

# MASS AND ENERGY ASSESSMENT OF THE PYROLYSIS OF LOW LIPID MICROALGAE (DUNALIELLA SALINA)

**Yashim Afuwai<sup>1</sup>, Auwal Aliyu<sup>1,\*</sup>**

<sup>1</sup>Ahmadu Bello University, Zaria

Email: [afushim@gmail.com](mailto:afushim@gmail.com), [auwala@abu.edu.ng](mailto:auwala@abu.edu.ng)\*

\*Corresponding author: Auwal Aliyu

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## ABSTRACT

This study is a computational mass and energy assessment based on secondary literature data obtained from (Xun et al., 2014). As a sustainable and renewable source of energy, microalgae derived biofuel has a growing potential to solve the problem of global energy crisis as a result of higher demand for energy, as well as environmental impact such as global warming associated with fossil fuel. Mass and energy assessment of the pyrolysis of low lipid microalgae *Dunaliella salina* was carried out to produce 1kg of bio-oil. A fixed bed tubular reactor was used to carry out direct pyrolysis on the microalgae biomass at 300 – 700°C. Mass and energy assessment was done to estimate the products yield, mass ratio, energy ratio, energy efficiency, higher heating value (HHV) and energy consumption ratio (ECR) of the biofuel. The maximum yield of bio-oil, bio-char and biogas at 500°C were 64.9%, 28.0% and 3.9% respectively. The maximum mass ratio and energy ratio of the bio-oil were 0.649 and 77.98%. The higher heating value (HHV) and energy efficiency of the bio-oil at 500°C were obtained as 25.47MJ/kg and 74.50%. The maximum energy consumption ratio (ECR) of the pyrolysis process at 500°C was 0.043. The ECR is less than 1, which shows that the pyrolysis process was favourable since it exhibits net energy products with higher energy content than that required for the reaction to occur. The results obtained from mass and energy balances show that pyrolysis temperature has a great influence on the distribution yield and energy efficiency of the products. The production of 1kg of bio-oil from the algae biomass feedstock was obtained via pyrolysis of low lipid microalgae.

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## 1 INTRODUCTION

The use of sustainable energy sources and renewable energy sources is highly pertinent in Nigeria due to the fact that the country's energy sector still focuses largely on conventional fossil fuel sources of energy despite its great potential to generate renewable energy. By diversifying energy sources by the use of biofuel and other forms of renewable sources of energy, the issue of energy sustainability could be addressed along with minimizing the reliance on traditional sources of energy generated from petroleum sources. The biomass resource that can be used is that of microalgae since it can be processed to form energy products using processes like pyrolysis. Thus, conversion of microalgae biomass to bio-oil would help the country use resources in an innovative way.

The current study is thus in line with the International Conference on Engineering Innovation for Sustainable Development (ICESID) 2026 theme "Innovating Tomorrow: Leveraging Engineering for the Sustainable Development of Nigeria," especially through the themes of Innovative Resource Utilization and Sustainable Engineering Processes. Evaluation of the microalgae pyrolysis and bio-oil generation processes offers a basis for demonstrating the use of engineering analysis to assess the other possible routes for renewable biomass transformation into energy products. The study results can offer an insight into the evaluation of the technical and energy aspects of microalgae utilization and may form part of future research studies on renewable biomass utilization in Nigeria.

Energy is an essential component of human existence. Every sector, including industry, agriculture, healthcare, transportation, and domestic activities, relies on the use of energy (Mckendry, 2002). The increasing global demand for energy, along with the environmental consequences such as global warming linked to fossil fuels and their diminishing availability, has prompted the exploration of alternative energy sources from various biomass feedstock (Christi, 2012). The combustion of fossil fuels emits vast quantities of carbon dioxide, which is considered a primary contributor to global warming (International Energy Agency, 2015). Unlike the greenhouse gas emissions resulting from fossil fuel combustion, biomass represents a valuable feedstock for generating biofuels and other important chemicals. Renewable biomass feedstock comprises aquatic biomass, terrestrial biomass, municipal waste, agricultural solid waste, forest residue, and industrial waste (Jay, 2010).

Recent advancements in biotechnology have prompted researchers to investigate microalgae as a promising feedstock for sustainable biofuel production. Microalgae comprise a diverse group of aquatic, photosynthetic microorganisms, typically unicellular or multicellular, and are classified as third-generation biofuels (Veillette, 2012). Through the process of photosynthesis, algae and seaweed use sunlight to absorb carbon dioxide from the atmosphere and release oxygen (Kumar et al., 2016). Despite making up only 0.5% of all plant biomass, algae create roughly 60–75% of the oxygen required by people and animals, and every pound of algae biomass reduces carbon dioxide by 1.8 pounds (Wolkers et al., 2011). High photosynthetic efficiency, increased oil production productivity, and a high capacity to store significant amounts of lipids are characteristics of microalgae. The aforementioned qualities make microalgae one of the most exceptional sources of biofuel (Mohammad et al., 2015).

