

Article

Life Cycle Cost and Sensitivity Analysis of *Reutealis trisperma* as Non-Edible Feedstock for Future Biodiesel Production

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Received: 4 April 2017; Accepted: 22 June 2017; Published: 29 June 2017

Abstract: The use of non-edible, second-generation feedstocks for the production of biodiesel has been an active area of research, due to its potential in replacing fossil diesel as well as its environmentally friendly qualities. Despite this, more needs to be done to remove the technical barriers associated with biodiesel production and usage, to increase its quality as well as to widen the choice of available feedstocks; so as to avoid over-dependence on limited sources. This paper assesses the feasibility of using a local plant, *Reutealis trisperma*, whose seeds contain a high percentage of oil of up to 51%, as one of the possible feedstocks. The techno-economic and sensitivity analysis of biodiesel production from *Reutealis trisperma* oil as well as implementation aspects and environmental effects of the biodiesel plant are discussed. Analysis indicates that the 50 kt *Reutealis trisperma* biodiesel production plant has a life cycle cost of approximately \$710 million, yielding a payback period of 4.34 years. The unit cost of the biodiesel is calculated to be \$0.69/L with the feedstock cost accounting for the bulk of the cost. The most important finding from this study is that the biodiesel from *Reutealis trisperma* oil can compete with fossil diesel, provided that appropriate policies of tax exemptions and subsidies can be put in place. To conclude, further studies on biodiesel production and its limitations are necessary before the use of biodiesel from *Reutealis trisperma* oil may be used as a fuel source to replace fossil diesel.

Keywords: biodiesel; non-edible oil; *Reutealis trisperma*; life cycle cost; biofuel economy

1. Introduction

The diminishing supply of fossil fuel reserves and increasing environmental problems associated with the burning of fossil fuel have made renewable energies very promising as future alternative energy sources [1–3]. Among the renewable energies, biodiesel has been touted as one of the most important renewable energy sources, especially in the context of Malaysia [4,5]. Biodiesel is defined as mono-alkyl esters derived from long chain fatty acids contained in animal fats and vegetable oils, and processed using alcohol and a catalyst. It is environmentally friendly, non-toxic, and of course, abundant in nature [6–8].

Reference [9] focuses on the engine performance of biodiesel when used in diesel engines. The research reveals that fuels from biodiesel, made through transesterification of waste vegetable

oil, may be used without significant impacts on the performance of direct injection (DI) and indirect injection (IDI) diesel engines. In reference [10], the authors conducted experiments to investigate the benefits of mixing biodiesels with petrol diesel fuel, with one-cylinder diesel engines using a wide range of biodiesel blends from linseed oil and conclusive results were obtained showing that a mixture of B20 (Biodiesel 20%) produces the optimum thermal efficiency and emissions for the engine. In other studies, it has been shown that 10% biodiesel blends of non-edible oils; *Jatropha curcas*, *Ceiba pentandra*, and *Calophyllum inophyllum*, provides the best engine performance in terms of thermal efficiency, engine power, engine torque, and fuel consumption of a Compression Ignition (CI) engine [11]. These studies serve to demonstrate the huge potential of biodiesel to supplement or even replace fossil diesel fuel, without requiring engine modifications and without experiencing deterioration in engine performance. Furthermore, the use of biodiesel can extend the life of the diesel engine; due to its better lubricating properties as compared to petrol diesel [12].

There are different types of feedstocks; from animal fats, vegetable oils, and algae, that may be used to produce environmentally friendly biodiesel. First generation feedstocks, produced directly from food crops and edible vegetable oils, such as rapeseed and soybean oils are the most commonly used raw materials for the production of biodiesel. However, the use of first generation feedstock has somehow been given negative publicity recently and has attracted the attention of researchers due to the issue of “food versus fuel”. As first generation feedstocks are essentially food crops, its use for the production of biodiesel has driven away a large chunk of food crops from the global food consumption market; causing an inevitable increase in its price.

Hence, a number of researchers have turned their attention to second generation feedstocks. These second generation feedstocks are generally produced from non-edible food crops or non-edible vegetable oils such as wood, waste, etc., in order to avoid the conflict associated with the first generation feedstocks. Included in the second generation feedstocks is waste or used cooking oil [13–15]. Numerous works have reported the potential of non-edible vegetable oils due to its physicochemical properties, its environmental friendliness, and availability; allowing the production of biodiesel in a sustainable manner.

In addition, recent studies also present third generation feedstocks, taking advantage of specifically engineered energy crops such as microalgae for biodiesel production. References [16–18] have reported the economic advantages of using microalgae as feedstocks, in terms of the minimal land required as well as higher oil extraction capability of microalgae as compared to other feedstocks. Microalgae can also be grown on land and water unsuitable for food agriculture; reducing the strain on fertile lands and our already-depleted water sources. Because of these, third generation feedstocks have huge potential to be the future source of feedstocks for the production of biodiesel.

The production of biodiesel from feedstocks may be achieved using different techniques such as direct/blends [19,20], micro-emulsion [21], pyrolysis [22,23], and transesterification [24,25]; with the transesterification reaction with a catalytic process being the most commonly adopted technique for production [26]. Commonly, homogeneous catalysts such as Sodium Hydroxide (NaOH) and Potassium Hydroxide (KOH) are used. Recently, the use of new heterogeneous catalysts in transesterification processes has become an interesting option for researchers. References [27–33] address the use of different heterogeneous catalysts for the production of biodiesel using different feedstocks. The authors in reference [30] investigated biodiesel production from *Jatropha* oil using nanometer magnetic base catalysts and have shown that a 95–99% biodiesel yield is achievable under optimal conditions. These studies have demonstrated that the use of heterogeneous catalysts has reduced the effects of using low quality feedstocks, whilst providing high biodiesel yields under optimal conditions. Another interesting technique for biodiesel production is through catalyst-free techniques as demonstrated in references [34,35]; with a maximum biodiesel yield of 99.6% obtained in reference [35] for biodiesel production from *Jatropha* oil. Despite all these advancements, the determining factor in the choice of catalysts to be used in biodiesel production still hinges on the

economic viability of the resulting biodiesel fuel; and hence, the current popularity of NaOH and KOH due to its relatively cheap price.

It is believed that the production of biodiesel should not rely on one source of feedstocks and the use of a single catalyst only. By taking lessons from our past dependency on fossil fuels, the over reliance on a single feedstock or catalyst will result in the fundamental economic problem of resource scarcity, especially in the long term. As such, the research communities continue to explore new possible source of feedstocks and catalysts for biodiesel production; the more varieties of feedstocks that are available and tested, the more assured is biodiesel in terms of sustainability and feasibility. Several examples of research efforts on crops for the production of biodiesel are *calophyllum inophyllum* [36], *pongamia glabra* (koroch seed) [37], *jatropha curcas* [38,39], *eruca sativa*. L [40], *Hevea brasiliensis* and *Ricinus communis* [41] *pongamia pinnata* (karanja) [42,43], *sterculia foetida* [44], *azadirachta indica* (neem) [45], *madhuca indica* (mahua) [46], soap nut [47,48], milkweed (*Calotropis gigantean*) [49], *guizotia abyssinica* [50], *tung* [51], *pistacia chinensis* [52], and *algae* [18].

This paper attempts to expand the body of knowledge on possible feedstocks for the production of biodiesel. It is noted that there is very little information available in the literature on the production of biodiesel from *Reutealis trisperma* [53]; despite its abundance in the Southeast Asian region. Therefore, the objective of the present paper is to examine the opportunity of biodiesel production from *Reutealis trisperma* oil as a potential source of future energy supply and to explore its implementation aspects. These are important in the context of Southeast Asia as feedstocks for biodiesel usually depends on the availability of that feedstock in its geographical region [54].

