Production of Liquid Hydrocarbon and Electricity via Gasification of Microalgae: Process Modelling and Techno-Economic Analysis

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Abstract
Fossil fuel continues to be the major source of energy supply globally and its negative impact on the environment remains an unresolved issue. Valorisation of lignocellulosic biomass as an alternative energy source into synthesis fuel via gasification is highly characterised with tar formation. Several attempts have been used to reduce tar formation which include the application of catalyst. However, these processes generate high volume of carbon dioxide which in turn affect the syngas quality. Studies have suggested feedstock switching to a low lignin material such as microalgae, which have several environmental benefits. In this work, a conceptual process design of algal-based (Scenedesmus obliquus) liquid hydrocarbons and electricity production via gasification is proposed. Then a steady-state process simulation is performed to calculate the mass and energy analysis of the whole process to produce liquid hydrocarbons (C_5-C_{10}). Monte Carlo simulation software (Crystal ball) is used to calculate the minimum fuel selling price (MFSP) and the process economics uncertainty. The MFSP of the liquid hydrocarbon is found at US$ 1.391 /kg with an energy output from renewable liquid fuels of about 4110.17 kW/hr. This value is comparable with the previously reported value in the literature. In addition, the sensitivity analysis is performed to identify the key process variables that influence the economics of the algal based liquid hydrocarbon production.

Keywords: **Gasification, Microalgae, Liquid hydrocarbon, Simulation, Syngas, Techno-economic.**

I. Introduction

The demand for energy to satisfy global needs is increasing continuously as the global population increase with time. Currently, fossil fuel remains the major source of energy supply globally and the diminishing fossil fuel reserve is becoming alarming. It is believed that the proven fossil fuel reserves will be exhausted in 60–80 years (Sharma et al., 2011). In addition, the continuous usage of fossil fuels such as coal, oil and gas lead to the generation of greenhouse gases. Recently, there are two kinds of important issues, environmental and energy crisis issues. The environmental issue is related to the utilisation of fossil fuel, which at the end accelerate the global warming. Market instability of crude oil prices constitutes another serious challenge (Manirafasha *et al*., 2020). Consequently, a significant growth in energy demand calls for an environmentally friendly renewable energy sources such as solar, wind and biomass. Among the renewable energy sources, biomass has been proven to be suitable and environmentally friendly alternative energy source, having carbon in its building blocks that can be converted to liquid fuel known as biofuel. This may provide a carbon-neutral and sustainable solution because the carbon dioxide generated during fuel utilisation can be consumed during biomass cultivation (Wang *et al*., 2014). In addition, biomass can improve national energy security by reducing the reliance on foreign sources.

Biofuels are renewable fuel which can be produced from biomass through two broad methods. This includes biochemical and thermochemical pathways. The biochemical process consists of pre-treatment, hydrolysis, and fermentation. This is achieved with the aid of biocatalyst or enzymes that facilitate the conversion of the feedstock into desired biofuel. However, this method requires biomass with specific physicochemical properties such as high holocellulose and moisture contents and extremely low lignin content. On the other hand, thermochemical route includes combustion, hydrothermal liquefaction, gasification, and pyrolysis. These technologies can handle any type of biomass feedstock to generate biofuel and biofuels intermediates**.** Among thermochemical conversions methods, gasification is considered to have the highest conversion efficiency. Nearly 72% of energy content of biomass can be recovered via gasification. In the presence of a gasifying agent (GA), biomass is converted to a multifunctional gaseous mixture, usually called syngas or synthesis gas, which can be used to produce energy (heat and/or electricity generation), chemicals, and biofuels. Gasification followed by Fischer–Tropsch synthesis (FTS) is currently the most promising method for high-value liquid fuels and chemicals from syngas (Aziz & Zaini, 2017).

Gasification of terrestrial plant into biofuel, biofuel intermediates and chemicals have been reported in the literature**. Kern et al. (2013)** studied the gasification of *azadirachta indica* (neem leaf) in a dual fluidized bed gasifier with product gas consisting mainly hydrogen, carbon monoxide, carbon dioxide and methane. However, low hydrogen/carbon monoxide ratio was recorded in addition to high contents of heavy molecular weight hydrocarbons and tar. This could be linked to the physicochemical properties of the source biomass, particularly, the lignin content. High tar formation has also been reported from the gasification of corn cobs (Biagini et al., 2014). Schulzke (2019) studied the gasification of forest residues into heat, electricity and base chemicals. The authors reported high tar formation which was linked to the lignocellulosic nature of the biomass. Zhang and Pang (2019) reported gasification of corn stover, radiata pine wood and rice husk in a dual fluidized bed gasifier at 700 ^oC and 800 ^oC. The results of their findings show that increase in the gasification temperature leads to an increase in the producer gases with a corresponding decrease in tar formation. However, the authors further stated that effects of the gasification temperature varied with biomass species which can be attributed to differences in biomass chemical composition (cellulose, hemicellulose and lignin).

In recent years, there is a remarkable advancement in the gasification technology towards limiting tar production with the aid of catalyst. Sınağ *et al*. (2011) investigated the effect of nano-sized and bulky ZnO and SnO_2 at 573 K on the water-gas shift reaction in gasification of cellulose. They reported that the water-gas shift reaction proceeded faster over the catalysts with improved yield of hydrogen. Dalai *et al.* (2013) investigated the performance of CaO catalyst on various biomass materials (cellulose, Cedar, and Aspen) using temperature-programmed gasification (TPG) and constant-temperature gasification (CTG) methods in order to produce H_2-rich gas by varying the catalyst loading from 0 to 8.9 wt %. They reported that the use of CaO as a primary catalyst, reduced the maximum gasification temperature by 150 ^oC with significant increase in the yield of hydrogen and carbon monoxide. Pengmei Lv *et al.* (2014) Studied the production of hydrogen-rich gas from biomass via catalytic gasification. They reported that nearly complete conversion of tar at 700–800 ºC was achieved using Malaga dolomite as catalyst under steam reforming conditions. However, they also observed a marked increase in CH_4 and C_2H_4 at lower temperatures. According to Jiao et al. (2019), catalytic steam gasification of sawdust char on K-based composite catalyst at high and low temperatures favours hydrogen production and limit CH_4 composition in the product gas. However, high composition of CO_2 in the product gas is of great concern. Similarly, Mandal et al. (2019) studied the catalytic steam gasification of biomass in dual-bed gasifier for producing tar-free syngas, the authors reported that gasification of different biomass using separate alkali catalyst supported on alumina or silica-alumina, eliminates tar formation completely, with high H_2/CO ratio above 10 under the process conditions of temperature range of 500−750 °C, at atmospheric pressure, catalyst-to-biomass ratio in the range of 10−20, and steam-to-biomass ratio of 1.0. the authors noted high composition of CO_2 in syngas, which was attributed to the catalyst activities in the gasification process. Generally, catalytic gasification with steam/oxygen improved hydrogen/carbon monoxide ratio suitable for synthetic hydrocarbon production and limit tar production. The use of catalyst is considered as an additional expense, which makes the entire process more capital intensive. Utilisation of alternative material with different chemical composition from the terrestrial biomass coupled with cheap technology will no doubt enhance the economic viability of biomass gasification.

