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## Research

**Keywords:** Biomass Valorization, Napier Grass, Oil Palm Petiole, Torrefaction

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# Torrefaction of Napier Grass and Oil Palm Petiole Waste

## Using Drop-type Pyrolysis Reactor

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### 1. Abstract

Interest in torrefaction has improved along the recent years and it has been studied extensively as a mean of preparing solid fuels. Biomass to be considered as a renewable source of energy must endeavor improvement continuously and where it is more sustainable going forward in which can come from waste product, wild and cultivated plant. The aim of this study is to investigate the effect of temperature and residence time of wild Napier grass and Oil palm petiole from waste. The torrefied samples were derived by pyrolysis reactor mimicking torrefaction procedure. The temperature parameter ranges between 220 and 300 °C while residence time parameter is from 10 minutes to 50 minutes of reaction. It was found that as temperature and time increasing, moisture content and amount of O and H

19 atoms decreases as well as both mass and energy yield, but calorific value and the energy density increase  
20 along with both two parameters. Between the two parameters, the temperature variation shows more  
21 significant changes to the torrefied samples as compared time. The optimized temperature and time are  
22 found to be 260 °C and 30 minutes, respectively. Remarkably, the usage of pyrolyzer as torrefaction  
23 reaction has proved to be a good option since they share similar characteristics while can also produce  
24 product with similar properties reflecting torrefaction process.

25  
26 Keywords: Biomass Valorization, Napier Grass, Oil Palm Petiole, Torrefaction

## 28 **2. Introduction**

29 Sustainable and renewable source of energy is one of the main concerns into the upcoming years  
30 as fear of depleting fossil fuel is growing. Among the promising sources of renewable energy is via biomass  
31 utilization in form of solid, liquid and gas fuels. Biomass has been researched extensively for it to be  
32 partnered, mixed and eventually become an alternative to fossil fuel. Even though it is promising, a few  
33 challenges has to be addressed for it to be competitive with the current fossil fuels; (1) high consumption  
34 of energy during feedstock collection, (2) heterogenous and inconsistent composition, (3) low calorific  
35 value and (4) difficulty in transportation (Uemura et al. 2011).

36 Torrefaction is a thermochemical treatment in which it is carried out in relatively low  
37 temperature of 200-300 °C and conducted in an inert environment. It is sometimes called as mild pyrolysis

38 and functions to drive out moisture, volatile matter while at same time, decompose the polysaccharide  
39 chains. According to Chen et al., torrefaction possess four main advantages: (1) increases heating value  
40 or energy density, (2) lowering the moisture content, hydrogen-to-carbon (H/C) and oxygen-to-carbon  
41 (O/C) ratios, (3) improve resistivity against water and (4) enhance reactivity and grindability (Chen et al.  
42 2015). In most of researches in torrefaction, three main conditions have been studied to affect the  
43 performance of the torrefied material which are biomass properties, torrefaction temperature and  
44 duration of reaction time of torrefaction but the latter two are more widely analyzed. Torrefaction has  
45 widely conducted using wood-based and grass-based biomass such as oil palm fruit bunches (Uemura et  
46 al. 2011), willow (Bridgeman et al. 2008), Juniper wood (Eseltine et al. 2013), bamboo (Rousset et al.  
47 2011), wheat (Bridgeman et al. 2008; Satpathy et al. 2014) and rice husk (Chen et al. 2011). Torrefied  
48 materials can be used for co-firing of fuel, iron-making and pollutant adsorbent and pretreated material  
49 for gasification and pyrolysis (Chen et al. 2021). Despite their close thermal characteristics between  
50 torrefaction and pyrolysis however to author knowledge there is no trial on utilizing pyrolysis reactor for  
51 torrefaction reaction process.

52 Napier grass which is also known as elephant grass is a fast-growing plantation that can be found  
53 in several regions around the globe. It is classified as herbaceous plant and belongs to the Poaceae family.  
54 As researched by Mohammed et. al., Napier grass has shown to have high volatile matter contents,  
55 heating value and carbon content while also having low ash, nitrogen and sulfur contents (Mohammed  
56 et al. 2015). Among its other advantages are ability to minimize deforestation damage, fast cycle, high  
57 productivity and high ratio of energy output to the energy input to grow the grass to be about 25:1  
58 (Samson et al. 2005). Oil palm is one of the main plantations and Malaysia has been the second largest  
59 producer of palm oil with 19.67 million tons of palm oil produced. Oil palm frond is one of the biomass  
60 products that can be harvested from an oil palm plant. Although it is one of the highest contents of

61 lignocellulosic component from the oil palm harvest, it was previously considered as waste and has been  
62 underutilized. Almost 46,837 kilotons of oil palm fronds along with its petiole was wasted in the year of  
63 2007 (Goh et al. 2010).

64 In this study, we focused on torrefaction of Napier grass and oil palm petiole which exist in  
65 abundance around Malaysia. The effect of reaction temperature and reaction time were studied with the  
66 two biomass feedstocks to observe the performance on the torrefied material. Pyrolysis reactor is used  
67 in this study in place for torrefaction to compare the results as compared to a standard torrefaction  
68 reactor.

### 69 **3. Experimental**

#### 70 *3.1 Materials*

71 Oil palm petiole (OPP) were collected from Felcra Nasaruddin, Bota Kanan, Perak while the  
72 Napier grass (NG) was collected from Teluk Bakong, Perak. The samples were washed cut and let to dried  
73 under sunlight for 1 week. The raw samples were dried in oven at 105 °C for 24 hours. The dried sample  
74 is granulated to 2.5 mm in size and further grinded to about 500 µm. The lignocellulose composition of  
75 both biomass sources is shown in Table 1.

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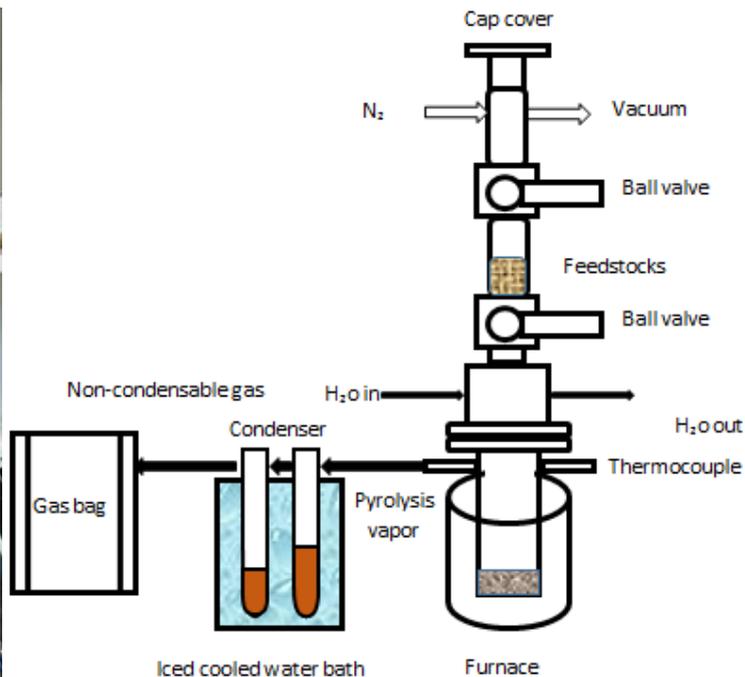
Table 1: Composition of Napier grass and Oil palm petiole

Biomass sources	Percentage, %		
	Cellulose	Hemicellulose	Lignin
Napier grass	39-68	16-34	17-27
Oil palm petiole	35	18	22-25

78

79 *3.2 Torrefaction process*

80 A drop-type pyrolyzer was used for the torrefaction process as shown in Figure 1. Nitrogen gas  
81 was let to purge the reactor for 5 minutes to remove oxygen from the reactor in order to prevent  
82 combustion. The reactor was calibrated before and after the sample was placed in the reactor. 5 runs  
83 were conducted to both samples for 30 minutes of residence time with varying temperature (220 °C, 240  
84 °C, 260 °C, 280 °C and 300 °C). Another 5 runs were conducted with fixed temperature of 260 °C with  
85 varying residence time (10, 20, 30, 40 and 50 minutes).