2. Material and Methods

2.1. Materials

Reutealis trisperma, also known as *Philippine tung*, is a monotypic plant genus in the *Euphorbiaceae* family [55]. It is a tall tree native to the Philippines and Southeast Asia; however, it has also been cultivated elsewhere due to its suitability as a timber species. For the same reason, the tree has also been classified by the International Union for Conservation of Nature and Natural Resources (IUCN) as being “Vulnerable” [56]. Figure 1 shows the distribution map of the *Reutealis trisperma* plant around the world.

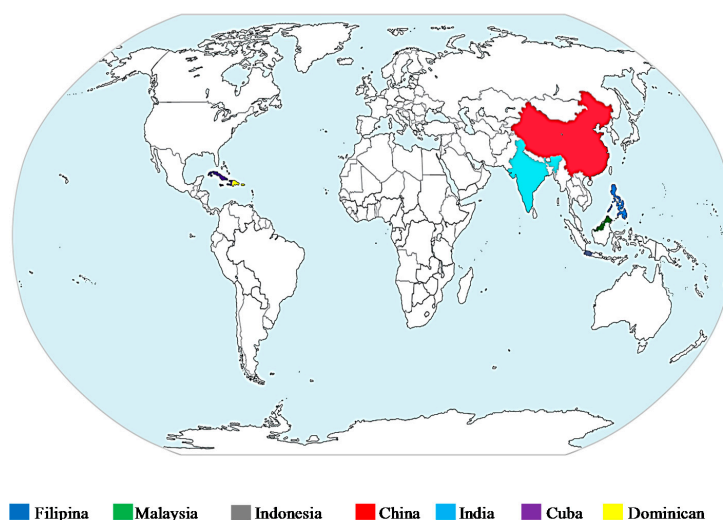


Figure 1. Distribution map of the *Reutealis trisperma* plant around the world.

Reutealis trisperma has the right characteristics for environmental rehabilitation plants; it is able to prevent land erosion and is an excellent producer of oxygen to the environment. It has been suggested

in reference [57] that the tree be planted as part of plantations, in part to support the land rehabilitation program in Indonesia. The tree produces plenty of non-edible fruits, containing seeds and shells. Figure 2 depicts the tree, fruit, seeds, and kernels of the *Reutealis trisperma* plant. The seeds of this plant contain a high percentage of oil, up to 56% oil content [58]; consisting of palmitic acid, stearic acid, oleic acid, linoleic acid, and α -eaeostrearcic acid, and can be used as an environmentally friendly alternative fuel. Due to the presence of α -eaeostrearcic acid, the seed oil is non-edible and hence, the feedstock is classified as a second generation feedstock. Furthermore, the waste from processing can be used as natural pesticides and organic fertilizers [53,57]. Thus the growing of *Reutealis trisperma* serves several purposes; as a tool for land rehabilitation, for processing of its seed into biodiesel, and for the production of natural pesticides and organic fertilizers.

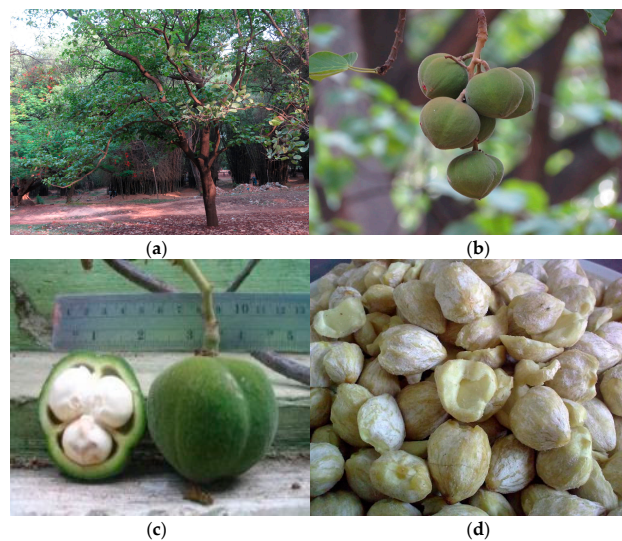


Figure 2. *Reutealis trisperma*: (a) Tree; (b) Fruits; (c) seeds; and (d) Kernels.

Before even considering the use of *Reutealis trisperma* as a source of feedstock for a biodiesel plant, it is important to first assess the suitability of the feedstocks in terms of physicochemical properties, to ensure that it is in agreement with biodiesel standard limits, particularly the ASTM D6751 and EN 14214 biodiesel standards. Laboratory experiments shall be performed to measure the physicochemical properties such as calorific value, density, etc., and these values shall be compared with the standards, to ensure compliance to the standards. Furthermore, the values obtained from this experiment shall also be used in subsequent sections in this paper.

2.2. Method

2.2.1. Data Collection

Data are collected from various sources such as research papers, technical notes, and reports from subject-matter experts as well as from the latest market prices, in addition to the data from experimental results. Where no specific data on the matter is available, assumptions shall be made using comparable data. Furthermore, sensitivity analysis shall be performed to identify the most important data as well as the effects of variations from the true values.

Generally, the basis of study on the biodiesel production plant shall be based on the production capacity of the plant. A common production capacity value of 50 kt shall be assumed.

2.2.2. Life Cycle Cost

Life cycle costs of the plant may be used to evaluate the economic benefits of the plant. Sometimes referred to in the literature as total ownership cost, the life cycle cost must consider all costs associated

with the plant; from its inception to decommissioning. For our purpose, the life cycle costs of the plant for the production of biodiesel oil from *Reutealis trisperma* may be divided into six (6) parameters; initial capital cost, operating cost, maintenance cost, feedstock costs, salvage value, and by-product credits, and are related as follow:

$$LCC = CC + OC + MC + FC - SV - BP \quad (1)$$

Recently, present value calculation is widely used in the economics and business to compare cast flows at different times. By applying the given approach, the present value model for the life cycle cost is presented as follows:

$$LCC = CC + \sum_{i=1}^n \frac{OC_i + MC_i + FC_i}{(1+r)^i} - \frac{SV}{(1+r)^n} - \sum_{i=1}^n \frac{BP_i}{(1+r)^i} \quad (2)$$

Present Worth Factor

The present value factor (*PVF*) is the total estimated value of the project that is currently collected from future cash flows. The feasibility of investing in a biodiesel production plant is determined by using the present worth factors (*PVF*) with a given rate of interest. For years *i*, *PVF* is given as follows:

$$PVF = \frac{1}{(1+r)^i} \quad (3)$$

Summing this over a project period of *n* years yields the compound present worth factor (*CPW*),

$$CPW = \sum_{i=1}^n \frac{1}{(1+r)^i} \quad (4)$$

$$CPW = \frac{(1+r)^n - 1}{r(1+r)^n} \quad (5)$$

Capital Cost

Capital cost of the plant includes the initial costs for installation of the plant to allow for its operation; from the cost of the land, building cost, equipment, testing etc. Normally, capital cost is dependent on the production capacity of the plant. For this paper, capital cost is approximated based on reference [59], whereby three (3) possible initial capital costs may be considered based on the production capacity of the plant; maximum CC_{high} , average CC_{avg} , and minimum CC_{low} initial capital costs of the biofuel plant. These 3 possible initial capital costs of the biofuel production plant are given as follow:

$$CC_{high} = -517.76 \times PC^2 + 252928 \times PC + 3446300 \quad (6)$$

$$CC_{avg} = -430.13 \times PC^2 + 205235 \times PC + 2696000 \quad (7)$$

$$CC_{low} = -342.49 \times PC^2 + 157542 \times PC + 1945700 \quad (8)$$

Operating Cost

The operating cost include factory costs, transportation costs, utilities costs, administrative expenses, laboratory services, supervision costs, labor costs, and all other material and energy flows excluding the cost of the feedstocks. Costs for waste and sewage sludge treatments are also included in the operating cost. The operating cost consists of fixed and variable operating costs and by assuming that the plant is producing biodiesel at its maximum production capacity, the operating cost per ton of biodiesel produced may be introduced.

