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Techno-economic analysis and feasibility of industrial-scale biodiesel production from spent coffee grounds

Yamuna Thoppil, Sharif H. Zein*

Department of Chemical Engineering, Faculty of Science and Engineering,

University of Hull (UoH), Kingston Upon Hull, HU6 7RX, U.K.

Abstract

The depletion of the overall provision of crude oil has contributed to the penury for replacing diesel inside the tape drive industry to mitigate their impact. The purpose of the study is to perform an economic analysis to key out the viability of developing biodiesel from the coffee oil extracted from spent coffee grounds (SCG) with the backing of both technological and economic validity. The choice of the most effective extraction and conversion operation for biodiesel production allowed for a preliminary flow diagram to be outlined. A detailed description of the overall production process was described, and detailed equipment specifications that include the sizing of equipment and utility requirements were also given. The project's investment is about $123 million, and the revenues generated from biodiesel's sales are low. In the 15-year life of the plant, the cost of the task based on the baseline assumptions suggests that fixed and capital costs that can be recovered following the life of a plant will not be able to be retrieved. Therefore, the venture would not be profitable and, therefore, not recommended, based on the economic analysis results derived from many assumptions. However, with detailed process economic calculations that considered accurate cost estimations constructed from sensible mass and energy balances, a much better judgement can be made.

Keywords: Coffee oil; spent coffee grounds (SCG); Biodiesel; Techno-economic analysis; internal rate of return (IRR); net present value (NPV); Return on investment (ROI).

***Corresponding Author**: E-mail: s.h.zein@hull.ac.uk, Tel: +40 1482 466 753.

Abbreviations

CC: Contingency Cost

EC: Engineering Cost

FFA: Free Fatty Acids

IRR: Internal Rate of Return

ISBL: Inside Battery Limit

MACRS: Modified Accelerated Cost Recovery System

NPV: Net Present Value

OPEX: Operating Expenditure

OSBL: Outside Battery Limits

ROI: Return on Investment

SCG: Spent Coffee Grounds

1.0 Introduction

The exploitation of conventional fuels has resulted in an environmental pollution crisis and the uncertainty of sustainability that it already faces. The uncertainty is speculated in the trends that show the drop-off in applications that use conventional fuel. The need for alternative fuels can be seen in many countries worldwide, such as the United States, Brazil, France and Germany, where there has been a significantly increased demand for biodiesel. With the technology associated with bioenergy development and its drawbacks, it is possible to integrate bioenergy into the energy sector and biomass to be considered great importance in the post-petroleum future. When considering the establishment of a biological fuel programme, energy density and biomass productivity are considered. There is a state-level effort to implement greener energy generation (World Energy Council, 2018). As stated in the report, the United States' most significant challenge is securing a sustainable energy supply for the midterm while simultaneously attempting to establish a greener energy source for the long term.

The energy demand and environmental concerns can be tackled with the use of biodiesel. Biodiesel is a biofuel produced from biomass feedstock and hence is a viable alternative solution to these issues. However, there are controversies concerning biomass raw materials because of their disturbance in food reserves and security balance. Phimsen et al. (2016) noted that virgin edible oils increase feedstocks' cost. Numerous studies have been conducted on the use of spent coffee grounds (SCG) to produce biodiesel. Blinová et al. (2015) mentioned that biodiesel's yield from the oil of SCG requires the collection and transportation of the coffee residues, drying, oil extraction, and biodiesel production. Kwon et al. (2013) highlighted biodiesel energy source feasibility due to its compatibility with modern combustion engines and existing distribution networks. It would also be desirable to utilise the waste-to-energy concept through harnessing waste biomass (Kwon et al., 2012). The expenses associated with biodiesel are higher than fossil fuels due to the cost of production of biodiesel from the feedstock, where the availability of low cost and good quality feedstock is not assessed, and hence this substantially limits its application (Nelson, 1994). Recently, Brito et al. (2020) showed the production of eco-green biodiesel from domestic cooking oil by transesterification using LiOH with NaOH or KOH catalyst mixtures. The importance of their work is linked to lithium's presence (as a catalyst), which can be obtained using a spent Li-ion battery. The recycling process eliminates Li-ion battery waste and oily contaminants from the environment and allows for a green power source.

The process route taken for biodiesel production consists of solvent extraction of the oil, hydrolysis of the oil to convert triglycerides to its constituent fatty acids and wet glycerol, and the esterification FFAs to form the biodiesel. Extracting oil from the SCG is the first phase of biodiesel production, so maximising the amount removed is critical. The extraction of Soxhlet (SE) is the most widely used solid-liquid extraction (SLE) technique. However, the temperature is limited by the selected solvent's boiling point, long extraction times and substantial solvent losses (Luque de Castro, 2010). Both polar and non-polar elements within the oil extraction solvent have to tackle to ensure a high extraction percentage. When the extraction is low, it is generally due to the solvent only interacting with one of the elements. Ceatano et al. (2014) suggested that the introduction of isopropanol to form the solvent mixture hexane-isopropanol at a 50:50 ratio can increase the extraction percentage to 21.5%. The other limitation of SE is the use of volatile organic solvents hazardous to the environment and human health (Karmee, 2018).

Addressing the shortcomings of using a Soxhlet appliance served as a starting point for developing other SLE processes. Especially supercritical fluid extraction (SFE), ultrasonic-assisted extraction (UAE), accelerated solvent extraction (ASE), and microwave-assisted extraction (MAE) were utilised as an alternative to Soxhlet. In SFE, carbon dioxide or methanol can be used as a green solvent to extract (Karmee, 2018). Fernández et al., 2015 performed SFE-methanol and fractionation of *Jatropha curcas* L. oil. They examined the impact of operating conditions on oil yield, the free fatty acid content of Jatropha curcas L. oil and oil quality. The synthesis of biodiesel by SFE-methanol has the disadvantage of being expensive due to the high temperatures and pressures involved (Calixto et L., 2011). Besides, sophisticated equipment is required (Karmee, 2018). UAE extraction efficiency from oilseeds was at or above that of SE, but with a drastic reduction in extraction time (Luque-García and Luque, de Castro, 2004). In recovering tobacco seed oil, UAE was less effective than the SE (Stanisavljević, Lazić and Veljković, 2007). However, although it is relatively easy to do at the laboratory level, industry expansion is challenging (Vinatoru, 2001). ASE combines high temperatures and pressures with fluid solvents to extract materials. ASE is useful from a solvent perspective, but its use has been limited due to its high cost (Giergielewicz-Możajska, Dąbrowski and Namieśnik (2001). MAE method can be performed at temperatures below those attained in SE (Cravotto et al., 2008). Besides, MAE offers fast heating of the extraction mixture via microwave irradiation (Zein et al., 2017). Recently, Hibbert et al. (2019) have shown that the MAE method is more efficient, producing more oil while requiring a fraction of the time and losing less solvent than the conventional SE method. They showed that using hexane as the MAE solvent could extract more oil than SE with a 24-time decrease and used less volume. The MAE also benefitted from the water content in the SCG, previously believed to obstruct such a procedure. However, there are difficulties in scaling up.