The evaluation of mass and energy regarding microalgae biofuel indicates that the cultivation, harvesting, drying, and processing of microalgae biomass can yield an environmentally sustainable feedstock for biofuel generation (Yanfen et al., 2012). Using a low lipid microalgae (*Dunaliella salina*) as feedstock for pyrolysis is a reasonable alternative because of the low cost and high oil yield. *Dunaliella salina* is a type of green microalgae mostly found in sea salt fields (Chen et al., 2012). The low lipid content strains of microalgae result in its cost lower with faster growth rates (Aresta et al., 2005). In this study, direct pyrolysis pathway is used to evaluate the mass and energy assessment of pyrolysis of low lipid microalgae (*Dunaliella salina*) at different temperatures from 300-700°C (Xun et al., 2014).

## 2 MATERIALS AND METHODS

### 2.1 Description of Pathways for Biofuel from Microalgae Pyrolysis

This study is a computational mass and energy assessment based on secondary literature data obtained from (Xun et al., 2014). This research examines the direct pyrolytic processes for producing bio-oil from microalgae (*Dunaliella salina*) at temperatures ranging from 300 to 700°C. Direct pyrolysis

deals with the method of pyrolysing the entire microalgae, resulting in bio-oil that predominantly consists of long-chain hydrocarbons including various terminal groups. This study examined the direct pyrolysis pathway by closely examining the mass ratio, energy ratio, energy efficiency, and energy consumption ratio (ECR). GC-MS (Agilent 7890A-5975C workstation software) was used to examine and identify bio-crude composition and the chemical constituents through the direct pyrolysis process. The area percentage approach was used to quantitatively analyse the composition of pyrolysis oil (Tang et al., 2015). The higher heating value of the bio-oil was calculated by equation (2.1) below: (Ferdinand et al., 2012).

$$HHV(kJ/kg) = 35098C + 116050H + 6267N - 11073O \quad \text{Equation 2.1}$$

Where: C, H, N, O are the fractions of the elements of carbon, hydrogen, nitrogen and oxygen in the compound respectively which can be obtained from the ultimate analysis for bio-char and bio-oil as shown in table (2.1) and (2.2) below.

Table 2.1: Ultimate Analysis (wt %) and HHV of Dunaliella salina (Bio-char) (Xun et al., 2014).

| Temperature (°C) | C    | H   | N    | S   | O    | HHV (MJ/kg) |
|------------------|------|-----|------|-----|------|-------------|
| 300              | 57.9 | 4.7 | 10.7 | 0.6 | 11.3 | 25.4        |
| 400              | 57.2 | 3.8 | 9.8  | 0.5 | 6.3  | 24.1        |
| 500              | 55.2 | 2.9 | 9.0  | 0.3 | 3.7  | 21.8        |
| 600              | 54.7 | 2.2 | 8.2  | 0.2 | 2.2  | 20.6        |
| 700              | 54.0 | 2.0 | 7.4  | 0.2 | 1.7  | 19.6        |

Table 2.2: Ultimate Analysis (wt %) and HHV of Dunaliella salina (Bio-oil) (Xun et al., 2014).

| Temperature (°C) | C    | H   | N    | S   | O    | HHV (MJ/kg) |
|------------------|------|-----|------|-----|------|-------------|
| 300              | 32.0 | 9.0 | 8.1  | 0.4 | 50.6 | 16.6        |
| 400              | 45.8 | 8.7 | 8.3  | 0.2 | 37.0 | 22.6        |
| 500              | 53.0 | 8.3 | 8.6  | 0.3 | 29.8 | 25.5        |
| 600              | 55.6 | 8.2 | 9.4  | 0.2 | 26.5 | 26.6        |
| 700              | 56.3 | 7.8 | 10.8 | 0.2 | 24.8 | 26.7        |

## 2.2 Mass and Energy Assessment

A fixed bed tubular reactor operating at 300–700°C was used to carry out the pyrolysis experiment as seen in (Xun et al., 2014). The mass balance efficiency was evaluated using the maximum bio-oil yield. The yields of the pyrolysis products were used to calculate the mass balance. The equations utilized in the mass and energy assessment are displayed in equations (2.2) to (2.5) (Yang et al., 2014).

Equation (2.2) defines mass ratio as seen below:

$$\eta_m = \frac{m_{fuel}}{m_{biomass}} \quad \text{Equation 2.2}$$

Where:  $\eta_m$  = Mass ratio  $m_{fuel}$  = Mass of liquid fuel (kg)  $m_{biomass}$  = Mass of biomass (kg)

The energy ratio is defined as:

$$\eta_{ef} = \frac{m_{fuel} \times HHV_{fuel}}{m_{biomass} \times HHV_{biomass}} \quad \text{Equation 2.3}$$

Where:  $\eta_{ef}$  = Energy ratio  $HHV_{fuel}$  = Higher heating value of fuel (MJ/kg)

$HHV_{biomass}$  = Higher heating value of biomass (MJ/kg)

