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Rubber seed oil: Potential feedstock for aviation biofuel production

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ABSTRACT

The aviation industry is responsible for 12% of transport-related GHG emissions and 2–3% of the global GHG emissions, thus raising concerns for sustainable alternatives such as aviation biofuels. This study sought to analyze the potential of producing aviation fuel from rubber seed oil. Rubber seed oil (RSO) was extracted and the physicochemical properties investigated as well as the fatty acid composition. This result was simulated in ASPEN plus to determine the potential aviation biofuel produced using the UOP HEFA process. The study shows that the golden yellowish oil derived from rubber seed possessed a density 0.9 g/cm3 and pH of 6, refractive index of 1.48, heating value of 23.75 MJ/kg and composed of 75% area of FFA with Oleic and Linoleic acid been the most dominant. The HEFA process on ASPEN Plus showed 81% of feedstock was converted to hydrocarbons with aviation biofuel yield of 46%. It was estimated that the installation of the plant for aviation biofuel production has a total capital cost of $ 8,650,480 and a total operation cost of $ 328,728. The economic analysis shows that at a cost of USD 4/kg (USD 3.01/liter) of aviation biofuel has an Internal rate of return of 18.62% profitability of 1.18 and payback period of 14.9 years of the plant operating. This study established that rubber seed oil shows suitability and potential for sustainable aviation biofuel production.

Introduction

The utilization of fossil derived fuels is the major contributor to air pollution and human induced climate change. Recent scientific evidences highlight the necessity to rapidly cut down the emission of greenhouse gas globally more than ever and in 2018 emissions related to energy consumption reached the highest value in history at a rate of 2.9% [1] . At present, commercial aircrafts are solely operated on liquid fossil fuels, with the expectation that the current technologies will be supported by more sustainable fuels such as hydrogen, electricity and liquid biofuel in years to come to achieve the global aspiration of reduced greenhouse gas emission [2]. For example, [3] reported that cryogenic energy conversion using su-

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perconducting machines possess five times more power density than existing counterparts giving hydrogen fuel in electric propulsion an advantage in zero emission propulsion for regional aircrafts in the future. The aviation sector accounts for 12% of the greenhouse gas emissions related to the transportation sector globally and responsible for 2-3% of total anthropogenic emissions [4]. The aviation industry therefore contributes a significant role in combating climate change through global warming. Even though clean technologies for aircraft propulsion are in development such as cryogenic and electric propulsion, these technologies will only be commercially ready after 2050 [5] . To achieve the significant reductions in aviation emissions proposed by the International Civil Aviation Organisation (ICAO) and other international organizations, the production and consumption of alternative fuels is necessary [5] . Renewable aviation biofuels are capable of reducing CO_2 emissions by 80% over their life cycle, thus making them suitable candidates for Sustainable Aviation Fuels [6].

Some challenges have been associated with the production of biofuel from edible sources including food-fuel conflict and high fuel price [7]. The use of biofuels has been subjected to criticisms based on the conflict between energy crops (first generation feedstocks) and food production for available limited resources such as fertile lands. Also, the loss of biodiversity and changes in landscape due to deforestation of woodlands is also another concern for biofuel production. This implies some processes of the fuel production supply chain can lead to high global warming potentials taking into account indirect land use among others [8]. This calls for sustainable development and industrialization of alternative aviation fuels produced from renewable nonedible resources. Second-generation feed stocks such as energy crops are recognized as pacesetters to the development of commercial alternative aviation fuels as they mitigate the food-fuel crisis caused by first generation biofuel. On the other hand, fuel cost comprises of over one third the cost of airlines operations hence the unwillingness of airlines to pay higher prices for alternative jet fuels compared to other transport modes [9]. Until the price of biofuel is competitive with conventional fuel the production of biofuel will be limited, despite the call for greener alternatives to aircraft propulsion and the raising prices of fossil fuels. According to [10] biofuel can be more competitive if it is produced as a secondary product to be cross- subsidized by incomes from other products [11] is also of the view that the access to sustained low-cost feedstock is relevant in bridging the price gap between fossil fuels and biofuels.

Several studies exploring various production processes and feedstock for economical viable biofuels. These approaches include the use of mass and energy balance, feedstock variability, conversion pathways and energy crop cultivation processes [12]. It is established that feedstock contributes largely to the cost of biofuel production (70—80%). A study by [13] on jatropha shows that the major price contributors are cost of biochemicals purchase, cost of investment, and key process-inherent parameters such as oil content and conversion yield. According to [14] the production cost of Sustainable Aviation Fuel vary significantly from € 0.88 per liter or $1.0 per liter (for lipid based feedstock through the hydroprocessed esters and fatty acids (HEFA) process) to € 3.44per liter or $ 3.9 per liter (via Hydro processing of fermented sugars) which is about 2 to 8 times of the price for conventional jet fuel. [15] also reported that the average minimum fuel selling price of jet fuel from the HEFA production pathway is the lowest $1.2 per liter ($1.07–1.32 per liter) which is mainly attributed to its high production yield (>1000 per liter dry feed) and relatively lower capital costs ($ ~0.34 per liter). Both FT ($0.92–2.59 per liter) and ATJ ($0.75–2.77 per liter) routes show similar average minimum jet fuel selling price (MFSP) at $1.76 per liter. The highest average MFSP can be found in the Hydroprocessing of fermented sugars route, i.e. $ 4.27 per liter ($2.17–6.36 per liter).