An alternative method for biodiesel production is an in-situ transesterification method. It combines oil extraction, esterification and transesterification in a single stage for biodiesel production. Park et al., 2016 used wet SCG to make biodiesel using in-situ transesterification with methanol. However, solvents would need to be separated from the mix formed after the oil extraction and then recycled back into the extraction phase of the process to reduce biodiesel production cost. Liu et al., 2017 studied in-situ transesterification to make biodiesel from SCG without solvent extraction. SCG tend to have a high moisture content and therefore introduce water into the system after the extraction; separating the solvents from the water would be problematic.

Edible oils are conventionally used as a feedstock for the production of biodiesel. The US generates about 560 million pounds of biodiesel from soybeans (US Energy Information Administration, 2019). The demand for a diversification of energy sources to help ensure our energy supply has intensified (Song et al., 2008). Transitioning to oils generated from waste oils overcomes the issues surrounding the use of edible crops that can compete with the opportunity for food (Ajanovic, 2011). Social pressure regarding waste disposal and the reduction of greenhouse gases from industrial processes are prominent, and there has been a movement to address these issues. Processes are now being evaluated and modified to deal with waste streams and add value to them: this is typically seen with residues' characterisation as raw material for other processes. For industries such as the coffee industry, where there is a large amount of solid waste from brewing coffee grounds, research is being conducted to utilise the SCG (Blinová et al., 2017). The waste after brewing coffee has seen attention being gained from SCG as a new source of energy. Coffee is a much-traded commodity, and thus, utilising waste produced from its brewing is sustainable.

The movement within the industry to establish a circular economy has led to recycling initiatives that strive to eliminate the disposal of SCG from landfills. This movement has encouraged innovative technologies and processes for utilising the SCG, and there are various studies on these applications of SCG. Haile (2014) explored the possibility of using SCG to produce biodiesel and its by-products to produce pelletised fuel. The composition of biodiesel from the SCG and preliminary cost estimates were addressed by Kondamudi et al. (2008). Mussatto et al. (2011) assessed the extraction of sugars from SCG and, in 2012, Mussatto et al., investigated ethanol production from SCG. Cruz et al. (2012a) evaluated the impact of SCG on carotenoid and chlorophyll content in lettuce. They have also studied SCG's richness in bioactive compounds (Cruz et al., 2012 b). Natural antioxidants have been extracted from the SCG for nutritional supplements, foods and cosmetic additives (Panusa et al., 2013). Composting of SCG and the quality of the finished product were studied by Santos et al. (2017). Anastopoulos et al. (2017) examined SCG performance within the water purification industry. Rattanapan et al. (2017) reported on the potential of SCG to make activated carbon.

Thus, this movement has established a competitive market with biodiesel production from waste coffee grounds to utilise the same feedstock. Kourmentza et al. (2018) suggested that due to the increase in environmental awareness globally, there have been stricter regulations with handling been waste streams and thus increased waste disposal scrutiny. Therefore, sustainable projects have been increasingly implemented in industry, which has forced innovation and efficient methodologies regarding these waste streams. Optimisation models are performed to various parameters to ensure that the processes are optimised. The techno-economic analysis would look into the impact of significant cost categories on the efficiency of the process and their sustainability. Harahap et al. (2019) investigate the cost competitiveness of palm oil biodiesel production in Indonesia. Net present value (NPV), Internal Rate of Return (IRR), Return on Investment (ROI) were utilised due to being common indicators for economic analysis and thus concluding the feasibility and profitability of a system. The sensitivity analysis addressed the uncertainties related to biodiesel production from palm oil, including the raw material prices, interest rate, overhead and maintenance costs, and capital cost.

With the global dependency on unsustainable fossil fuels, in addition to the growing environmental issues that organic waste materials contribute to and the push for the adoption of the circular economy within the chemical industry, the viability of carbonaceous waste for the derivation of fuel as an alternative to fossil fuels and crops are questioned. There have been studies that have confirmed the valorisation of SCG. However, they all state the need for techno-economic analysis and industrial-scale fuel production (Karmee, 2018). The United States has contributed to improving its environmental sustainability, resulting from its renewable energy sector growth. Renewable energy generated inherently lower emissions of pollution and correlated with reducing emissions within the US by 0.5% (World Energy Council, 2017). The decline in energy demand and the reduction of emissions are vital for the transition into clean energy. The US has seen a 0.6% reduction in greenhouse gas emissions based on measurements from 2011-2014, which is modest. It still, however, is the second-largest emitter, with China taking the lead. This reduction can be coupled with the knowledge that the United States has a large coffee shop market, as stated by Newhart (2018), making it a viable location for biodiesel production from SCG.

This work intends to evaluate the yield of biodiesel from SCG at large-scale industrial production. Economic analysis is eventually required to validate processes by identifying the favourable scenarios that need to be present for the valorisation of the feedstocks. Hence, the choice of the most effective extraction and conversion operation for biodiesel production will allow for a preliminary flow diagram to be outlined. Material and energy balances will also supply additional information that can be utilised to select appropriate equipment, and the process model can thereby be introduced as a process flow diagram (PFD). The production process's costs and benefits can then be quantified and compared to the current costs of producing biodiesel from crops. An economic analysis will be conducted with appropriate tools and will determine if the production process is an investment to be pursued. The analysis will be projected over 15 years, encompassing the years leading up to and slightly beyond 2030, a milestone year for sustainable development. The ambition in sustainable development goals is that by 2030 there should be universal access to affordable, reliable and modern energy services (United Nations, 2015).

2.0 Process and Unit Description

The stream flow rate and the individual component flow rates are presented in Table 1 and can be used in combination with the flow diagram Figure 1 to understand the process. Summary of unit and process descriptions is given in Supplemental Reading of Table S1. Specifications and details on the flow diagram's various units are provided in Supplemental Reading of Unit Descriptions and associated Table S2 – S14.

The wet SCG are collected from various coffee shops and are then delivered to appropriate storage tanks, where they are conveyed to the mixing unit (V-101) as required (S1). The wet SCG that initiates the process enters at a rate of 3712.1 kg/h into the mixing vessel (V-101) and subsequently extractor (V-102), together with solvents that will extract the coffee oil from the wet SCG (S4). The solvents that enter the extraction phase of the process with the SCG is a hexane-isopropanol mix of a 50:50 mass ratio, which is made up of two streams (S2, S3) enter at a rate of 20,747.8 kg/h. The optimum residence time of the extraction process within the mixing vessel (V-101) is 30 minutes. After that, it enters the extractor (V-102), a solid-liquid centrifuge decanter type temperature and pressure are 303.15K and 2.1 bara, respectively, and the mixture is separated here.

The solid grounds that remain after the solvents-oil-water are removed then exits the extractor at the bottom and is conveyed to the appropriate equipment needed to produce coffee pellets from the solid biomass (S5). The solvents-oil-water mixture leaves the extractor from the top outlet and is directed to the flash drum vessel (T-101), where the oil-water mixture (S12) is separated from the solvents to form a solvent recovery (S9). The temperature is 358.15K, and the pressure is 0.5 bara within the flash drum vessel, although the solvents-oil-water mixture that enters the equipment is at a temperature of 303.15K. This unit would have a utility requirement as electricity is needed to heat the mixture to reach 358.15K for the phases to separate. Additional solvents can be acquired from the solids that leave the extractor. The quantity of solvent is absorbed into the SCG. Thus, they are directed as vapour from the rotary dryer (V-201), where they are evaporated (S8).