86

87 Figure 1: (a) Fixed-bed pyrolyzer used for the torrefaction process, (b) Schematic Diagram of torrefaction  
 88 experiment in fixed bed drop-type pyrolyzer

89 *3.3 Elemental analysis*

90 Element of carbon (C), hydrogen (H), nitrogen (N) and sulfur (S) in the samples were determined  
 91 using LECO 932 CHNS analyzer in accordance to 2mgChem80s method. It was assumed that the elements  
 92 other than oxygen does not take a significant amount, therefore the oxygen (O) content was determined  
 93 by the difference of the total CHNS contents from 100%. The result from the CHNS analyzer is in the form  
 94 of weight percentage therefore, to get the number of atoms of the particular element, some calculations  
 95 are done using the following Equation 1:

96 
$$\text{Number of atoms} = \frac{w\%}{100} \times M \times \frac{1}{MW} \times AN \quad (1)$$

97 Where %w is the weight percentage of the element,  $M$  is the mass of sample,  $MW$  is the atomic weight  
98 of the element and  $AN$  is the Avogadro's number which is  $6.0221 \times 10^{23}$  per mole.

### 99 3.4 Moisture content and calorific value

100 The moisture content was determined in accordance to BS EN ISO 18134-3 Solid fuels –  
101 Determination of Moisture Content – Oven Dry method. 1 g of sample was placed in oven at 105 °C until  
102 constant mass had been achieved. Constant mass is defined as the changes of mass after 1 hour not  
103 exceeding 1 mg, in which up to 180 minutes of heating for drying time is required. The sample is placed  
104 in a desiccator and later weighed. The moisture content is calculated using the following Equation 2:

$$105 \quad \text{Moisture content} = \frac{M_2 - M_3}{M_2 - M_1} \times 100\% \quad (2)$$

106 where  $M_1$  is the mass of empty dish,  $M_2$  is the mass of empty dish with test sample before drying and  
107  $M_3$  is the mass of empty dish plus test sample after drying.

108 Calorific value (CV) is defined as the energy content or the heating value released during the  
109 process of complete combustion. Lower heating value is more suitable to be used as the energy content  
110 since higher heating value also included the latent heat of vaporization which is not fully converted into  
111 useful energy. The calorific value was determined using the BS EN ISO 18125 Solid Biofuels - Determination  
112 of Calorific Value standards.

### 3.5 Mass yield, energy yield and energy density

Mass yield is defined as the percentage ratio of the torrefied sample to the raw biomass sample as shown in the Equation 3:

$$\text{Mass yield} = \frac{M_{\text{torrefied}}}{M_{\text{raw}}} \times 100\% \quad (3)$$

where  $M_{\text{torrefied}}$  is the mass of torrefied biomass and  $M_{\text{raw}}$  is the mass of raw biomass sample.

Energy yield is the usable energy in the remaining sample after torrefaction process. It is calculated using Equation 4:

$$\text{Energy yield} = \text{Mass yield} \times \frac{CV_t}{CV_r} \quad (4)$$

where  $CV_t$  is the calorific value of the torrefied biomass in MJ/kg and  $CV_r$  is the calorific value of the raw biomass

Energy density is amount of energy stored in the torrefied biomass per unit mass. It is calculated as the ratio of energy yield to the mass yield as shown in Equation 5 below:

$$\text{Energy density} = \frac{\text{Energy yield}}{\text{Mass yield}} \quad (5)$$

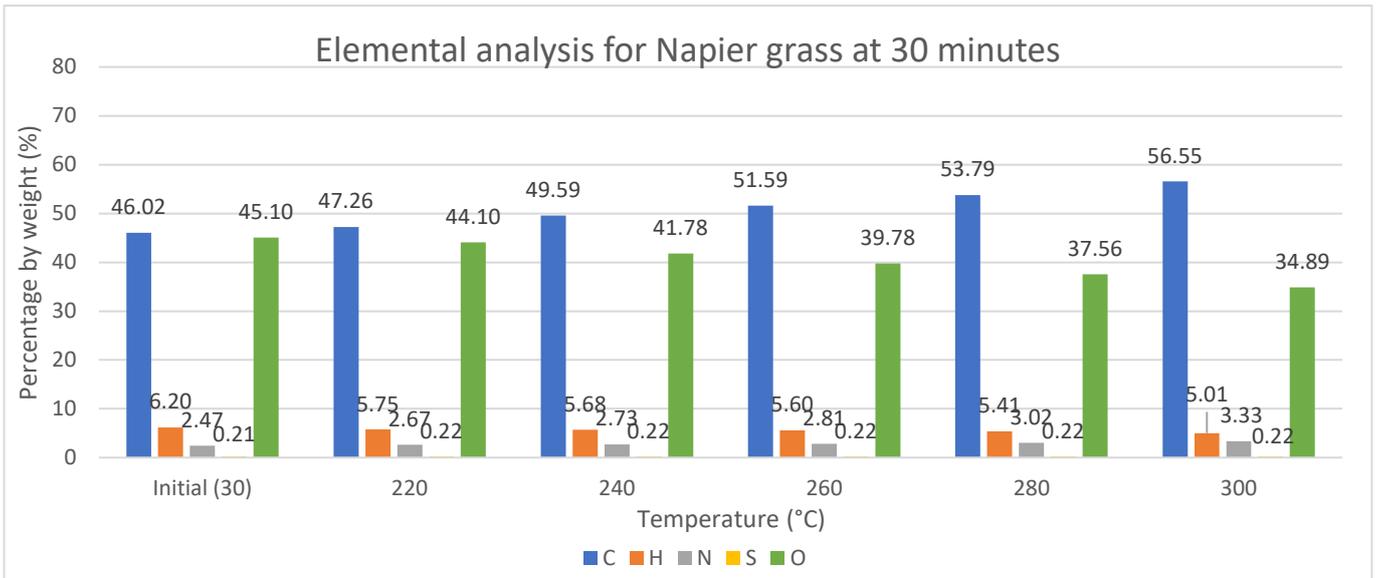
## 4. Results and discussion

#### 4.1 Elemental Analysis

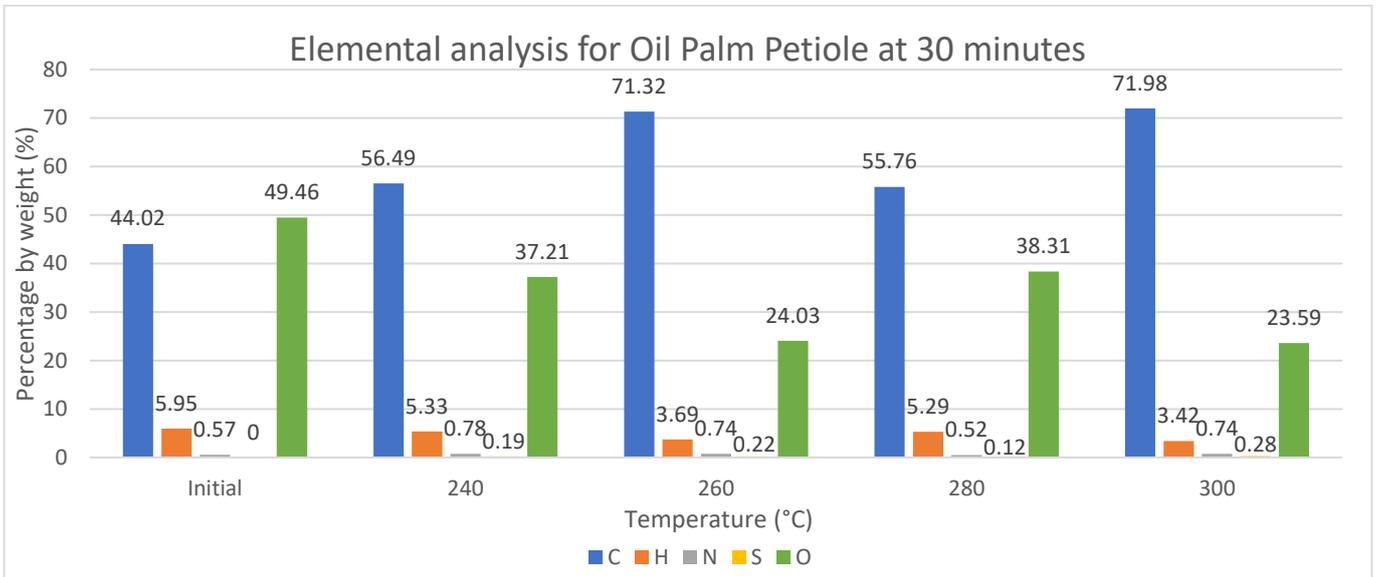
Typically, there are five main elements are present in the biomass composition which carbon (C), hydrogen (H), oxygen (O), nitrogen (N) and sulphur (S). For Napier grass, the initial composition is taken which consist of 46.02 wt% of carbon, 6.20 wt% of hydrogen, 2.47 wt% of nitrogen, 45.10 wt% of oxygen and 0.21 wt% of sulphur while the initial composition of OPP is reported according to literature to be 44.02 wt% of carbon, 49.02 wt% of oxygen, 5.95 wt% of hydrogen and 0.57 wt% content of nitrogen (Roslan et al. 2014). The high composition of oxygen can contribute to the fuel combustion but can also affect the calorific value. Both biomasses have low sulfur content which means better combustion and less production of SO<sub>x</sub>.