In the search for sustainable and economical feedstocks for biofuel production, seeds from the rubber tree (*Hevea brasiliensis*) are gaining attention as a non-edible versatile bioenergy crop for the production of biofuels. Rubber tree plantations are cultivated mainly as a source of latex, with little focus on the utilization of the seeds. Typically, a hectare of rubber plantation comprises of 350 - 500 trees with each tree yielding about 800 seeds yearly. It is estimated that 70–500 kg of seeds are produced annually from a hectare of rubber plantation [7]. FAO reports that globally, 14,845,068.7734 metric ton (11,602 hg/ha) of natural rubber (latex) was produced in 2020 with a harvested area of 12,795,267 ha [16]. Studies have been conducted on the oil yield of rubber seed oil using various extraction process with an average of 30 wt% and maximum of up to 49.36 wt% using Soxhlet extraction process [17]. As part of the various studies exploring the biodiesel potential of rubber seed oil a study by [18] compared the performance and emission of biodiesel from various oil based feedstocks and found rubber seed oil as a suitable feedstock for biodiesel production. In addition, it was discovered that rubber seed oil-based biodiesel had the lowest emission rates of CO_2 and NO_2. A study by [19] revealed that with a combined capacity of 717,750 ha of rubber plantation, Sub- Saharan countries have the capacity to produce 16,691.025 metric tonnes of biodiesel. Another study by [20] shows that Southeast Asia has the capacity to produce 1.80 Mt of biodiesel annually from 7.48 Mha of rubber tree plantation.

Despite the numerous studies on the use of rubber seed oil for biofuel production, there is a gap in the study of the utilization of rubber seed oil for aviation biofuel production. Rubber seed oil, poses as an attractive feedstock for aviation biofuel production considering the existing scale of rubber plantations under cultivation hence serves as a secondary product that will prevent competition with food crops for land space and lower the price of feedstock acquisition. This study therefore has the objective to investigate the potential of rubber seed oil for aviation biofuel production through oil extraction, physicochemical property analysis and simulation of aviation biofuel production as well as cost analysis using ASPEN Plus. Results from the study could set the pace for the exploration of aviation biofuel production in Sub- Saharan Africa.

Materials and methods

Rubber seed oil extraction and characterization

Seed preparation

Rubber seeds were obtained from Ghana Rubber Estate Limited (GREL). The seeds were de-shelled manually using laboratory mortar and pestle. The seeds, shells and kernels were weighed separately and their weights recorded. Seed kernels were size reduced with a mill and dried overnight at 105°C using an oven to obtain constant weight. using Eq. (1). The processed kernel was milled to particle size less than 1 mm for maximum oil yield [19].

$$\text{Moisture content } \% = \left(\frac{mass\ of\ wet\ kernel\ -\ mass\ of\ dried\ kernel}{mass\ of\ dried\ kernel} \right) \times 100 \tag{1}$$

Extraction of rubber seed oil

Rubber seed oil was extracted using accelerated solvent extraction using hexane as a solvent at elevated temperature and pressure. A Thermo Scientific Dionex ASE Prep DE accelerated solvent extractor was used for the extraction process at Chemical Engineering Lab, KNUST. The oil was extracted at 100°C and 1300 Psi for 25 min with 200 ml of hexane. After the extraction was completed, hexane was recovered from the oil-solvent mixture under vacuum at 60°C using rotary evaporator The oil yield was determined using Eq. (2).

$$\text{The RSO yield (wt.\%)} = \frac{mass\ of\ extracted\ oil\ (g)}{mass\ of\ rubber\ seed\ kernel\ used\ (g)} \times 100 \tag{2}$$

Characterization of rubber seed oil

Determination of density, refractive index and pH of rubber seed oil. The physicochemical properties of the extracted oil were analyzed at the Chemical Engineering Lab, KNUST using standard experimental methods and instruments to determine density (KRUSS Density meter DS7800 in accordance with ASTM D4052-16), refractive index (KRUSS digital refractometer DR6300-T) and Thermo Scientific ORION STAR A211 pH meter.

Analysis of fatty acids in rubber seed oil. The composition of fatty acid in the extracted rubber seed oil was determined by the conversion of all fatty acids present to the corresponding fatty acid methylesters (FAME) after which the fatty acid analysis was carried out using GC – MS [21]. A sample of 10 μL rubber seed oil was reacted with 0.5% of methanolic NaOH (0.5 mL). The reactant was kept in incubation at 60°C for a duration of 20 min. Hexane was used to extract the methylesters for a duration of 1 min, washed away with 0.2 mL distilled water and the methylesters dried over anhydrous sodium sulphate.

A Thermo Scientific, ISQ Single Quadruple MS, TG-5 MS fused silica capillary column (30 m, 0.251 mm, 0.1 mm film thickness) equipment with an ionization energy of 70 eV was used at the Central Laboratory, KNUST. Helium was used as a carrier gas at a constant flow rate of 1 ml/min. The column oven temperature was initially held at 60°C and then increased to 200°C at a heating rate of 5°C/min and maintained for 2 min. The temperature was finally increased to 280°C at a heating rate of 10°C /min).

