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Simulation of Plant for the Production of Bio-Fuel via the Pyrolysis of *Chlorella vulgaris*

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ABSTRACT

This study is focused on the simulation of Chlorella vulgaris (microalgae) pyrolysis plant for the commercial production of biofuel via the use of ASPEN Plus and the techno-economical assessment of the plant capacity. The bubbling fluidized- bed reactor incorporated in the ASPEN Plus was used to pyrolyze microalgae (Chlorella vulgaris) under optimal operating conditions to maximize the yield of bio-fuel, bio-char and bio-gas. Simulation results gave optimum yield of 52.40%, 0.18% and 47.45% for bio-fuel; bio-gas and bio-char respectively. The pyrolysis temperatures, inert gas feed rate and particle size were operating parameters that affected the yield of products. An energy balance analysis was carried out to ascertain the energy consumption of the pyrolysis process and the energy efficiency which is an important factor in determining the performance of the pyrolysis process was found to be 74%. The Fixed Capital Investment as well as the production cost of the commercial scale pyrolysis plant was estimated. The microalgae strain (Chlorella vulgaris) was found to be a promising biomass feed stock due to its high yield in bio-fuel. Using the bubbling fluidized bed reactor which is thus suitable for fast pyrolysis process and the commercial production of biofuel. The challenge of high cost of biofuel production can actually be minimised by increasing the plant capacity as well as the right choice of biomass feed stock.

Keywords: Pyrolysis, *Chlorella Vulgaris*, Simulation, Bubbling Fluidized Bed Reactor, Techno-economic Analysis.

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1. INTRODUCTION

Algae are plants that do not have leaves, stems or roots. They are of two categories, the aquatic and terrestrial and are macroscopic as well as microscopic in nature. Algae are carbon fixing and oxygenating organisms; they have primitive methods of reproduction and inhabit a wide range of aquatic environment. Algae are naturally found in most aquatic ecosystem.

Microalgae are eukaryotic or prokaryotic microorganisms. They are photosynthetic and can grow rapidly as well as live in harsh conditions due to their unicellular or simple multicellular structure and have cell factories that converts carbon dioxide to potential bio fuels, foods, feeds and high value bio actives (Walter *et al.,* 2005; Spolaore *et al.,* 2006). Like plants, algae require primarily three components to grow, that is Sunlight, water and CO_2. Examples of prokaryotic microalgae include; Cyanobacteria (*Cyanophyceae*) and eukaryotic microalgae are for example, green algae (*Chlorophyta*) and diatoms (*Bacillaiorphyta*) (Liy *et al.,* 2008).

Alga is usually found in damp places or bodies of water and thus is common in terrestrial as well as aquatic environments. They are found in all existing earth ecosystems, not just aquatic but also terrestrial, representing a variety of species inhabiting in a wide range of environmental conditions.

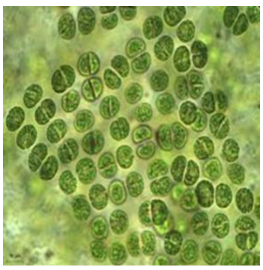


Figure 1: A Microalgae Strain (*Chlorella Vulgaris*) and a Crushed Dry Microalgae

More than 50,000 species have been estimated to exist but only a limited number of about 30,000 have been studied to be potentially employed in an economically effective manner to produce different bio-fuels that is environmentally sustainable.

Fuel, whose source of energy is derived from biological carbon fixation, is known as biofuel and can be produced by various forms of feed stocks like plant, vegetable oil, algae etc. Bio-fuel are generally more ecologically acceptable compared to fossil fuel because of its close carbon cycle resulting in low carbon dioxide (CO_2) emission while carbon dioxide (CO_2) emission from fossil fuel is high because it's non closed carbon cycle which is a way foot print (i.e. from ground to the atmosphere). This high emission of CO_2 results in global warming and environmental pollution.

Biomass can be converted to bio-fuel via different thermal, biological and physical processes. Among the biomass to energy conversion processes, pyrolysis has attracted more interest in producing liquid fuel product because of its advantages in storage, transport and versatility in application such as combustion engines, boilers, turbines, etc. In addition, solid biomass and waste are very difficult and costly to manage which also gives impetus to pyrolysis research.