Energy efficiency is determined using equation (2.4) below. It evaluates all of the energy inputs needed for the conversion process as well as the energy contained in the original feedstock and the desired fuel.

$$\eta_{ef}^1 = \frac{m_{fuel} \times HHV_{fuel}}{m_{biomass} \times HHV_{biomass} + Q_{input}} \quad \text{Equation 2.3}$$

Where:  $\eta_{ef}^1$  = Energy efficiency  $Q_{input}$  = Net process energy

Each process's energy balance can be evaluated using the energy consumption ratio (ECR). The energy needed to heat the microalgae cells to reaction temperature is divided by the energy of the oil, gas, and char that are produced to determine the ECR (Chaiwong et al., 2013). Since the product has more energy than what is needed for the reaction, the reaction is energy favorable if  $ECR < 1$ . However, if  $ECR > 1$ , the total energy used to make the bio-oil exceeds the energy in the fuel. The energy consumption ratio (ECR), of the pyrolysis process is expressed as seen in equation (2.5) below:

$$ECR = \frac{Q}{H_{oil}Y_{oil} + H_{char}Y_{char} + H_{gas}Y_{gas}} \quad \text{Equation 2.4}$$

Where:  $H_{oil}$ ,  $H_{gas}$  and  $H_{char}$  = HHVs of the bio-oil, bio-gas and bio-char

$Y_{oil}$ ,  $Y_{gas}$  and  $Y_{char}$  = Yield of the bio-oil, bio-gas and bio-char

### 2.3 Pyrolysis Process

It was estimated that 1 kg of bio-oil (wet basis) would be produced by direct pyrolysis at 300, 400, 500, 600, and 700°C. The pyrolysis distribution yield of products for *Dunaliella salina* is displayed in Table 2.3.

Table 2.3: Pyrolysis Distribution Yield of Products (Biofuel) (Xun et al., 2014)

| Temperature<br>(°C) | Bio-gas<br>(% mass) | Bio-oil<br>(% mass) | Bio-char<br>(% mass) | Undetected<br>(% mass) |
|---------------------|---------------------|---------------------|----------------------|------------------------|
| 300                 | 0.4                 | 32.3                | 57.7                 | 9.5                    |
| 400                 | 2.7                 | 53.5                | 34.0                 | 9.7                    |
| 500                 | 3.9                 | 64.9                | 28.0                 | 3.2                    |
| 600                 | 8.0                 | 59.9                | 24.2                 | 7.9                    |
| 700                 | 15.5                | 52.6                | 22.1                 | 9.8                    |

According to (Xun et al., 2014), a fixed-bed tubular reactor was used for the pyrolysis experiment. For this investigation, 1g (0.001kg) of each microalgae sample was utilized. 20 minutes (1200 seconds) was determined to be the residence time needed to finish the pyrolysis process. At 500°C, the maximum output of bio-oil (wet basis) for *Dunaliella salina* was 64.9%. The elemental compositions of table (2.2) were used to estimate the HHVs of the bio-oil using (Ferdinand et al., 2012) method of equation (2.1). The direct pyrolysis route flow chart, which includes bio-oil, bio-char, and biogas, is depicted in Figure (2.1).

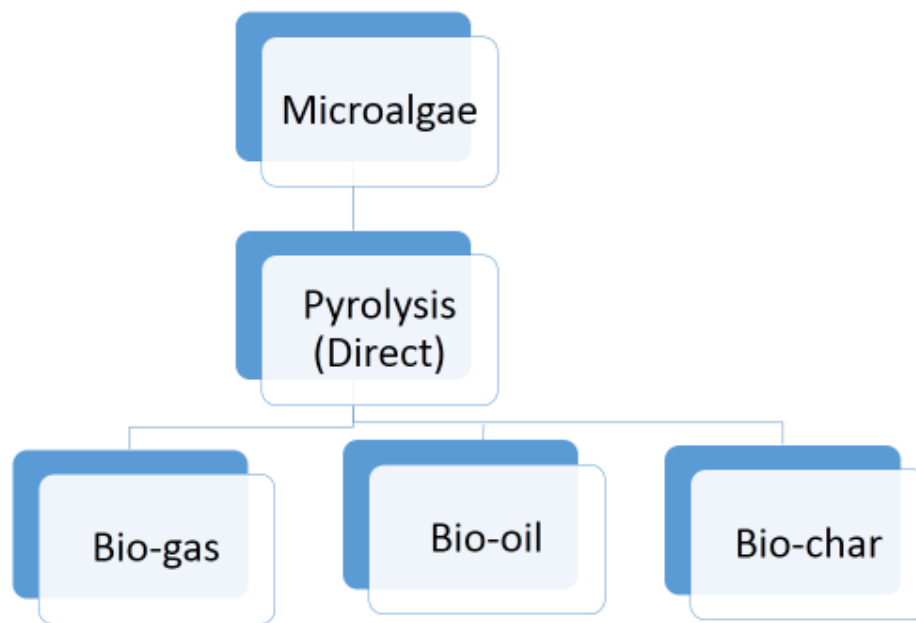


Figure 2.1: Flow chart of direct pyrolysis pathway for biofuel production

### 3 RESULT AND DISCUSSION

In this evaluation study, low-lipid microalgae (*Dunaliella salina*) were directly pyrolysed to produce 1 kg of bio-oil from algae biomass feedstock.