Ultimate analysis and high heating value (HHV) calculation. Elemental composition of the oil (C, H, N, O, S) were determined at the Soil Science Laboratory, KNUST. Through the micro Kjeldahl technique the Nitrogen content was estimated. The Walkely and Black procedure which is a modification of the wet oxidation method based on the reduction of the $Cr_2O_7^{2-}$ by organic matter was used to determine the percentage content of Carbon. The sulphur content was estimated by first digesting the oil with HNO_3 and $HCLO_4$ to form sulphate, which is subsequently titrated with $BaCl_2$. Hydrogen content was estimated by titration whilst the oxygen content was determined by difference. The experiments were repeated twice and average results taken.

The HHV was calculated using modified Eq. (3) from [22].

$$HHV\ (MJ/kg) = 0.3491C + 1.1783H + 0.105S - 0.1034O - 0.0151N \tag{3}$$

where C, H, O, N S, are percentages of the various elements identified.

Production of aviation biofuel from rubber seed oil

The process for the production of aviation biofuel was simulated using ASPEN Plus.

Simulation considerations

The study adopts a simulation approach in the production of aviation biofuel using the properties of the characterized rubber fuel extracted. The honeywell UOP Ecofining SPK process was modelled on ASPEN Plus to simulate the process of aviation biofuel production. The process comprises of two main processes. First is the highly exothermic deoxygenation process and followed by a concurrent isomerization and hydrocracking process which is common to the processing refinery for conventional transport fuels, before the biojet fuel is separated through distillation. The resulting product can be blended with conventional aviation fuel at a ratio up to 50% [6].

The triglycerides were modelled based on normalized results obtained in the GC-MS analysis of the rubber seed oil. The hydrodeoxygenation and decarboxylation processes were carried out in the first reactor (RSTOIC reactor). The process was modelled with the system receiving rubber oil at a flow rate of 100 kg/h and a hydrogen at a rate of 2.30 kg/h (20 H_2/ oil mol/mol) to prevent the formation of coke as presented by [23], and to produce straight chain alkanes with carbon chain ranging from C_{15} –C_{18} as shown in the Eq. (3).

The hydrocracking and hydro-isomerization reaction were modelled using the yield reactor according to [24]. Isomerization was carried out to improve the cold properties of the fuel and the cracking produced carbon chains corresponding to the range of aviation fuel.

[25] Reports optimal temperatures for cracking long chain of oils to short chains ranges from 400 to 450 °C which is necessary in achieving aviation fuel properties. Product of this run was fractionally distilled assuming binary distillation

Economic analysis

Integrating the economic analysis into the conceptual design of a project fosters the assessment of the design process to estimate the profitability of the project while reducing cost from infeasible processes. A good project is one that ensures the profitability during its life cycle. ASPEN Economic Analyzer (APEA) was employed to analyze the cost estimations from implementation and running of an aviation fuel bio-refinery considering the above process for aviation fuel production from rubber seed.

Techno-economic models that describe the processes and production cost estimations of a conceptual bio-fuel production pathway have been proposed by the National Renewable Energy Laboratory. Considering a simulated biofuel conversion pathway ASPEN plus generate material balance, mass flow and energy balance parameters. This data was used to size the equipment to estimate the cost of equipment, raw material and cost of operation. The financial analysis was conducted assuming a plant life span of 30 years operating for 7920 h a year on a bath operating mode. The tax rate was 15%, interest rate of 25% and a straight-line depreciation method in similarity with [12]. Information on the price of the various materials were adopted from [26]. The cost of hydrogen was estimated based on the amount utilized in the reactor with a 40% increase to cater for the catalyst used in the reaction. The cost of rubber seed oil was estimated based on the cost involved in mechanical press extraction and assuming a yield of 30%. The cost of the Rubber seed oil was assumed to be USD 172 / metric ton and for the coproducts, Diesel and Naphtha were calculated at USD 1524/ metric ton and USD 770/ metric ton

Due to lack of information on biofuel projects, the simulation used some default parameters in ASPEN plus with modification to some parameters applicable to Ghana. The dollar currency was used for uniformity with other studies and stability of the currency and an exchange rate of GHS 1 to USD 0.17 [27] was used for conversion where necessary. The Association for Advancement of cost Engineering (AACE) proposed a 30% margin of accuracy for this methodology of cost estimation.

Using 2018 as the base year the cost in acquiring the equipment for the refinery including installation were estimated using the power – law relationship between the equipment price, size and index of inflation. The new prices were calculated within the application using the Eqs. (4) and (5).

$$\text{New Equipment Cost} = \text{Original Equipment Cost (New size /Original size)}^{\text{exp}} \tag{4}$$

$$\text{Installed Equipment cost} = \text{Equipment cost x installation Factor} \tag{5}$$

Where exp takes values from 0 to 1

Economic indicators

Internal rate of return (IRR): Also referred to as the Discounted Cash-Flow Rate of Return, it is the rate at which the present value of all cash flow is zero. It is determined at the end of the economic life of the project with the assumption that the working capital and salvage value are recouped.

Payout period This is the number of years after which it is expected that the original investment in the project will be recovered. Hence the length of operating time of the plant needed to recoup the working capital and total capital cost (initial capital investment).

Profitability index (PI) This indicates the relative profitability of a project and determined by Eq. (6)

$$\mathrm{PI} = \frac{Present\ Value\ of\ the\ Cumulative\ Cash\ Inflows}{Present\ Value\ of\ the\ Cumulative\ Cash\ Outflows} \tag{6}$$

Where if PI > 1; project profitable.

PI < 1; project not profitable.

PI = 0; no losses or gains (break-even point).

