and like the seed decorticator is expected to be widely used in the fields under the UAS biodiesel production model. The mix of seed husk and kernels from decortication were input into the expeller in twelve different increments. Data were collected with methods adapted from Pradhan et al. [89]. The mass of the cake (M_{cake}) is multiplied by the oil content of the cake (O_{cake}), and then is divided by the recorded mass of the sample (M_{sample}), multiplied by the initial oil content of the seed (O_{seed}) to obtain a value of oil recovery (OR). The result from the above calculation is then is subtracted from 1 and multiplied by 100 to get a percentage [89].

Further, the initial oil content of the seeds was determined using chemical extraction and the mechanical data were compared statistically using an independent sample *t*-test to determine and compare their efficiency [88]. To determine a more accurate oil yield from the seed I used the Soxhlet method of chemical extraction that involved the extraction of oil from the solid material by repeated washing with an organic solvent, which in my case was diethyl ether, followed by gravimetric determination [90].

Figure 7. The reactor set up used for transesterification.

Oil transesterification

The seed oil that was extracted in the above process was then converted into biodiesel using simple transesterification (Figure 7). On the basis of the acid-value I chose to do a one-stage transesterification. However, my acid-value was in a range where it could have benefited from a two-stage transesterification that involves an acid esterification pre-treatment [91]. In the process of transesterification the triglycerides from the *Simarouba glauca* oil are converted into fatty acid methyl ester using a short

chain alcohol (methanol) and alkaline catalyst (Sodium Hydroxide) [20]. In most biodiesel production models methanol or ethanol is used as the alcohol and sodium hydroxide or potassium hydroxide as alkaline catalyst to produce biodiesel [20]. The process was carried out in 1L batches at atmospheric pressure in a closed vessel at a constant temperature of 60 °C [92]. Once, the oil reached a constant temperature in the vessel a mixture of methanol and sodium hydroxide were added. The amount of sodium hydroxide was determined using the acid value and the following equation:

$$\text{Amount catalyst} = 3.5\text{g sodium hydroxide} + A$$

where A is the acid number of the oil.

The oil, methanol, and sodium hydroxide were mixed continuously for 1-1.25 h [92]. The liquid from the vessel is placed in a separating funnel where the denser glycerin sinks down the bottom where it is easily separated. The process of separation can be seen in Figure 8. Following separation the biodiesel was washed once with 1000ml of hot water acidified with organic acids, and then several washes of just hot water. Finally, the biodiesel was heated to a temperature of 120 °C to remove the moisture from the mixture [91].

Identification of *Simarouba glauca* oil and biodiesel fuel properties

Testing procedures for the identification of the fuel properties of *Simarouba glauca* oil and biodiesel were adapted from the UAS model and Sadasivam and Manickams' *Biochemical methods* [86, 91]. The testing procedures used by UAS are comparable but not fully up to date with the testing procedures required for certification under ASTM standards, Indian standards, or European standards [76, 86]. Fuel properties

tested for include acid value, viscosity, iodine value, density, calorific value, flash point, pour point, and ash contents [91].

Figure 8. Separator funnel with the *Simarouba glauca* biodiesel on the top and the denser un-reacted material at the bottom.

Acid value

Determining the acid value, also known as the estimation of free fatty acids for the oil or biodiesel, was accomplished by titrating the sample against potassium hydroxide (KOH) and a phenolphthalein indicator [91]. The acid number is the milligram of KOH required to neutralize the free fatty acids present in 1 gram of sample. The free fatty acid content is expressed as oleic acid equivalent [91].

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where A is the acid value in mg; R is the titrate value of KOH (ml); N is the normality of KOH; and W is the weight of the biodiesel sample (gm).

The free fatty acid (F) in percent is calculated as oleic acid using the equation:

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Iodine number

The iodine number of the oil or biodiesel (I) is a measure of the degree of unsaturation present in the sample. It is expressed as the grams of iodine absorbed by 100 grams of sample, where the excess iodine remaining is estimated by titrating against sodium thiosulphate [91].

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where V_1 is the volume of sodium thiosulphate in (ml) used for blank; V_2 is volume of sodium thiosulphate used for sample; N is normality of sodium thiosulphate.