Marine plants such as micro algae seem to be another attractive biomass material, as they offer a range of solutions to environmental challenges such as carbon fixation in addition to rapid biomass production for biofuel and valuable chemicals (Mohammed et al., 2018). Generally, the chemical composition of microalgae includes carbohydrate, lipid and protein. This differs from chemical composition of the terrestrial biomass. Chakinala et al. (2010) reported gasification of microalgae under super critical water condition at 550 °C using quartz capillary microreactors in the presence and absence of catalyst. Their findings revealed that higher temperatures, low algae dosage, and longer residence times favoured the gasification efficiency (GE). It was further reported that the addition of catalysts to the process resulted in higher yields of hydrogen and lower CO yields via enhanced water-gas shift activity. Similar findings have been reported by Liu et al. (2018). The authors stated that Fe_2O_3 as oxygen carrier improved microalgae thermal conversion and synthesis gas production performance. However high generation of CO_2 is associated with the syngas, which in turn decreasing the gas lower heating value (LHV). According to Adnan et al. (2020), wet gasification of microalgae generates H_2-rich syngas through a careful control of equivalence ratio and steam/carbon ratio. The authors further stated that this strategy promotes significantly tar conversion. Studies on microalgae valorisation is still at the production of fuel precursors. Production of fuel grade intermediates from microalgae via gasification route is very limited due to lack of realistic estimation and sketchy process thermodynamics. Only recently, the thermodynamic analysis of hydrothermal gasification of a typical microalga was reported using Aspen Plus (Mustapha et al., 2021b). The authors evaluated impact of process variable on the derived products from micro algae. The economic implication of the entire process and the product cost is still lacking, which is one of the focuses of this research work. This is very necessary for reliable thermodynamic parameters for predicting operating conditions with a high precision.

Recently, Techno-Economic analysis (TEA) and Life-cycle analysis (LCA) have emerged as critical tools to evaluate the economic feasibility and environmental sustainability of the algae-based biofuel production. These assessments techniques support the evaluation of the performance of biofuel production system and identify the targets and priorities for further research and development (Quinn & Davis, 2015). Wiatrowski et al. (2022) reported that reducing the cost of the algal production would be one of the options to make the large-scale production of algal biofuels to be more feasible economically. To overcome these challenges, the use of the wastewater-based algal system has received considerable attention in recent years (Sutherland et al., 2015; Xin et al., 2016). Although much work has been done to date on gasification of different microalgae. However, development of an integrated plant for the production of liquid hydrocarbon and electricity from microalgae (*Scenedesmus Obliquus*) via gasification route is very limited.

This study focuses on a conceptual process design on the production of algal-based liquid hydrocarbon and electricity through gasification process. The conceptual process model includes gasification unit, syngas to liquid hydrocarbon unit and heat generation unit. A steady-state simulation of the mass and energy flows of the process design is carried out using the commercial software code (Aspen Plus Version 11). The simulation results are then used to study the techno-economic assessment of liquid hydrocarbon production from microalgae. The techno-economic assessment is focused on economic feasibility which is determined for the integrated processes design by calculating economic investment criteria of net present value (NPV). Further, the sensitivity analysis is done on the economic output parameters by variation of some of the critical parameters which influence the economics of the integrated process and the economic uncertainty using Monte Carlo simulation software was carried out together with the minimum fuel selling price (MFSP).

MATERIALS AND METHODS

2.1 Process Description

Fig. 1 represents the process flow diagram for liquid hydrocarbon production from microalgae, which consists of four main units: (i) Dryer (ii) Pyrolysis, (iii) Gasification (Combustion and Reduction) (iv) Heat integration unit. For performance analysis, microalgae biomass (*Scenedesmus Obliquus*) will be considered as feedstock. The properties of these microalgae species are presented in Table 1. High purity oxygen from air will be used as the gasifying agents. The simulations will be executed for microalgae biomass (*Scenedesmus Obliquus)* feed rate of 50 kg/h to the Drying zone (RStoic) in which the moisture content of the biomass will be reduced and removed from the dryer in form of vapour and the product from the dryer will be sent into the Pyrolysis/Decomposition zone (RYield). In this zone, biomass is converted into char, volatile matters and tar. It also removes moisture from the produced char. The pyrolysis products will be to send to the Gasification/Reaction zone (RGibbs), the gaseous product is directed to the combustion zone. In the combustion zone, the gaseous pyrolysis products react with the gasifying agent (air) to give desired syngas product. Air Separation Unit (ASU) is employed to separate O_2 from air and then supply oxygen.