Table 1
Physiochemical properties of rubber seed oil.

Property	Value	Other Studies	Sources
Colour	**Golden Yellow**	Dark brown, Golden yellow	Omorogbe et al. 2013, Asuquo et al. 2012
Density (g/cm3)	**0.92 ±0.002**	0.85-0.94	(Onoji, 2017)
Specific gravity 20/20	**0.93 ±0.004**	0.91	(Onoji, 2017)
°API gravity	**19.49**	24.1	(Onoji, 2017)
Refractive index	**1.48 ±0.001**	1.46-1.47	Asuquo et al. 2012 [17]
pH	**6.49 ±1.16**	6	Asuquo et al. 2012 (Onoji, 2017)
FFA % area	**75.59**		
Sucrose % Brix	**76.33±0.53**		
Glucose % Brix	**78.38 ±0.57**		
Fructose % Brix	**78.38 ±0.62**		
Inverted sugar % Brix	**78.29 ±0.62**		
Absorbance	**4.58 ±0.027**		
Transmittance %	**0.003 ±0**		
Heating value MJ/kg	**23.75**	36.1–44	(Onoji, 2017)

Results and discussion

Rubber seed oil extraction and physiochemical properties

Characteristics of rubber seed

From the seeds sampled from the GREL, it was observed that the average weight of a good rubber seed was 2.8 g with a mean kernel weight of 1.5 g. A good seed (fresh kernel) could weigh as much as 3.73 g and bad seed (rotten kernel) weighs less than 1.8g. This average seed comprises of 54% kernel and 46% shell which is consistent with the study by [17].

Rubber seed preparation

After processing a total of 127 g of rubber seed through the various processes 68.15 g as kernel was obtained and milled to obtain 63.84 g of milled kernel. After 5 h of drying at 105°C and over 12 h of drying at 50°C a mass of 59.97 g of milled kernel was achieved. This implies a loss of 6% moisture content by drying to achieve no significant change in weight [28] reports that after drying rubber seed kernel in an oven at 105°C for 4 h, the rubber seed oil should contain 7% of moisture content. Furthermore [29], revealed that the presence of moisture in seeds act as mediums for heat transfer during oil extraction and aid in protein coagulation which promotes oil yield. Rubber seeds were therefore optimally prepared for oil extraction. Moisture in oil seeds during extraction serves as heat transfer medium and helps in the coagulation of protein which aids oil yield. Loss of moisture occurs with increasing temperature and hardens seeds which increases bond of oil with proteins and may account for low yields at high temperatures.

Oil yield

The extraction of oil was carried out through the accelerated solvent extraction process at high temperatures and pressure. A 25 g of milled rubber seed oil yielded about 8 ml of rubber seed oil implying 30.2 wt% yield. The resulting yield is close to the maximum oil yield of 32% obtained by [30] using the ultrasonic-assisted solvent extraction process. The study obtained an optimum yield of 30.3 ± 0.3% using 5:1 hexane – rubber seed kernel ratio, reaction time of 15 min, temperature of 60 ± 5°C and resonance amplitude of 50 mm. However [31], recorded a maximum yield of 49% using mechanical press extraction with intermittent addition of n- Hexane with solvent to seed ratio of 0.8:1 [19] also achieved a maximum yield of 40.3% using Soxhlet extraction with hexane and particle size of 0.5 mm. This implies a relatively low yield however within the average yield.

Physicochemical characterization of rubber seed oil

The physical and chemical properties of the extracted rubber seed oil were studied and summarized in Table 1. The extracted oil from *Hevea brasiliensis* was golden yellow. This is consistent with the colour from [32] using Hexane as solvent. Some studies also reported dark brown oil extract from rubber seed [7]. The clear golden yellow oil extracted was observed to be free from visible droplets of water. Golden yellow colour reduces the need for bleaching to remove undesirable colour in the fuel [29]. High presence of water or moisture content promotes oxidation of the oil which turns the oil milky hence reducing the quality and shelf life of the oil. Low presence of water therefore implies the oil can be stored for a long duration without the deterioration of its quality with time [33]. The oil tested to have a pH of 6.49 which implies slightly acidic and this is favorably compared with other studies on the extraction of rubber seed oil [7] and it is acidic similar to oils obtained from castor oil. The level of acidity indicates the presence of reasonable amount of free fatty acids in the oil. This makes the oil favorable to produce soap.

The oil has a density of 0.92 g/cm^3 at 25°C and a relative density of 0.93 at 20°C and 0.9982 g/cm^3 density of water. This implies the oil is less dense than water. The oil also measured a specific gravity of 0.92 at 20°C relative to 1 g/cm^3 of water a 4°C and a calculated °API gravity of 19.49.

Table 2
Percentage elemental composition of rubber seed oil.

Element	wt%	[41]
Carbon	55.33 ±0.61	64.5
Hydrogen	6.72 ±0.24	8.2
Oxygen	37.36 ±0.85	23.4
Nitrogen	0.59 ±0.01	3.6
Sulfur	3.71 ±0.14	0.3

$$°API = (141.5 / SG) - 131.5 \tag{6}$$

where °API = Degrees API Gravity, SG = Specific Gravity (at 60°F)

The specific gravity of the oil indicates the energy content of the fuel. Fuels with low °API gravity (high specific gravity) tend to have higher heating values than fuels with high °API gravity (low specific gravity). The higher the energy density of a fuel, the lesser the storage space required. Also it influences the level of adulteration of the oil and it is an important factor for approval of the oils as a potential feedstock and defines the dimensions of pipes and pumps in the construction/ installation of a plant [34]. Refining low-gravity crude oil requires more complex and expensive processing equipment, more processing steps and energy; therefore, it costs more. However, rubber seed oil is in the range of medium gravity crude oil, which can be conveniently refined using existing infrastructure.