However, it is still at an early stage in development and needs to overcome a number of technical and economic barriers to compete with traditional fossil fuel-based techniques (Bridgwater, 2004; Downie, 2007). Pyrolysis is a thermal decomposition of material at elevated temperatures in an inert atmosphere such as vacuum or nitrogen gas. It involves the change of chemical composition and is irreversible.

Pyrolysis can be classified into three main categories: Slow, fast and flash pyrolysis depending on the operating condition. These differ in process temperature, heating rate, solid residence time, biomass particle size, etc. However, relative distribution of products is dependent on pyrolysis type and pyrolysis operating parameters as shown in Table 1.

According to Bridgwater (2004) and Venderbosch *et al.* (2010), the production of bio-fuel through fast pyrolysis has received more attention in recent years due to the following potential advantages: Low cost and neutral CO_2 balance; Transportability and storability of liquid fuels; Secondary conversion to special chemicals or additives, motor-fuels; Biofuel for turbine, engine, boiler, industrial processes and power generation; Feasibility of separating minerals on the site of liquid fuel production to be recycled as nutrient to the soil; Primary separation of the starch and lignin component of the biomass with subsequent further upgrading; Application of second generation bio-fuel as feed stocks and waste materials (forest residue, municipal and industrial waste, etc.); Efficient energy density compared to fuel gases from atmospheric gasification of biomass.

Roy *et al.* (1990) conducted experiments on the vacuum pyrolysis. In this work, a step-by-step approach was used, starting from bench-scale batch systems, to a process development unit and lastly a pilot plant, to experiment and development of vacuum pyrolysis of waste wood. It had been reported that the yield is 55% oil, 25% carbon black, 9% steel, 5% fibre and 6% gas.

The use of renewable energy solves the problem of global warming and other environmental problems associated with fossil fuel, its commercialization has been a major challenge as a result of high cost of production and suitable feedstock. This research work therefore, addressed the issue of commercialization of biofuel in Nigeria by employing pyrolysis which is a promising biomass conversion technology with high yield in bio-crude and microalgae which has advantages over agro-base feedstock.

Table 1: Typical Operating Parameters and Products for Pyrolysis Process

Pyrolysis Process	Solid Residence Time (s)	Heating Rate (k/s)	Particle Size (mm)	Temp. (K)	Product Yield (%)		
					Oil	Char	Gas
Slow	450–550	0.1–1	5–50	550–950	30	35	35
Fast	0.5–10	10–200	<1	850–1250	50	20	30
Flash	<0.5	>1000	<0.2	1050–1300	75	12	13

(Sources: Bridgwater, 2007; Balat *et al.,* 2009)

The aim of this research is to use Aspen plus simulation software to simulate the production of biofuel using 400,000 ton/yr of wet microalgae (*Chlorella vulgaris*).This aim is achieved through the following objectives: by carrying out a computer-aided simulation of the pyrolysis plant, considering the effect of temperature, gas flow rate and particle size on product distribution and also the evaluation of the thermal efficiency, sizing of the major process equipment and computer-aided cost analysis of the production plant.

2. MATERIALS AND METHODS

2.1 Materials

Plant for alternative fuel production on an industrial scale with the capacity (400,000 tonnes/ year dry feed), was designed via Aspen plus V.8.7 Simulator. The validity of the simulation is backed up by bench scale experimental data for indirectly heated, non-catalytic pyrolysis process of green microalgae (Chlorella Vulgaris) as shown in Table 2. To carry out the simulation of Chlorella vulgaris and successfully input it as a component in Aspen Plus, it has to be defined as a non-conventional solid. The compositional analyses such as the proximate, ultimate and sulphur analyses is required. In order to perform the above. Aspen plus simulator will calculate the enthalpy and density of the component using this information and a set of correlation-based models. Correlation based models that will be used to define non-conventional components for heat capacity and density determination were HCOALGEN and DCOALIGT respectively and are thus employed for the purpose of this research. All chemical reactions and physical processes involving mass change (i.e. drying), must be user defined by FORTRAN subroutines or MATLAB due to the fact that Aspen Plus cannot perform equilibrium calculations with non-conventional solids.

Table 2: Experimental Data of Microalgae (Chlorella Vulgaris Sp.)