From Figure 2 and Figure 3, the carbon and nitrogen content increase slightly while the hydrogen and oxygen content decrease with longer reaction time and higher temperature. This is due to the breakage of C-H-O bonds and causes liberation of water molecules and volatile matter which also emitted lipophilic extractives. Much of the carbon atoms remains in the structure upon decomposition of hemicellulose and this increases the ash and fixed carbon content (Boersma et al. 2005). This result is consistent with previous studies done by Uemura et al. and Chen et al (Bridgeman et al. 2008; Uemura et al. 2011).

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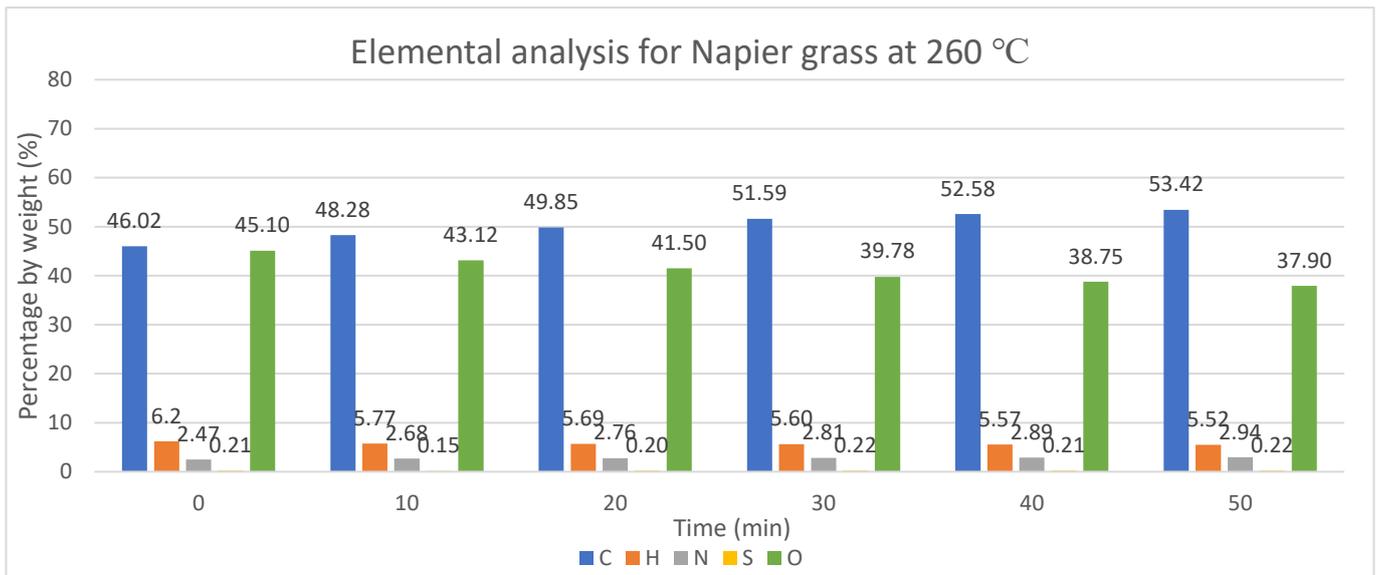


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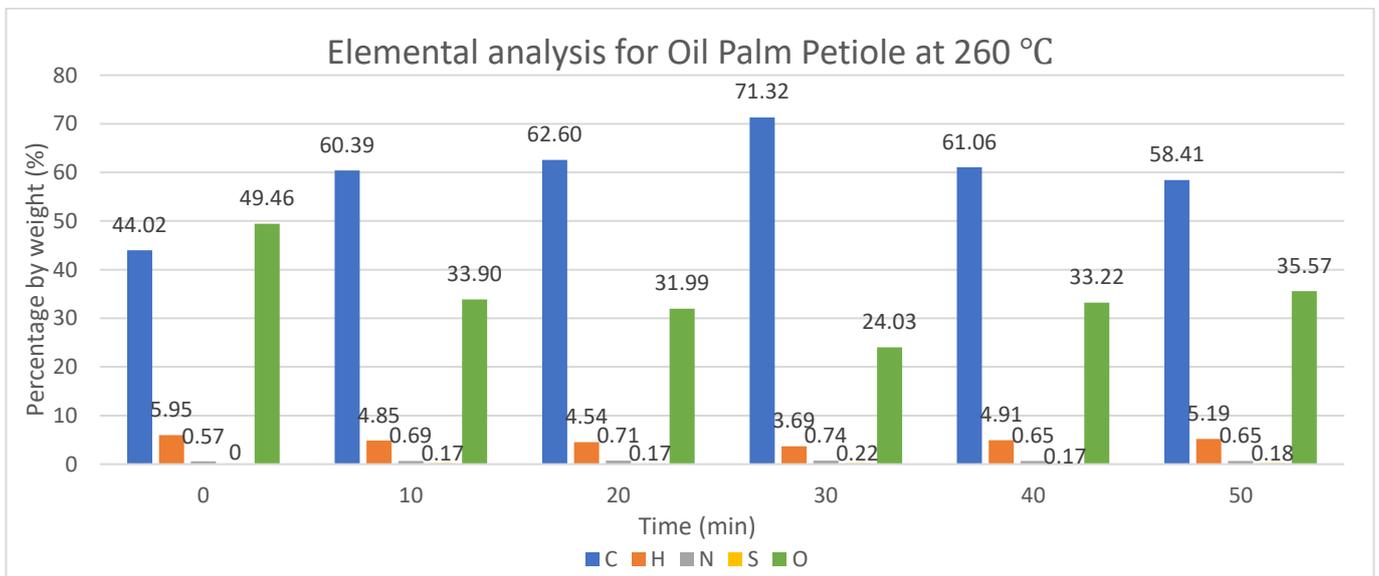