The rubber seed oil also possesses some significant percentages of sugars 76.33% Brix Sucrose, Glucose of 78.38% Brix, Fructose 78.38% Brix and Inverted sugar 78.29% Brix. Degrees Brix (°Bx), is the number of grams of sugars (glucose, fructose and sucrose) present per 100 grams of liquid. The presence of sugars makes the cake favourable for animal feed after oil extraction. [28] also found significant percentages of elements of omega-3 fatty acid which plays an important role in metabolism. Earlier studies also showed rubber seed cake to contain 19.9 wt% carbohydrate and 30 wt% protein, all agreeing to the potential of using rubber seed cake as food for livestock and a source of value addition and resource displacement in the biofuel production process using rubber seed [33].

The refractive index is a dimensionless optical parameter that describes the propagation of light in a medium. The ratio of the velocity of light in vacuum to that of rubber seed oil (a medium) at 25°C was determined to be 1.46 which does not vary significantly from similar studies on rubber seed oil. The refractive index (RI) indicates the level of saturation of the oil as well as serves as an indication of possibility of the oil to develop rancidity. A high refractive index implies a higher chance spoilage through oxidation [35]. The refractive index of the rubber seed oil falls within the acceptable range

Ultimate analysis. The Table 2 summarizes the various percentages of the elements identified in the elemental analysis. It is evident that over half of the oil comprised of Carbon (55%) followed by 37% of oxygen and the 6.72% hydrogen. Sulphur and nitrogen were contained in small quantities (less than 5%). The high proportions of oxygen in the rubber seed oil reduces the HHV since during combustion of the oil, H_2O (water) is formed and CO_2 emitted [22].

SO_2 is a major pollutant in the combustion of transport fuels hence the presence of Sulphur in fuels is undesirable. SO_2 reacts with moisture in the air to form acid rain which is corrosive. Sulphur content in aviation fuels should not exceed 0.3%, hence the oil has over 10 times the allowable percentage for aviation fuel hence will require further refinery to reduce the sulphur content.

The physicochemical properties such as density and energy content are influenced by the various proportions of hydrocarbons present. However, the presence of oxygen, sulphur and nitrogen compounds affect the corrosiveness, cold properties and stability of the fuel, hence are reduced to improve fuel quality [36].

The heating value of the oil was estimated to be 23.75 MJ/kg based on information from the elemental composition of the rubber seed oil. Other studies have shown rubber seed oil to possess a high heating value ranging from 36.1 to 44 MJ/kg. Hence the oil under study has low HHV compared to literature. This can be attributed to the high percentage of oxygen which reduces the overall HHV as evident in Eq. (3).

Fatty acid composition

The oil sample was subjected to GC-MS analysis to determine the composition of fatty acids in the oil and results presented in Table 3.

Rubber seed oil composed of significant number of fatty acids. Oleic acid was identified to be the most dominant constituting about 25.19% area in the spectrum. Linoleic acids were the second most abundant fatty acid with 17.22% area. Palmitic and Stearic Acids occur in low proportions constituting about 10% of fatty acid composition. Other significant fatty acids identified are alpha-Linoleic acid with 7.17% area and Asclepic acid 8.890% area. Fatty acids made up 75.59% of the rubber seed oil which is consistent with other literature in the studies [37] show high percentage in linoleic acids followed by Oleic acid. The composition of the majority fatty acids in the study is consistent with other studies such as [17,21] and others that show Oleic and Linoleic acids in significant proportions in rubber seed oil of up to 80%.

The values of the fatty acid composition in the oils vary based on the process of extraction, method of analysis and geographical location of the trees [7]. The high percentage of fatty acids can be attributed to how long the seeds have

Table 3
GCMS analysis results.

#	Retention Time	Area %	Methyl Ester	Molecular formular	Molecular mass	[37]
1	15.595	4.855	Palmitic acid	$C_{16}H_{32}O_2$	256.42	17.7
2	20.087	17.220	Linoleic acid	$C_{19}H_{34}O_2$	294.5	43.2
3	20.289	25.192	Oleic Acid	$C_{19}H_{36}O_2$	296.5	45.1
4	20.967	6.179	Stearic Acid	$C_{19}H_{38}O_2$	298.5	3.9
5	26.284	2.1	others			3.1
#	RT	Area %	FFA	Molecular formular	Molecular mass	
6	21.517	7.173	alpha-Linoleic acid	$C_{18}H_{32}O_2$	280.4	
7	21.682	8.890	cis-Vaccenic acid / Asclepic acid	$C_{18}H_{34}O_2$	282.5	
8	22.214	2.016	Stearic acid	$C_{18}H_{36}O_2$	284.5	
9	24.066	0.874	others			
10	24.579	1.093	others	$C_{26}H_{52}O_2$	396.69	