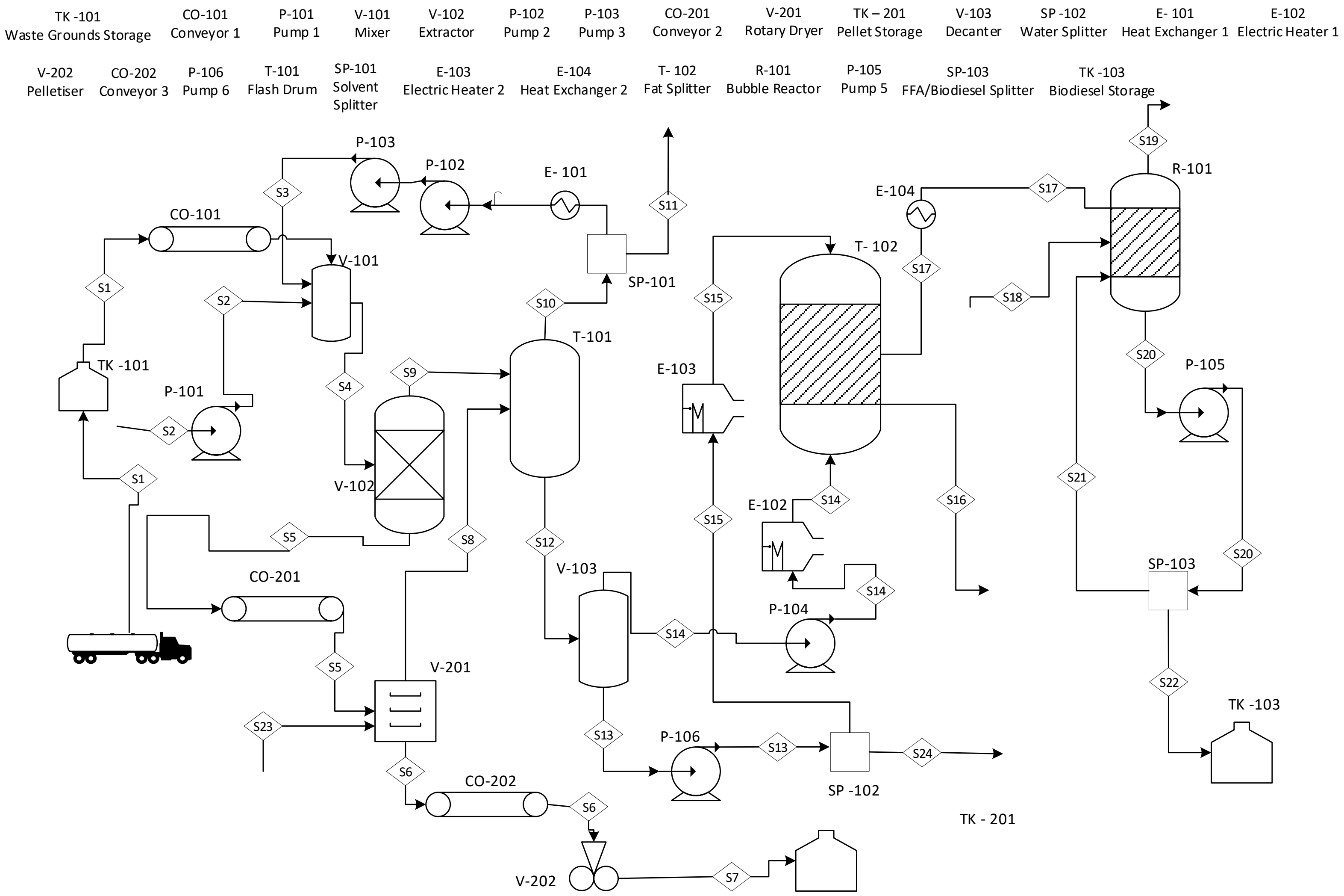

Figure 1: Process Flow Diagram for the Biodiesel Production

Table 1: Mass Balance for the Biodiesel Production

Stream No.		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
Description	Units												
Wet SCG	kg/h	3712.1			3712.12								
Dried SCG	kg/h					1006.8	1006.8						
Coffee Pellets	kg/h							1006.8					
Coffee Oil	kg/h									255.3			255.3
Water	kg/h					42.6			42.6	2407.4			2450.0
Hexane	kg/h		77.5	10296.4	10373.9	726.2			726.2	9647.8	10373.9	77.5	
Isopropanol	kg/h		77.5	10296.4	10373.9	726.2			726.2	9647.8	10373.9	77.5	
Nitrogen	kg/h								21086.8		21086.8		
Total	kg/h	3712.1	155.0	20592.8	24460.1	2501.8	1006.8	1006.8	22581.8	21958.2	41834.6	155.0	2705.3
Temperature	K	303.15	303.15	303.15	303.15	303.15	383.15	298.15	383.15	303.15	358.15	358.15	358.15
Pressure	Bara	0	2.1	2.1	2.1	0	1.0	1.0	1.0	2.1	0.5	0.5	0.5

Table 1: Mass Balance for the Biodiesel Production Cont.

Stream No.		S13	S14	S15	S16	S17	S18	S19	S20	S21	S22	S23	S24
Description	Units												
Coffee Oil	kg/h		255.3										
Water	kg/h	2450.0		117.5	4.5			29.6					2232.5
Hexane	kg/h												
Isopropanol	kg/h												
Nitrogen	kg/h											21086.8	
Free Fatty Acids	kg/h					335.5			15.5	11.4	0.8		
Glycerol	kg/h				32.8								
Methanol	kg/h						71.8	4.0					
Biodiesel	kg/h								2567.8	2261.6	309.2		
Total	kg/h	2450.0	255.3	117.5	37.3	335.5	71.8	33.6	2583.3	2273.3	310.0	21086.8	2232.5
Temperature	K	358.15	523.15	523.15	523.15	*523.15/333.15	333.15	333.15	333.15	333.15	333.15	303.15	358.15
Pressure	Bara	50	50	50	1.0	*0/2.1	2.1	2.1	2.1	2.1	2.1	0	50

*temperature before heat exchange

The solvents leave the flash drum vessel from the top as they are evaporated (S10), and a purge is used to expel the undesired impurities within the stream (S11). This solvent stream is sent back to the extractor via a heat exchanger (E-101) and two pumps in series (P-102, P-103) as a recycle stream to continue to extract coffee oil from the SCG that will enter the process (S3).

The pelletising phase of the process begins from the SCG that exit the extractor and enter the rotary dryer after being conveyed (S5). In this unit, the water and solvents that the SCG has absorbed are removed. It can be estimated that the solids here have a moisture content of 66%. The dryer is required to lower the moisture content of the SCG solids substantially as high-quality biomass pellets have a moisture content between 6-12%. The temperature and pressure within the rotary dryer are 383.15K and 1.0 bara, respectively. A stream (S23) comprised of nitrogen is required as a carrier gas to deal with the flammable tendencies that the solvents absorbed in the grounds have. Nitrogen enters the rotary dryer at 21086.8 kg/hr and is evaporated along with the water and solvents that are directed to the flash drum vessel (T-101). The solids then head to the pelletiser (V-202) on a conveyer (CO-202).