145 Figure 2: Elemental analysis at reaction time of 30 minutes for (a) Napier grass and (b) oil palm petiole

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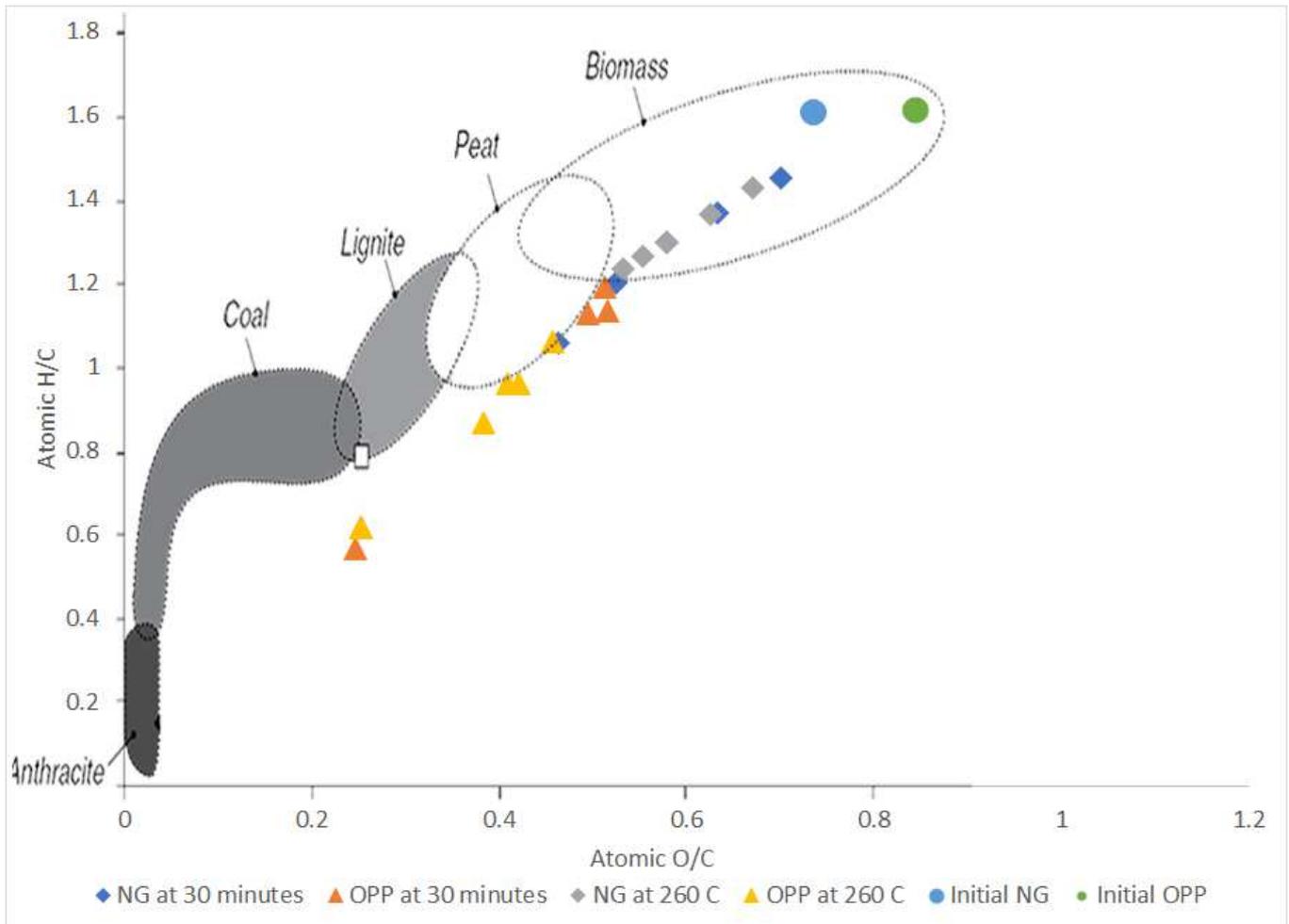
149 Figure 3: Elemental analysis at reaction temperature of 260 °C of reaction time for (a) Napier grass and  
 150 (b) oil palm petiole

151

152 The changes in the elemental content can also be visualized using atomic hydrogen-to-carbon  
 153 (H/C) ratio and oxygen-to-carbon (O/C) ratio. Generally, the H/C ratio and O/C ratio decrease significantly

154 with torrefaction from H/C of 0.135 for both biomass sample and O/C of 0.980 and 1.124 for NG and OPP  
155 respectively. The change in H/C from the initial elemental content are in the ranges of 9.6-34.24% for NG  
156 and 26-64% for OPP while change in O/C ranges from 4.8-37 % and 39-71 % for NG and OPP respectively.

157           The ratios of atomic H/C and O/C can be plotted into Van Krevelen diagram to compare the loss  
158 of hydrogen and oxygen by torrefaction. From Figure 4, the initial atomic ratio of H/C and O/C of NG and  
159 OPP is located within the biomass region as expected. The trend is showing a decline of O/C and H/C when  
160 the temperature and the reaction time rises. OPP seems to have a sharper decline in H/C and O/C where  
161 the difference from the initial is quite significant and even located outside of the biomass region. For NG,  
162 torrefaction only change the ratios slightly which the ratios of O/C and H/C for the torrefied NG still lies  
163 in the biomass region. It can also be seen that the effect of temperature is more notable than effect of  
164 reaction time. This is shown by the more widely disperse points on the Van Krevelen diagram when  
165 temperature is varied. As temperature and time increase, much more hydrogen and oxygen are released  
166 as water, leaving only more carbon in which makes them closer to coal. This observation is similar to  
167 Granados et al. (Granados et al. 2017) and Poudel et al. (Poudel et al. 2018) using poplar wood and waste  
168 wood respectively. This shows that the potential of torrefied NG is relatively low since it can be matched  
169 by other raw biomass feedstocks.



170

171

Figure 4: Van Krevelen diagram of the torrefied biomass

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173

*4.2 Moisture content and calorific value*

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The data for moisture content and calorific value are listed in Table 2 and 3. From Figure 5, it can be seen that the moisture content is inversely proportional with increasing reaction temperature and time. As the temperature increases from 220 °C to 300 °C, the moisture content decreases by 66% and 78% for Napier grass and oil palm petiole, respectively. As for the increasing reaction time from 10 minutes to 50 minutes, Napier grass loses its moisture content by 66% while oil palm petiole loses by 78%. Along

179 the increment in temperature above 200 °C, hemicellulose decomposed, C-H-O bonds are broken, and  
 180 water molecules are formed via condensation reaction. When the temperature rises above 270 °C, more  
 181 devolatilization and carbonization of hemicellulose which leads to more water molecules are released.  
 182 This is evident in the slow reduction of moisture from 220 °C to 260 °C but rapidly decline after 260 °C.

183 Table 2: The physical properties of torrefied NG and OPP at constant reaction time of 30 minutes

Temp. (°C)	Moisture content, %		Calorific value (MJ/kg)		Mass yield, %		Energy yield, %		Energy Density	
	NG	OPP	NG	OPP	NG	OPP	NG	OPP	NG	OPP
220	4.608	5.047	18.69	22.36	81.74	84.90	87.04	98.67	1.06	1.16
240	3.956	4.521	19.96	22.23	75.22	72.80	85.56	84.12	1.14	1.16
260	3.587	2.995	21.23	26.23	68.62	64.55	83.03	88.03	1.21	1.36
280	2.511	1.787	22.98	21.61	53.71	53.20	70.35	59.77	1.31	1.12
300	1.589	1.134	24.33	27.84	49.06	43.90	68.02	63.52	1.39	1.45

184

185

Table 3: The physical properties of torrefied biomass at constant reaction temperature of 260 °C

Reaction time (min)	Moisture content, %		Calorific value, (MJ/kg)		Mass yield, %		Energy yield, %		Energy Density	
	NG	OPP	NG	OPP	NG	OPP	NG	OPP	NG	OPP
10	5.571	3.683	20.57	23.45	72.19	67.25	84.61	81.97	1.17	1.22
20	4.826	3.439	20.80	24.14	70.34	65.40	83.37	82.08	1.19	1.26
30	3.587	2.995	21.23	26.23	68.62	64.55	83.03	88.03	1.21	1.36
40	2.982	2.717	21.76	25.15	65.31	62.90	81.00	82.23	1.24	1.31
50	2.075	2.515	22.32	22.28	60.57	61.05	77.05	70.70	1.27	1.16