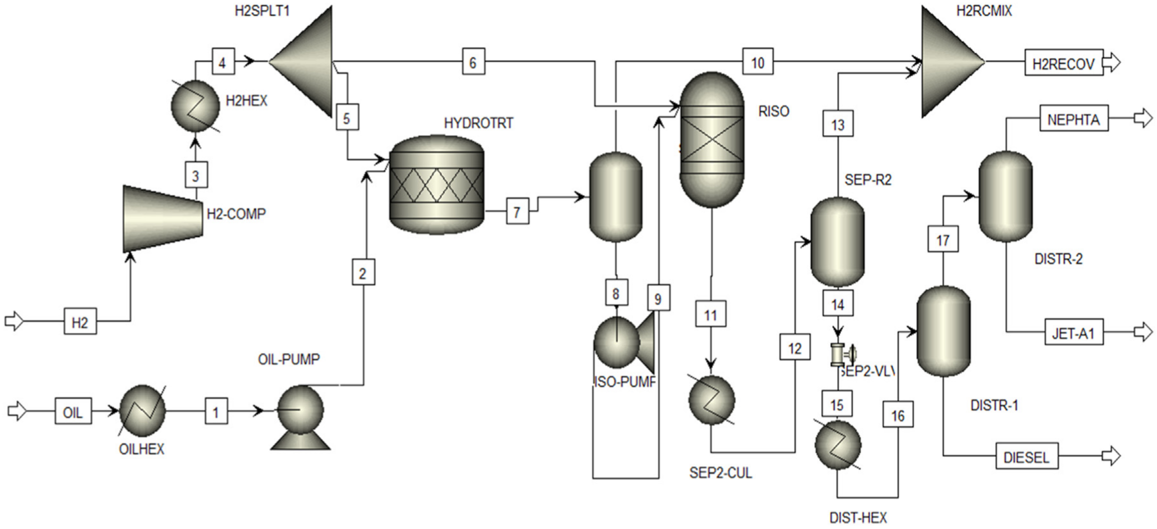

Fig. 1. Process flow diagram for the production of aviation biofuel.

been stored before processing. A study on the physicochemical properties of rubber seed oil by [31] discovered that over a storage time of two months, the free fatty acid (FFA) composition increased from 2 wt% in fresh rubber seeds to 45 wt.% under room temperature. It is therefore inferential to say that the seeds developed more fatty acids after over 5 months of storage. It also explains the needs for convenient processing and storage of seeds for biofuel production.

Lipid based oils with fatty acids of C_{18} produce low yield in aviation fuel production of about 40 wt%. This challenge common to vegetable oils is mainly as a result of the hydrocracking process which converts C_{16} -C_{19} alkanes into paraffin range of aviation fuel (C_8-C_{16}) [38].

Outcome of simulation of aviation biofuel production process

Process description

The feed stream for the first stage of hydrogenation was pre-conditioned before introduction in the reactor. This process required the used of compressor and turbine to increase the pressures of the H_2 gas and rubber oil to 40 bar. Heat exchangers were employed to increase the temperatures of both feed streams to 350 °C.

A study by [23] reported the power consumption in preconditioning H_2 in the process was the highest of about 54.5% of the total power consumption. It was observed that the optimum design arrangement for the pretreatment process for the oil is the heating of the oil before pressuring. This prevents significant pressure drop (-15 bar) in the oil before been introduced into the reactor. However, heating the H_2 gas before compressing required more heat duty and cooling of the gas (from ≈700 °C–350 °C) before introduction into the reactor which is not suitable. Hence the H_2 was compressed and heated to ensure minimum demand of heat and electricity in the process.

Hydrogenation reaction

The process of aviation fuel production was simulated using the UOP process is presented in Fig. 1. The Table 4 shows the mass balance for the hydrogenation process.

Table 4
Mass balance of production process.

Component	Inlet (kg/hr)	hydrogenation reaction Outlet (kg/hr)	Isomerization and hydrocracking output (kg/hr)	Distillation Diesel	Naphtha	Jet A1
Pressure (bar)		40	40	1	0.99	0.99
Temperature °C		350	450	>215	< 180	180–215
Triolein	40.0000	0.0008				
Trilinolein	40.0000	0.0008				
Tripalmitin	10.0000	0.0002				
Tristearin	10.0000	0.0018				
HYDROGEN	2.3034	0.1678				
STEARIN	0	0.0252				
PALMITIC	0	0.0028				
PROPANE	0	5.0385				
CO2	0	10.2582				
CO	0	0.2880				
WATER	0	3.7633				
C4	0		0.0008	0.0000	0.0007	0.0000
C5	0		0.0273	0.0001	0.0250	0.0015
C6	0		0.0273	0.0002	0.0243	0.0026
C7	0		0.0273	0.0004	0.0227	0.0042
C8	0		1.4068	0.0251	1.1195	0.2595
C9	0		7.3649	0.2586	4.6064	2.4986
C10	0		11.8335	0.6438	5.8096	5.3794
C11	0		13.7368	1.1131	5.0197	7.6037
C12	0		13.7368	1.6751	3.3721	8.6896
C13	0		11.4197	2.0646	1.7119	7.6432
C14	0		10.6750	2.7304	0.9417	7.0029
C15	0	5.6042	6.0420	2.1001	0.2933	3.6486
C16	0	2.4377	4.4691	2.0092	0.1148	2.3451
C17	0	52.1804	1.7482	0.9823	0.0213	0.7446
C18	0	22.5337	0.2362	0.1556	0.0014	0.0792
Total	**102.3034**	**19.5474**		**13.7587**	**23.0843**	**45.9027**