#### 3.1 Pyrolysis Distribution Yield of Products (Biofuel)

The product yield distribution of *D. salina* via the direct pyrolysis pathway at 300–700°C is displayed in Figure 3.1. The data for the pyrolysis distribution yield of products (biofuel) in table 2.3 are used to produce Figure 3.1.

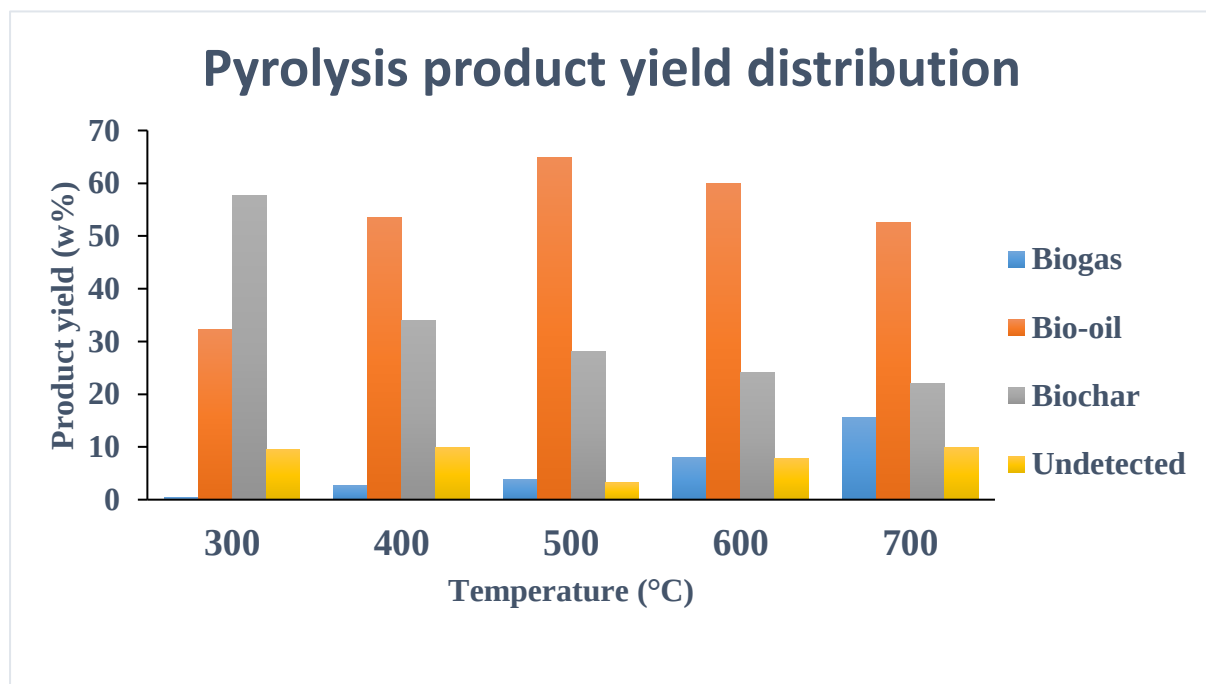


Figure 3.1: Pyrolysis product yield distribution

Figure 3.1 shows a graphical representation of the product yield distribution of *Dunaliella salina*, with a significant percentage of undetected biogas, bio-oil, and bio-char. Over the course of the

analysis, the percentage of undetected cases was less than 10%. Figure 3.1 shows that at 500°C, the maximum yield of bio-oil estimated in the assessment was 64.9%. The biogas yield rose from 0.4 to 15.5% while the bio-char yield fell from 57.7 to 22.1% as the temperature ranged from 300–700°C. The yield of bio-oil increased between 300 – 500°C, reaching over 60% at the microalgae's reactor temperature of 500°C. The yields of bio-oil, bio-char, and biogas from the pyrolysis of *Chlorella vulgaris* and *Dunaliella salina* at different temperatures between 300 – 500°C, were assessed by (Xun et al., 2014), who reported bio-oil yields of 49.2%wt for *Chlorella vulgaris* and 55.4%wt for *Dunaliella salina* at both 500°C. The bio-oil yield estimated in the present computational assessment was 64.9 wt%, compared with 55.4 wt.% reported by (Xun et al., 2014) for *D. salina* at 500 °C. The difference of 9.5% is associated with differences in the calculation procedure, process assumptions, product definition, or operating conditions.” Additionally, at 600°C, *Nannochloropsis* microalgae produced a 60%wt bio-oil yield (Tang et al., 2015). The results shows that pyrolysis temperature has a significant effect on the distribution yield of products.