Furthermore, assuming that the operating cost per ton of the plant are fixed throughout its project lifetime, the total operating costs (OC) throughout the project lifetime, using present value calculations, may be given as follows:

$$OC = \sum_{i=1}^n \frac{OR \times PC}{(1+r)^i} \quad (9)$$

Maintenance Cost

Service and periodic maintenance costs may be taken to be a given percentage (MR) of the initial capital cost (CC) and assumed to be constant for the whole project life span. The total maintenance costs (MC) throughout the project lifetime, using present value calculations, may be given as follows:

$$MC = \sum_{i=1}^n \frac{MR \times CC}{(1+r)^i} \quad (10)$$

Feedstock Cost

Annual feedstock consumption (FU) of the plant is determined by the capacity of the plant (PC); after accounting for the biodiesel conversion efficiency (CE) which is the efficiency in which the feedstock is converted into biodiesel. Further, it is assumed that annual feedstock consumption (FU) is constant throughout the project lifetime and is given by:

$$FU = \frac{PC}{CE} \quad (11)$$

The total feedstock costs (FC) throughout the project lifetime, using present value calculations may be given as follows:

$$FC = \sum_{i=1}^n \frac{FP \times FU}{(1+r)^i} \quad (12)$$

Salvage Value

The salvage value is the remaining value of components and assets of the project at the end of its lifetime; however, instead of using the initial capital cost as the basis for the calculation, the cost of replacing the plant and its assets i.e., the replacement cost (RC), is used. This is because intuitively the salvage value of the plant at the end of its lifetime is determined by the capital cost at the end of the project lifetime, after discounting for depreciations. A constant annual depreciation rate (d) is assumed in this study. The salvage value, using present value calculations, may be estimated by the following equation:

$$SV = RC \times (1-d)^{n-1} \quad (13)$$

Therefore, the current value of the salvage cost is expressed by the following equation:

$$SV_{PV} = \sum_{i=1}^n \frac{RC \times (1-d)^{n-1}}{(1+r)^i} \quad (14)$$

By-Product Credits

Glycerol is a by-product of the biodiesel production process. Although unusable for biodiesel use, it may be further converted into different products such as Fuel Oxygenates (additive), propylene glycol (liquid alcohol that is used as a solvent, in antifreeze, and in the food, plastics, and perfume industries), Reforming Syngas, Glycerol Carbonate, etc. The authors in [60] state that glycerol can be converted and used as a solvent, antifreeze, in pharmaceutical applications, and numerous other products through catalytic conversion. As such, Glycerol may actually be sold further as a useful by-product.

Of course, the receivables from the sale of Glycerol, as a by-product of the plant, is determined by the actual amount of Glycerol that is produced. Given a glycerol conversion factor of GCF , the by-product credit obtained from the sale of Glycerol over the project lifetime, using present value calculations, may be given as:

$$BP = \sum_{i=1}^n \frac{GP \times GCF \times PC \times 1000}{(1+r)^i} \quad (15)$$

Payback Period

The feasibility and viability of the plant may be evaluated using a simple method called the payback period (PP). To put it simply, the payback period may be interpreted as the time required to gain financial return from the plant equal to the initial investment costs for the plant. Taking the initial investment costs of the plant as the initial capital cost (CC), the payback period is calculated as the ratio of capital cost to net annual income obtained from the plant and given by the following equation:

$$PP = \frac{CC}{TBS - TPC - TAX} \quad (16)$$

where,

$$TBS = \frac{BFP \times PC}{\rho} \quad (17)$$

$$TPC = 1.1 \times \frac{LCC}{n} \quad (18)$$

$$TAX = (TBS - TPC) \times TR \quad (19)$$

Total Biodiesel Cost

The Annual Total Production Cost (TPC) of the biodiesel consists of the life cycle cost distributed over the life of the project of n years and the reasonable profit margin. Assuming a profit margin of 10% over the distributed LCC , the annual total production cost (TPC) of the biodiesel may be calculated as follows:

$$TPC = 1.1 \times \frac{LCC}{n} \quad (20)$$

Final Biodiesel Unit Cost

It is also important to determine the minimum sales price per unit of biodiesel fuel that would cover the costs of producing the biodiesel as well as provide the required profit margin; in this paper, this is taken to be 10%. This value is equivalent to the Final Biodiesel Cost (FBC) per unit, which is given by the ratio of the annual total production cost (TPC) of the biodiesel to the annual total amount of biodiesel that is produced from the plant. The Final Biodiesel Cost (FBC) is given by:

$$FBC = \frac{TPC \times \rho}{PC} \quad (21)$$

2.2.3. Potential Fuel Saving

Biodiesel and diesel fuels have some dissimilarity in heating value or calorific value. Therefore, the biodiesel to diesel fuel substitution ratio is expressed as the following equation:

$$SR_w = \frac{HVG}{HVB} \quad (22)$$

The sum of the diesel fuel substitution is a function of the yearly diesel fuel consumption with a substitution ratio, which is presented by applying the equation below:

$$GR_i = \eta \times GC_i \quad (23)$$

The total biodiesel required for replacing the diesel fuel is estimated by the diesel fuel substitution multiplied by the biodiesel to diesel fuel substitution ratio which is shown in the equation below:

$$BC_i = GR_i \times SR_w \quad (24)$$

The fossil diesel fuel potential energy savings can be calculated by using the following equation:

$$TGS = \sum_i^n GR_i \times EC \quad (25)$$

2.2.4. Sensitivity Analysis

The key variables such as Life Cycle Cost (*LCC*), Payback Period (*PP*), and Final Biodiesel unit Cost (*FBC*), which form the basis of determining the feasibility/viability of the project and its economic benefits, are calculated based on key assumptions and projections. Some of the assumptions made are on the price of feedstocks (*FP*), replacement cost (*RC*) of the plant, operating rate (*OR*), etc. Uncertainty in the market due to demand/supply, technologies, and other factors, may cause some of these values to vary from these key assumptions and projections, such that it may change the outcome and performance of the project.

Sensitivity analysis may be used to assess the effect of variations in key assumptions and projections, on the projected performance of the project. For the sensitivity analysis, there are several important variables that must be considered: feedstock prices, initial capital costs, operating costs, and discount rate.

The most important of these variables is the feedstock price. It is expected that the price of the feedstock will follow its market value and be sensitive to other related markets such as energy supply/demand, the market value of its substitute such as crude oil and increasing on biodiesel prices. Generally, the price of feedstock shall rise if the demand for it exceeds the supply and vice-versa. The increase in demand for the feedstocks may be caused by several factors such as an increase in demand of the biodiesel due to limited supply of crude oil, etc., with the price increase on the feedstock acting as a throttle to control biodiesel production. Similarly, the decrease in supply of the feedstock caused by, for example, natural disasters, may also increase the price of the feedstock. The feedstock used in this paper comes from *Reutealis trisperma*, a second generation feedstock and hence, it is comparatively price-stable as it does not need to compete with the food market unlike the first generation feedstock.

2.2.5. Biodiesel Taxation and Subsidy Scenarios

Policies on taxation and subsidies on a biodiesel product and its substitutes have an influence on the final cost of biodiesel in the country. Analyses are normally performed to compare the effect of different taxation and subsidy scenarios on the final price of biodiesel, to give insights to policy-maker on ways to encourage the use of biodiesel. These analyses may be based on the adoption of different policies; different tax rates, total tax exemption, and different costs of subsidy, and may also include studies on the effect of variation in the values of important input variables such as feedstock price as well as the price of its substitutes, to determine whether or not policy intervention is required to stimulate the biodiesel market.