After reaction, the combustion product is sent to the reduction zone, where it reacts with the solid char received from the combustion zone. The gasifier product is sent to Separation zone (Sep) in order to remove the unconverted char from the syngas. The high purity syngas from separator will be directly sent to the Fischer-Tropsch reactor (R-Yield) to convert it to liquid hydrocarbons and excess heat. The excess heat from the gasifier product will be sent to heat integrated system so as to generate electricity. The converted liquid hydrocarbons from Fischer-Tropsch reactor (R-Yield) are then sent to the refinery for further separation into different biofuels. A detailed description of the reactions that happen in the gasification process can be the following (Cao et al., 2016; Rajvanshi & Goswami, 2012):

$$C_nH_mO_p \rightarrow CO_2 + H_2O + CH_4 + CO + H_2 + (C_2 - C_5) \quad \ldots (1)$$

$$C + O_2 \rightarrow CO_2 \quad \ldots (2)$$

$$C + \tfrac{1}{2}O_2 \rightarrow CO_2 \quad \ldots (3)$$

$$H_2 + \tfrac{1}{2}O_2 \rightarrow H_2O \quad \ldots (4)$$

$$C + H_2O \rightarrow CO + H_2 \quad \ldots (5)$$

$$C + 2H_2O \rightarrow CO_2 + 2H_2 \quad \ldots (6)$$

$$C + CO_2 \rightarrow 2CO \quad \ldots (7)$$

$$C + 2H \rightarrow CH_4 \quad \ldots (8)$$

$$CO + 3H \rightarrow CH_4 + H_2O \quad \ldots (9)$$

$$C + H_2O \rightarrow \tfrac{1}{2}CH_4 + \tfrac{1}{2}CO_2 \quad \ldots (10)$$

Table 1. Properties of Microalgae (*Scenedesmus Obliquus*) (*Ido et al., 2019; Silva et al., 2020*).

Proximate Analysis	**(wt. %)**
Moisture	8.0
Volatile matter	79.6
Fixed carbon	14.2
Ash content	6.2
Protein	56
Carbohydrates	17
Lipids	14
Ultimate Analysis	
Carbon	75.6
Hydrogen	6.1

Oxygen	10.3
Nitrogen	1.8
HHV (MJ/Kg)	37.4

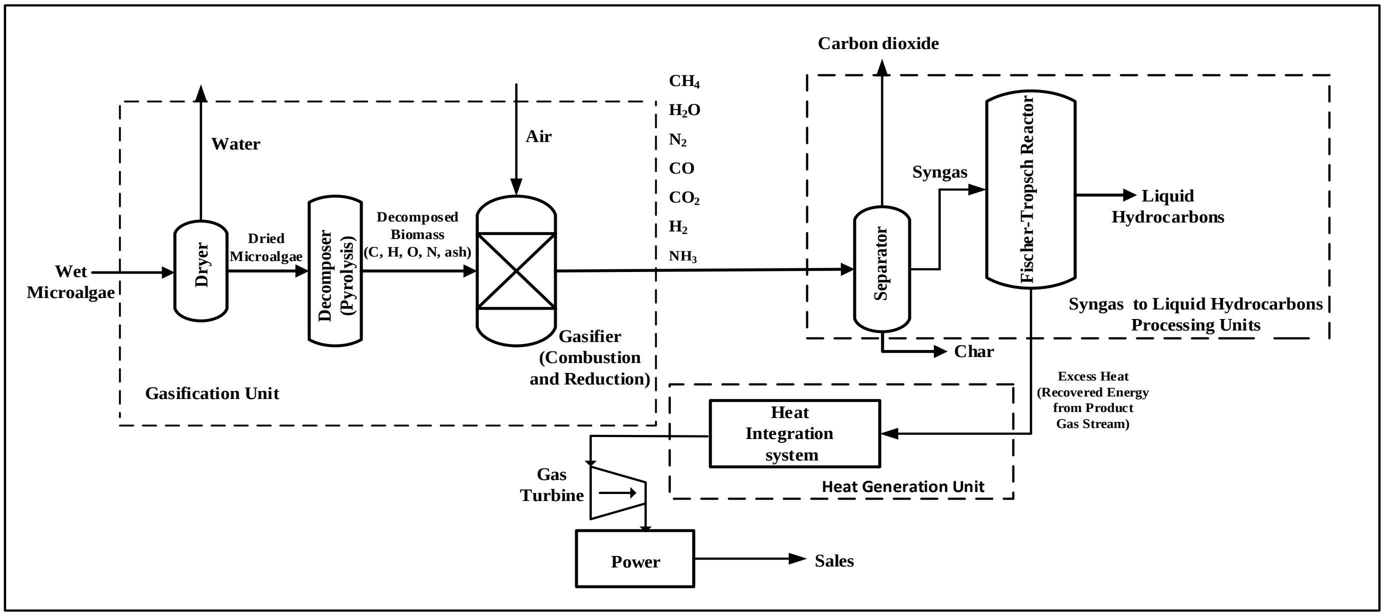

Fig. 1: *Process Flow Diagram for liquid hydrocarbon production from microalgae.*

1.2. Techno- Economic Analysis

TEA conducted with the purpose of informing and prioritizing process development and optimization will focus on capital expenditure or total capital investment (CAPEX or TCI, measured in total dollars), Operating expenses or annual operating cost (AOC or OPEX, measured in US dollars ($) per year and minimum product selling price (MSP, measured in dollars per kg product or volume of fuel) after cash flow analysis (Baral et al., 2019; Scown et al., 2021). Minimum product selling price (MSP) is a commonly reported metric in published TEAs and is determined based on the unit price needed to reach a net present value (NPV) of zero for an established facility lifetime, given a set internal rate of return (IRR), which is often set at 10% for biorefineries to remain consistent with the Humbird et al. report (Humbird et al., 2019). In contrast, private companies seeking to evaluate potential investments are generally more interested in simpler profit-related indicators that do not account for the time value of money, such as revenues (Eq. 1), gross margin (%) (Eq. 2), return on investment (ROI, %), (Eq. 3) payback period (in years) (Eq. 4) and net present value (NPV, %) (Eq. 5) (Peters, 2003; Scown et al., 2021). Policymakers have an entirely different objective in using the results of TEAs. For policy-making, the question is whether a novel renewable fuel or product can be viable in the long term and what level of economic incentives are needed to make near-term production profitable. Scown et al. (2021) provided an excellent example of results that directly inform researchers, industry, and policymakers by estimating payback time with and without RINs and LCFS credits across multiple potential fuel selling prices and Yang et al. (2020) employed a similar approach to explore the economics of carbon capture in biorefineries with and without policy supports.

$$Revenue, \$/_{yr} = Product\ sales. {}^{Kg}/_{yr}\ X\ Product\ selling\ price\ {}^{\$}/_{Kg} \quad \ldots \quad (11)$$

$$Gross\ margin, \% = \frac{Annual\ revenue, \$ - Annual\ operating\ cost, \$}{Annual\ revenue, \$}\ X\ 100 \quad \ldots \quad (12)$$

$$Return\ on\ investment\ (ROI), \% = \frac{Annual\ net\ profit, \$}{Total\ capital\ investment, \$}\ X\ 100 \quad \ldots \quad (13)$$

$$Payback\ period, yr = \frac{Total\ capital\ investment, \$}{Annual\ average\ net\ cash\ flow, \$} \quad \ldots \quad (14)$$

$$Net\ present\ value\ (NPV), \% = \frac{R_t}{(1+i)^t}\ X\ 100 \quad \ldots \quad (15)$$