Saponification

When the triglycerides in the sample are heated with KOH, they are saponified and release fatty acid and glycerol. The fatty acid neutralizes the KOH and a titration with hydrochloric acid (HCl) is used to determine the amount of alkali used for saponification (SV) [91].

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where V_1 is the volume of Hydrochloric acid in ml used for blank; V_2 is the volume of Hydrochloric acid used for sample; N_{HCl} is the normality of Hydrochloric acid.

Viscosity

The viscosity of the oil and biodiesel was determined using a Redwood No 1 viscometer. The apparatus determines the viscosity of the sample by releasing it through a standard orifice into another standard collecting jar at a specific temperature. The viscosity (V) is expressed as the time of flow in seconds (R). [91].

Calorific value

A Macro Scientific Works bomb calorimeter model number 506 was used to determine calorific value (CV). A bomb calorimeter is commonly used device to determine the heating or calorific value of a solid or liquid fuel sample at a constant volume. It basically works by burning a sample of the fuel that transfers its heat into a known mass of water. Using the weight of the sample in grams (W) burned and the temperature rise of the water (T), the calorific value can be calculated. The bomb calorimeter gives a calorific value that represents the gross heat of combustion per unit mass of a sample [91].

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where G is the mass of water; C is the specific heat of water; E is the calories of heat combustion required for the fuse and wire to burn.

Cloud point and pour point

Cloud point and pour point for the biodiesel was determined using a UAS custom made apparatus that is combined with Indian standard specific thermometers and volumetric containers. The sample is put into a test jar that is protected by a jacket and inserted into several containers with decreasing temperature. The cloud point and pour point are observed and recorded visually [91].

Density

Density was determined using a hydrometer of Indian standard similarly to the low temperature thermometers used above. A sample of the oil is placed in a volumetric container. The hydrometer is immersed in the sample and gives a density reading [91].

Flash point

To determine the flash point of the biodiesel a Pensky Martens flash point apparatus was used. It has a smooth operating cover mechanism that slides a shutter open and applies a test flame to the sample at the turn of a knob. The flash point is identified visually and the temperature of the oil is recorded [91].

Performance of biodiesel blends with conventional diesel in a diesel test engine

For the diesel-powered engine experiments procedures from *Energy Conversion Engineering Lab Manual* from K.S. Institute of Technology, Bangalore were used [93]. The methods were similar to Kalbande and colleagues [94]. The procedure involves

setting up a test generator in a matter that allows to measure exact fuel consumption per unit of time and the output generated for a given fuel blend [94]. Then the overall output efficiency was determined by dividing the energy output by the consumption of biodiesel [93]. The engine can be seen in Figure 9 and the engine specifications in Table 3. Four blends of biodiesel were tested and their performance was compared with conventional diesel. The four blends of biodiesel were at dilution levels of 5%, 10%, 20% and 50%.

Figure 9. The diesel test engine used in the experiment.

Table 3. Diesel Test Engine specification

Compression ratio	16:1
Bore	80cm
Length of stroke	110mm
Rated speed	1200rpm
Rated power	3.68KW
Brake drum diameter	350mm
Rope diameter	0.015m

For each blend the engine was restarted. The test engine was started by cranking. The engine was run until it maintained a constant speed and that speed was recorded. The mechanical load was applied to the brake drum at 2kg, 4kg, 6kg, 8kg, and 10kg. The quantity of fuel supply required for each different load was then recorded [93].

Data Analysis

All data were analyzed using IBM SPSS Statistics 19. An independent sample *t*-test was applied to the chemical extraction procedure data and the mechanical extraction data to test the variability and difference in means. A linear regression was used to test the relationship between time and different output variables to see how much the time variable affects the output of a process [88]. For all the fuel properties test were done in triplicate and results are the mean of the three test.

IV. Results

The following chapter contains the results of the manuscript. It describes the conversion efficiency of the UAS production model being used to convert *Simarouba glauca* oil into biodiesel. Then, it describes the fuel properties of *Simarouba glauca* biodiesel and oil obtained using the UAS lab methods and facilities. The chapter concludes with the performance results of *Simarouba glauca* biodiesel mixed with conventional diesel fuel in a diesel test engine.