Analyses	Parameters	Values
Proximate (wt% dry basis)	Moisture	5.47
	Volatile matter	71.38
	Fixed carbon	16.07
	Ash	7.08
Ultimate (wt% dry basis)		

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	C	45.60
	H	5.90
	N	9.05
	S	0.36
	O*	31.95
Biochemical Composition	(wt% dry basis)	
	Lipids	13.99
	Proteins	31.17
	Carbohydrates*	22.70
Heating value (MJ/kg)		
	HHV	18.77
Molecular weight (g/mol)[b]	Mw	360
Specific heat (kJ/kg·K)[b]	C_p	1.57

*By difference
(Source: Neeranuch *et al.,* 2018; [b]Grierson *et al.,* 2009)

2.2 Methods

The design of the major process equipment that is, the Bubbling fluidized bed reactor was performed followed by a techno economic evaluation of the production plant.

Capacity:

The capacity of the plant producing commercial grade biofuel is $400000\frac{ton}{yr}\left(400\times10^6\frac{kg}{yr}\right)$ of bio-fuel.

Basis:

One-hour production of pyrolysis oil =

$$\left(\frac{400\times10^6}{330\times24}\right)=50505\frac{kg}{hr}$$

Plant operates 330 days per year and 24 hours a day.

The summary of Steps/Unit operations leading to the production of biofuel from microalgae via pyrolysis is represented in a block diagram in Figure 2.

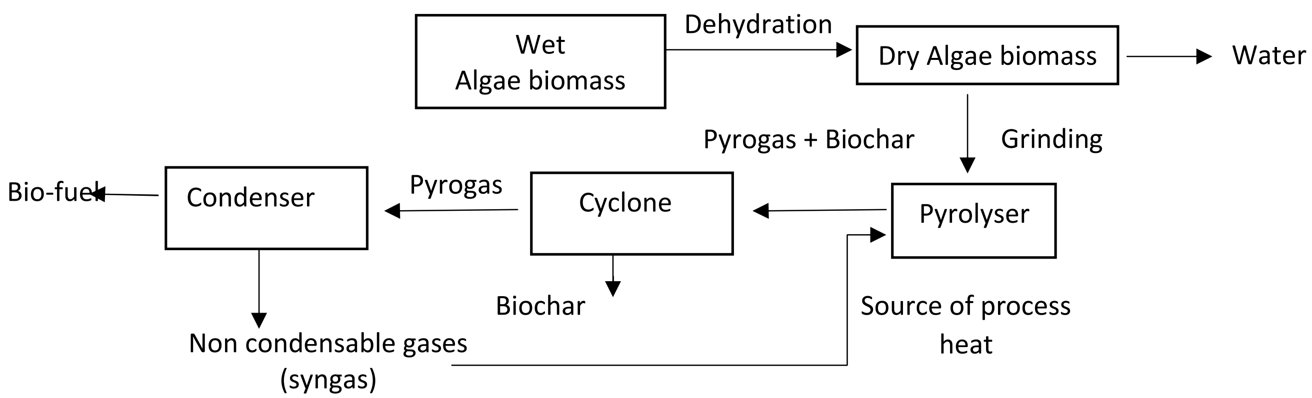

Figure 2: Block Diagram Depicting Steps Involved in the Pyrolysis of Microalgae (Chindah, 2019)

2.2.1 Process Design and Simulation

Aspen plus was used in the simulation of a complete industrial scale plant for the pyrolysis process of chlorella vulgaris as depicted in the process flow diagram in Figure 3. below and was divided into the following sections: (a) material preparation. This section was made up of the following unit operations; drying and grinding of the biomass slurry. (b) Decomposition and pyrolysis of the material; this section is comprised of the RYield and the RGibbs reactors, and finally (c), the product separation phase section which comprises of the cyclone and oil separator.

Table 3: Process Equipment Name and its Aspen Block

Equipment name	Aspen block	Description
RStoic	Dryer	Simulates the drying of the biomass.
Crusher	Crusher	Simulates the particle size reduction of the biomass
RYield	Decomp	Simulates the decomposition of fuels into components and energy output.
RGibbs	Pyroreac	Calculates the reaction of the fuel and the resultant temperatures of the products.
Cyclone	Cyclone	Simulates the withdrawal of solid product.
SEP	Oilsep	Separates the syngas and bio-fuel.