Where:
R_t = net cash flow at time t
= Discount rate
t = time of the cash flow

Several reports were generated from the simulations of the developed process model in this study, and the data were analysed to determine process yields and economics. All economic calculations were performed for the Year 2022. The cost of the microalgae used for liquid hydrocarbon production and the cost of electricity was obtained in previous research (Breuer et al. (2013); PHCN access, 2022).In addition, the resulting mass and energy balance outputs from the Aspen models were used to evaluate all capital and operating costs in order to establish the total cost of production. All capital costs for algal oil production were estimated based on vendor quotes, prior literature studies, or standard engineering estimates (Anex et al., 2010; Carvalho et al., 2017; Hennig & Haase, 2021). The profitability of the microalgae-based biorefinery was calculated in terms of internal rate of return (IRR) that accounts for integral economic parameters such as capital investment, revenue, depreciation, and time value of money, for assessing the economic performance of the processes for a given period (Kumar et al., 2021). The sizing of all process equipment's is performed using Aspen Plus economic analyser software (ASPA). The purchased and installed costs for all the sized units are calculated in terms of United State of American Dollar ($) using ASPEN Plus simulation software.

2.3 Sensitivity analysis and Uncertainty analysis (Monte Carlo simulation)

Sensitivity analyses (one factor at a time) poses a limitation of not strictly representing real-life scenarios when more than one orthogonal parameter could vary simultaneously, making the analysis complicated. Processes under evaluation are strongly affected by uncertainties that are associated with the process design and model development, or can be associated with raw material variability, volatile prices of products, investment cost, etc Mustapha et al.,2021. To establish the confidence in the new developed technologies, possible uncertainties and the risks should be carefully analysed. In this context, Monte Carlo simulation method was used as an interesting method for solving stochastic system problems. This method provides approximate solutions to a variety of mathematical problems by performing statistical sampling experiments on a computer Mustapha et al.,2021. To achieve this, a probabilistic model based on Monte Carlo method was developed with varying process parameters and various economic parameters. The model consists of equations that separately estimated the total revenue, and operational costs associated with the process to calculate NPVs. Normal and triangular distribution functions were used to describe the uncertainties of the model input parameters. The process model was developed on Microsoft excel. Random numbers were generated for each variable between two bounds decided based on the subject matter understanding and relevance for the project and probability distribution were generated to ascertain the possibility of uncertainty in NPV. The variable that is considered to be the most significant ones affecting the economic viability of the project is the selling price of liquid hydrocarbon ($/kg. Other variables were kept constant during this analysis. Sensitivity bounds for the above variable followed normal distribution with median, mean ± standard deviations of all variables except lipid content of feedstock which followed triangular distribution (Table 2).

Based on scientific literature and communication with experts within Nigeria, we selected appropriate range for all the variables. A triangular distribution was assumed for the liquid hydrocarbon so that uncertainties associated with preconceived lower and upper bounds can be evaluated. These input uncertainties will translate over NPV as corresponding output in the simulation model. The Monte Carlo simulation was conducted for a total of 10,000 iterations.

Table 2. Details of input parameters used in the Monte Carlo simulation.

Parameter	**Mean**	**Median**	**Standard Deviation**	**Distribution**
Liquid Hydrocarbon **($/kg)**	64,422.77	64,422.93	2.94407632	Normal

3.0 Results and Discussion

The process models were simulated to conduct a comprehensive material and energy balances for the micro-algae liquid hydrocarbon and electricity production via gasification and to determine overall process yields, capital expenditures (CAPEX), operating expenses (OPEX), raw material, utilities used in the plant, conduct sensitivity analysis on key process variables and conduct economic uncertainty using Monte-Carlo simulation software to determine the minimum fuel selling prices.

3.1: Techno-economic analysis (TEA).

Table 3. Summary of economic analysis of the plant.

Description	Value
Total Capital Cost [USD]	1856660
Total Operating Cost [USD/Year]	1.1399E+11
Total Raw Materials Cost [USD/Year]	23690200
Total Product Sales [USD/Year]	1.88785E+11
Total Utilities Cost [USD/Year]	1.05522E+11
Desired Rate of Return [Percent/'Year]	20
P.O. Period [Year]	7
Equipment Cost [USD]	391700
Total Installed Cost [USD]	1616200

The summary of the result obtained from the economic analysis of the development of the production of liquid hydrocarbon and electricity via micro-algae gasification carried out with the aid of Aspen Plus Economic Analyzer was given in Table 3, the results contained in the table pointed out to the fact that the process would be economically viable amount spent in setting up the plant could be recovered within seven years. whereas, the project has short desired rate of return.

3.2: Sensitivity analysis

In this section, the results of the sensitivity analysis of key component over a range of temperature variable with all other parameters kept constant on the overall micro-algae liquid hydrocarbon production system, the system is sub-divided into four units namely (i) Gasification Unit (ii) Syngas to liquid hydrocarbons production unit, (iii) Heat generation unit. and (iv) Steam generation unit.