Seed decortication

Out of the 200kg of seed processed in the decorticator there was 91.89kg of useable material for expelling. There was 68.82kg of seed husk and whole seeds that failed to separate in the machine. The total time the decorticator was run was 676 minutes. The average yield percentage of the process was estimated to be,

$$\frac{91.89}{200} \times 100 = 45.94\% \quad \text{and} \quad \frac{68.82}{200} \times 100 = 34.41\%.$$

The mixture of mostly husk and whole seed were manually sifted to remove whole seeds.

The husks were used as mulch.

A linear regression analysis was conducted to evaluate if the amount of time (T) the decorticator was operational in each batch had a relationship on the amount of kernel and seeds that were separated (D). The study hypothesis was that the two are linearly related in that as overall time increases so does the amount of kernel and seeds that are separated. The estimated regression equation is:

$$D = 0.015 T + 4.101 \quad R^2 = 0.048, \quad n = 20 \\ (SE=0.016) \quad (SE=0.544)$$

The 95% confidence interval for the slope is -.018 to .048, meaning that the amount of kernels separated was not significantly related to the amount of time the machine was run. Figure 10 presents the regression analysis showing how the time has no significant pattern with the output of the decorticator.

Oil expelling and extraction

Out of the 91.89kg of seed kernel/husk mixture obtained from decortication, an amount of 88kg was input into the expeller for expelling. About 3kg were lost during the transfer of seed kernel from one process to the other. The process of expelling at the UAS yielded 9.223kg of *Simarouba glauca* seed oil in 190 minutes. The average yield in percent of the oil expeller was $(9.223/88) \times 100 = 10.49\%$ at 0.46kg/min. After expelling there was about 59.42kg of seed cake, a value added by-product that is used for fertilizers, manures and pesticides, plus 19.357kg of residue that was separated from the oil by letting it settle and filtering.

Using the Soxtherm method of extraction it was found that the seed kernel plus husk mixture used for expelling had an oil percentage of 29.74%. The left over cake and residue were also tested using the Soxtherm method of extraction and their oil percentages were 10.49% and 69.06%, respectively. Lastly, the chemical extraction method was used to determine the percent of oil for the seed kernel (60.25%) by itself and the full seed (14.87%).

An independent-samples t-test was conducted to evaluate if the mechanical expelling of the *Simarouba glauca* oil using the UAS model expeller was comparable to the Soxtherm chemical extraction [89, 90]. The test was significant $t(-19.633) = -21.022$, $p < .001$. The mechanical expelling ($M = 7.333\%$, $SD = 2.109$) had a lower mean percent oil

recovery than the chemical extraction ($M=29.736\%$, $SD= 3.030$) as expected, but the mean for the mechanical expeller was lower than anticipated.

Equal variances was assumed because the Levene's test for equality was not significant ($p=0.18$) meaning the assumption of equality of variances was not violated. The 95% confidence interval for the difference in means was narrow ranging from -24.629 to -20.178 [88]. Figure 11 is a box plot that shows how big the difference is between the average distributions of the oil recovery of the mechanical expeller and the chemical extraction.

Figure 10. The estimated regression of the output of decortications over the duration of decortications.

Figure 11. The average oil recovery for both the mechanical expelling method and Soxtherm chemical extraction method made in SPSS

Oil Transesterification

From the 9.223kg mechanically expelled oil, 9L of oil was separated leaving about 100ml of simarouba oil as excess from the whole process. The oil was converted into biodiesel in nine 1L batches and 8.122L of biodiesel was produced. The average yield percentage of transesterification was $(8.122/9.223) \times 100 = 90.24\%$. There was 2.712L of unreacted material, which was mostly glycerin (another value added product) separated from the oil.

Table 4. Data collected from the transesterification

BATCH	Oil (ml)	Methanol + Catalyst (ml)	Biodiesel Recovered (ml)	Un-reacted Material	Time (min)	Percent Recovery
1	1000	250	901	305	60	90.1
2	1000	250	898	300	60	89.8
3	1000	250	900	298	60	90
4	1000	250	910	295	60	91
5	1000	250	911	290	60	91.1
6	1000	250	305	302	75	90.5
7	1000	250	895	310	75	89.5
8	1000	250	301	300	75	90.1
9	1000	250	301	312	75	90.1
MEAN	1000	250	902.44	301.33	66.67	90.24

Fuel properties

Table 4 shows the fuel properties obtained *Simarouba glauca* biodiesel and oil according to the procedures and apparatus available at UAS. All fuel properties were determined in triplicate and the result shown is the average of the three trials.