The pelletiser compresses the solids into perforations to produce the coffee pellets. The action of pressing the biomass through the precisely shaped holes generates high pressures, increasing the frictional force and thus the temperature. The increase in temperature allows for the binding agents within the SCG to soften, and when cooled, they solidify and strengthen the pellets. The pellets produced can then be transported to a storage facility, where they can be stored in conditions that do not propagate degradation. The pellets are also considered a fuel source and can be used to generate heat. The storage vessel (TK-103) would need to be large to ensure that the pellets can be accumulated for monthly deliveries.

The method chosen for converting coffee oils to biodiesel is an esterification reaction of free fatty acids (FFA). This optimised production route was selected to ensure that biodiesel's conversion rate was the highest and that the FFA present in the oil and the triglycerides were utilised. The oil first enters the fat splitter at the bottom of the unit after being heated by an electric heater (E-102) to a temperature of 523.15K (S14) to ensure only FFA in the oil enters the reactor. Simultaneously the water stream that leaves the decanter (V-103) is pressurised (S13) and split into two streams, where one stream heads to the fat splitter (S15) and the other becomes a wastewater stream (S24). The stream fed to the fat splitter is at 523.15K as it is heated by an electric heater (E-102) beforehand. This stream is approx—45% of the rate of oil on a mass basis. The triglycerides within the oil react with the water in the fat splitter, and from this reaction, FFA is formed with a glycerol by-product, and although undesired, this by-product can still generate revenue. The glycerol stream that exits the fat splitter also contains water and would require purifying. A unit's addition to doing this separation process would not be cost-effective regarding producing biodiesel, and thus purifying steps would need to be done by the end-user (S16). The glycerol produced is 88% by mass basis glycerol, and thus annually, 313,320 kg is produced. The typical price for glycerol would cost \$0.33/kg, and therefore selling this by-product generated \$103,395.60 can be achieved.

The stream that is composed of FFA and small amounts of other compounds is cooled in a heat exchanger (E-104) with cooling water lowering its temperature from 523.15K to 333.15K (S17), and along with methanol which is the other inlet, stream enters the reactor (S18). The methanol is needed as its reaction with the FFA produces a theoretical conversion of 95%. The reactor has a packed with heterogeneous catalyst (SiO_2-HF) beads. On the first passing of the material through the reactor, the biodiesel quality is not sufficient to meet the required standards. Thus the products are recycled back into the reactor to increase the conversion (S20, S21). The large amount (>0.06%) of FFA that is still present in these streams can react with the methanol to produce biodiesel, so a conversion rate of approx. 99.5% can be achieved. This method is preferred over the addition of a unit for the separation of FFA from biodiesel, as it would be more cost-effective. The biodiesel can then be directed to a storage vessel (S22). The storage vessel (TK-103) that stores the biodiesel has a large enough capacity to store a month's worth of throughput, which can then be transported to biodiesel consumers.

2.1 Material Balance

Within the United States, the location that would provide a sustainable supply of SCG would be Seattle, WA. The city is rated as the second-highest coffee consumption within the country (Crespo, 2016) and has one of the highest coffee shops' concentrations per population density (Kauffman, 2017). Consideration of these parameters is important for locating the biodiesel plant as the supply's proximity limits the greenhouse gas emissions associated with transportation. It also reduces the costs required to fuel the vehicles. The following companies based in Washington provide biodiesel at a year capacity of approx. Ten million gallons (approx. 2.6 kt) (U.S. Energy Information Administration, 2020).

There are 843 coffee shops within Seattle, WA, that can source the SCG. This total is made up of both independent and large coffee chain shops (Crespo, 2016). Collection of the grounds would need to be done on alternative days to ensure that enough time is given for the SCG to accumulate to a sufficient amount that would be required for processing. The collection schedule also ensures that the grounds would not be compromised from the transportation conditions or handling. Appropriate vehicles would be required to collect the SCG from the coffee establishments and to deliver it to the facility, where it can be stored in a storage tank and await processing. To produce approximately 2.6 kt of biodiesel per year, 7,430 kg of product needs to be produced per day and 310 kg per hour. Further information for the project calculation is provided in Supplemental Reading (Table S15).

The plant operation is continuous, and the results are given on a mass basis per hour. The material balance considerations are listed below, and relevant calculations can be found in Figure S1 in Supplemental Reading.

- The process is continuous and steady-state.
- The moisture content of the SCG fed is assumed to be 66%, and therefore the oil and dried solid grounds make up the remaining mass fraction. The weight percentage of oil is approximately 20.2%, and the solid is 79.8%.
- The coffee oil and water within the grounds are miscible with the solvent. Thus, it can be assumed that approximately 98% of the water is removed within the extractor. A further 2% can be removed within the dryer through evaporation.
- The nitrogen gas, used in the process to mitigate hazards in the dryer, is recycled back to the process.
- The solvents used in the process are recycled and 93% being reintroduced into the mixing vessel and then the extractor, and 7% purged into a solvent splitter, with a new feed necessary to complete the initial uptake of solvents.
- The fat splitter only requires a fraction of the water present after it passes through the decanter. Of the total amount of water, 5 % is required, and 95 % is wastewater. The percentage of water entering the fat divider is a percentage weight of the oil directed towards the fat splitter. Similarly, there is an assumption that the conversion rate of triglycerides and water to FFA and wet glycerol is 90%, and of that conversion, 90% fraction of FFA is formed with 10% wet glycerol formed. The wet glycerol contains about 12% of water and 88% of glycerol.
- To produce a yearly 2.6 kt of biodiesel, 310 kg of biodiesel needs to be produced each hour, assuming 8400 operational hours. Hence, approximately 3712 kg of SCG is required to be fed to the process each for each of those hours.

- The initial reaction conversion rate is approximately 95%, of which 88% is recycled back into the reactor. The final conversion rate is 99.7%. Around 6% of the methanol is unreacted due to the conversion rate within the reactor.

3.0 Methods

The economic analysis will be conducted by looking at biodiesel production's total financial costs in the specified capacity. It would briefly consider the benefits that relate to the process regarding the environmental and social impacts, in which the lack of acknowledging and handling could contribute to the expenses. An advantage of the process is producing a solid waste that remains after the oil extraction containing the biodiesel fuel. These solid waste by-products can also undergo different processes to produce coffee pellets that can be sold and used for energy generation. In this circumstance, the pellets can be used to provide energy for the plant's operation. The combination of the total financial cost and the benefits is used to evaluate biodiesel production from SCG through economic assessment tools.

3.1 Model Analysis

3.1.1 Total Capital Investment Summary

The total capital investment for a project is the sum of the fixed capital investment needed for erecting the plant, the working capital required for the plant's initial operation, and the starting expense.

3.1.1.1 Fixed Capital Cost

The fixed capital investment is a vital estimate for establishing a plant and refers to the total cost of designing, constructing, installing, and modifying a plant (Sinnott & Towler, 2009). Accurate cost estimations are essential to provide realistic budgeting and prevent unsuccessful operations, ensuring that appropriate assumptions are made. Risk analysis is performed in the early stages of design allows for this. The Association for the Advancement of Cost Estimating International classifies cost estimating in five different categories, each with its accuracy and purpose. In comparison to other process plants, biorefineries are considered pioneering. The technology used tends to be new and unproven in some circumstances, so the class 5 model can be used in magnitude estimates. They have an accuracy of between ± 30-50% and introduce limitations to cost and design details needed for comprehensive decisions. A class 3 model is more suitable for estimates and has an accuracy of ± 10-15%, using a flow sheet based on approximate sizing of major equipment. However, taking a value of ± 20% for accuracy will ensure a cover for lack of detail. KiOR and Range Biofuels serve as examples of plants that suffered disasters from inaccurate cost estimations. KiOR faced foreclosure due to an unsuccessful operation (McCarty & Doom, 2014), and Range Biofuels faced bankruptcy due to failed technology, costing the taxpayers $80 million (Rapier, 2011). The fixed capital investment is calculated as the sum of the inside battery limits (ISBL), the outside battery limits (OSBL), the engineering cost, and the contingency cost.