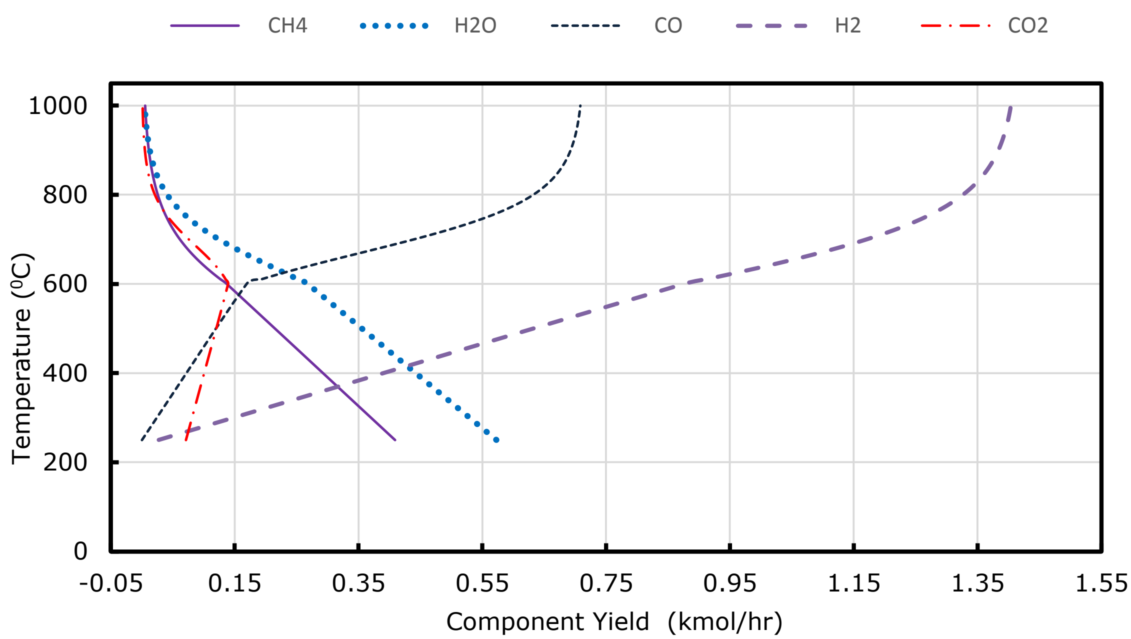

Fig. 3: Graph of Fractional Component Against Temperature.

3.3: Sensitivity analysis within the gasification unit

In the gasification process, impact of process variables such as gasification temperature on the syngas composition value were evaluated to determine the accuracy of the simulation result by comparing with experimental data in the literature. The results of steady simulation of the sensitivity analysis around the gasification zone showed in Fig. 3 with the aims to point out the effect of temperature among the gasification product which are (methane-CH_4, water-H_2O, nitrogen-N_2, carbon monoxide-CO, hydrogen gas- H_2 and carbondioxide-CO_2,) from the above figure, it shows that temperate impact significantly within these zones that favour the main target product which are CO and H_2 at a high temperature of 1000^oC and 1 bar pressure with fractions of component 0.708511 and 1.403793 kmol/hr of CO and H_2 respectively, with a corresponding decrease in CO_2 with fraction of 0.001441. Increasing temperature from 600 °C (Fig. 3) resulted in continuous decline in CO_2, while the H_2 and CO increased significantly Mohammed et al.,2022. However, an experimental investigation revealed by Mustapha et al.,2021 at higher temperature above 500 °C result in decrease of hydrocarbon yield and promote gas production. The authors also stated that H_2 and CO were the main gas components at higher temperature. These observations from experimental investigation is in good agreements with the simulation results obtained. Fig. 3 showed the significant impact of reactor temperature on the product distribution. More so, the addition of air into the combustion/reduction reactor provides necessary component for the production of liquid hydrocarbon via micro-algae processing. More recently, Ebhodaghe et al. (2022) investigated the effect of reaction temperature, stoichiometric ratio (SR) and steam flowrate (SFR) on H_2/CO ratio in produced syngas. The work evaluated the efficiency of three different Chinese algae for gasification process while using air and steam as the gasifying agents. From the study, 44.8 g/kg maximum hydrogen yield was obtained at 950 °C. which shows that the higher the temperature, the more the H_2/CO yield will be obtained. Mustapha et al. (2021a) investigated the effect of temperature on *Scenedesmus obliquus*. The temperature was varied from 400 to 700°C. The low mole fraction of H_2 was observed at lower temperatures. But at higher temperature, a significant increase in the mole fraction of H_2 was observed, favouring the production of more H_2 compared to other syngas.

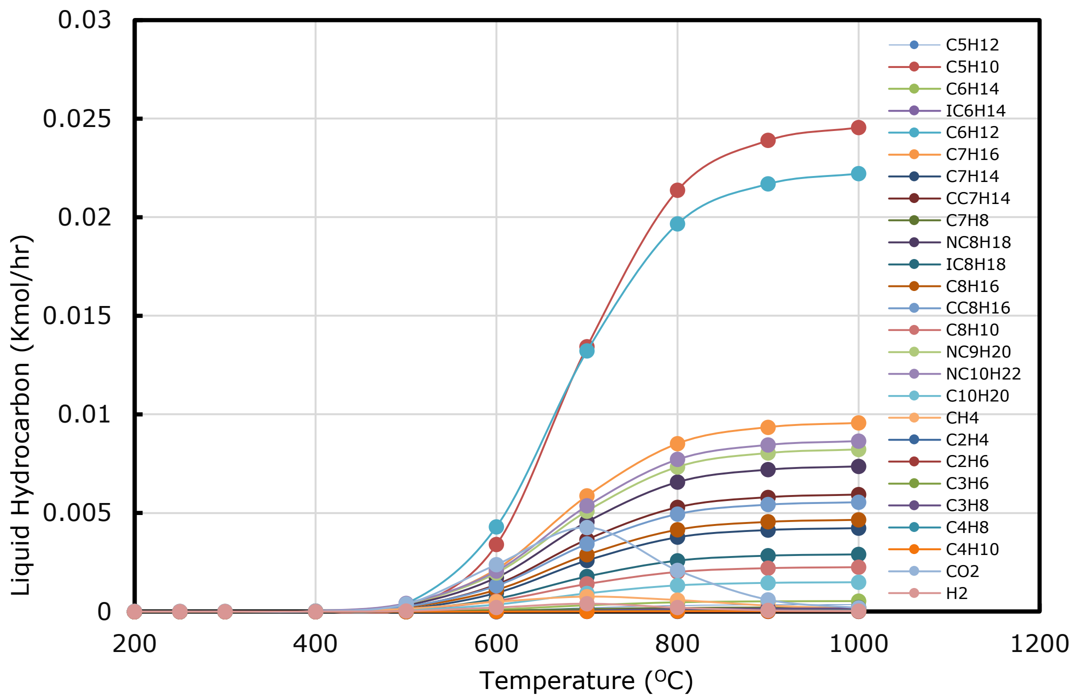

Fig. 4: Graph of liquid hydrocarbon against temperature.