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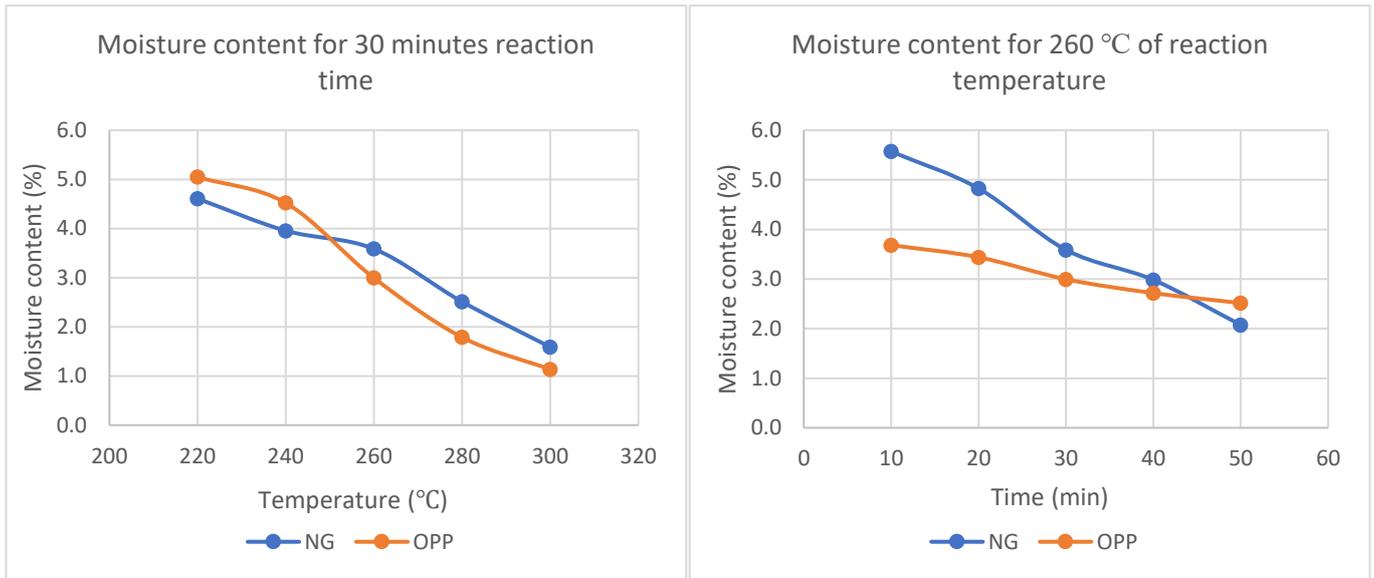
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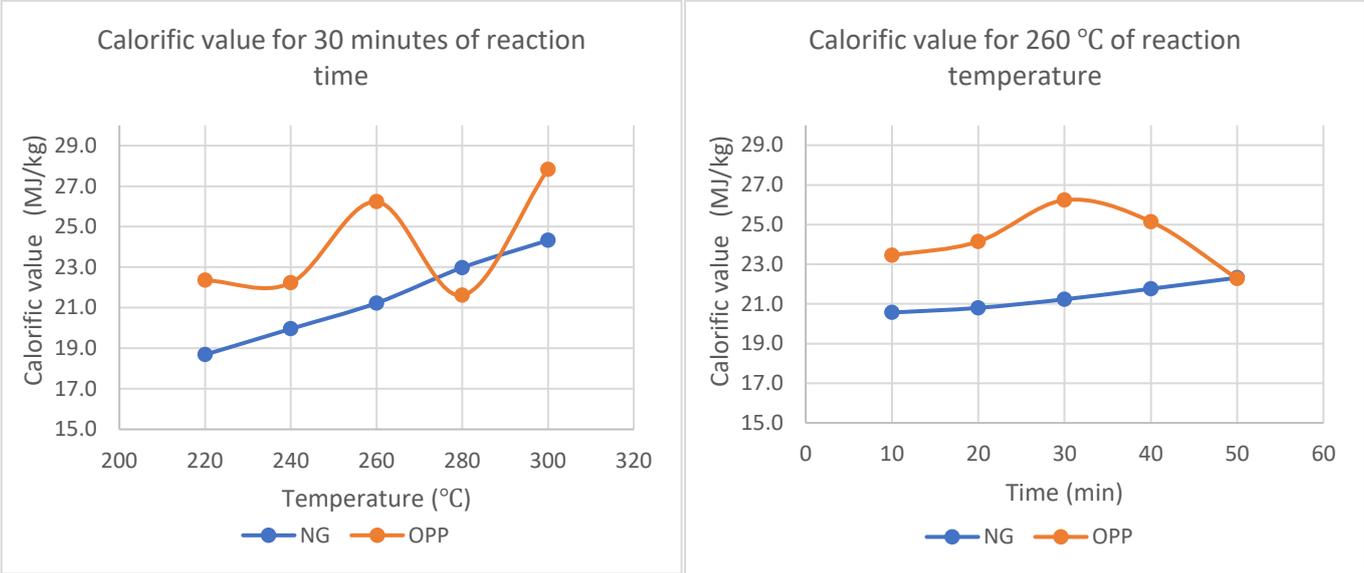
After the torrefaction process is done, hydroxyl groups are destroyed, preventing the formation of hydrogen bonding which makes the torrefied biomass to be more hydrophobic. This hydrophobicity effect is likely due to the hydroxyl group removal and formation of micropores on the surface as reported by Chen et al. (Chen et al. 2014). The reduction in moisture content was also attributed by tar condensation within the torrefied biomass which also prevent moisture absorption as reported by Felfli et al (Felfli et al. 2005). Similar effect can also be found when other biomasses are used such as Marula seeds, blue gum wood (Mamvura et al. 2018) and rice husk (Chen et al. 2012).



194  
 195 Figure 5: Moisture content (a) against temperature at constant reaction time of 30 minutes and (b)  
 196 against reaction time at constant temperature of 260 °C

197  
 198 The main objective of torrefaction is to enhance the CV of biomass for it to be suitable as fossil  
 199 fuel co-firing as well as an alternative. For NG, the CV increases almost linearly with the two process  
 200 variables, but the increment is not the same for OPP where its value varies with increasing temperature  
 201 and time. The maximum CV occur after 30 minutes of torrefaction in 300 °C which is 24.33 MJ/kg and  
 202 27.84 MJ/kg for NG and OPP, respectively as shown in Figure 6. Torrefied OPP has higher CV except at 280  
 203 °C where the value for OPP fell to around 22.61 MJ/kg as compared to NG having 22.98 MJ/kg. The value  
 204 for CV in OPP increases with reaction time achieving maximum at 30 minutes and then decreases  
 205 gradually. A similar trend was also found by Baskoti et al. in which attributed to the release of carbon  
 206 content after long exposure to high temperature (Baskoti et al. 2018). With reduction of O atoms, the  
 207 calorific value increase since it can inefficiently affect the combustion and energy release property of  
 208 samples. From the two process conditions, the temperature seems to have the prominent effect. Since

209 OPP generally has higher CV than NG, it shows its potential to be further process to be a viable fuel source.  
210 Table 4 compares the results obtained to indicative commercial solid fuels.



211  
212 Figure 6: Calorific value of torrefied biomasses (a) against temperature at constant reaction time of 30  
213 minutes and (b) against reaction time at constant temperature of 260 °C

Table 4: Comparison of properties of our results with indicative fuels (Sun et al. 2012)

	Torrefied NG*	Torrefied OPP*	Charcoal	Coal	Wood pellets
Moisture content (%)	1.59-5.57	1.13-5.05	1-5	10-15	7-10
Calorific value (MJ/kg)	18.7-24.3	21.6-26.2	30-32	23-28	15-16

\*this study

#### 4.3 Mass yield, energy yield and energy density

The obtained results for mass yield, energy yield and energy density are reported in Table 2 and Table 3. For a fixed torrefaction reaction time, it can be seen that the mass and energy yield consistently decrease with increasing temperature. The mass loss for Napier grass is slightly less than OPP by about 40% from the lowest temperature while OPP loses its mass by 48% from the lowest temperature as shown in Figure 7. This can be attributed to the degradation and decomposition of hemicellulose in which normally occurred starting from 255 °C (Getabelew et al. 2018). At temperature higher than 255 °C, most of the components that still exist would be lignin since they are the most thermally stable component. According to Chen and Kuo (Chen and Kuo 2011), within the torrefaction temperature ranges, hemicellulose and the residue of cellulose are the major degraded components while lignin would only be affected slightly. Within this temperature range, the hemicellulose will undergo devolatilization and carbonization process. This resulted in tremendous decrease of solid mass yield. Cheng et al. (Cheng et al. 2019) have also proved there is an increment in torrefaction rate with increasing temperature using wheat straw as the feedstock. Similarly, the prolonged reaction time causes greater amount of hemicellulose to be degraded, allowing more devolatilization of component and therefore producing larger mass loss.