3.1.1.2 Inside Battery Limit (ISBL)

The estimated ISBL can significantly impact the overall process economics of a project. Thus miscalculations should be avoided, and care, therefore, needs to be taken to define the scope of the ISBL properly. Bridgewater's method will be employed to determine this estimate (Bridgewater & Mumford, 1979). This method uses a correlation of plant cost against the number of processing steps and is suitable for plants that process liquids and solids. This method is an order of magnitude estimate that can be done if a similar plant cannot be used as a basis for a scaled estimate. There is more design information available other than the production rate.

The information required for this method is the plant capacity in metric tonnes per year, the reactor conversion based on the mass of the desired product per mass of the mass fed into the reactor, and the number of functional units used in the processing plant. The functional units are all major unit operations that would be of substantial cost, and usually, pumps and heat exchangers do generally not consider this. Therefore, the number of functional units based on a preliminary flow diagram is 11. Similarly, the plant capacity required is 2.604 kt per year, which equates to 2604 metric tonnes per year, where the reactor conversion is estimated to be 95%. Two relevant equations can be used as part of Bridgewater's method, and the selection of the appropriate one depends on the plant capacity. Since this project's plant capacity is less than 60,000 metric tonnes per year, Equation 1 can be used (Sinnott and Towler, 2009).

$$C = 280{,}000\, N \left(\frac{Q}{s}\right)^{0.3} \tag{1}$$

Where C = ISBL capital cost; Q = plant capacity; s = reactor conversion (mass of desired product per mass fed to the reactor); N = number of functional units. Cost estimates can be improved by considering the purchased cost of major equipment based on detailed equipment specifications. The specifications are determined from the major equipment's size based on a flow sheet prepared with knowledge of material and energy balances. Details on the material of construction are also contributed. The installation cost can add to the cost estimate's accuracy using the proposed installation factors (Sinnott and Towler, 2009). It should be noted that changes in the relative cost of material and labour from when the factors were suggested would produce some error to the estimated value.

Thus far, the ISBL capital cost estimate's estimations are on a US Gulf Coast 2000 basis. Therefore, a cost escalation index and the location factor need a more accurate representation of the ISBL value. The plant location is on the west coast of the US, and thus the ISBL value will have to be manipulated to obtain the cost related to building the plant in that location as opposed to the US Gulf Coast. The location factor is obtained from the International Construction Cost Factor Location Manual, published in 2003 and can be found in Sinnott & Towler (2009). For the US Gulf Coast, the factor is 1.00, and for the US West Coast, it is 1.07. The cost escalation index used in the processing plant is based on data published by the journal Chemical Engineering which provides the index for US processing plants. This value is known as the Chemical Engineering Plant Cost Index (CEPCI). The CEPCI value published in the year 2000 is 394.1, and for the year 2018 is 603.1.

3.1.1.3 Outside Battery Limits (OSBL)

The OSBL is the off-site cost and includes the cost associated with the modification and improvements required for the site infrastructure. This cost is taken as an estimated proportion of the ISBL. Hence this is why an accurate calculation of the ISBL was needed. This value can range from 10-100% of the ISBL. The OSBL that is taken in the current case is 40%. This is based on the lack of information on the site's condition and knowledge of the site's infrastructure's additions.

3.1.1.4 Engineering Cost (EC)

A contractor would charge for the services they offer, and although this charge strongly depends on the economic climate and the state of the order of goods. A rule of thumb can estimate the cost for a large scale process, and the engineering cost can be taken as 10% of the direct capital cost (ISBL+OSBL).

3.1.1.5 Contingency Cost (CC)

The minimum contingency cost that is placed on all projects is 10% of the direct capital cost. However, the uncertainty of technology increases this value by 50%. It is assumed that the contingency will be 10% due to the technology being considerably conventional, with many of the processes applied to other biofuel producing processes.

3.1.1.5 Working Capital

The cost associated with the plant's operation, following its design, build and commissioning, is the working capital. The working capital is estimated in detail at seven weeks of the cash cost of production minus two weeks of feedstock cost, and the addition of 1% of the fixed capital investment and this gives a value at a 10% greater estimate to the alternative method of calculating working capital from 15% of the fixed capital investment (Sinnott & Towler, 2009). Taking the working capital as an estimate based on the casting cost of production instead of capital investment is beneficial, especially considering that the working capital is recovered at the end of the project. However, this report will calculate the working capital as 15% of the direct capital cost (ISBL+OSBL) for cost estimations.

3.1.1.6 Start-Up Expense

The start-up expense can be estimated as 10% of the direct capital cost (ISBL + OSBL).

3.1.2 Operating Expenditure (OPEX)

3.1.2.1 Fixed Cost of Production Summary

The fixed production costs incurred for the project, regardless of the plant operating at optimum levels or not. It is essential to consider this cost as it can significantly affect the cost estimations associated with the project. Very little can be done regarding the optimisation of the plant's operation to improve the cost estimate. One of the main variables within estimating a fixed cost of production is the labour cost, which is the cost of paying wages to both plant operators and supervisors, which will be present during operating hours, independent of the production rate. Labour cost is a function of the operators per shift position within the process plant. The variables that will be estimated and their relevant assumptions in the calculations are summarised in Table 2.

Table 2: Fixed Cost of Production Summary

Parameter	Assumption
Operating Labour	$60,000 USGC basis average salary per shift position, per year. The process plant will be producing fluids in the form of biodiesel, glycerol, and solid coffee pellets. The estimation of a minimum number of shift positions as stated in figure 6.9 (Sinnott & Towler, 2009), is 3 shift positions with the addition of 1 extra position of the coffee pellet handling section.
Supervision	25% of operating labour
Overhead	40-60% of operating labour + supervision. To err on the side of caution, it will be assumed to be approx. 50% of the operating labour + supervision.
Maintenance	3-5 % of the ISBL investment cost. As the plant has a considerable amount of moving equipment, such as the conveyors and solid handling processes, the maintenance assumption can be 5% of the ISBL investment.
Property Taxes and Insurance	1-2% of the ISBL investment, the percentage that will be considered in the estimate will be 2% of the ISBL investment.
Rent of land	Typically it is stated to be 1-2% ISBL+OSBL. It is assumed that like most projects that the land is rented instead of outright purchased. This means that the cost is not added to the fixed capital investment and recovered at the end. To err on the side of caution, it will be assumed that the rent of the land is 2% of the ISBL + OSBL.
General Plant Overhead	It is taken as 65% of the sum of operating labour, supervision, direct overhead and maintenance.
Environmental charges	1% of ISBL + OSBL Charges to cover the Superfund payment.