Promotion of the micro-algae gasification product (syngas) to produce liquid hydrocarbons and electricity, this was deportment using Fischer-Tropsch reactor in syngas to liquid hydrocarbon processing unit. In the first stage, the syngas was separated from char and then forward to the Fischer-Tropsch reactor for liquid hydrocarbon production, in addition heat integration system is attached to the reactor coupled with a turbine to generate electricity. Fig. 4 showed the results of sensitivity analysis conducted around the Fischer-Tropsch reactor, this is to access the effect of temperature scenarios run with all other parameters kept constant at the Fischer-Tropsch reactor. where, various yield composition of liquid hydrocarbon was appraised. Form the figure, it can be spotted that the range of hydrocarbons from C_4H_8-$C_{10}H_{20}$ rise steadily from 500^0C to 1000^0C, this is because higher alkanes are liquid in nature and they are more likely to vaporized at high temperature attribute to the work of Mustapha et al. (2021a) . Also, the results from the figure showed that the maximum yield of liquid hydrocarbon can be obtained at 1000^0C and among the other liquid hydrocarbons C_5H_{10}, C_6H_{12}, C_7H_{16} and $nC_{10}H_{22}$ have the highest yield composition of 0.025, 0.0225, 0.0089 and 0.0864 kmol/hr respectively. Similarly, the yield of alkene component C_2H_6, C_3H_6 and C_3H_8 with their corresponding yield 0.000012, 0.0000146 and 0.0000389kmol/hr respectively rises steadily from 600^{0}C to 1000^{0}C, this happened due to the present of double bond, this indicates high temperature in favour of the reaction than that of alkane. However, other compound presented within the liquid hydrocarbon component $C0_2$ and H_2 gases disappear with increases in temperature as revealed from the figure. Studies have been reported by Mustapha et al. (2021a) and Ebhodaghe et al. (2022) that liquid hydrocarbon yield increase by increasing temperature, this come with an agreement with this current research finding in the liquid hydrocarbon processing unit.

3.4: Process economic uncertainty using Monte Carlo simulation

Oracle crystal ball software (Version 2020) were used to conduct as Monte Carlo simulation to generate a distribution function of the likely hood outcome, thus input uncertainties depend inherently on the raw material composition and other parameters which depend on the market forces causing the price fluctuation in the feed stock and different product, the ranges of probability density of micro-algae buying price, liquid hydrocarbon selling price, energy consumption during process and electricity generation were evaluated to estimate NPV which is most reasonable acceptable indicator for financial risk assessment Pengmei et al.,2014.

Table 4. Monte Carlo simulation of process economic uncertainty.

MONTE CARLO SIMULATION OF PROCESS ECONOMIC UNCERTAINTY	
Number of samples	1000
NPV	2.61E+11
NPV-Mean	2.61665E+11
NPV-Standard Deviation	4.1367E+11
Minimum	-4.27252E+11
Maximum	6.31772E+11
Profitability Index	65%
5% Percentile	-3.88127E+11
Cumulative Frequency	158%

Table 4 showed the result of monte Carlo simulation of the process economic uncertainties, from the result it be observed that the net present value number NPVN of this current research is about 2.616E+11 with mean value of 2.61665E+11, this shows almost the same value, that means there is no much variation in NPVN over the period of plant operation. This is a very good indicator that the process will subject to lesser economic uncertainty. According to an investigation revealed that mean of a certain number give the exact change in that number for certain number of counts, therefore it has been recommended to predict economic uncertainty in an economic analysis kumar et al., (2021).

Also, the NPV-standard deviation, maximum NPVN, minimum NPVN and profitability index with the following values 4.1367E+11, -4.2725E+11 6.31772E+1 and 65% respectively are other dials that the economic aspect of this current research work, the micro-algae liquid hydrocarbon product and electricity production is economic certainty and cumulative frequency of 158 % this shows steady profit rate over a long time without much problem.

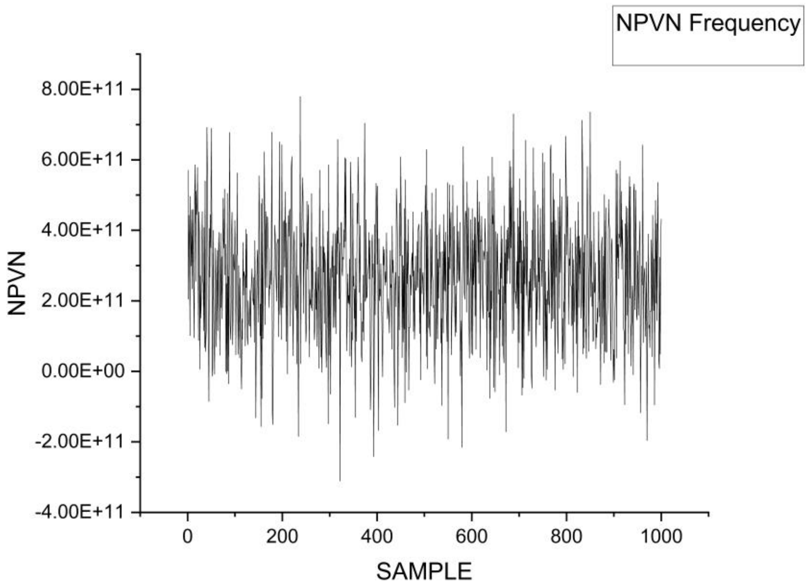

Fig. 5: Frequency response NPVN.

Frequency response is statistical tools used to assured the variation of a certain number over a period of time. Fig. 5 showed the frequency response of NPVN over 1000 sample of analysis, as it can be observed there is no much variation within samples. However, 300,400,700 and 900 respectively are the only samples which showed deviation, but the economic stability of the process is likely certain, since there is no more gap among the samples.