Table 5. List of fuel properties obtained for *Simarouba glauca* biodiesel and oil

Properties	<i>S. glauca</i> biodiesel	<i>S. glauca</i> Oil
Acid Value (mg KOH/g) -	0.24905	2.2465
Viscosity at 40C (mm ² /s)-	12.609	60.535
Calorification (MJ/kg) -	32,143	
Saponification-	179.561	185.9317
Density-	867	
Cloud Point (Celsius)-	18	Room Temperature
Pour Point (Celsius)-	15	
Iodine Number-	56.03	54.28
Flash Point (Celsius)-	160	
Ash Content (%) -	0.00485	

The acid value for the *Simarouba glauca* biodiesel was 0.249mg KOH/g and for the oil of *Simarouba glauca* it was 2.246mg KOH/g. The iodine number for the *Simarouba glauca* biodiesel was 56.03 and the iodine number for the oil was 54.28. The iodine number is expressed as the number of grams of iodine absorbed by 100 grams of sample. The saponification or amount of sodium hydroxide needed to neutralize the fatty acids for the *Simarouba glauca* biodiesel was 179.561 and 85.9317 for the oil. The viscosity for the *Simarouba glauca* biodiesel was 12.609mm²/s at 40 degrees Celsius. The *Simarouba glauca* oil has a viscosity of 60.535mm²/s at 40 degrees Celsius. The calorification of the *Simarouba glauca* biodiesel was 32,143 mega joules per kilogram. The cloud point and pour point for the *Simarouba glauca* oil were at room temperature. The cloud point and pour point for the biodiesel were 18 degrees Celsius and 15 degrees Celsius, respectively. The density of the *Simarouba glauca* biodiesel was 867kg/m³. The

flash point of the biodiesel was determined to be 160 degrees Celsius using the Pensky Marten flash point apparatus.

Performance in engine test

In order to calculate the results of the performance test in the diesel engine the calorific content and density of each blend was required. When the Simarouba biodiesel was mixed with the diesel the calorific content increased, the viscosity was reduced, the cloud point dropped, and the density fell as the percent of conventional diesel was increased. Table 6 shows how the blends are affected by the mix of different proportions of conventional diesel fuel.

Table 6. Fuel properties for the conventional diesel fuel tested and the blends of

Simarouba glauca biodiesel and the conventional diesel

	Cal Conent	Cloudpoint (C)	Viscosity	Density
Diesel	37100.089	-3	4.9	822
B5	36446.708	0	5.3	825
B10	36287.804	2	5.5	827
B20	34436.499	4	6.2	830
B50	32716.527	9	6.6	844
B100	32143.18	18	12.609	867

Using the data recorded from the engine test and the energy conversion lab manual I was able to calculate brake power (BP), break thermal efficiency (BTE), and break specific fuel consumption (BSFC) at each load for all the blends and conventional diesel fuel. I also recorded the exhaust gas temperature (EGT) at every load for every blend, plus the conventional diesel fuel. I graphed the BP versus the BSFC (Figure 12), BTE (Figure 13), and EGT (Figure 14) similarly to previous other studies [93].

Figure 12. Power curve for break specific fuel against break power for conventional diesel fuel and four blends of *Simarouba glauca* biodiesel with conventional diesel fuel

BSFC VS. BP

Figure 13. Power curve for of break thermal efficiency against break power for conventional diesel fuel and four blends of *Simarouba glauca* biodiesel with conventional diesel fuel

Figure 14. Power curve for exhaust gas temperature against break power for conventional diesel fuel and four blends of *Simarouba glauca* biodiesel with conventional diesel fuel

V. Discussion

UAS production model efficiency

The UAS production model exhibited some efficient aspect and some not so efficient ones. Figure 15 shows a flow chart of the UAS production system. Out of the 200kg of *Simarouba glauca* that was obtained in the beginning of the research 8.122L of usable biodiesel was obtained (1L of biodiesel weighed roughly one kg). When the total amount of biodiesel obtained was divided by the total amount of seeds that was started with and then multiplied by 100 it gives an idea of the total efficiency of the process, which was $(8.122/200) \times 100 = 4.06$ percent. This low percentage however is somewhat misleading because there were many value added by-products of the process obtained. By having a small scale community production model UAS is able to take advantage of these by products that would not be possible in a large scale biodiesel production operation.