3.1.2.2 Variable Cost of Production Summary

The biodiesel plant's variable cost of production has a proportional relationship to the operation rate and output. It is comprised of the cost associated: the raw materials that are required for the process, the utilities that are utilised for optimal operation, the consumables needed, the appropriate disposal of the waste streams produced, and the packing and shipping costs required for the distribution of the products. With the increase in detail to the design and operation, the more accurate the estimate for this variable cost, optimisation to either the design or operation can decrease this cost.

It is assumed that the SCG, which is the raw material in this project, will be donated to the plant to produce biodiesel. Thus the cost associated with acquiring the material will relate to the collection of the SCG from the coffee shops. The utilities required for biodiesel production are electricity, cooling water, and chilled water. The consumables utilised are Hexane, Isopropanol, Nitrogen, Methanol, and the Silicon dioxide – Hydrogen Flouride bead catalyst. It is assumed that the utilities' cost is approximately 20% of the total quantity of biodiesel produced. Similarly, the cost of the consumable is 35% of the total amount of biodiesel produced.

3.1.2.3 Revenues

The revenues associated with the project is the income obtained from the sale of products for both the desired product and any by-products produced. The main product is biodiesel, with the by-products produced being the coffee pellets and the wet glycerol produced. The composition of the final product stream contains both biodiesel and a small fraction of FFA impurities. However, purification of this stream is not necessary as the biodiesel meets the required standards. Coffee pellets make up the solid by-product produced in the pelletising phase of biodiesel's overall production.

On the other hand, the wet glycerol makes up the liquid by-product within the fat splitter in the biodiesel production process. It is possible to purify this stream. However, an additional unit would be required for this, which would add to the purchase cost. A by-product can be considered feasible when it has a greater net benefit than \$200,000 per year (Sinnott & Towler, 2009).

3.1.2.4 Margin

When the cost of the raw material is taken into consideration with regards to the revenues generated from the sale of products in the project, then it can be summarised by the following Equation 2:

$$\text{Gross Margin} = \text{Revenues} - \text{Raw Material Cost} \qquad (2)$$

Identifying the gross margin allows for a greater understanding of the sales revenues retained after production that does not contribute to production costs. When assuming that retailers donate the raw materials, it can be assumed that the revenues can be equated to the gross margin.

3.1.2.5 Profits

For the project's profit to be estimated, the cash cost of production is needed. It is essential to identify the cost of making the product without excluding any return on the equity capital invested. The cash cost of production is the sum of all the variable cost of production, excluding by-product revenue and the sum of all the fixed cost of production. The by-product revenues are discarded in this calculation as they are considered a credit and typically included in the variable cost of production.

The Cash cost of production (CCOP) can be deducted from the biodiesel revenues for the gross profit to be realised. This profit generated is subjected to corporation tax to determine the cash flow after tax has been taken. Then, the net profit can be calculated by subtracting the tax from the gross profit. The amount of tax that would need to be paid every year would vary and would need to be determined to get the best representation of after-tax cash flow. Equation 3 estimates the amount of tax paid where the taxable income is determined by the subtraction of tax allowance from the gross profit. Depreciation is the most common form of the tax allowance.

$$\text{The Amount of Tax Paid} = \text{The Taxable Income} \times \text{The Tax Rate} \quad (3)$$

where the taxable income is determined by the subtraction of tax allowance from the gross profit. Depreciation is the most common form of the tax allowance.

3.1.2.6 Corporation Tax

The tax to which profits are subjected is referred to as corporate taxes. The United States Federal Corporate Tax Rate in 2018 stood at 21%, though it should be noted that for the last decade, within 2009-2017, the corporate tax stood at 35% and averaged at 32.58% of the previous century (Tradingeconomics.com, 2019).

3.1.2.7 Depreciation

The Modified Accelerated Cost Recovery System (MACRS) depreciation method is used to determine the depreciation charges that cash flow will be subjected to. Biorefineries are treated as chemical manufacturing facilities to be designated a class life of 9.5 years. Thus, a recovery period of 5 years, the associate depreciation charges would be applied to the project's cost estimation calculation.

3.1.2.8 Interest Rate

The interest rate is assumed to be 11%.

3.2 General Assumptions for Baseline Projections

The baseline projection will be the calculations that do not consider the changes in the volatile parameters, which are accounted for in the sensitivity analysis. Instead, it is the assessment with the most probable values of each parameter. The baseline projections based on the following assumptions will then be compared to the sensitivity analysis results, allowing for the most favourable conditions to be identified. It is assumed that the period that this economic assessment will cover is 15 years. This time frame would provide sufficient data to evaluate and subsequently inform potential investors on the viability of the process and the project's profitability for investing. The discount rate, also known as the interest rate, is considered 11%.

3.3 General Assumptions for Sensitivity Analysis

The sensitivity analysis accounts for the volatile parameters and examines the effects these uncertainties have on the project's overall viability. Selected parameters can be adjusted using a range of variation for each factor stated in Sinnott and Towler (2009). The changes to the biodiesel product's sale price will be investigated as this is susceptible to change depending on its demand as petroleum fuel is phased out. Assuming that the fuel price's base range is 100%, then the range looked at will be 80% to 120%.

4.0 Baseline Projections Results

This section illustrates the results that have been obtained from the economic analysis that took into consideration baseline assumptions and employed process economic equations. The sensitivity analysis was attempted manually when processing the results and evaluating the discount rate's effect on the NPV**.** The NPV is calculated using Equation 4, where CF_n = the cash flow in year n, t = the project life in years and i = interest rate (Sinnott & Towler, 2009).

$$NPV = \sum_{n=1}^{n=t} \frac{CF_n}{(1+i)^n} \qquad (4)$$

Figure 2 shows the NPV obtained from the net cash flow over the 15-year lifetime. This result was based on the discount rate of 11%, which calculates the NPV to be approximately negative \$44 million. A negative NPV is unfavourable and, therefore, not viable. Consequently, it can be concluded that calculations based on the baseline assumptions indicate that this scenario cannot be pursued. Year one of the project is assumed to be the designing phase of the project, and it can be seen in the figure as the starting point of the cash flow. The second year of the project is focused on construction. The entirety of the fixed capital investment is put into the project, which is reflected in the extremely negative decline in the diagram. It is assumed that production starts immediately after the plant's construction, and it would be operated at full production capacity.

ROI and pre-tax ROI and IRR were calculated using Equations 5 – 7 where CFn = the cash flow in year n, t = the project life in years and i' = the discounted cash flow rate return (Sinnott & Towler, 2009). IRR and ROI were calculated to be 2% and negative 86%, respectively. The payback period can be seen to be three years. Table 3 summarises the calculation of the NPV. The discount rate was varied to obtain a better understanding of its impact on the net present value. The Total Capital Investment summary is given in Table 4, and Table 5 summarises the project output. Figure 3 shows that with the increase in the discount rate, the net present value decreased.