Like other new technologies, subsidies may be inevitable for biodiesel to be on par with the fossil diesel price. The subsidy cost is usually selected based on the current subsidy cost of its substitute; namely the subsidy of diesel fuel in certain countries.

2.2.6. Potential Environmental Impact

In this study, the potential environmental impact of the biodiesel plant on emissions and crop land use for biodiesel feedstocks is measured.

Total Carbon Saving

Biodiesel is comparatively cleaner when compared to fossil diesel, in terms of carbon emission. This is one of the reasons for active research in the area and the position of biodiesel as one of the possible efficient substitutes for fossil diesel. To measure the benefits of adopting biodiesel, total carbon saving (*TCS*) may be used; which is defined as the amount of carbon emission that may be avoided by substituting fossil diesel with biodiesel. Total carbon saving (*TCS*) is given by the following equation:

$$TCS_i = NAE \times BC_i \quad (26)$$

Cropland Needed

The use of feedstock for biodiesel production requires the use of cropland which could otherwise be utilized for other purposes. It is important to estimate the cropland needed (*CLR*) for the feedstock; calculated simply as the ratio of the feedstock needed to facilitate the fuel substitution to the feedstock yield per acre of cropland

$$CLR = \frac{BC \times 1000}{EY} \quad (27)$$

Ecosystem Carbon Payback Period

The ecosystem carbon payback period is the period from the commencement of the project to the point in time where the overall carbon balance equals the carbon storage before the project. It may be estimated by dividing the difference between the carbons stock from converting the natural land into biodiesel feedstock cropland with the yearly carbon savings by utilizing the biodiesel fuel. Thus, the ecosystem carbon payback period (*CPP*) may be calculated as follows:

$$CPP = \frac{LSC - BCC}{TCS/CLR} \quad (28)$$

3. Results and Discussion

In this study, laboratory experiments were conducted to find the physicochemical properties of *Reutealis trisperma* methyl ester (RTME) biodiesel. To achieve optimal conditions for esterification and transesterification processes for *Reutealis trisperma* oil, an ultrasonic bath stirrer method with the maximum total power of 40 KHz was used. The esterification process was performed using 2% (*v/v*) sulfuric acid (H_2SO_4), with a Methanol-to-oil molar ratio of 60% at a temperature of 55 °C for 1 hour at 1000 rpm stirring speed. For the transesterification process, a catalyst of 0.5 wt % Potassium hydroxide (KOH) was used with a Methanol-to-oil molar ratio of 60% at a temperature of 60 °C for 1.5 hours at a stirrer speed of 1000 rpm.

The results of the laboratory experiments are tabulated in Table 1. Also tabulated are the physicochemical properties of other selected biodiesel sources; *Sterculia foetida* methyl ester (SFME) [44], *Calophyllum inophyllum* methyl ester (CIME) [61], and *Ceiba pentandra* methyl ester (CPME) [62], for comparison purposes. Furthermore, ASTM D6751 and EN 14214 biodiesel standard limits are also tabulated; to ensure compliance with these standards.

It is clearly demonstrated in the table that the properties of *Reutealis trisperma* are in agreement with the two biodiesel standard limits and hence, it can be concluded that *Reutealis trisperma* is a potential feedstock to be used for the production of biodiesel.

Table 1. Physicochemical properties of *Reutealis trisperma* biodiesel and others biodiesel.

Properties	Unit	ASTM D6751 Limit	EN 14214 Limit	RTME ^a	SFME [44]	CIME [61]	CPME [62]
Kinematic viscosity at 40 °C	mm ² /s	1.9–6.0	3.5–5.0	6.48	3.96	3.45	4.61
Density at 15 °C	kg/m ³	880	860–900	892	879.1	877.6	876.9
Flash point	°C	Min 130	Min 120	206.5	160.5	165.5	156.5
Pour point	°C	–15 to 16	-	–2	–3.0	2.0	2.8
Cloud point	°C	–3 to 12	-	–1	–3.0	2.0	3.0
Calorific value	MJ/kg	-	35	40.098	40.427	41.442	40.493
Acid value	mg KOH/g	0.5 max	0.5 max	0.26	0.14	0.34	0.38
Copper corrosion strip	-	3 max	-	1b	-	1a	1
Water content	% vol.	0.05 max	500a max	-	-	0.015	0.045
Sulfur content (S 15 grade)	ppm	15 max	-	14.85	-	6.23	13.97
FAME content	% m/m	-	96.5 max	-	-	98.7	98.6

^a Results.

3.1. Economic Indicator

Table 2 shows the summary of the economic data indicators used in this study for a typical 50 kt biodiesel plant in Malaysia. The lifetime of the project has been set to 20 years, which includes the first year for the construction and startup of the plant. It is assumed that the plant shall operate at 100% capacity throughout the duration of the project. Capital costs for the project are assumed to be paid through private investment and no loans are taken for the project; to make our calculations simpler, as no repayment on the loans need to be considered. The capital costs for the plant are calculated based on the required land area, equipment and instrumentations, as well as the cost for building construction. The feedstock under consideration in this paper is *Reutealis trisperma* oil which shall be used for the production of biodiesel oil. To operate at maximum capacity, approximately 57 kt of crude *Reutealis trisperma* oil is required to produce 50 kt of biodiesel, assuming a biodiesel conversion efficiency (*CE*) of 98%. The selling price of biodiesel is taken to be \$0.47/L for the first ten years and \$2.00/L for the rest of the project lifetime.

Table 2. Summary of economic data and indicators.

Input Data	Data
Year Enacted	2018
Project Lifetime (<i>N</i> , Year)	20 [63]
Interest Rate (<i>R</i> , %)	8.0% [63]
Plant Capacity (t/Year)	50,000 [63]
Feedstock Cost, <i>S</i> (%)	2.0%
Feedstock Price (\$/t)	50
Operating Cost/Unit (<i>OR</i> , \$/t/Fame)	250
Maintenance (% of capital cost)	2.50%
Yield of Biodiesel (Fame) Conversion	87%
Feedstock Price, Feedstock Consumption (<i>FP-FU</i> , t)	57,471
Depreciation Model (<i>D</i> , %)	10% [63]
Replacement Cost (\$Million)	10,000,000 [63]
Glycerol Conversion Factor From Feedstock Oil (<i>GCF</i> , kg/t)	100
By Product Price (\$/t Glycerol)	300
Glycerol Price By Product (t)	5747.13
By Product Price Increase Ratio (%)	0%
Tax (%)	15% [63]
Subsidy For Biodiesel Cost (\$/L) G 1	0.10 [63]
Subsidy For Biodiesel Cost (\$/L) G 2	0.18 [63]
Diesel (Fossil) Selling Price (\$/L)	0.58 [63]
Biodiesel Selling Price For First To Tenth Year (\$/L)	0.58
Biodiesel Selling Price For Eleven To Till The End (\$/L)	2
Density (kg/m ³)	892 [64]

3.2. Life Cycle Cost Analysis and Payback Period

The data from Table 2 above are used to calculate the life cycle cost and payback period for biodiesel plant using *Reutealis trisperma* oil in Malaysia. Results of the calculations are shown in Table 3 and Figure 3. Results from the analysis indicate that the total life cycle cost of the project is approximately \$710 million, giving a unit cost of the biodiesel fuel of \$0.696/L of biodiesel. The unit price of \$0.696/L of biodiesel is lower than the \$0.78/L price calculated in reference [65] for biodiesel from *jatropha curcas*, however, it is higher than \$0.64/L price calculated in reference [63] for biodiesel from palm oil. It is also higher than the retail price of \$0.58/L for fossil diesel in Malaysia. The feedstock costs from crude *Reutealis trisperma* oil are the biggest contributors to the life cycle cost of the project; with a percentage of around 83% of the total life cycle cost or \$0.5896 for every liter of biodiesel produced. This is followed by its operating costs; with a percentage of around 17% of the total life cycle cost or \$0.13 for every liter of biodiesel produced during the 20 years project lifetime, the sale of glycerol, by-product of the plant, contributing \$16,927,840. This is equivalent to the plant clawing back \$0.0169 for every liter of biodiesel produced. The time for the project to recoup its initial capital investment of \$11,882,425 or its payback period is 4.34 years and thus, the payback period is less than one fourth of the lifetime of the project. These results indicate the economic feasibility of the project.