The triglycerides were conversion occurred at 0.99998 efficiency with the various deoxygenation reaction producing CO_2, CO and Water at different proportions (0.9971% conversion). N-heptadecane made up 63% of the alkane conversion, followed by n-octadecane (27%), n-pentadecane (7%) and n-hexadecane (3%) respectively. This implies majority of the alkanes produced fall outside the range of the carbon chain for aviation fuel (C_8-C_{16}). The alkanes therefore underwent hydrocracking and isomerization which was carried out in the next reaction to achieve jet fuel favorable hydrocarbons. The outflow of the hydrogenation reaction possesses high temperature and pressure which has to be reduced before separation. The gaseous products of H_2, CO_2, CO and Water were separated from the hydrocarbons through a fractionation separator (Radfrac). A water gas shift reactor can be employed to produce H_2. The propane gas produced was channeled into the light gas recovery unit or pressure-swing-adsorption (PSA) unit to produce H_2 for the process ($CO + H_2O \rightarrow CO_2 + H_2$). The propane can also be separated and used as a fuel for heating the plant. But this was not modelled as it is out of the scope of the study. The hydrogen used in the process was calculated through the difference in the inlet and outlet.

Hydro-isomerization and hydrocracking process

Prior to the Hydro-isomerization and cracking reaction, the temperature and pressure for the input stream was elevated to 450°C and 40 bar. The reaction was modelled according to the study by [24] using a yield reactor as the results presented in Table 4. The process produced about 82.75% yield of hydrocarbons from the oil feed stream. The hydrogen was later extracted from the products using a flash reactor a 15°C and 39.9 bar. The product was then heated and channeled for distillation to the various hydrocarbons.

Product separation

The products were separated assuming binary distillation. The components were separated using two flash drums. The first separation at 215°C and pressure 1 bar to produce green diesel and a mixture of Jet fuel and naphtha, while the second at 180°C and 0.99 bar. The composition of the various distillate is presented in the Table 4.

About 83% of the oil feed stream was converted into fuel hydrocarbons using the UOP process. This is similar to the study by [39] that produced 82% of hydrocarbons. However, the distillation sequence in this study produced a higher yield of 45.9% of jet fuel range hydrocarbons as compared to 22% in the study by [39]. Green diesel was 13.75% and naphtha 23.08%. A similar study by [24] yielded 77.1% jet fuel and 22.9% diesel while [40] produced 18.62% aviation fuel from jatropha. The difference in the fatty acid composition besides the refinery process is responsible for the difference in aviation oil yield.

The result from the modelling shows that rubber seed oil has a significant potential in the production of aviation fuel. Over 45% of the oil can produce aviation fuel using UOP process. The refinery process also produced significant amount of CO_2, H_2O, CO and propane with CO_2 been the largest at 10.3 kg/hr.

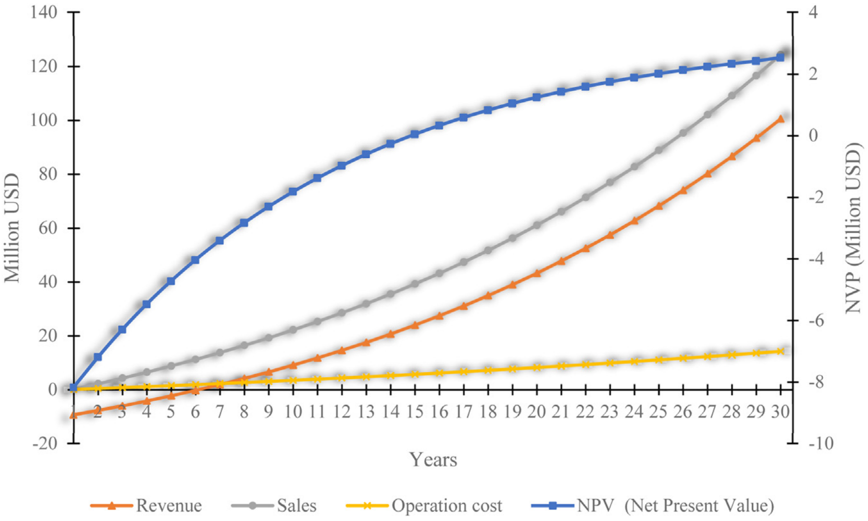

Fig. 2. Cumulative cash flow curve.

Economic analysis

Capital cost and operations cost

The analysis shows that it will cost USD 8,650,480 to design and install a biorefinery plant. The total cost takes into account the auxiliary engineering services such as piping for material flow, civil engineering works and electrical installation assuming a digital control system. It was also assumed that the startup period for the project is 3 months after installation of equipment. Also USD 137,682 will be require in the procurement of the raw materials and a utility of USD 65,666.5.

Total project operating cost is USD 328,728 with a maintenance cost of USD 22,671, Operating Labor Cost of USD 44,668.8 and plant overhead cost of USD 33,669.9. The G and A cost of USD 24,350.2 represents general and administrative costs incurred during production such as administrative salaries/expenses, R&D, product distribution and sales costs.

Financial indicators

The results of the economic analysis of aviation biofuel production are discuss in this section. The Fig. 2 below shows the cumulative curve for the various cost in the production process over the 30 year life cycle of the plant. The economic analysis shows that for a total product sales of USD 1,806,760 and at a cost of USD 4/kg (USD 3.01/liter) of aviation biofuel the Net Present value is zero at an Internal rate of return of 18.62% and positive after 14. years. This implies investors will recoup their investment after 14.9 years of the plant operating with a profitability index of 1.1808.