Seed Decortication

The first step of the UAS biodiesel production process that was analyzed was the decortication or the separation of seed husk from seed kernel. The process of seed decortication did not seem efficient from observation, out of the 200kg of seed that were processed only 91.89kg or 45.95% that were useable for oil extraction in the next phase of production. The husks were used as mulch, which is beneficial to the community. One observation was that the machine was not being run long enough for all the seeds to move through, but the data indicated that the amount of useable seeds that were output from the decorticator had no relation with the amount of time that the machine was operated.

Figure 15. Flow chart with the different process involved in the UAS production model.

Some of the missing weight can be attributed to these whole seeds that were not separated or to husks that were ground into a thin powder.

While there is limited research on the decortication of non-edible feedstock for the production of biodiesel, I was able to find an article that decorticated *Jatropha curcas* in a similar manner; only difference was that their design used manual power instead of mechanical. They found that decortication worked more efficiently as the moisture content decreases. However, they also found that as the moisture content increased there was a decrease in the amount of broken seed and dust [87]. The moisture content of the seeds was not recorded in detail in my research and could be a parameter that could explain the poor efficiency of the decortication process. It is recommended that based on the information gathered in my research further studies take into account moisture content in any testing of seed decortication with *Simarouba glauca*.

Oil expelling and extraction

The next step of the UAS biodiesel production process was expelling the oil from the *Simarouba glauca* seed kernels. The process of oil expelling yielded 9.233kg of oil from the initial 91.89kg of seed kernels and husk that was input into the expeller or 10.05 percent. When compared with the more accurate Soxtherm chemical solvent extraction method the average percent of expelling was significantly lower. Furthermore, the percent of oil expelled mechanically divided by the more accurate chemical extraction gives an idea of the efficiency of the mechanical process. This efficiency was $(10.49/29.74) \times 100 = 35.27$ percent. The low percentage might be attributed to a lot of oil being left in the oil residue and seed cake that could not be used. There was 59.42kg of seed cake that had an average oil content of 10.49%, meaning that there was about 6.23kg

cake. Plus, there was 19.357kg of residue that had an average oil content of 69.06%. That meant that there was an estimated 19.6kg of oil trapped just in the cake (6.23kg) and the residue (13.37kg).

The percent recovery was very low compared to other published expelling studies that reported a recovery rate between 86-92% of oil from oilseeds [89]. Studies have shown that adjusting certain parameters of the expeller such as internal pressure of the screw press can result in a decrease in the amount of oil left in the cake increasing the efficiency of oil recovery [89]. Also, further pretreatment of the oilseed for example cleaning, cooking, and drying have been said to enhance oil recovery as well [89]. From visual observation it seems that applying a filter between the oil collection and the oil expeller would also help minimize the amount of residue left in the oil.

At UAS the *Simarouba glauca* cake was being used to amend fields directly as a green manure or mixed in with organic composting and then applied to fields [86]. While there are not many studies on the cake of *Simarouba glauca*, the past research suggest that it has a high protein content of about 48 percent [66]. They also suggest that it is a rich source of protein for livestock meal with 92% solubility, in vitro protein digestibility of 88%, and amino acid based computed nutritional indices [66]. In comparison *Jatropha curcas* only had an in vitro protein digestibility of 75 percent [66]. However, both *Simarouba glauca* and *Jatropha curcas* cake require detoxification before they could be utilized in feed/ food formulas. *Simarouba glauca* seed cake would require detoxification from saponin, alkaloid, phenolics, and phytic acid [66]. The UAS was working on ways of detoxifying the cake as well; at the time of my research there was a group of different

researchers at UAS testing several different protocols for the detoxification of the *Simarouba glauca* seed cake and the use of its protein [86].