### 3.2 Mass and Energy Assessment

Table 3.1 and 3.2 shows the mass and energy assessment parameters for direct pyrolysis route in the production of 1kg of bio-oil from *Dunaliella salina*. The mass and energy assessment parameters include mass balance, mass ratio ( $\eta_m$ ), energy ratio ( $\eta_{ef}$ ), higher heating value (HHV), energy efficiency ( $\eta_{ef}^1$ ) and energy consumption ratio (ECR) of the pyrolysis at 300 – 700°C. At 500°C, the bio-oil's maximum mass ratio and energy ratio were 0.649 and 77.98% respectively. As the temperature rises from 300°C to 500°C, the bio-oil's mass ratio and energy ratio vary from 0.323 to 0.649 and 25.26 to 77.98% respectively. As the temperature rises from 300 to 500°C, the mass and energy ratios of biogas and bio-char are inversely correlated. At 300–500°C, the bio-oil's higher heating value (HHV) and energy efficiency rise from 16.58 to 25.47 MJ/kg and 24.10 to 74.50% respectively. The higher heating value of the bio-oil exceeds the higher heating value of the algal biomass at 500°C. A high heating value is achieved by increasing the temperature for thermal decomposition of the microalgae. The maximum energy consumption ratio (ECR) of the pyrolysis process at 500°C was 0.043 (4.3%). The ECR is less than 1, which shows that the pyrolysis process is favourable since it exhibits net energy products with high energy content than that required for the reaction.

Table 3.1: Mass assessment for direct pyrolysis pathway of *Dunaliella salina*

| Temp | $m_{\text{biogas}}$ | $m_{\text{bio-oil}}$ | $m_{\text{biochar}}$ | $m_{\text{undetected}}$ | $m_{\text{biomass}}$ | Biogas       | Bio-oil      | Biochar      |
|------|---------------------|----------------------|----------------------|-------------------------|----------------------|--------------|--------------|--------------|
| (°C) | (kg)                | (kg)                 | (kg)                 | (kg)                    | (kg)                 | ( $\eta_m$ ) | ( $\eta_m$ ) | ( $\eta_m$ ) |
| 300  | 0.012               | 1.000                | 1.786                | 0.297                   | 3.095                | 0.004        | 0.323        | 0.577        |
| 400  | 0.050               | 1.000                | 0.636                | 0.183                   | 1.869                | 0.027        | 0.535        | 0.340        |
| 500  | 0.060               | 1.000                | 0.431                | 0.049                   | 1.540                | 0.039        | 0.649        | 0.280        |
| 600  | 0.134               | 1.000                | 0.404                | 0.132                   | 1.670                | 0.080        | 0.599        | 0.242        |
| 700  | 0.295               | 1.000                | 0.420                | 0.186                   | 1.901                | 0.155        | 0.526        | 0.221        |