Table 3. Summary of total production cost and payback period of the biodiesel production plant.

Indicator	Life Cycle Cost (\$)	Unit Cost (\$/L of Biodiesel)
Capital cost	11,882,425	0.0119
Operating cost	122,726,843	0.1227
Maintenance cost	2,916,585	0.0029
Feedstock cost	589,522,106	0.5896
Salvage value	260,841	0.0003
By product credit	16,927,840	0.0169
Total biodiesel cost	709,959,278	0.6966
Payback period (year)		4.34

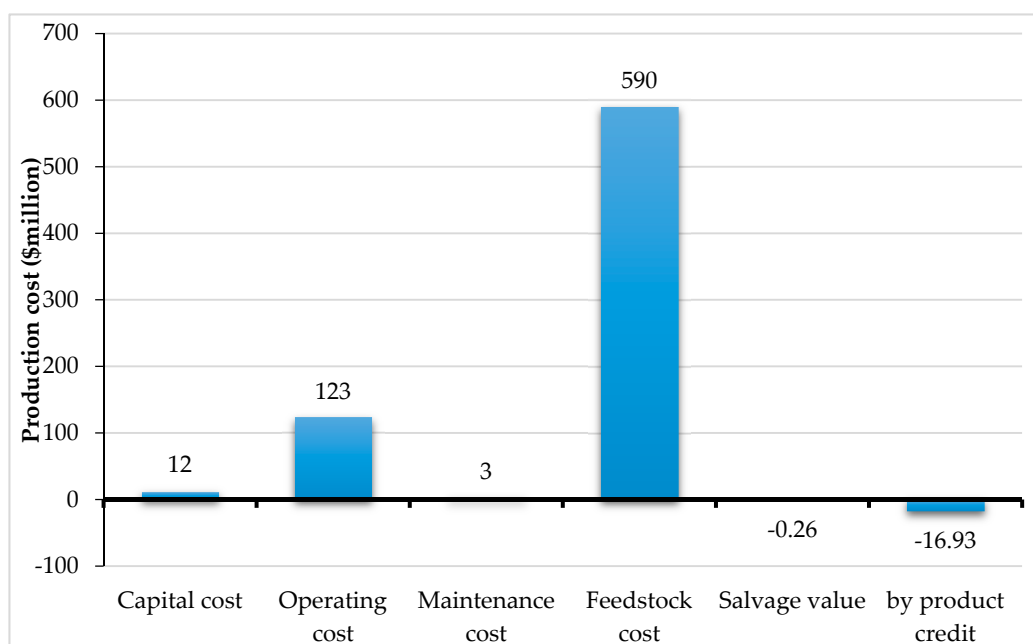


Figure 3. Distribution of *Reutealis trisperma* biodiesel production cost.

3.3. Potential Fuel Saving

The sum of diesel fuel substitution is a function of the yearly diesel fuel consumption with a substitution ratio with biodiesel. The total biodiesel required for replacing the diesel fuel is estimated by the diesel fuel substitution multiplied by the biodiesel to diesel fuel substitution ratio. Since biodiesel and diesel fuels have some dissimilarity in heating value or calorific value, there are different amounts of biofuel required to replace fossil diesel fuel. The fossil diesel consumption and potential diesel replacement are tabulated in Table 4.

Table 4. Fossil diesel consumption and potential diesel replacement.

Year	Diesel Consumption		Diesel Replacement/Saving	
	(Million Liters)	(Tons)	(Million Liters)	(Tons)
2018	9907	8,291,846	495	414,592
2019	10,187	8,526,812	509	425,341
2020	10,468	8,761,778	523	438,089
2021	10,749	8,996,743	537	449,837
2022	11,030	9,231,709	551	461,585
2023	11,310	9,466,675	566	473,334
2024	11,591	9,701,641	580	485,082
2025	11,872	9,936,607	594	496,830
2026	12,152	10,171,573	608	508,579
2027	12,433	10,406,539	622	520,327
2028	12,741	10,641,505	636	532,075
2029	12,995	10,876,471	650	543,824
2030	13,275	11,111,437	664	555,572
2031	13,556	11,346,403	678	567,320
2032	13,837	11,581,369	692	579,068
2033	14,117	11,816,335	706	590,817
2034	14,398	12,051,301	720	602,565
2035	14,679	12,286,267	734	614,313
2036	14,960	12,521,233	748	626,062
2037	15,240	12,756,198	762	637,810

3.4. Sensitivity Analysis

Sensitivity analysis is performed to investigate the effect of variations on some input parameters on the life cycle cost of the project. Five (5) input variables of the model are chosen for the analysis; feedstock unit price (*FP*), operating rate (*OR*), initial capital cost (*CC*), interest rate/discount rate (*r*), and biodiesel conversion efficiency or oil conversion yield (*CE*). The feedstock cost (*FC*), operating cost (*OC*), and initial capital cost (*CC*) are three of the dominant costs associated with the *LCC* as identified in Equation (1) and are demonstrated in Table 3 and Figure 3; with feedstock cost and operating cost determined by the feedstock unit price (*FP*) and operating rate (*OR*), respectively. As present value calculations are employed, the interest rate value (*r*) also influences the *LCC* of the project; a higher interest rate is expected to reduce the *LCC* of the project and vice versa. Finally, since the plant is assumed to produce at its maximum capacity of 50 kt of biodiesel, the biodiesel conversion efficiency (*CE*) dictates the amount of feedstock that should be fed into the plant to produce the required output. Figure 4 below demonstrates the effect of varying the five (5) input variables on the *LCC* of the biodiesel project. The left side of the figure shows the possible values of the variables; “favorable”, “assumed”, and “unfavorable” values on the order of appearance. For instance, the “assumed” value of the feedstock price (\$980/t) is the value used in the *LCC* calculations, giving a *LCC* value indicated by the mid-line on the figure. A reduction in the feedstock price to the “favorable” value (\$680/t) lowers the *LCC* value to less than approximately \$530 million and its increase to “unfavorable” value (\$1280/t), increases the *LCC* value to approximately \$890 million.