Taking advantage of the protein rich cake locally is one of the important aspects of having an efficient small scale production model [73]. The UAS understands the value of the seed cake locally and is incorporating small on farm oil expeller into their community production system. The farmers can expel the oil on site and distribute the cake where it is needed. Figure 16 is a picture of the cake right after oil expelling. In addition to *Simarouba glauca*, UAS was working with a variety of feedstock such as neem, *Jatropha curcas*, and pongamia [86]. The beneficial properties of the seed cake vary depending on the feedstock and farmers could distribute the type of seed cake by their specific need. For example, the cake from neem has qualities that deter pest and can be applied to areas where pest might be a problem [86]. Further, if UAS discovers an efficient protocol for detoxification of *Simarouba glauca* seed cake it can collect the cake the same way they collect the oil for transesterification and use it as an animal meal. The addition of animal meal would increase the overall efficiency of the biodiesel production model and add another value added product to the communities where it is produced.

Figure 16. *Simarouba glauca* seed cake right after expelling of oil

Transesterification

The last phase of the UAS production model that was examined was the transesterification process. The transesterification process seemed the most efficient of all the processes out of the 9.223Kgs of oil used 8.122L were converted to biodiesel. There were some interesting variables such as time of reaction that would have been tested had there been more oil from the whole process. Time had some effects on the amount of FAME recovered, but there were not enough data to statistically confirm these results.

Because the acid value (2.25) was a little high an acid catalyst esterification pre-treatment process could have been beneficial to the overall recovery of FAME from the *Simarouba glauca* oil, but it would have required a lot more chemical materials [14]. The UAS does the two-step process on oil that has an acid value greater than two [86, 91]. However, the one step transesterification yielded 8.122L biodiesel from the 9L of *Simarouba glauca* oil input or 90.24 percent oil recovery. The transesterification process seemed pretty efficient in comparison to the other parts of the production process. In addition, the 2.712L of un-reacted material that was mostly glycerol was added to collection of glycerol for the production of soap by the UAS laboratories and if further purified could be sold for industrial processes.

Fuel Properties

To analyze the quality of the *Simarouba glauca* biodiesel and oil they were compared to ASTM D 6751 and European Standards EN 14214, which are the two of the most popular quality standards of biodiesel throughout the world [51, 76]. See table 7 for comparison. The *Simarouba glauca* biodiesel fuel properties were also compared to the

fuel properties popular edible and non-edible feedstock [51]. The fuel properties of the *Simarouba glauca* biodiesel produced using the UAS model met some important quality standards for biodiesel fuels and failed to meet others. The unaltered *Simarouba glauca* oil did not meet any of the fuel standards for diesel fuels.

While the means of determining the fuel properties were not the most update by standard means they produced results that were comparable to standards and helped determine many aspects of the fuel quality. Quality testing of biodiesel is one of the larger impediments to the success of small scale biofuel production models [73]. By using these less expensive and complicated fuel property testing procedures, the UAS model is able to determine some quality standards of the fuel they are producing. Further, by using these cheaper low tech solutions they can implement more quality control in the community.

The acid value of the *Simarouba glauca* biodiesel was 0.24905 mg KOH/g and 2.25 mg KOH/g for the oil. The ASTM and European Standards for acid value are <0.8 mg KOH/g and <0.50 mg KOH/g, respectively [76]. Again, see table 7 for comparison. The acid value for the *Simarouba glauca* biodiesel was less than the acid value for *Jatropha curcas*, but not less than other popular feedstock such as rubber seed and palm [51]. That means that the acid value was of an acceptable quality for the biodiesel that was produced using the UAS model. The viscosity (12.609mm²/s at 40 degrees Celsius) for the *Simarouba glauca* biodiesel did not fall in the range of the accepted viscosity for the European standard (3.5-5.0 mm²/s at 40 degrees Celsius) or the ASTM standard (1.9-6.0 mm²/s at 40 degrees Celsius)[76]. In fact it was way above the standard and all the other biodiesels that it was compared with. Not meeting the viscosity standard is

important because viscosity is believed to be one of the major contributing causes of carbon deposits in diesel engines. Viscosity affects the atomization and injection characteristics of the fuel [43, 44]. On a positive note, when the *Simarouba glauca* biodiesel was blended with conventional diesel fuel the viscosity was decreased to within expectable standard levels. The results of blending can be found on Table 6.