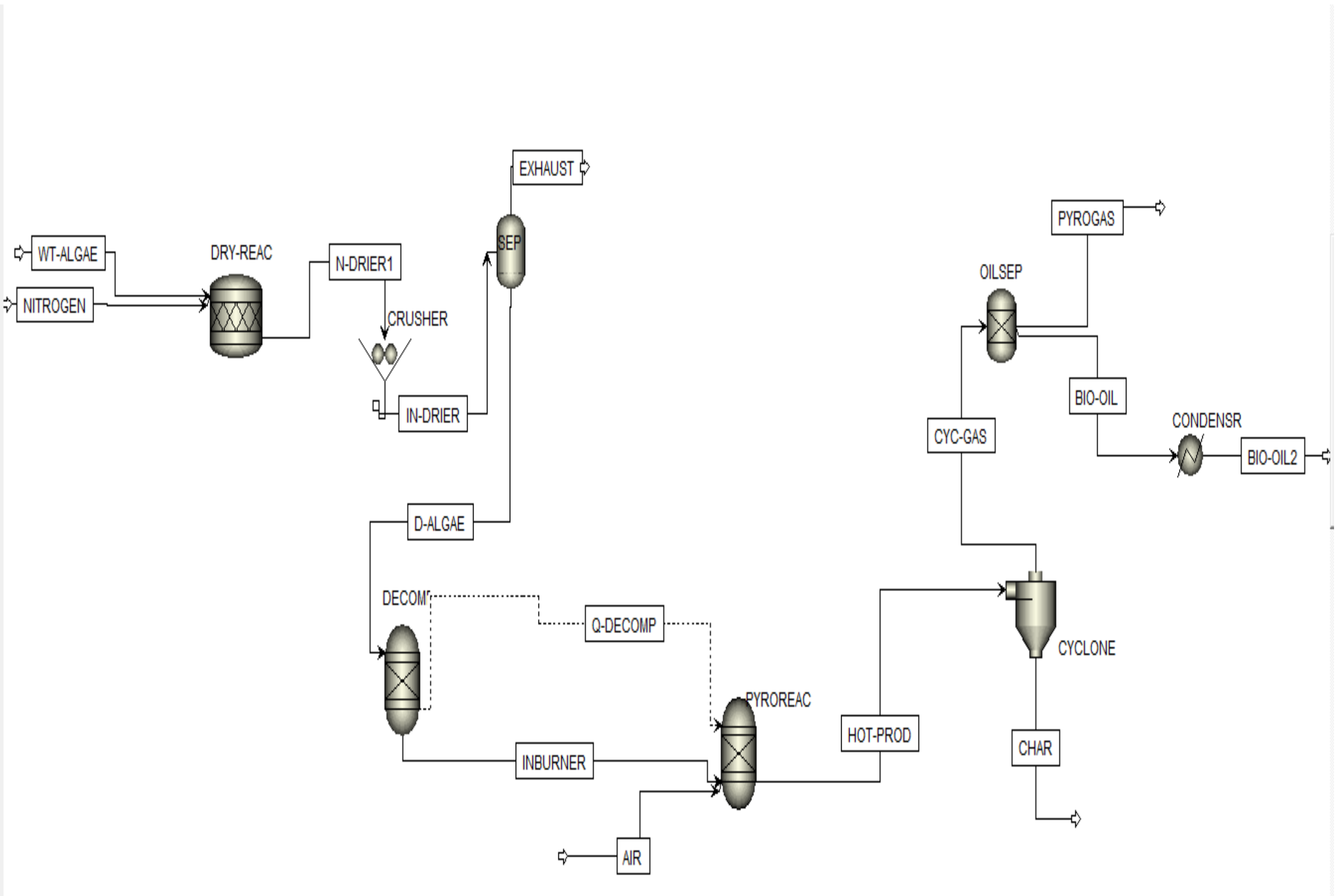

Figure 3: Process Flow Diagrams (PFD) of Microalgae Pyrolysis (Chindah, 2019)

2.2.2 Process Description

The raw materials (*Chlorella Vulgaris* with moisture content of about 80 Wt %) was introduced to the dryer (DRY-REAC) where about 70% of the moisture was removed and subsequently fed into the crusher for size reduction. The powdered dry *Chlorella vulgaris* (D-ALGAE) was then charged into a separator and the water removed was channelled out.