Table 3.2: Energy assessment for direct pyrolysis pathway of Dunaliella salina

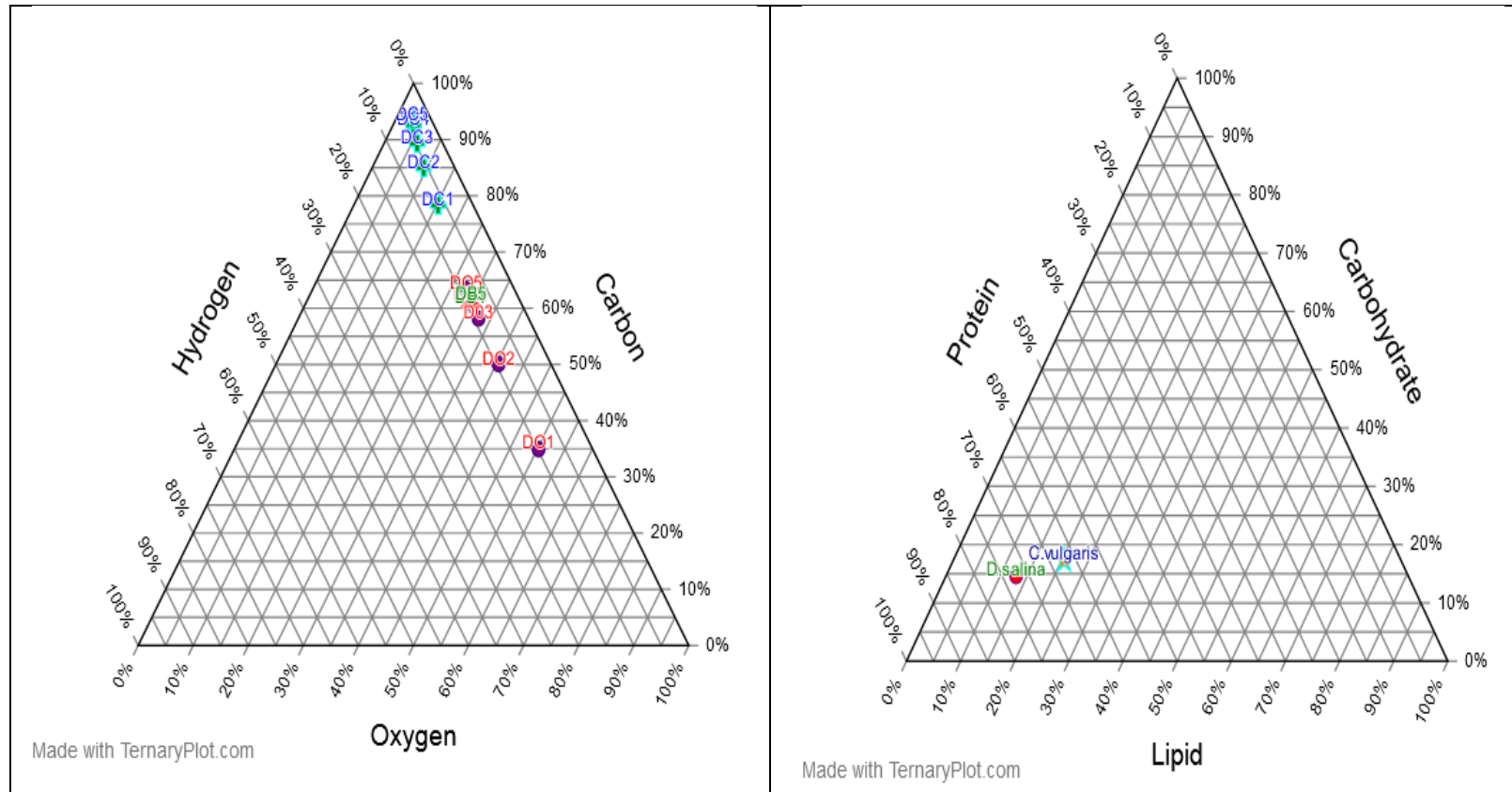
| Temp       | HHV <sub>B/gas</sub> | HHV <sub>B/oil</sub> | HHV <sub>B/char</sub> | HHV <sub>B/mass</sub> | $\eta_{ef}$<br>B/gas | $\eta_{ef}$<br>B/oil | $\eta_{ef}$<br>B/char | $\eta_{ef}^1$<br>B/gas | $\eta_{ef}^1$<br>B/oil | $\eta_{ef}^1$<br>B/char | Q <sub>inp</sub> | ECR |
|------------|----------------------|----------------------|-----------------------|-----------------------|----------------------|----------------------|-----------------------|------------------------|------------------------|-------------------------|------------------|-----|
| (°C)       | MJ/kg                | MJ/kg                | MJ/kg                 | MJ/kg                 | %                    | %                    | %                     | %                      | %                      | %                       | MJ               | %   |
| <b>300</b> | 35.90                | 16.58                | 25.40                 | 21.20                 | 0.68                 | 25.26                | 69.13                 | 0.60                   | 24.10                  | 65.90                   | 3.12             | 5.0 |
| <b>400</b> | 17.10                | 22.59                | 24.10                 | 21.20                 | 2.18                 | 57.02                | 38.65                 | 2.10                   | 54.40                  | 36.90                   | 1.86             | 4.8 |
| <b>500</b> | 20.60                | 25.47                | 21.80                 | 21.20                 | 3.79                 | 77.98                | 28.79                 | 3.60                   | 74.50                  | 27.50                   | 1.55             | 4.3 |
| <b>600</b> | 19.20                | 26.68                | 20.6                  | 21.20                 | 7.25                 | 75.39                | 23.51                 | 6.90                   | 72.00                  | 22.50                   | 1.65             | 4.4 |
| <b>700</b> | 21.30                | 26.74                | 19.6                  | 21.20                 | 15.57                | 66.35                | 20.43                 | 14.90                  | 63.40                  | 19.50                   | 1.90             | 4.6 |

### 3.3 Elemental Mass Balance for the Production of 1kg of bio-oil

Table 3.3 shows the elemental balance for the production of 1kg of bio-oil via direct pyrolysis from the microalgae biomass. The HHV of bio-oil increases with decrease in H/C and O/C ratio. The atomic hydrogen/carbon and oxygen/carbon of the bio-oil were determined as shown in table 3.3 The H/C and O/C ratios decreases from 0.28 to 0.12 and from 1.59 to 0.44 as temperature increases from 300 – 700°C respectively.