As shown in table 7 the density (867kg/m^3) of the *Simarouba glauca* biodiesel fell in the desired range given by the European Standard ($860\text{-}900\text{kg/m}^3$) and was not compared to any other biodiesel. However, in order to conduct the fuel performance test in the diesel engine the density for each blend was required and it was found that as the amount of conventional diesel fuel was increased the density was reduced. None of the density for the blends met the European standard quality [76].

The flash point for the *Simarouba glauca* biodiesel of 160 degrees Celsius was higher than the minimum given in both the European standard (>120 degrees Celsius) and American Standards (>130 degrees Celsius) [76]. The flash point of the *Simarouba glauca* biodiesel was also higher than that of *Jatropha curcas* and soybean biodiesel, but not higher than that of oil palm biodiesel [51]. The cloud point was higher than most values compared and so was the pour point. However, they were comparable to that of oil palm oil, a very popular feedstock in the tropic areas [51]. Cloud point testing was performed for all the *Simarouba glauca* biodiesel blends and as the percent of conventional diesel fuel was increased the cloud point temperature was decreased. The results are on table 6.

The saponification and iodine number of the *Simarouba glauca* oil was compared to a previous study on *Simarouba glauca* seeds. The previous study found the saponification and iodine number of expelled *Simarouba glauca* oil to be 192.3 and 52.8, respectively. That was similar to the values this research found for the saponification (185.93) and iodine number (54.28) of the *Simarouba glauca* oil [22]. The calorific content of *Simarouba glauca* biodiesel was 32,143MJ/kg, which was lower than the calorific content of *Jatropha curcas* biodiesel (39,230MJ/kg) and soybean biodiesel (39,760MJ/kg) [51]. Furthermore, this was the other fuel property that was required for the fuel performance test in the diesel engine and was determined for all the *Simarouba glauca* biodiesel blends with conventional diesel fuel. Results showed that as the proportion of conventional diesel was increased so did the calorific content. Again, results can be seen in Table 6.

Performance in engine test

The result of the engine test were inconclusive; while the results collected yielded similar power curve to previous studies, there were not enough data collected to confidently report the findings [94]. In addition, there were some unforeseen complications with the quality of the diesel obtained to blend with the biodiesel and test. The conventional diesel fuel that was purchased to be blended with the biodiesel for testing in the diesel engine appeared to have been altered. By the time I realized that the conventional diesel fuel was not of acceptable quality all the fuels had already been blended. Given that there was only about 8L of *Simarouba glauca* biodiesel produced to begin with, the test had to be run with the blend of our biodiesel and the altered diesel

purchased at the filling station. The diesel was purchased at a local filling station in the city of Bangalore in the state of Karnataka, a major developed city.

Table 7. Fuel properties tested for Simarouba glauca oil and its biodiesel compared to ASTM standards, European standards, and other biodiesels.

Properties	SG B100	SG Oil	Jatropha B100	Rubber Seed	Palm	Soybean	Diesel	ASTM D 6751-02	EN 14214
Acid Value (mg KOH/g) -	0.24905	2.2465	0.4	0.118	0.08			<0.8	<0.50
Viscosity at 40C (mm ² /s)-	12.609	60.535	4.8	5.81	4.42	4.08	2.6	1.9-6.0	3.5-5.0
Calorification (MJ/kg) -	32,143		39,230	36,500		39,760			
Saponification-	179.561	185.9317							
Density-	867								860-900
Cloud Point (Celsius)-	18	Room Temperature		4	15				
Pour Point (Celsius)-	15		2		15		-20		
Iodine Number-	56.03	54.28							
Flash Point (Celsius)-	160		135	130	182	69	68	>130	>120
Ash Content (%) -	0.00485		0.012		0.02		0.01	<0.02	<0.02

VI. Conclusion

During my research I determined how efficient the production process of *Simarouba glauca* biodiesel at UAS, Bangalore was by converting 200kg of *Simarouba glauca* seeds into oil and then converting the oil into biodiesel. I determined that there are three major processes involved in the UAS biodiesel production system: seed decortication, oil expelling, and transesterification. I was able to estimate the efficiency of each part of the process and recorded data that might help future studies. Furthermore, I determined fuel properties for the *Simarouba glauca* biodiesel and oil produced using the UAS biofuels laboratories. The fuel properties determined were then compared to popular feedstock and quality standards. Finally, the *Simarouba glauca* biodiesel was blended with conventional diesel fuel and tested in a diesel test engine to determine its performance characteristics.