$$ROI = \frac{cumulative\ net\ profit}{plant\ life \times intial\ investment} \times 100 \tag{5}$$

$$pre\ tax\ ROI = \frac{cumulative\ pre{-}tax\ cash\ flow}{plant\ life \times intial\ investment} \times 100 \tag{6}$$

$$IRR = \sum_{n=1}^{n=t} \frac{CF_n}{(1+i')^n} = 0 \tag{7}$$

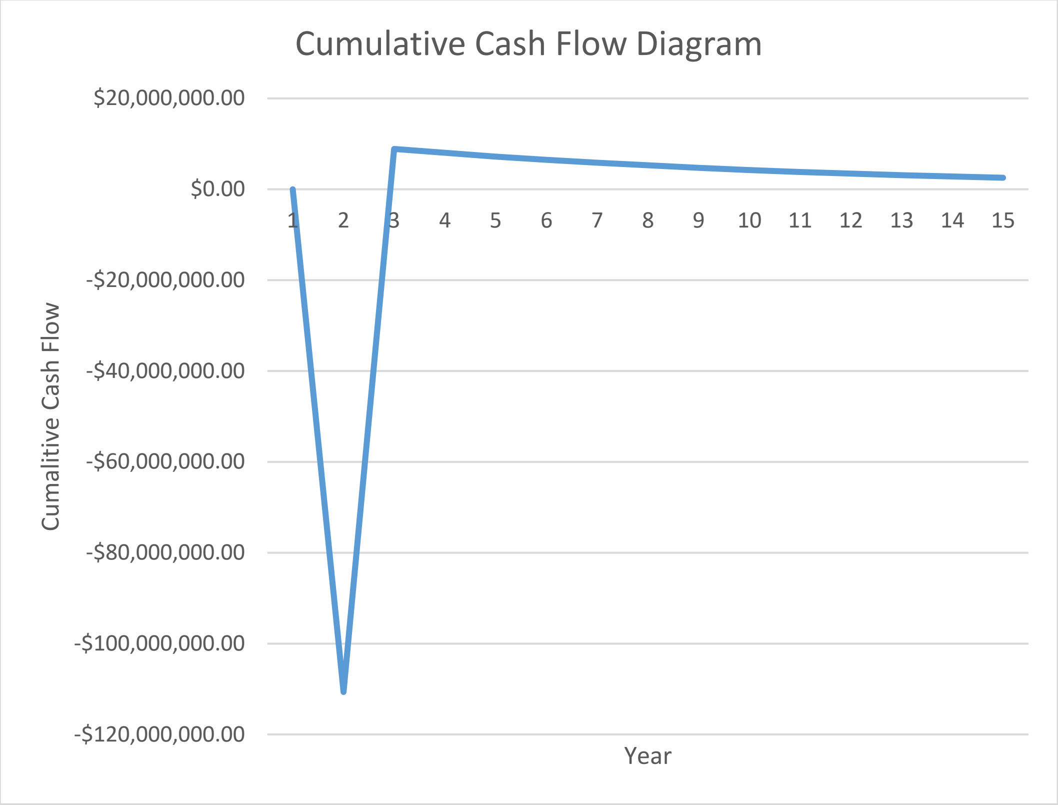

Figure 2: Cumulative Cash Flow Diagram.