The dry algae (D-ALGAE) were then charged into the second block called DECOMP for the decomposition of the dried biomass and the equipment used for this purpose is called the RYield reactor. This RYield block which predicts the decomposition of the biomass, requires that the yields of the products per unit mass of the feed be specified. The third block named PYROREAC is an RGibbs reactor that completes the pyrolysis. It takes in the decomposed biomass and the inert gas. The RGibbs block applies Gibbs energy minimization. Aspen plus simulates the RYield and RGibbs blocks as a bubbling fluidized bed reactor. The stream from the RGibbs block called HOT-PROD was quickly fed into the CYCLONE where the CHAR was withdrawn and the pyrolysis vapour named CYC-GAS, comprising of condensable and non-condensable gases were channelled to split unit called OILSEP, where the condensable vapours was withdrawn as BIO-FUEL and the non-condensable gases withdrawn as PYROGAS.

3 RESULTS AND DISCUSSION

3.1 Results

The results of biofuel production plant of 400,000tons/yr of chlorella vulgaris on a wet basis for the various pyrolysis products at temperature of 500^{o}C and pressure 1.7 bar, from the bubbling fluidized bed reactor are shown in the Table 4.

Table 4: Predicted Percentage Yield of Pyrolysis Products for *Chlorella Vulgaris*

Stream	Flow rate (kg/hr)		Yield (wt% dry basis)
	(in)	(out)	
Feed	38027	-	-
Bio-fuel	-	199925	52.40
Syngas	-	67.1609	0.18
Bio-char	-	18044	47.45
Total	38027	38027	100

The simulation result showed an average yield of bio-fuel which was 52.40wt% of the feedstock and the lowest yield of 0.18wt% of syngas, while 47.45wt% in bio-char was recorded.

3.2 Effect of Pyrolysis Temperature

Figure 4 shows the yields of products from the pyrolysis at various temperatures. The yield of syngas and bio-char increases with temperature while the bio-fuel produced decreased. The pyrolysis temperature was varied within the temperature range of 350^{0}C – 550^{0}C and it was observed that an optimum yield of bio-fuel was predicted at pyrolysis temperature of 350^{0}C. Bio-fuel yield of 52.40wt% predicted in this study was relatively high compared to the maximum bio-fuel yield of 28.6 % from pyrolysis of algal biomass (*Chlorella sp.*) in a microwave oven carried out by Du *et al.* (2011). Also, the results from the research by Miao *et al.* (2004) showed a bio-fuel yield of 17.5wt% and 23.7wt% for *Chlorella Protothecoides* and *M. Aeruginosa* respectively from the fast pyrolysis in a fluidized bed at 500^{o}C. A further increase in the temperature led to a decrease in the yield of bio-fuel and a subsequent increase in the yield of non-condensable gases (Syngas) and bio-char. This result was due to a secondary decomposition reaction which occurred at higher pyrolysis temperatures resulting in secondary cracking of condensable vapours to non-condensable gas (Park *et al.,* 2009).

The energy balance analysis using aspen plus to ascertain the energy consumption and the energy efficiency, an important factor in determining the performance of the pyrolysis process was 74%.

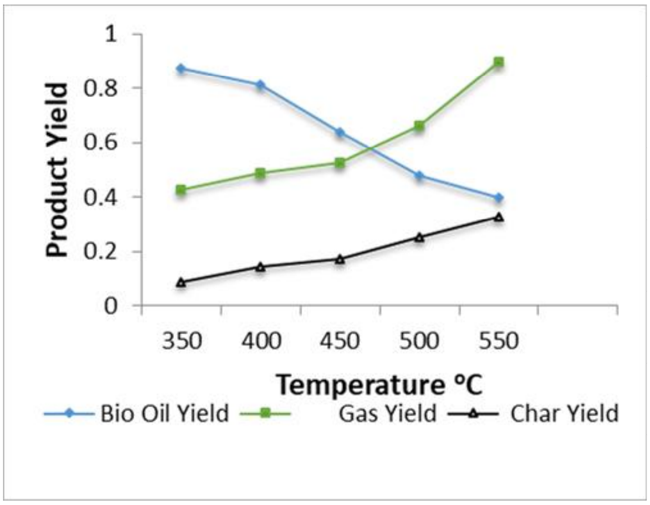

Figure 4: Effect of Pyrolysis Temperature on Product Yields.

3.3 Effect of Carrier Gas Flow Rate

Figure 5 shows the effect of fluidization velocity on the yields of products. To simulate this effect on the product yield, the air flow rates was varied within the range of 2-5L/min (120-300kg/h). Increasing the gas (air) flow rate on the reactor led to an increase in bio-fuel yield. From the simulation result, a bio-fuel yield of 52.4wt% was recorded at a flow rate of 4.5L/min (270kg/h) while a decrease in the yield of bio-char was observed. The bio-gas was high at the initial stage but along the line it starts decreasing with increasing flow rates. This indicates that higher flow rates of the carrier gas did not favour the yield of bio-fuel due to the fact that most volatile were carried away from the pyrolysis system without an effective condensation resulting in decrease in gas yield.