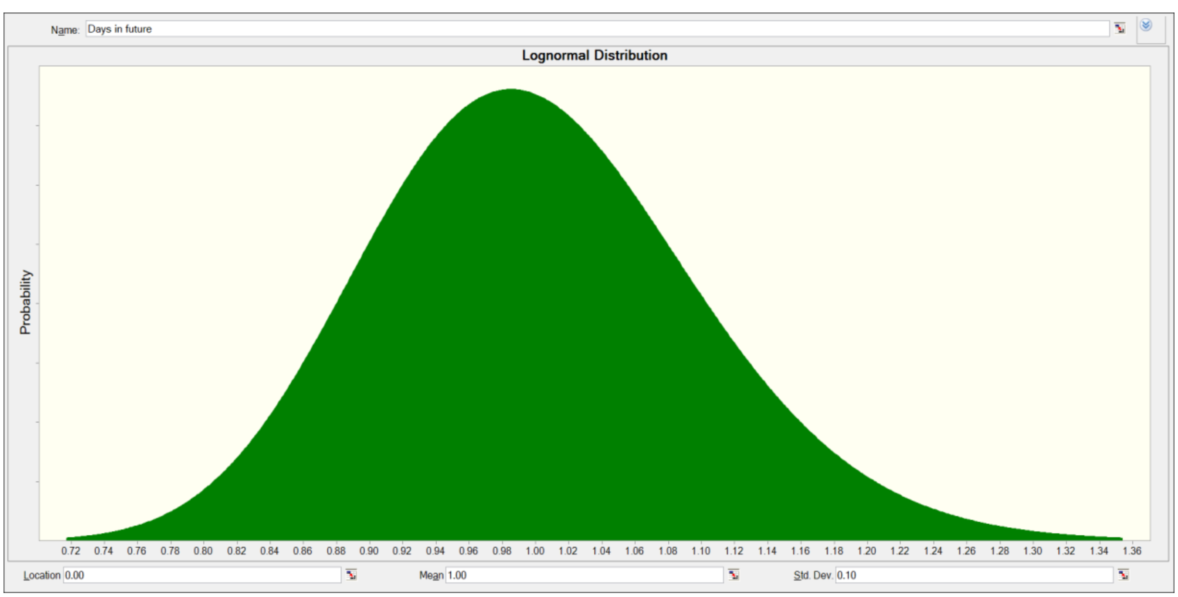

Fig. 6: Normal distribution of NPVN.

The price of biomass (micro-algae) is up to $ 55 /kg. In Fig. 6, the area under the green normal distribution curve shows probability of NPV > 0, which indicates the probability of plant profitability, the curve has short tail, which indicate low futuristic probability of extreme losses. Moreover, the curve shows smooth rise and fall within the range, which indicate there is lower risk in the production process. This possibility is not far from reality in today's volatile market, especially when micro-algae price is steady due to consistent availability of micro-algae domestic and international market, and it has been established that raw material price controls the fate of liquid hydrocarbon production cost. However, the result of Fig. 6 shows how the frequency curve disperse over certain period which indicate NPV is ok over the desire rate of return of seven years as presented in Table4.

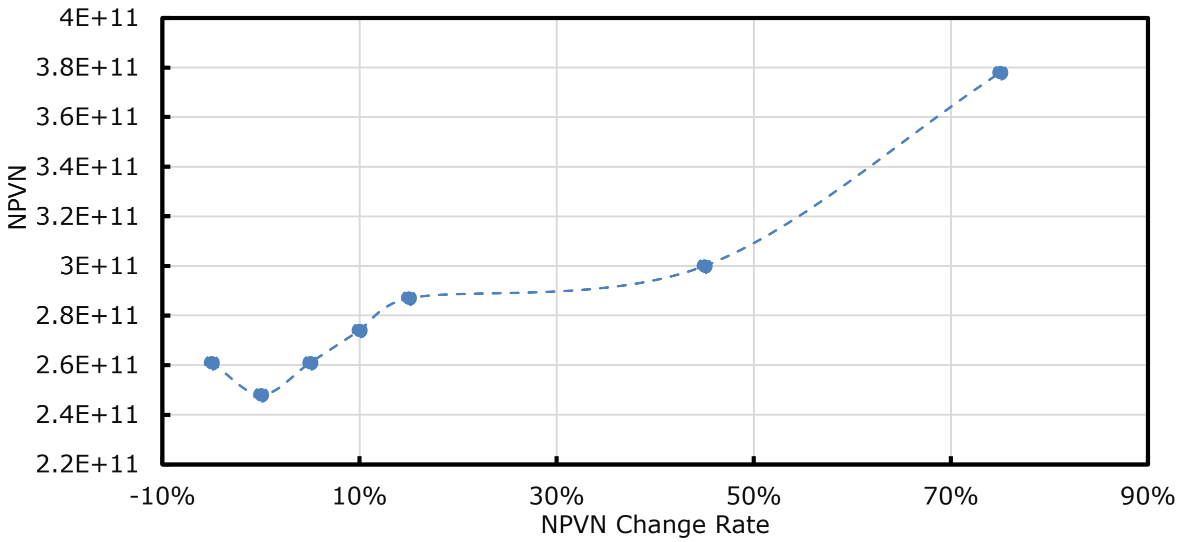

Figure 8: NPVN against NPVN Rate change

Table 5. Sensitivity Analysis Monte Carlo.

Sensitivity Analysis Monte Carlo	
NPV rate	2.61E+11
-5%	2.48E+11
0%	2.61E+11
5%	2.74E+11
10%	2.87E+11
15%	3.00E+11
45%	3.78E+11
75%	4.57E+11

The result of the sensitivity analysis Monte Carlo of the NPV summarized in Table 5. NPVN is the best economic indicator (Mohammed et al.,2019). The NPVN rate change in the following percentage change of -5%,0%,5%,10%,15%,45% and 75% with respect to 2.61E+11, 2.48E+11, 2.61E+11, 2.74E+11, 2.87E+11, 3.00E+11, 3.78E+11 and4.57E+11

NPVN values comparing with the literature, it has been reported that Biofuels from microalgae biomass -5%,0%,10%,15%,30% and 70% with respect to 1.761E+11, 1.48E+11, 1.61E+11, 1.74E+11, 1.87E+11, 2.00E+11, 2.78E+11 and 3.57E+11 NPVN values respectively (Ebhodaghe et al.,2022). Fig.8. showed the trend of NPVN rate with change in NPVN value, this indicates slow change from -5% to 10% rate change, while steadily increase from 15% to -75% rate change. Moreover, increase growth rate led to increase in NPVN this showed that NPVN depend on the growth rate of the production process of micro-algae gasification to product liquid hydrocarbon and electricity.