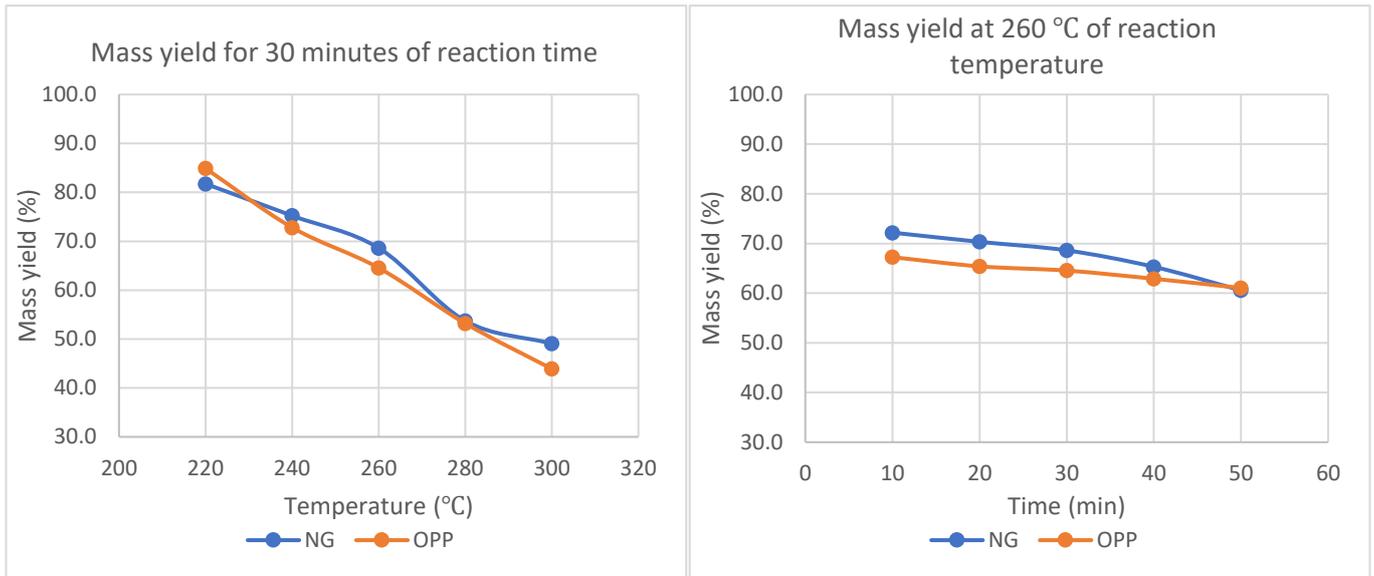


Figure 7: Mass yield (a) against temperature at constant reaction time of 30 minutes and (b) against reaction time at constant temperature of 260 °C

Energy yield is defined as the energy remained after the torrefaction process. From Figure 8, energy yield decreases generally when both variables increase but the reaction temperature causes a more prominent effect. The reaction time causes a significant decrease of about 21.9 % as compared to 8.9 % for NG and 35.6% as compared to 13.7% for OPP. This is due to the decomposition of hemicellulose as well as condensation reaction at these temperatures. During the process, oxygen and hydrogen is released in form of H<sub>2</sub>O molecules, and energy content is preserved in the lipids and organic compounds.

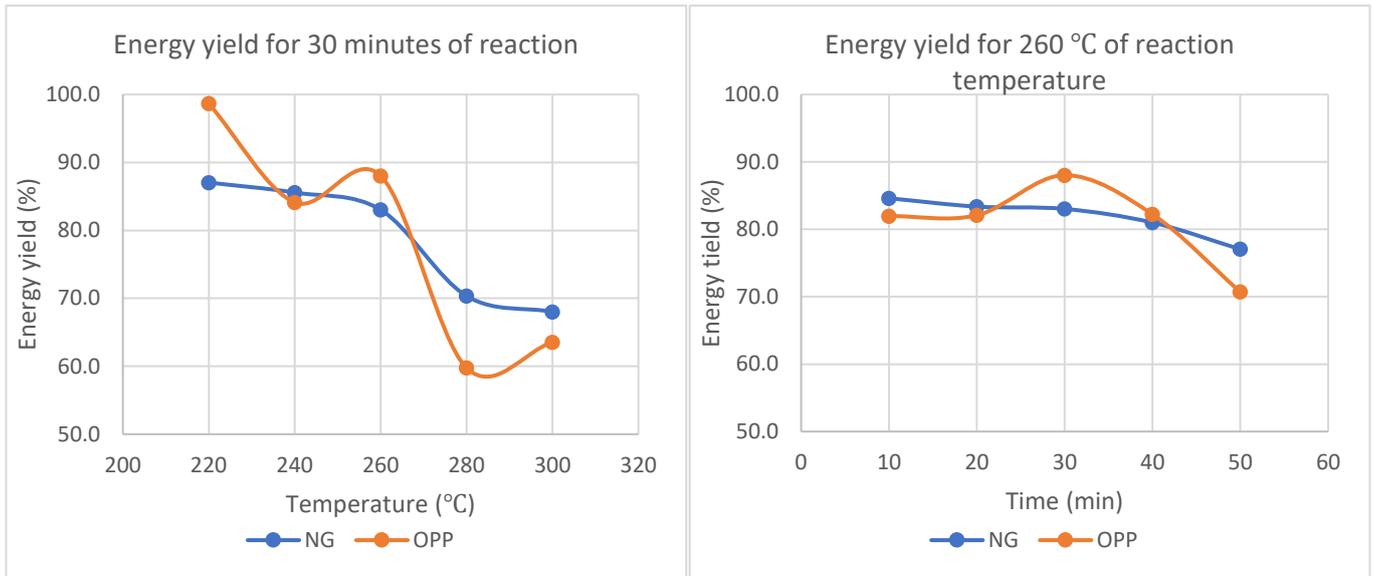
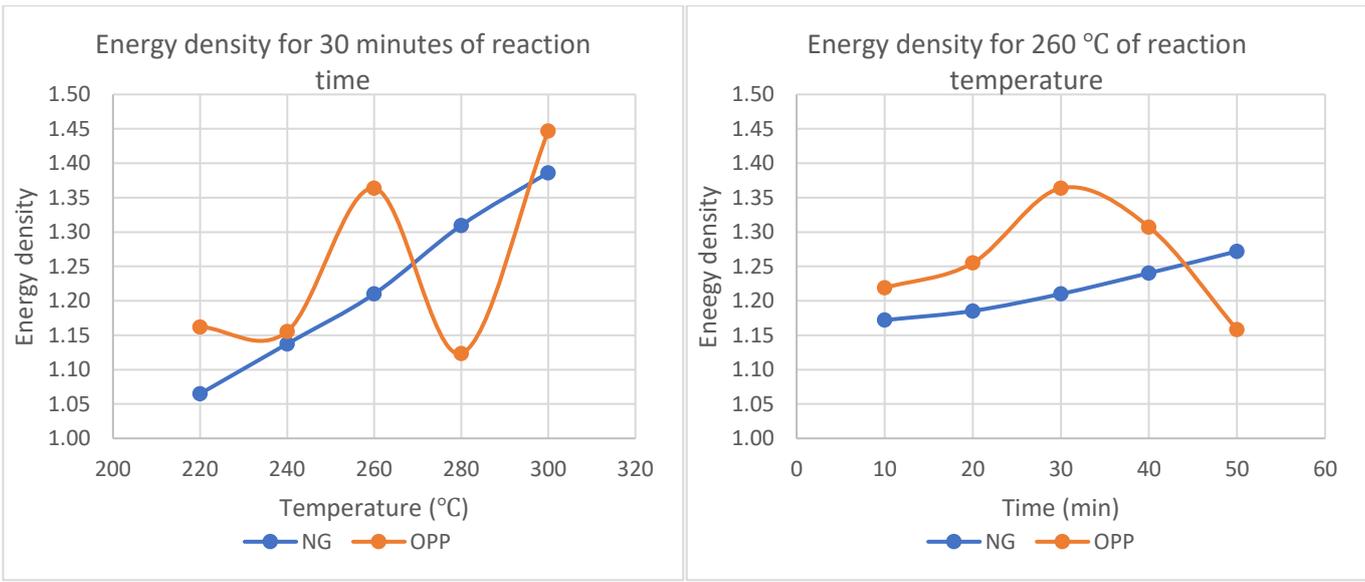


Figure 8: Energy yield (a) against temperature at constant reaction time of 30 minutes and (b) against reaction time at constant temperature of 260 °C

From Figure 9, the energy density for NG increases steadily with reaction temperature and reaction time. For OPP, as the temperature and reaction time increases, the energy density increases linearly but after reaches 30 minutes, the value drops. As written in literature, the energy density is supposed to increase with rising temperature (Chen et al. 2015). This is due to the moisture and volatile matter being released but the fixed carbon and ash remains in the torrefied biomass. The increment in the energy density may be attributed to the more significant decrease in mass yield.