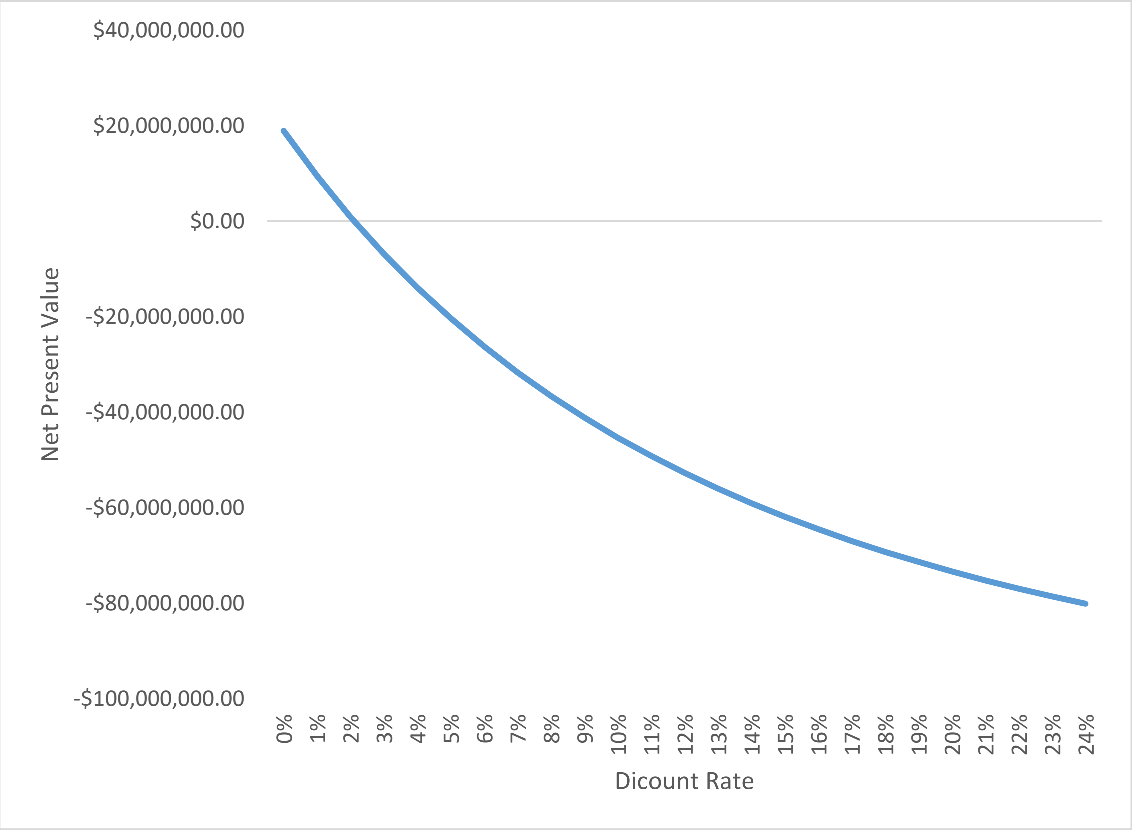

Figure 3: NPV Profile

Table 3: NPV summary

Year of Project	Year	Investment %	Procution Capacity	Depreciation Charge	Investment	Operating Expence	Gross Proft	Depreciation Expence	Tax Income	Taxes Paid	Cash Flow	Discounted Cash Flow	PreTax Cash Flow
1	2019	0	0	0	0	0	0	0	0	0	0	$0.00	$0.00
2	2020	100	0	0	-$122,828,695.22	0	0	0	0	0	-$122,828,695.22	-$110,656,482.18	-$122,828,695.22
3	2021	0	100	0.2	0	-$9,928,728.7	$1,209,960.2	$241,992.05	$967,968.19	$203,273.32	$10,935,415.61	$8,875,428.63	$10,732,142.29
4	2022	0	100	0.32	0	-$9,928,728.7	$1,209,960.2	$387,187.28	$822,772.96	$172,782.32	$10,965,906.61	$8,018,176.40	$10,793,124.29
5	2023	0	100	0.192	0	-$9,928,728.7	$1,209,960.2	$232,312.37	$977,647.87	$205,306.05	$10,933,382.88	$7,202,157.95	$10,728,076.83
6	2024	0	100	0.1152	0	-$9,928,728.7	$1,209,960.2	$139,387.42	$1,070,572.82	$224,820.29	$10,913,868.64	$6,476,849.84	$10,689,048.35
7	2025	0	100	0.1152	0	-$9,928,728.7	$1,209,960.2	$139,387.42	$1,070,572.82	$224,820.29	$10,913,868.64	$5,834,999.86	$10,689,048.35
8	2026	0	100	0.0576	0	-$9,928,728.7	$1,209,960.2	$69,693.71	$1,140,266.53	$239,455.97	$10,899,232.96	$5,249,707.23	$10,659,776.99
9	2027	0	100	0	0	-$9,928,728.7	$1,209,960.2	$0.00	$1,209,960.24	$254,091.65	$10,884,597.28	$4,723,115.16	$10,630,505.63
10	2028	0	100	0	0	-$9,928,728.7	$1,209,960.2	$0.00	$1,209,960.24	$254,091.65	$10,884,597.28	$4,255,058.70	$10,630,505.63
11	2029	0	100	0	0	-$9,928,728.70	$1,209,960.24	$0.00	$1,209,960.24	$254,091.65	$10,884,597.28	$3,833,386.22	$10,630,505.63
12	2030	0	100	0	0	-$9,928,728.70	$1,209,960.24	$0.00	$1,209,960.24	$254,091.65	$10,884,597.28	$3,453,501.10	$10,630,505.63
13	2031	0	100	0	0	-$9,928,728.70	$1,209,960.24	$0.00	$1,209,960.24	$254,091.65	$10,884,597.28	$3,111,262.25	$10,630,505.63
14	2032	0	100	0	0	-$9,928,728.70	$1,209,960.24	$0.00	$1,209,960.24	$254,091.65	$10,884,597.28	$2,802,938.97	$10,630,505.63
15	2033	0	100	0	0	-$9,928,728.70	$1,209,960.24	$0.00	$1,209,960.24	$254,091.65	$10,884,597.28	$2,525,170.24	$10,630,505.63
												NPV	-$44,294,729.6

Table 4: Total Capital Investment Summary

Cost Parameter	Cost
ISBL	$33,107,465
OSBL	$13,242,986
Contingency Cost	$4,635,045
Engineering Cost	$4,635,045
Fixed Capital Cost	$55,620,541
Working Capital	$6,952,568
Start Up Expense	$4,635,045
Total Capital Investment	$122,828,695

Table 5: Product Throughput

Material	**Quantity (kg/year)**
Biodiesel	2,604,000
Wet glycerol	313,320
Coffee Pellets	8,457,120

The biodiesel production plant that is proposed will produce a throughput of 2.6 kt /year by capitalising on approximately 31.2 kt /year of SCG collected from coffee establishments. In addition to biodiesel production, coffee pellets and wet glycerol are produced, with 8.5 kt /year and 313,320 kg/year made, respectively. Summary of project calculation and estimation is given in Supplemental Reading of Table S15. The plant will be located within Seattle, Washington, in the United States, taking advantage of their state policy that propagates biodiesel production. Many coffee establishments within the city allow for efficient collection of SCG without severe environmental impacts. The process route taken for biodiesel production consists of solvent extraction of the oil, hydrolysis of the oil to convert triglycerides to its constituent fatty acids and wet glycerol, and FFA esterification to form the biodiesel. When considering the FFA in oil, the process method is different from conventional biodiesel production, taking into account both an esterification and transesterification reaction. Thus steps that are associated with the removal of impurities can be eliminated. Optimisation within the plant follows through utilising the grounds following oil extraction, where coffee pellets are formed through drying of the SCG and subsequent pelletising.

Process economic calculations were performed to evaluate the profitability of an economic analysis of producing biodiesel from oils extracted from SCG, employing standard techniques to do so. A sensitivity analysis was also attempted to identify the desirable conditions required for the successful implementation of the venture, with biodiesel's sales price being the parameter considered. The NPV obtained based on the baseline assumptions provided was negative $44 million, relating to this value, the IRR was 2%, and in the third year, the ROI was negative 86%.

As seen in Table 5, the product comprises biodiesel, wet glycerol and coffee pellets. The current biodiesel prices, wet glycerol and coffee pellets are $0.95 /kg (US Department of Energy, 2020), $ 0.15/kg (Kumar et al., 2020) and $1.51/kg. Coffee pellets were based on the price of coffee logs produced by Bio-Bean, UK (Wickes, 2020). Kumar et al. (2020) also reported that biodiesel's unit production cost using microbial oil production was estimated to be $5.9/ kg biodiesel. The study concludes that biodiesel production is not viable based on baseline productions. However, with detailed process economic calculations taken into account, a much better judgement can be made. The fault can lie with biodiesel price, with the sale price having to be substantially larger per quantity to generate a positive profit. It is also the case for the sale price of the coffee pellets. Additional alternative scenarios need to be examined, with the highest sensitivity identified, to accurately assess biodiesel production's overall viability from coffee oil and coffee oil mixed with waste cooking oil and explain the biodiesel quality and improve the profitability.

Campbell et al. (2018) investigated biofuels' financial viability and biochar production from forest biomass in the face of market price volatility and uncertainty, where inherently unpredictable changes to critical variables with time considered. The Monte Carlo Method was utilised in this study and identified the following; the market price for biodiesel and biochar has the most significant impact on the NPV, which could be associated with the uncertainty in future costs. The production route that positively influenced the NPV was identified. Backhurst and Harker (1973;p.47), cited in Ray and Sneesby (1998), summarises that the viability of an investment is swayed more by the changes governed by the economist and financial experts. Amendments to the bank rates would affect the profitability of the project and the equipment's efficiency, which is a statement that loosely applies to the results found, where the increase to discount rate has shown a decrease in net present value.

5.0 Conclusion

The biodiesel production plant that is proposed will produce a throughput of 2.6 kt /year by capitalising on approximately 31.2 kt /year of SCG collected from coffee establishments. In addition to biodiesel production, coffee pellets and wet glycerol are produced, with 8.5 kt /year and 313,320 kg/year made, respectively. Process economic calculations were performed to evaluate biodiesel's profitability from oils extracted from SCG, employing common techniques. A sensitivity analysis was also attempted to identify the desirable conditions required for the successful implementation of the venture, with biodiesel's sales price being the parameter considered. The rudimentary sensitivity analysis was manually conducted and concluded that the increment in sales price for biodiesel would greatly affect the NPV. The revenues generated need to be large for the quantity produced to attain the operational cost to be set off.

The study concludes that biodiesel production is not viable based on baseline productions. The fault can lie with biodiesel price, with the sale price having to be substantially larger per quantity to generate a positive profit. It is also the case for the sale price of the coffee pellets. Future studies should examine environmental issues with related mitigation methods and details of relevant costs to better estimate costs. Similarly, process control piping and instrumentation and additional start-up and shutdown equipment should be considered. Cost assumptions regarding the collection of SCG, the cost of purchasing the collection vehicles, and the associated administration and operating costs should also be provided. Also, the distribution cost of the biodiesel and by-products should be considered. Additional alternative scenarios need to be examined, with the highest sensitivity identified, to accurately assess biodiesel production's overall viability from coffee oil and coffee oil mixed with waste cooking oil and explain the biodiesel quality and improve the profitability.

Finally, whereas this study considers that the plant will be located in Seattle, Washington, USA, taking advantage of state policy, future work could include areas that are most attractive for retrofitting as biorefineries for biodiesel production.

CRediT author statement

Yamuna Thoppil.: Investigation, Data curation, Writing- Original draft preparation.

Sharif Zein: Conceptualisation, Supervision, Writing- Reviewing and Editing.

Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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