Analysis from the study shows the designed process for aviation biofuel production from rubber seed oil is profitable leading to a payback period of about 15 years. However, this is not competitive enough to serve as an alternative to fossil aviation fuel. As of May 2022, the Ghana National Petroleum Authority reported the price of aviation fuel to cost USD 1324.95 / MT which is 3 times less than the estimated price of fuel sold to achieve profitability. This implies considering the case of this study rubber seed oil-based aviation biofuel can be a favorable alternative to conventional fuel with an increase in fossil fuel prices. Also, the price of USD 3.01 /liter is lower than the MJSP for Taiwan (USD 6.25/L), Thailand (USD 4.80/L) and Cambodia (USD 4.23/L) in the case of [12] which states high land acquisition and labour cost as factors. However [15], reported that HEFA production pathway can achieve the lowest average MJSP of $1.2 per liter ($1.07–1.32 per liter).

Sensitivity analysis. The study sought to understand the sensitivity of the profitability to the selling price of the fuel and the tax percentage imposed on the returns from the business. Fig. 3 illustrates the variation of fuel price at 25% tax rate and the variation of tax at US$ 4 fuel price with other assumptions kept constant.

From the illustration it can be deduced that the profitability is more sensitive to a unit change in the price of jet fuel than a unit change in tax. It is evident that, higher fuel price increases the profitability of the plant, however, the price of biofuels is already higher than conventional fossil fuels hence the need to explore cheaper sources of feedstock for aviation biofuel production as increasing the product price makes biofuel less competitive with fossil fuel. For example, the payback period can be shortened to about 8 years if prices are as high as USD 7 but can increase to about 21 years if sold at USD 4. The profitability of jet fuel considering the selling price also raises concerns as to when renewable liquid fuels will be sustainably competitive to fossil fuels. Possibly the full implementation of renewable jet fuel will be motivated by unprecedented increase in fossil fuel prices globally.

To achieve a more economically competitive aviation fuel from rubber seed oil, some recommendations have been made. There is a need to consider tax incentives in the production of liquid biofuels to make it competitive to fossil kerosene which

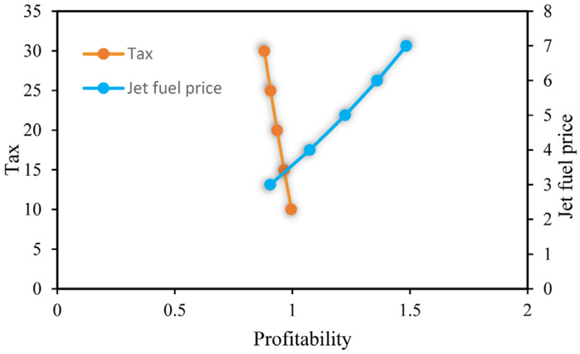

Fig. 3. Graph illustrating the sensitivity of tax and fuel price to the profitability of the production process.

involves government intervention. The use of second-generation oil crops is shown to be a promising source of affordable feedstock aviation biofuel production. It was also observed that, an increase in raw materials acquisition by 50% increases operations cost by about 26%. The advantage of rubber seed is the valuable latex tapped from the tree which significantly reduces the overall cost of cultivation unlike other energy crops. Furthermore, the use of locally generated hydrogen through gasification of biomass or electrolysis from renewable energy sources can offset the cost of importing hydrogen for aviation biofuel production. This provides an opportunity in utilizing local resource for energy production while improving the profitability of aviation biofuel in Ghana.

From the model, it can be deduced that a plant with capacity of 100 kg of oil per hour can process over 330 tons of aviation fuel per year. This is enough to satisfy the country biofuel needs in other to meet the set-out target in 2030. The overall cost in establishing a biorefinery for the production of aviation fuel falls within the government's estimation of $ 90 million.

Conclusions

Rubber seed contains appreciable amount of oil (>30%) for the production of aviation biofuel. The golden yellow slightly acidic oil produced from rubber seed oil possess a density and physicochemical properties similar to other vegetable oil sources used for biofuel production and therefore serve as a suitable non-edible oil substitute for the production of biofuel. The rich presence of free fatty acids in rubber seed oil makes the oil acidic and favourable for other applications such as soap and cosmetic production. The occurrence of sugars and other food nutrients in rubber seed supports suggestions in using the kernel cake for animal feed after extraction. This will go a long way in increasing the economic value of the product. The ability of rubber seed oil to oxidize easily reduces the high heating value over time and calls for proper storage and processing technologies in the utilization of rubber seed oil for biofuel production.

The UOP process which is a commercially certified process in the hydrotreatment of vegetable oil into aviation biofuel yielded converted 81% of the oil feed stream. The process yielded 46% of aviation fuel from a feed of 100kg/h of rubber seed oil. Other byproducts of the process are naphtha and green diesel at 23% and 14% respectively. The estimated total capital cost in the installation of a bio-refinery plant for aviation biofuel production cost $ 8,650,480. Considering a plant life span of 30 years and 7920 operating hours the total of cost of operation is $ 328,728. The economic analysis shows that at a cost of USD 4/kg (USD 3.01/liter) of aviation biofuel has an internal rate of return of 18.62% profitability of 1.18 and payback period of 14.9 years of the plant operating.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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