Table 3.3: Elemental mass balance for the production of 1kg of bio-oil via direct pyrolysis of Dunaliella salina

| Tem<br>p<br>(°C) | Ash  | C    | H    | N    | O    | S    | m <sub>bio</sub><br>mass<br>(kg) | C    | H    | N    | O    | S     | H/C  | O/C  | m <sub>bio</sub><br>oil<br>(kg) |
|------------------|------|------|------|------|------|------|----------------------------------|------|------|------|------|-------|------|------|---------------------------------|
| 300              | 0.22 | 1.49 | 0.22 | 0.29 | 0.72 | 0.03 | 3.09                             | 0.32 | 0.09 | 0.08 | 0.51 | 0.004 | 0.28 | 1.59 | 1.0                             |
| 400              | 0.13 | 0.90 | 0.13 | 0.18 | 0.44 | 0.02 | 1.86                             | 0.46 | 0.08 | 0.08 | 0.37 | 0.002 | 0.17 | 0.80 | 1.0                             |
| 500              | 0.11 | 0.74 | 0.11 | 0.14 | 0.36 | 0.01 | 1.54                             | 0.53 | 0.08 | 0.09 | 0.30 | 0.003 | 0.15 | 0.56 | 1.0                             |
| 600              | 0.12 | 0.80 | 0.12 | 0.16 | 0.39 | 0.02 | 1.67                             | 0.55 | 0.08 | 0.09 | 0.27 | 0.002 | 0.14 | 0.49 | 1.0                             |
| 700              | 0.14 | 0.91 | 0.13 | 0.18 | 0.44 | 0.02 | 1.90                             | 0.56 | 0.07 | 0.11 | 0.25 | 0.002 | 0.12 | 0.44 | 1.0                             |



- a) Migration of carbon, hydrogen and oxygen composition of microalgae  
Carbohydrate, protein and lipid distribution

b)

Figure 3.2: Ternary plot diagram

Keys for items in figure 3.2a

|                                |                           |
|--------------------------------|---------------------------|
| DO- Dunaliella salina bio-oil  | 1- Via pyrolysis at 300°C |
| DB- Dunaliella salina biomass  | 2- Via pyrolysis at 400°C |
| DC- Dunaliella salina bio-char | 3- Via pyrolysis at 500°C |
|                                | 4- Via pyrolysis at 600°C |
|                                | 5- Via pyrolysis at 700°C |

### 3.4 Ternary Plot Diagram

The ternary diagram was used to signify the microalgae pyrolysis process at 300 – 700°C, relative percentage of oxygen, hydrogen and carbon whose summation is 100% or a ratio of 1. It also compares the relative ratio of carbohydrate, protein and lipid composition. The Ternary plots in figure 3.2 below were created at [www.Ternaryplot.com](http://www.Ternaryplot.com). The carbohydrate, protein and lipid composition of *Dunaliella salina* and *Chlorella vulgaris* in figure 3.2b were adapted from (Xun et al., 2014). Table 3.1 for ultimate analysis of bio-char and table 3.3 for elemental balance of bio-oil and biomass were used to create the ternary plot in figure 3.2.

Figure 3.2a shows the ternary distribution of hydrogen, carbon, and oxygen for the products obtained at different operating temperatures. The positions of the points show the relative elemental composition of the resulting products; those located near the upper vertex have a higher relative carbon content, and shifts towards the lower-left and lower-right areas indicate increasing relative amounts of hydrogen and oxygen respectively. Hence, the way the points move across the ternary diagram provides useful evidence of the changes in elemental composition resulting from thermal conversion.

The DC points (DC1 to DC5) are mostly situated in the area dominated by carbon on the ternary diagram. This suggests that the DC products contain a higher proportion of carbon together with relatively smaller amounts of hydrogen and oxygen. As the DC points shift gradually towards the carbon-rich region, this shows that the degree of carbon richness increases with more intensive conversion conditions. This trend is consistent with the formation of carbon-rich bio-char through the stepwise thermal decomposition of the original biomass and the removal of the volatile compounds which contain hydrogen and oxygen. On the ternary diagram, the DO points show a clear trend. DO1 is located further away from the apex which is rich in carbon, whereas DO2 through DO5 are found at successively greater distances from this carbon-rich region. This indicates that the composition of the product alters as the temperature rises. The shift towards the carbon-rich area means that the carbon concentration increases together with a reduction in the amounts of hydrogen and oxygen relative to the other components. These kinds of changes are typical of the continuous deoxygenation and dehydrogenation processes that take place during thermal conversion.

The DB points are abundant in the ternary diagram's intermediate region, especially in the vicinity of the compositions that the higher-temperature DO products represent. The elemental composition between the very carbon-rich DC products and the less carbon-rich DO products is indicated by their placements. The DB points' comparatively tight distribution indicates that, under the conditions under investigation, the elemental composition of these products changes less than that of the DC products. The effect of temperature on the elemental composition of the products is demonstrated by the overall migration of the points toward the carbon-rich region with increasing temperature. As the temperature rises, more carbon-rich products are formed and molecules containing hydrogen and oxygen are broken down. As a result, the ternary distribution presents a graphic portrayal of how the starting biomass gradually converts into products with a bigger relative carbon content.