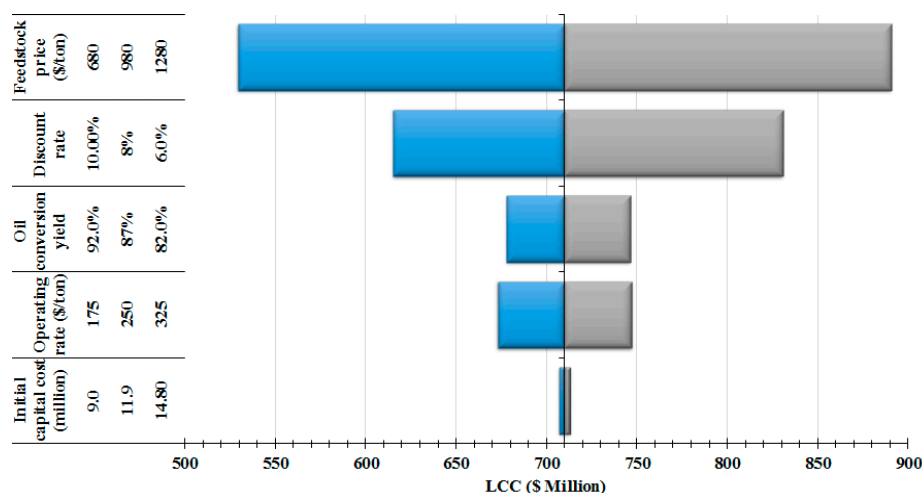


Figure 4. Sensitivity analysis of life cycle costs for *Reutealis trisperma* biodiesel production.

It can be seen from the figure that variations in feedstock prices have the most impact on the life cycle cost of the project; expected as the feedstock price was previously identified as the most dominant cost associated with the LCC. From the figure, a reduction in the price of *Reutealis trisperma* oil from \$980/t to \$680/t reduces the total life cycle cost from approximately \$710 million to \$529 million whilst an increase in price to \$1280/t gives a total life cycle cost of \$890 million. This is followed by the interest rate/discount rate used in the calculation of LCC. An increase of the interest rate to 10% per annum results in a 13% reduction in total life cycle cost whilst a decrease to 6% per annum results in a 17.5% increase in the total life cycle cost. For the operating rate; defined as the operating cost per ton of biodiesel produced, decreasing the rate to \$175/t reduces the total life cycle cost to \$673 million or a reduction of 5% from the original LCC. Increasing the operating rate to \$325/t increases the total life cycle cost to \$746 million, corresponding to a 5% increase. From the figure, the LCC value is least sensitive to variation in the Initial Capital Cost (CC) and is then followed by the biodiesel conversion efficiency (CE); from the five input variables considered in this study. The relationship between the market price of crude *Reutealis trisperma* oil prices and FBC is warranted and is given in Figure 5. It can be seen that the final biodiesel unit cost (FBC) has a linear correlation with the price of the feedstock; an increase in the price of *Reutealis trisperma* oil by \$0.1/kg results in an increase in the final biodiesel unit cost by \$0.05/L.

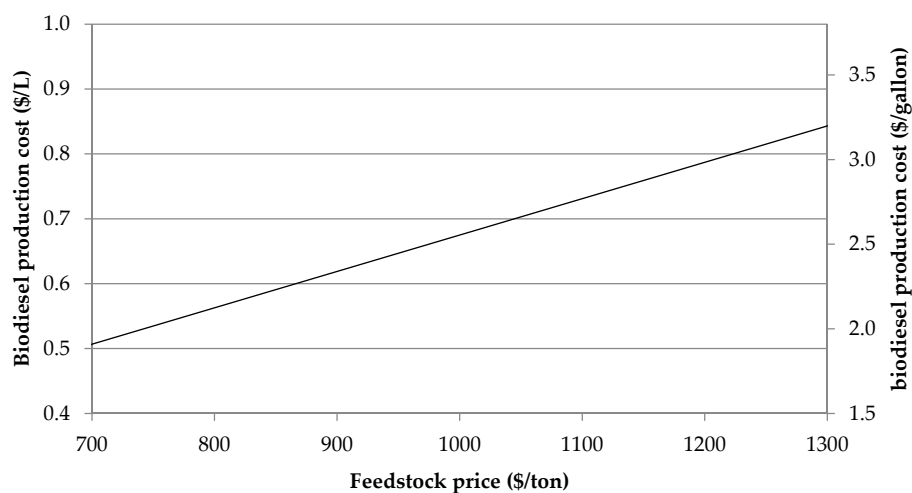


Figure 5. The impact of feedstock oil price on the biodiesel production cost.

3.5. Biodiesel Taxation and Subsidy Scenarios

Taxation and subsidy levels play important roles in encouraging the adoption of biodiesel as a replacement for fossil diesel, especially as biodiesel is less attractive economically when compared to fossil diesel. Imposing a high tax rate has the effect of increasing its selling price whilst giving a subsidy that helps biodiesel to be more competitive in the market. Table 5 provides a comparison on the effect of different taxation and subsidy policies on the competitiveness of the biodiesel, obtained from *Reutealis trisperma*. The scenarios with total tax exemption, a tax rate of 15%, and subsidy amounts of \$0.10/L and \$0.18/L on the biodiesel are analysed and compared with the price of fossil diesel; currently at \$0.58/L, the retail price of diesel fuel in Malaysia. It is noted that subsidy amounts of \$0.10/L and \$0.18/L are current subsidies given by the Malaysian government for petrol fuel and fossil diesel, respectively. The biodiesel to fossil diesel substitution ratio is taken to be 1.07. This allows for a like-for-like comparison of biodiesel and fossil diesel on the basis of energy production, instead of on the basis of volume. At a subsidy cost of \$0.18/L, the current subsidy for fossil diesel, the price of the biodiesel is actually lower than the fossil diesel. In fact, the subsidy cost at anything above \$0.12/L makes biodiesel have a lower price than fossil diesel and hence, is more competitive. Of course, this is based on the assumptions previously made on the different costs associated with the production of biodiesel from *Reutealis trisperma* oil; importantly the feedstock cost of \$980/t, subsidy cost for fossil diesel at \$0.18/L, as well as the retail price of fossil diesel at \$0.58/L.

Table 5. Biodiesel taxation and subsidy level scenarios at current production costs.

\$/L	Biodiesel				Fossil Diesel
	Total Tax Exemption	15% of Tax	Subsidy (\$0.10/L)	Subsidy (\$0.18/L)	
Biodiesel Cost (\$/L)	0.697	0.697	0.697	0.697	-
Taxes/Subsidy (\$/L)	-	0.104	0.10	0.18	-
Total (\$/L)	0.697	0.801	0.597	0.517	0.581
Total Cost (\$/L Diesel)	0.703	0.808	0.602	0.521	0.581

Naturally, the market prices of crude petroleum oil and *Reutealis trisperma* oil are important factors in determining whether biodiesel from *Reutealis trisperma* oil can actually compete with fossil diesel and if subsidies are required to encourage the use of biodiesel. Figure 6 presents the breakeven price of *Reutealis trisperma* oil used in the production of biodiesel at different prices of crude petroleum oil. For a given price of crude petroleum oil, *Reutealis trisperma* oil's prices above the line indicates that the subsidy is required for biodiesel to compete with fossil diesel whilst any prices below, indicates that no subsidy is required and savings may be expected by substituting fossil diesel with biodiesel. As an example, for the price of crude petroleum oil at \$100/barrel, any price above \$1585/t (on the line) for the *Reutealis trisperma* oil would require a biodiesel subsidy so that biodiesel would be able to compete with fossil diesel. Any price below \$1585/t would make biodiesel naturally attractive and savings may be expected by using biodiesel. The opposite is also true. For a given price of crude *Reutealis trisperma* oil (CRTO), the CRTO price to the left of the line indicates that the subsidy for biodiesel is required to encourage the use of biodiesel over fossil diesel. Whilst the CRTO price to the right indicates that savings can potentially be obtained by substituting from fossil diesel to biodiesel. Figure 7 plots the Final Biodiesel unit Cost (FBC) as a function of feedstock price (FP), with the fixed retail price of fossil diesel at \$0.58/L and fossil diesel subsidy of \$0.18/L. It can be seen that at feedstock prices below \$0.8/kg, biodiesel can compete with fossil diesel, provided that biodiesel is tax exempted. At biodiesel subsidy levels of \$0.10/L and \$0.18/L, biodiesel remains competitive against fossil diesel provided that the feedstock prices do not exceed \$1/kg and \$1.19/kg, respectively. Feedstock prices over these values would see the price of biodiesel be higher than fossil diesel.