Based on the results of the yields and energy density, there is a need for optimization of parameters on torrefaction to obtain the optimal condition. Although higher energy density is desired, the amount of usable end product must also be maximized for it to be industrially feasible. It is found that the optimal time would be at 30 minutes where the energy density is relatively high while also obtaining

255 a more significant amount of product mass. This result is comparable with result from Mamvura et. al  
256 (Mamvura et al. 2018). The optimized temperature would be 260 °C in which mass yield is substantial  
257 while also having high energy density. This is also supported by Batidzirai et al. which mentioned that mild  
258 torrefaction is more preferable optimal conditions according to its higher heating value, cost-effectiveness  
259 and adequate improvement on biomass characteristics (Batidzirai et al. 2013).



260

261 Figure 9: Energy density (a) against temperature at constant reaction time of 30 minutes and (b) against  
262 reaction time at constant temperature of 260 °C

#### 4.4 Using pyrolyzer for torrefaction

As mentioned by Chen et al. (Chen et al. 2021), torrefaction is considered as mild pyrolysis but using lower range of temperature and with the purpose of upgrading biomass into coal-like material. Since these two technologies shared similar properties, the same equipment can be used for both processes. Similar results can also be obtained from Mamvura et al (Mamvura et al. 2018) where usage of tube furnace was employed to do torrefaction process onto marula seeds and blue gum wood and resulted in 275 °C and 20 minutes. Almost similar results were found by Bridgeman et al. using reed canary grass, wheat straw and willow using torrefaction reactor.

Torrefaction is considered to be one of the pretreatment methods for production of bio-oil from pyrolysis reaction. By using pyrolyzer for torrefaction, there is no need for additional step between the two process. By doing so, it eliminates the need for re-purging the reaction chamber with gases. This can possibly lead to energy, time and cost saving when the same reactor is used for both processes. Winjobi et al. has proven that employing torrefaction before a fast pyrolysis does not add up to the bio-oil production cost when net present value is zero (Winjobi et al. 2016) which supported the reason for using the same reactor for both process.

The only drawback of using pyrolyzer as torrefaction reactor is the need for modification to accommodate the temperature and heating rate in accordance to torrefaction properties. Since torrefaction occur at temperature lower than pyrolysis, the reactor has to be fitted in order to maintain the temperature range. Despite this, modification onto pyrolyzer is fairly minor to be upgraded as compared to the purchasing cost of torrefaction reactor. The scale-up cost for industrial use is speculated to be not severe since only temperature and heating control must be upgraded.

## 5. Conclusions

Adding value into biomass to serve as raw material for end-uses application including fuel production has been the focus towards renewable and sustainable energy. Therefore, the feasibility of torrefaction to upgrade biomass properties as a feedstock has been evaluated. In this study, torrefaction of Napier grass and oil palm petiole with varying reaction temperature and time is exhibited. The elemental analysis has shown that the reduction of hydrogen and oxygen while carbon content seems to be preserved with the increasing temperature and time. As compared with other feedstock from Van Krevelen diagram, it is found that the torrefaction decreases the oxygen and more notably, the hydrogen. With increasing temperature and time, moisture content was significantly reduced, making the torrefied biomass to be more hydrophobic. The calorific values increase linearly for NG reaching maximum of 24.33 MJ/kg at 300 °C and 30 minutes. As for OPP, the value varies with temperature where it increases until 260 °C, go down and up again by 300 °C while the torrefied OPP's calorific value reaches maximum 30 minutes reaction before decrease gradually as time increases. Mass yield and energy yield after torrefaction also decreases steadily but more prominent effect can be seen with varying temperature. The energy density of the torrefied NG increase linearly with both conditions. For OPP, the energy density increases but drops at 280 °C and rise again to maximum of 1.45 at 300 °C while with increasing time, the energy density increases to a maximum of 1.36 at 260 °C followed by gradual decline. This study shows that torrefaction can be used as biomass treatment to enhance its fuel properties. Generally, temperature has more pronounced effect where the degradation of structure is more severe. Higher temperature seems to produce better physicochemical properties but also returning low yields, therefore optimization is needed to maximize the advantages. There is a need for optimization using both temperature and time which resulting to be optimized temperature and residence time are 260 °C and 30 minutes respectively.

306 Usage of pyrolysis reactor for torrefaction is feasible as the retrieved products exhibited properties of  
307 expected and predicted torrefied samples.

## 308 **6. Abbreviations**

CHNS analyzer	Carbon-hydrogen-nitrogen-sulfur analyzer
CHNS contents	Carbon-hydrogen-nitrogen-sulfur contents
CV	Calorific value
H/C ratio	Hydrogen-to-carbon ratio
NG	Napier grass
O/C ratio	Oxygen-to-carbon ratio
OPP	Oil Palm Petiole

309

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314 **8. Ethics declarations**

315 *8.1 Ethics approval and consent to participate*

316 Not applicable.

317 *8.2 Consent for publication*

318 Not applicable.

319 *8.3 Competing interests*

320 Not applicable.

321 *8.4 Availability of data and materials*

322 All the datasets obtained in this study are included in this article.

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### 10.2 Authors' contributions

SZAHS involved in data curation, writing and edit the manuscript. NBO contributed in conceptualization, methodology, supervision, validation, writing and editing the manuscript. MD and LSE contributed in data collection, data curation and writing original draft. All authors. All authors contributed significantly and have approved the final manuscript