It has been established that for a fast pyrolysis process that will favour the yield of bio-fuel, the residence time of the pyrolysis vapour will have to be short. In other words, the carrier gas flow rate affects residence time of vapour. This theory accounts for the high yield and low yield of pyrolysis products with respect to the flow rate of the carrier gas (Air). The trend of this graph is validated by the results obtained from previous studies. Heo *et al.* (2010) recorded an increase in bio-fuel yield from 53.0wt% to 57.0wt% with respect to the fluidization velocity range of 3L/min to 5L/min equivalent to 180kg/h to 300kg/h from the pyrolysis of sawdust. However, from the result obtained from Şensöz and Angin (2008), a further increase in the fluidization velocity from 100L/min to 200L/min led to a decrease in bio-fuel yield from 36.1wt% to 33.0wt%.

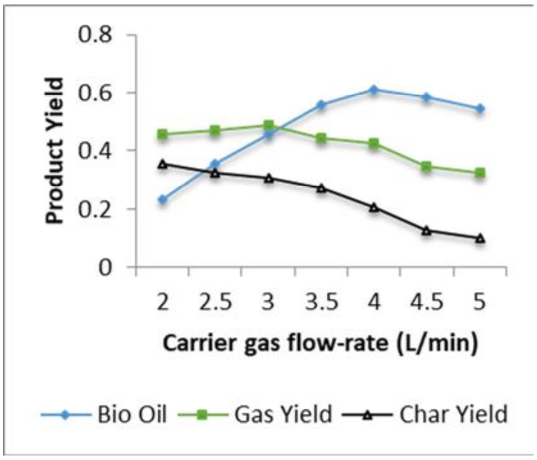

Figure 5: Effect of Carrier Gas Flow Rate on Yields.

3.4 Effect of Biomass Particle Size on Yields of Pyrolysis Products

Figure 6 depicts the particle size effect on the yield of the three pyrolysis products.

The feed particle size was varied within the range of 0.1 to 0.3mm to see how it affects the yields of the various pyrolysis products. The simulation results indicated that there was an increase in the yield of bio-char and a subsequent decreased in the yield of bio-fuel for a larger particle size while

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an increase in bio-fuel yield and a decreased in bio-char yield were recorded for a fine particle size of the feed. This was due to the fact that fine particle sizes, has higher surface area exposed to heat transfer and chemical reaction compare to coarse or intermediated particle size. This theory accounts for the high yield in bio-char for coarse particle size.

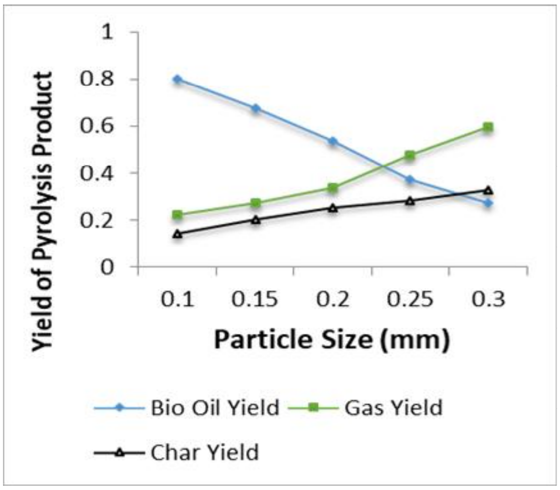

Figure 6: Effect of Particle Size on Yields of Pyrolysis Products

3.5 Techno Economic Analysis of the Bio-fuel Production Plant from Chlorella Vulgaris

The calculation of bio-fuel production for this research was based on plant capacity of 400,000tons/yr of wet biomass and a current retail value of microalgae Chlorella Vulgaris which is $36,000/ metric ton. Table 5 presents the size and cost of the process equipment used for the pyrolysis process. The cost estimation is based on the equipment sizing extracted from simulation result. This summary of the project capital from the IPE cost analysis did not include the cost of culture/cultivation of microalgae as well as its harvesting.