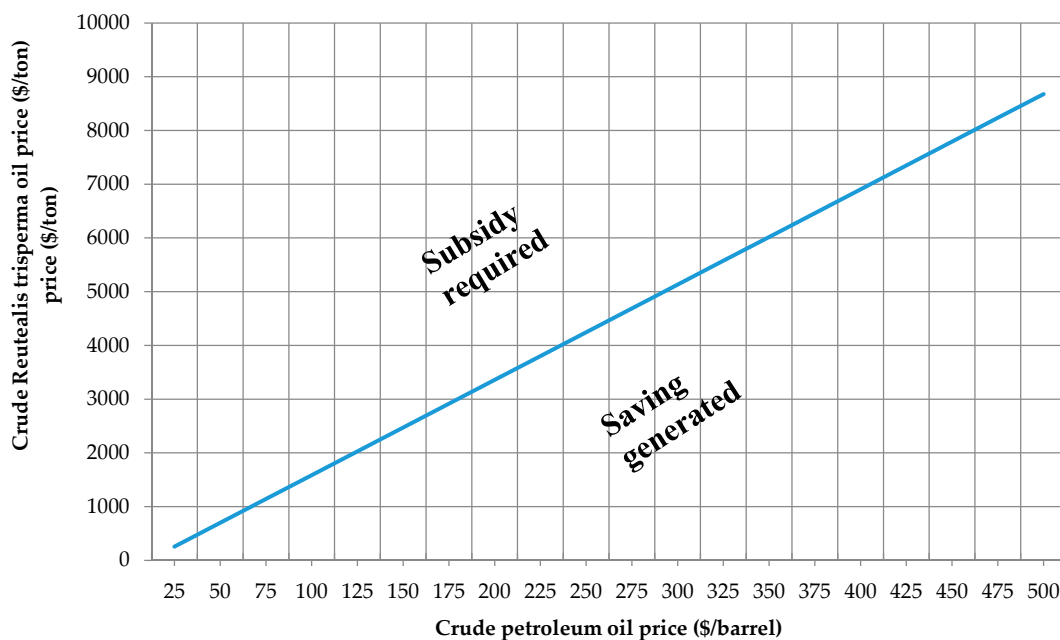


Figure 6. Breakeven price for biodiesel production at different petroleum and feedstock prices.

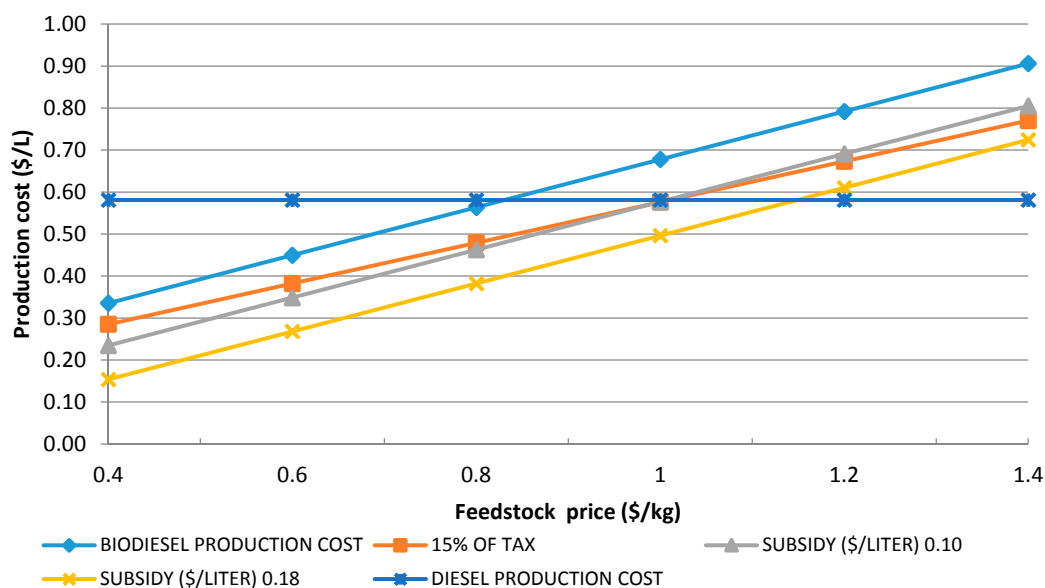


Figure 7. Taxation and subsidy scenarios of biodiesel production cost on feedstock price.

3.6. Potential Environmental Impact

Analysis on the potential environmental impact of adopting biodiesel includes potential emission reductions studies that may be achieved from substituting fossil diesel with biodiesel. This may simply be represented as the total energy saved (TGS_i) from foregoing fossil diesel as well as the potential reduction in carbon emission (TCS_i) from the substitution. Also, the estimates of the cropland required for the feedstocks (CLR_i) is important. The results from the analysis for different replacement rates η , for a fixed assumption on fossil diesel, are given in Table 6 below. An increase in the fossil diesel replacement rate increases the amount of biodiesel required to facilitate the biodiesel to fossil diesel substitution. This increase in the requirement for biodiesel necessitates more cropland to supply the increasing feedstock. Diesel replacement rates of 1%, 20% and 50% require 31 kHa, 626 kHa

and 1564 kHa respectively. Substituting fossil diesel with biodiesel, obviously reduces fossil diesel consumption which translates into total energy saving from fossil diesel. Furthermore, as biodiesel is more environmentally friendly than fossil diesel, in terms of carbon emission, the substitutions also translates into total carbon savings.

Table 6. The results, by changing the number of replacements for the cropland required, total energy saving and total carbon saving.

Diesel Consumption	Diesel Replacement Rate	Diesel Replacement Rate	Biodiesel Needed	Cropland Required	Total Energy Saving (Diesel)	Total Carbon Saving
<i>DC</i>		<i>DR</i>	<i>BC</i>	<i>CLR</i>	<i>TES</i>	<i>TCS</i>
8,291,846 (t)	(%)	(t)	(t)	(Ha)	(GJ)	(kg)
2018	1%	82,918	89,126	31,300	3,573,785	127,169
2019	2%	165,837	178,253	62,599	7,147,571	524,338
2020	3%	248,755	267,379	93,899	10,721,356	381,507
2021	4%	331,674	356,505	125,199	14,295,142	508,676
2022	5%	414,592	445,631	156,499	17,868,927	635,845
2023	6%	497,511	534,758	187,798	21,442,713	763,014
2024	7%	580,492	623,884	219,098	25,016,498	890,183
2025	8%	663,348	713,010	250,398	28,590,284	1,017,352
2026	9%	746,266	802,137	281,698	32,164,069	1,144,521
2027	10%	829,185	891,263	312,997	35,737,855	1,271,691
2028	15%	1,243,777	1,336,894	469,496	53,606,782	1,907,536
2029	20%	1,658,369	1,782,526	625,994	71,475,710	2,543,381
2030	25%	2,072,961	2,228,157	782,493	89,344,637	3,179,226
2031	30%	2,487,554	2,673,788	938,992	107,213,565	3,815,072
2032	35%	2,902,146	3,119,420	1,095,490	125,082,492	4,450,917
2033	40%	3,316,738	3,565,051	1,251,989	142,951,420	5,086,762
2034	45%	3,731,331	4,010,683	1,408,488	160,820,347	5,722,607
2035	50%	4,145,923	4,456,314	1,564,986	178,689,275	6,358,453

Figure 8 illustrates the total carbon emission from fossil diesel and biodiesel for different years having different diesel replacement rates. Although total carbon emissions from both fossil diesel and biodiesel increase with an increase in the diesel replacement rate, total carbon emissions from fossil diesel is clearly higher due to its higher carbon emission factor. The difference between the carbon emissions from fossil diesel and carbon emissions from biodiesel, gives the total carbon saving (*TCS*) due to the diesel substitutions; from a more polluting fossil diesel onto a more efficient biodiesel. From the table, the diesel replacement rate of 1% results in total energy savings from diesel (*TGS*) of 3,573,785 MJ and total carbon saving (*TCS*) of 127,169 kg, and at the diesel replacement rate of 20%, total energy savings from diesel (*TGS*) and total carbon saving (*TCS*) are 71,575,710 MJ and 2,543,381 kg, respectively. Increasing the displacement replacement rate further has been shown to further increase the *TGS* and *TCS* values. Meanwhile, the ecosystem carbon payback period may be estimated by dividing the difference between the carbon stock from converting the natural land into biodiesel feedstock cropland with the yearly carbon savings by utilizing biodiesel fuel, as given in Equation (27). A carbon payback period (*CPP*) value of 25 years is obtained.