Figure 3.2b was used to show the comparison in biochemical composition between *D. salina* and *C. vulgaris*. In order to explain more about the biochemical composition of the two microalgal bio-feedstocks, the use of the ternary diagram came in handy, when comparisons were made between *D. salina* and *C. vulgaris*. Both strains lie within the lipid-rich part of the ternary diagram, although not at the exact same point. While *D. salina* lies relatively closer to the lipid-rich part, this indicates that *D.*

salina has higher amounts of lipids. The variation in the placement of the two raw materials is an indication that there is some variation in the biochemical composition of both and this may affect their behaviours during thermal conversion processes. This variation is crucial in analysing the pyrolysis products since there are different thermal decomposition pathways for lipids, proteins, and carbohydrates which may lead to the formation of different levels of bio-oil, bio-char, and gas. Therefore, the initial biochemical composition of the microalgae is useful in explaining the variations in the elemental composition of the resulting products.

#### 4 CONCLUSIONS

Based on the mass and energy assessment carried out from the pyrolysis of low lipid microalgae *Dunaliella salina* at varying temperatures of 300-700°C, the maximum yield obtained for bio-oil at 500°C was 64.9%. The yield obtained for biogas and bio-char at 500°C was 3.9% and 28.0%. The results obtained for mass and energy balances show that pyrolysis temperature has a great influence on the distribution yield and energy efficiency of the products. Therefore, the production of 1kg of bio-oil from the algae biomass feedstock was obtained via direct pyrolysis of low lipid microalgae. The maximum mass ratio and energy ratio at 500°C for the bio-oil was 0.649 and 77.98%. The higher heating value (HHV), energy efficiency and energy consumption ratio (ECR) of the pyrolysis process at 500°C was 25.47 MJ/kg, 74.50% and 0.043 (4.3%). The ECR is below 1, indicating that the pyrolysis process is beneficial, as it generates products with higher energy content than what is needed for the reaction process.

From a Nigerian context, these findings highlight the prospect of using microalgae pyrolysis as another process through which renewable biomass and biofuels could be used. The production of bio-oil from microalgae biomass can help in the diversification of energy resources in Nigeria. This will facilitate the production of more sustainable engineering processes. Further studies are needed on the techno-economic, environmental and scale-up aspects of this process before it is implemented on a larger scale. These findings lay the foundation for future research on microalgae fuels as a supplement in the sustainable-energy system being developed in Nigeria.

#### 5 REFERENCES

- Aresta, M., Dibenedetto, A., Barberio, G. (2005). Utilization of microalgae for enhanced CO<sub>2</sub> fixation and biofuels production.
- Chaiwong, K., Kiatsiriroat, T., Vorayos, N., & Thararax, C. (2013). Study of bio-oil and bio-char production from algae by slow pyrolysis. *Biomass and Bioenergy*, 56, 600–606.
- Chen, C., Ma, X., & Hu, Z. (2012). A study on experimental characteristics of microwaveassisted pyrolysis of microalgae, *Bioresour. Technol* 107: 487-493.
- Christi, Y. (2012). Biodiesel from microalgae *Biotechnol*; 25: 294 - 306.
- International Energy Agency (I.E.A); CO<sub>2</sub> emission from fuel combustion; Highlights, (2015) edition.
- Jay, C. (2010). Introduction to Cheng, J (Ed), *Biomass to renewable energy processes*. Boca Raton pp.1-6
- Kumar, A., Patel, M., & Zhang, X. (2016). Techno-economic and life cycle assessment of lignocellulosic biomass thermochemical conversion technologies. A review renewable and sustainable energy. 53: 1486-1499.
- Mckendry, P. (2002). Energy production from biomass part 1: Overview of biomass, *Bioresour. Technol* 83.
- Mohammad, J.H. and Taha, H.M. (2015). *Chlorella sp.* As a source of biodiesel and by-product an integral study of Med-algae project: *Int Techno chem res*; 144-151.
- Tang, Y., Rosenberg, J. N., Bohutskyi, P., Yu, G., Betenbaugh, M. J., & Wang, F. (2015). Microalgae as a feedstock for biofuel precursors and value-added products: Green fuels and golden opportunities. *BioResources*, 11(1).

- Veillete M., Chamoumi M, Nikiema J, Faucheux N, Heitz M, (2012). Production of biodiesel from microalgae. In *Advances in Chemical Engineering*; In tech: Rijeka Croatia.
- Wolkers H, Barbosa M, Kleingris D.M, & Bosma, R. (2011). Editors *Microalgae; The green Gold of the future, large scale sustainable cultivation of microalgae for the production of bulk commodities*, 32 Netherlands; The Ministry of Economic Affairs; p.1
- Xun, G., Zhang, B., & Yang, Z. (2014). Investigation on pyrolysis of low lipid microalgae *Chlorella vulgaris* and *Dunaliella salina*. *Energy fuels*. 28: 95-103.
- Yanfen, L., Zehao, H., & Xiaoqian, M. (2012). *Energy policy*; 45: 142-152.
- Yang, F., & Wang, J. (2014). "Mixotrophic cultivation of microalgae for biodiesel production: status and prospects," *Applied Biochemistry and Biotechnology*, vol. 172, no. 7, pp. 3307– 3329.