Table 5: Equipment Size and Cost for Pyrolysis Chlorella Vulgaris to Produce Bio-fuel

Equipment	Type	Size (L) *10^6(mm)	Cost ($)
SEP	DVT Cylinder	13.53	21500
PYROREAC	DAT Reactor	21.00	62100
CYCLONE	EDC Cyclone	48.06	111600
OILSEP	DVT Cylinder	16.02	47000

Table 6: Summary of Techno Economic Analysis of Chlorella Vulgaris Pyrolysis Plant Simulated from Aspen Plus

Items	Basis	Amount	
		USD ($)	Naira(₦)
Plant capacity	50505 kg/hr	-	-
Plant life	10yr	-	-
Annual operating time	8,766hr/yr	-	-
Fixed capital investment	-	3,633,619.5	1,308,975,088.68
Annual operating cost	-	491,337.91	176,999,568.70

The cost analysis results obtained from this study was low compared to the cost analysis carried out by Badger *et al.* (2011) on a transportable fast pyrolysis plant of 90,718kg/day capacity. The feedstock (pine wood chips) annual cost was $1,460,000 assuming a purchase price of $25/green tonne. The cost analysis summary for the mobile fast pyrolysis plant gave a capital cost of $6,030,816 with a total annual cost of $3,315,863. These values were higher compared to that obtained from this study, which gave an operating cost of $491,337 for a stationary fast pyrolysis plant of 1,212,120kg/day capacity which is higher. This difference in cost is due to the cost of transportation and the difference in plant size which was in agreement with the fact that the higher the plant capacity the lesser the cost of production.

Figure 7 shows the cost of bio-fuel production with respect to the plant capacity. From the cost analysis carried out by Ringer *et al.* (2006), it could be deduced that bio-fuel production cost, decreased as the plant capacity increased. The cost of bio-fuel production via fast pyrolysis was relatively low and the co-products of pyrolysis allowed biofuel to compete with today's fossil fuel market (Badger *et al.,* 2011).

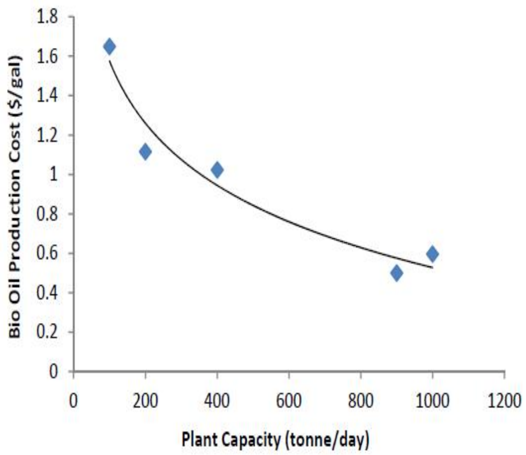

Figure 7: Bio-fuel Production Cost with Plant Size (Ringer *et al.,* 2006; Mullaney *et al.,* 2002; Islam & Ani, 2000).

4. CONCLUSION

4.1 Conclusion

The current rise in interest of researchers and companies towards commercializing the production of alternative fuel has formed the basis or motivation for this research. In order to investigate the feasibility of biofuel production, this research identified a pyrolysis technology with high stability under pyrolysis conditions and a biomass feedstock with high bio-fuel yield that can strive in any harsh environmental conditions, does not compete with food as well as agricultural land as it can be cultivated in a swampy area not used for agricultural practices. From the analysis thus far, the following conclusions were made:

i. The biomass (Chlorella Vulgaris) feedstock had a high potential of producing high bio-fuel for industrial scale biofuel production
ii. The bubbling fluidized bed reactor had high stability under pyrolysis conditions and is promising as it improves the yield of bio-fuel for fast pyrolysis operating conditions.
iii. Simulation results gave optimum yields of 52.40%, 0.18% and 47.45% for bio-fuel; bio-gas and bio-char respectively. The pyrolysis temperatures, inert gas feed rate as well as particle size were operating variables that affected the yield of products.
iv. The energy balance analysis was carried out to ascertain the energy consumption and the energy efficiency, an important factor in determining the performance of the pyrolysis process was found to be 74%.
v. The capacity or size of plant has little or no effect on the fixed cost except for the variable cost. This implies that with higher plant capacity, the cost of production will reduce compare to smaller plant capacity. The high cost of bio-fuel production could be minimized by increasing plant capacity. This can only be achieved by the right choice of biomass feedstock as well as the biomass conversion technology as these factors greatly affect the plant production capacity.

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