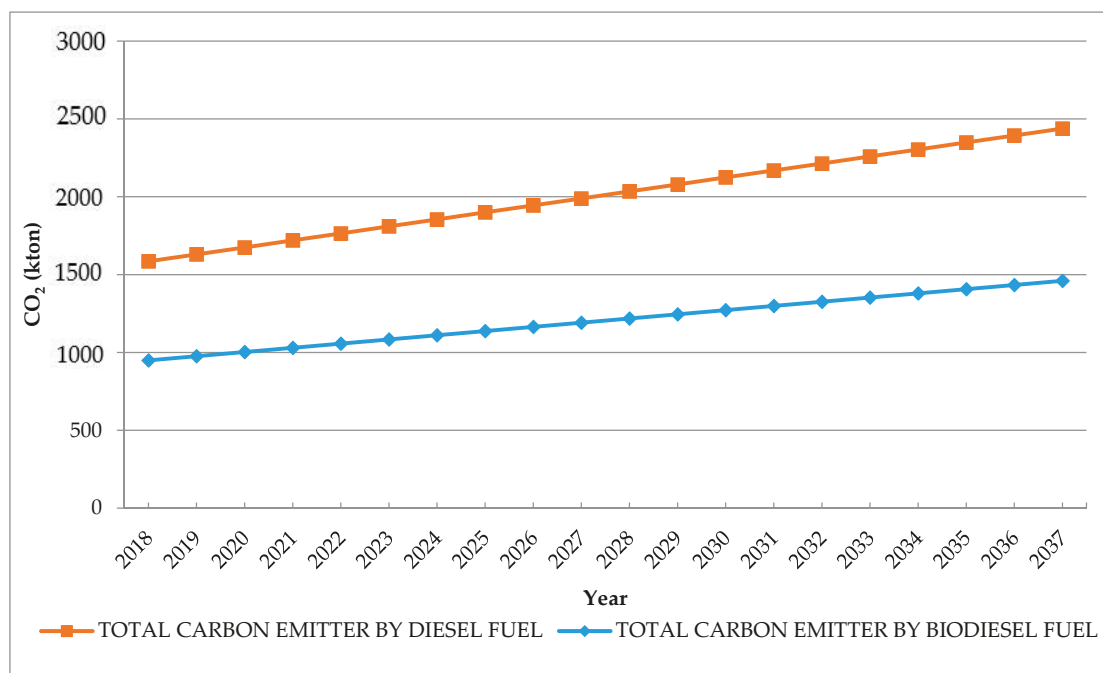


Figure 8. Comparison of total carbon emitter by diesel fuel and by biodiesel presented.

4. Conclusions

The techno-economic and sensitivity analyses of the *Reutealis trisperma* plant as a source of feedstocks for a biodiesel production plant in Malaysia have been outlined in this paper. Laboratory experiments have been performed to verify the suitability of *Reutealis trisperma* oil as a biodiesel feedstock. Consequently, models to calculate the feasibility of the plant based on life cycle costs, payback period, etc., as well as its sensitivity to changing input variables, have been developed for a 50 kt biodiesel production plant with an estimated lifetime of 20 years. The life cycle costs and payback period for the biodiesel plant from crude *Reutealis trisperma* oil are calculated to be approximately \$710 million and 4.34 years, respectively. The total biodiesel unit cost is estimated to be \$0.69/L; competitive with fossil diesel provided the appropriate taxation and subsidy policies are put into place. Implementation and environmental impact studies have also been conducted with encouraging results. However, further studies on limiting factors and methods of overcoming them are necessary before a biodiesel production plant can be implemented in Malaysia.

Acknowledgments: The authors would like to acknowledge that this research is supported by a Fundamental Research Grant Scheme (FRGS) through the Universiti Tenaga Nasional and the Ministry of Higher Education of Malaysia (MOHE) (20160101FRGS) and the University of Malaya for the financial support under BKP Special (BKS054-2017) and Postgraduate Research Grant (PPP: PG016-2015A).

Author Contributions: Teuku Meurah Indra Riayatsyah and Hwai Chyuan Ong conceived and designed the experiments; Teuku Meurah Indra Riayatsyah performed the experiments; Teuku Meurah Indra Riayatsyah, Lisa Aditya, and Heri analyzed the data; Teuku Meurah Indra Riayatsyah wrote the paper. Hwai Chyuan Ong, Chong Wen Tong, and Teuku Meurah Indra Mahlia checked and proofread the final version of the paper.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclatures

BC	Biodiesel needed (t)
BCC	Carbon stock for biodiesel cropland (t/ha)
BFP	Biodiesel fuel price (\$/L)
BP	By-product credits (\$)

CC	Capital cost (\$)
CLR	Cropland required (ha)
CPP	Carbon payback period (year)
CPW	Compound present worth factor (\$)
CRTO	Crude <i>Reutealis trisperma</i> oil
EC	Energy content of diesel fuel (GJ/t)
EY	Ethanol yield (kg/ha)
FBC	Final biodiesel unit cost (\$/L)
FC	Feedstock cost (\$)
FP	Feedstock price (\$)
FU	Feedstock consumption (t)
GC	Diesel consumption (t)
GCF	Glycerol Conversion Factor (\$)
GP	Glycerol Price (\$)
GR	Diesel replacement (t)
HVB	Heating value of biodiesel fuel (MJ/kg)
HVG	Heating value of diesel fuel (MJ/kg)
<i>i</i>	Project year (year)
LCC	Life cycle cost (\$)
LSC	Carbon stock for natural forest (t/ha)
MC	Maintenance cost (\$)
MR	Maintenance rate (%)
<i>n</i>	Project life time (year)
η	Fossil diesel replacement rate (%)
OC	Operating cost (\$)
OR	Operating rate (\$/t)
PC	Annual Biodiesel Production Capacity (t/year)
PP	Payback Period (year)
ρ	Density (kg/m ³)
<i>r</i>	Discount rate (%)
RC	Replacement cost (\$)
SR	Substitution ratio of biodiesel to diesel fuel (%)
SV	Salvage value (\$)
TAX	Annual total tax (\$/year)
TBS	Annual total biodiesel sales (\$/year)
TCS	Total carbon saving (t)
TPC	Annual total production cost (\$/year)
TR	Tax ratio (%)
\$	All monetary unit is in US dollar
EN	European standard
ASTM	American Society for Testing and Materials
RTME	<i>Reutealis trisperma</i> methyl ester
SFME	<i>Sterculia foetida</i> methyl ester
CIME	<i>Calophyllum inophyllum</i> methyl ester
CPME	<i>Ceiba pentandra</i> methyl ester
FAME	Fatty acid methyl ester

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