3.5: Minimum fuel selling price analysis

In this section, the result of the minimum fuel selling price (MSP) of the liquid hydrocarbon renewable fuels produced from the present integrated system is presented. Using the discounted cash flow method Annex *et al*.,2010, the minimum selling price of fuels at zero net present value (NPV) is calculated based on a 10% rate of return with the period of 20 years using excel spreadsheet calculation. MSP value for this plant is observed at US$ 1.391 /kg with daily volatility of 0.6% and 10.5% as present in Table 6. Furthermore, it can be observed from the table that the minimum fuel selling price (MFSP) variable is an accounting concept, not a real price. A higher value percentile of MFSP means that the final product (e.g., Micro-algal liquid hydrocarbon) needs to be sold at a higher value (for revenues and inflow cash) to breakeven the original capital investments. A higher value of MFSP also means less competitiveness of the project when compared to a project with a lower value percentile of MFSP. A negative percentile value of the MFSP simply means that, even if the liquid hydrocarbon is sold at a loss, the micro algae production facility would still be economically feasible. the actual selling price MFSP variable is an accounting concept, not a real price. Details on the economic inputs for the calculation of MFSP are available in the appendix. The mean fuel selling price $ 45,357.02 (US$ 1.391 /kg) and the median fuel selling price $ 45,357.18(US$ 1.391 /kg) which give the same values shows resistance to economic failure, this can be indicated from Fig. 7., the graph showed the variation of percentage change in prices of fuel within 345 days in the future in order to predict the price fluctuation and it can be observed from the figure that day 21,14,81,211 and 221 experience highest percentage change in price with the trend. Forecast analysis is an important tool in research and development, it can minimize the risk of investment failure to 98% Adana et al.,2020.

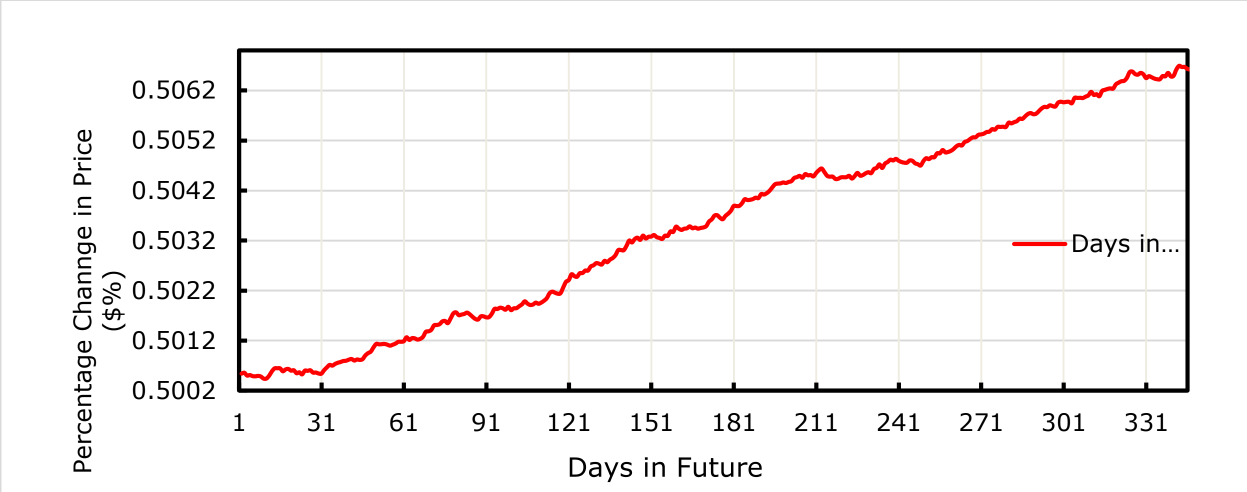

Fig. 7: Outcome of Future Price in Days

Table 6. Fuel selling price forecast.

Fuel Selling Price Forecast	
Starting Price	$ 45,479.85
Annual Volatility	10.5%
Daily Volatility	0.6%
Mean Price	$ 45,480.76
Median Price	$ 45,480.92
Standard Deviation	2.93939544
Percentiles	
5%	45480.424
95%	45481.3753
25%	45480.7017
75%	45481.1316
Minimum Price	$ 45,426.36
Maximum Price	$ 45,481.68
Profitability Profit	100%

3.6: Energy analysis

There are only three (3) equipment in the production process which will require power b1, b4 and b6 which are derived from drying, decomposition and gasification zone. The energy analysis of the micro-algae product process will be ascertain based on the rate of energy consumption and energy gain (electricity produce) via production of liquid hydrocarbon using Fischer-Tropsch Reactor. Decomposition (Ryield reactor) and gasification (RGibbs reactor) process require a large amount of heat in the present design which are about 42.208 kW and 42.208 kW respectively. the dryer (Rstioc reactor) consumes 3.06403 kw, Thus the total heat and power required for the integrated system is round about 87.480 kW. The energy output from renewable liquid fuels is about 4110.17 kW. The price for electricity generation is according to Nigerian electric regulation commission (NERC) BBC ,2020. is $0.15 per kwh this shows that the amount of electricity generated by 50kg/hr of micro-algae is capable to generate electricity of $616.5255 per kwh with 2.13% power supply to the facility and 97.871% of the power generated will be available for commercial scale.

4.0 Conclusion

In the present study, the process design of microalgae-based liquid fuels and electricity production via gasification is developed using Aspen Plus V11 software. Based on the process design, a steady-state process simulation is performed to calculate the mass and energy analysis of the integrated process system using Aspen Plus with an energy output from renewable liquid fuels of about 4110.17 kW/hr. A Minimum Fuel Selling Price (MFSP) of the liquid hydrocarbon is calculated using Monte Carlo simulation software and it is estimated at US$ 1.391 /kg. This value is in line with the previously reported in the literature (Ebhodaghe et al.,2022). Furthermore, a sensitivity analysis is performed to identify the effect of operating parameters such as temperature and pressure on the yield and composition of both the liquid hydrocarbon and gaseous products using algae as feedstocks. The results showed that reaction pressure exhibited minimal impact whereas temperature and feedstock composition had significant effects on the composition of gaseous products. It was also found that at high temperature (1000 °C) favoured the production of CO/H_2 and C_5-C_{10}. In contrast, low temperature (250 °C) favoured methane gas production. The highest mole fraction achieved for CO and H_2 was 0.708511 and 1.403793 kmol/hr. For CH_4 rich gas production, the highest mole fractions achieved was 0.409196 kmol/hr. This study has shown that liquid hydrocarbon and electricity can be produced from the gasification of microalgae a s a function of the reaction conditions and feedstock composition.

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