One of the main problems with biodiesel is that the feedstock is commonly edible oil or cooking oil [14]. In 2007 more than 90% of the oil used for biodiesel production came from edible oils. Using edible oils as fuels can create an increase in the competition for the oils in the global food market and alter some of its dynamics [51]. The use of edible feedstock for the production of biodiesel is a problem because there is a great demand for these edible-oils worldwide which may contribute to the food shortage [51]. Many recent debates have focused on how the lines between food and fuel economies are being blurred and many countries continue to allow deforestation practices to meet the increased demand [51].

Simarouba glauca is not produced on a large scale for food production, pharmaceuticals, or industry like other popular biodiesel feedstock such as soybean or rapeseed [21]. *Simarouba glauca* grows in semi-arid regions and has potential to grow on lands where other crops of economic value cannot be grown [22]. Therefore, it would have little to no competition with land to grow food. Finally, *Simarouba glauca* is a native to South Florida, South America, and Central America and any significant outcomes of my thesis research in India can be beneficial to research being conducted in these regions.

The UAS is using their community small scale production model taking advantage of the synergistic potential of several aspects of agriculture in a manner that can improve the ecological integrity of the system. They are taking advantage of this synergy by cycling of nutrients and energy using crops grown in the community to meet the demands in the community [75]. There is a growing consensus in the scientific community that small scale biofuel production systems have many on-farm benefits and have potential for community development [73]. Small scale biofuel production models have been particularly appropriate in places where petroleum fuels are expensive and hard to find [74]. In places like India these production models have the potential to increase sustainable development and reduce poverty by providing energy in areas that could not otherwise afford to have it [77].

Further, small scale production of biofuel has been reported to have the potential to strengthen agriculture markets, enhance agriculture productivity, and reduce the emission of harmful pollutants being released into the atmosphere in developing

countries [77, 78]. However, there are still many challenges associated with the small scale production of biodiesel. It is expensive to certify the quality of biodiesel and without certification producers assume the potential risk of any mechanical damage to their diesel engines [76]. By adapting low technological and less costly methods for testing at the production center UAS is helping minimize some of these risks, but they are still not the specifications required for proper certification.

While *Simarouba glauca* shows promise for being a feedstock for the small scale production of biodiesel in India it is important to remember the cautionary case of *Jatropha curcas*. Currently plantations of *Jatropha curcas* are gaining popularity again on small scales, despite all the criticism. However, it is important to take into consideration what happened with the crop recommending that a lot further research is needed before *Simarouba glauca* can be suggested for use as a feedstock for the production of biodiesel [68]. There is a need for further research when it comes to assessing the claims that *Simarouba glauca* can produce a substantial oil yield with low nutrient requirements, poor soil fertility, low water use, low labor inputs, and tolerance to pests or diseases. Gleaning the successes of *Jatropha curcas* and leaving behind its failures is just common sense. Therefore, it would be wise to conduct further and much more thorough research on *Simarouba glauca* before recommending that it be used for the production of biodiesel.

In conclusion, for the use of *Simarouba glauca* to be widely accepted as a feedstock for the production of biodiesel, further investigation is still required, especially on ways to improve conversion efficiency during oilseed preparation (pre-decortication),

decortication, oil recovery and final biodiesel combustion. The methodology developed in my study for *Simarouba glauca* can also be adapted to other oilseeds used in the UAS model in order to conduct a more comprehensive testing and to increase the overall efficiency of the entire model.

Further, the efficiency of the model could probably have been higher if it was catered just to *Simarouba glauca*, but the model at UAS is designed to process several feedstock. However, the diversification of feedstock was not perceived as a negative aspect of the model; through the diversification of feedstock the UAS has created a safety net. In the event that a crop harvest was affected by a pest/ disease or some other unforeseen scenario, they would still have some oil to process into biodiesel [86]. Moreover, there are studies that show that biodiesel can be produced from a blend of oils for example soybean and castor oils and that the biodiesel produced was found to satisfy standards for biodiesel [84]. Therefore, *Simarouba glauca* does seem like an efficient feedstock using the small scale biodiesel production model at UAS. Further, the UAS model takes advantage of several agricultural by-products of the process and returns them to community while adding some energy security that makes the process well worth it.

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