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# Figures

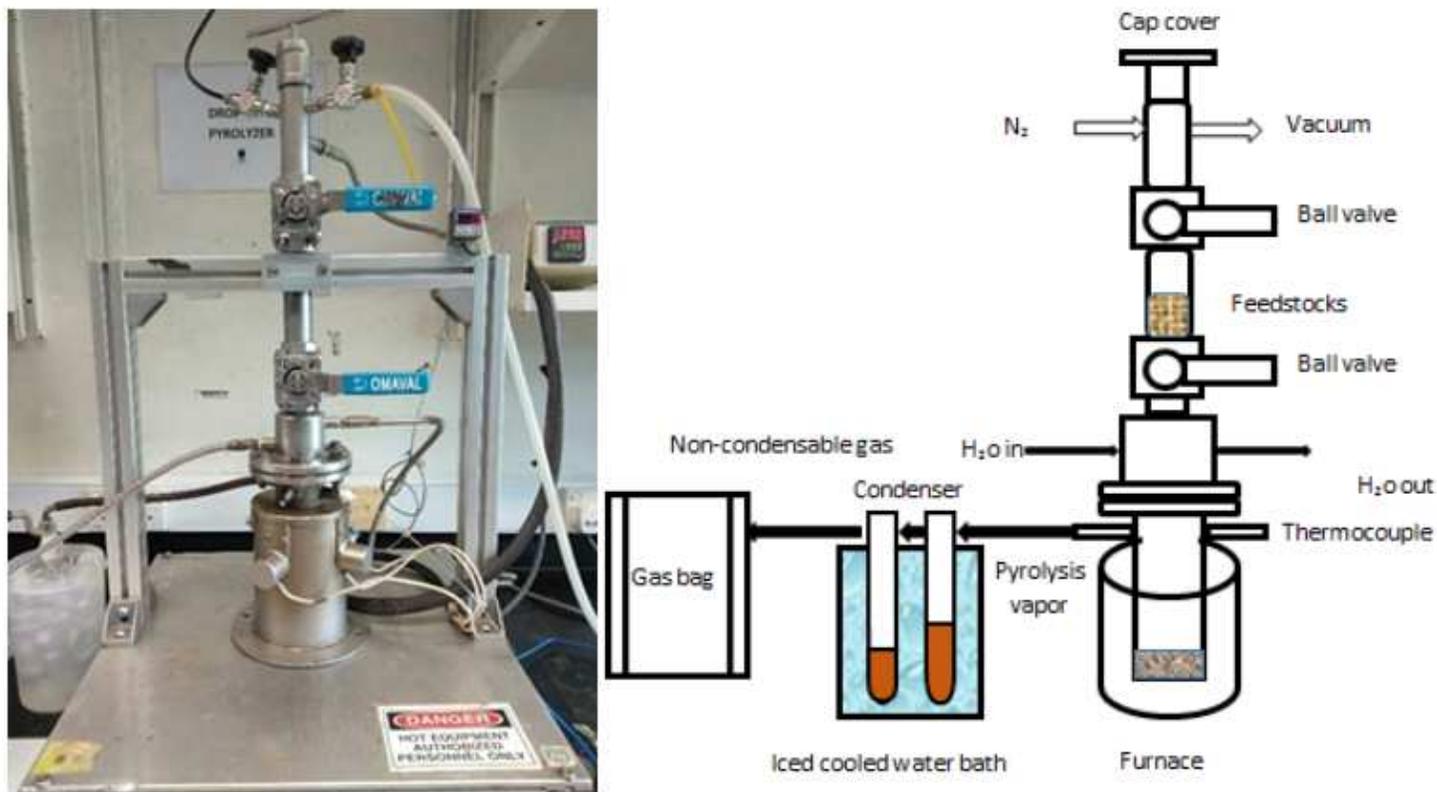
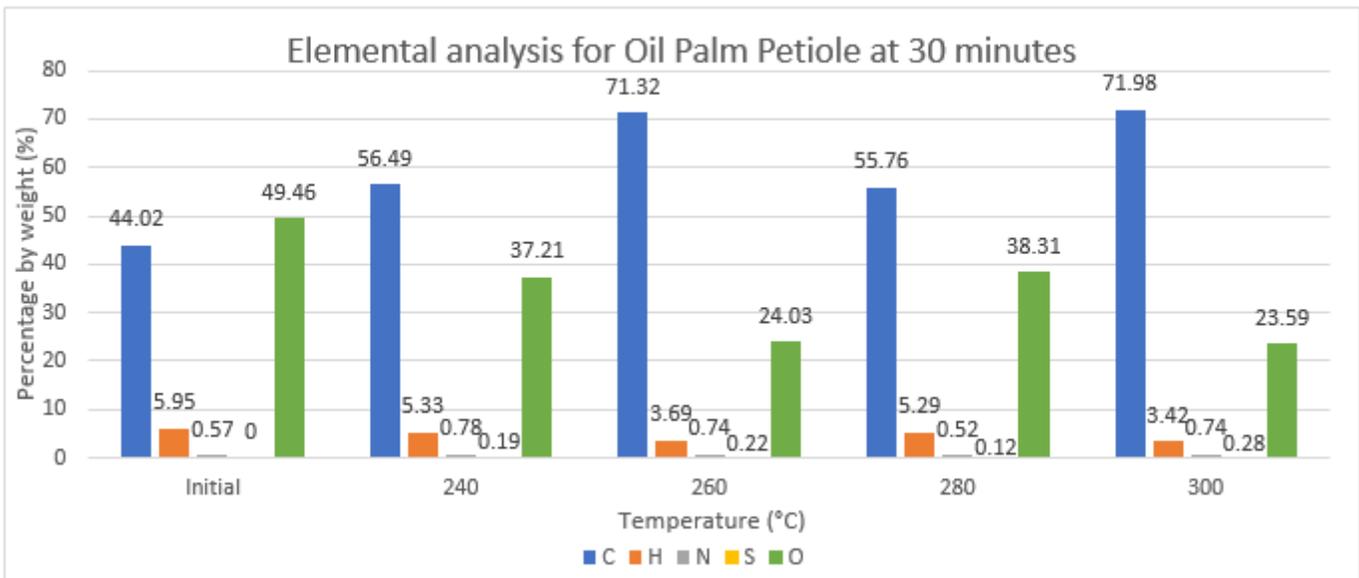
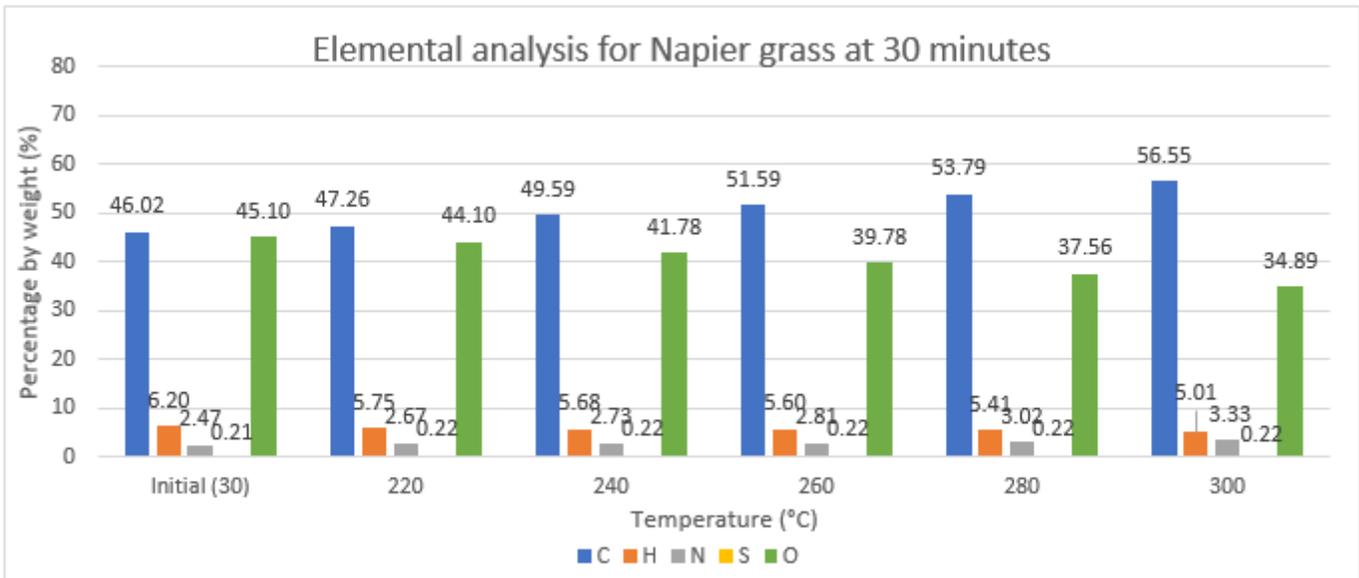


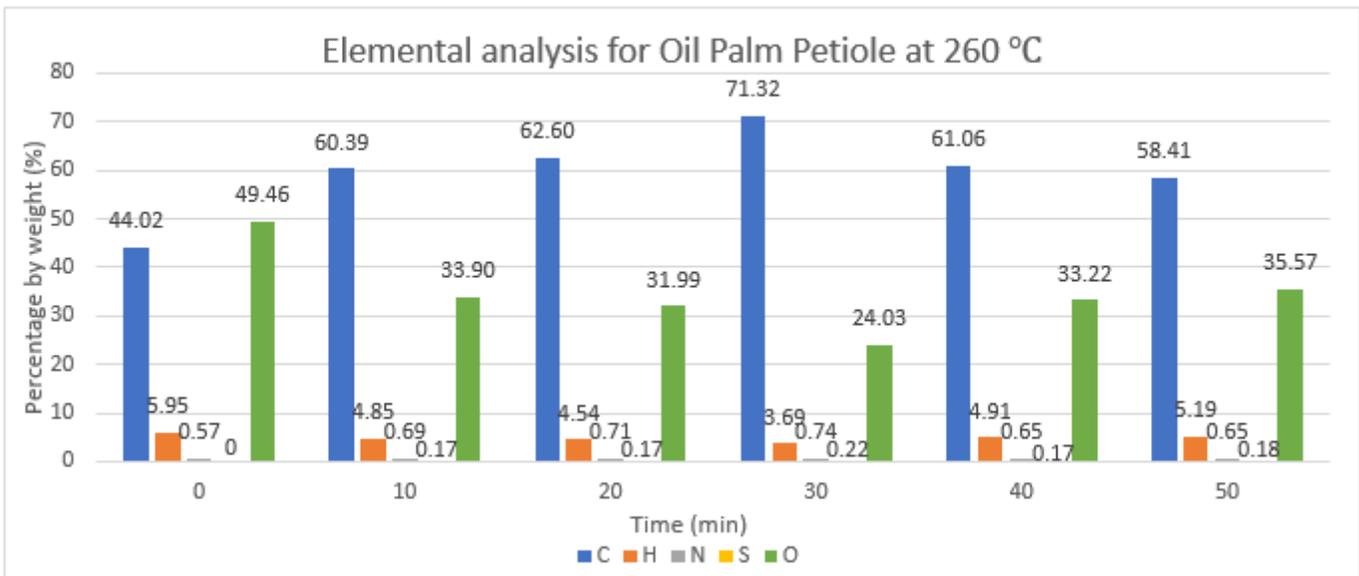
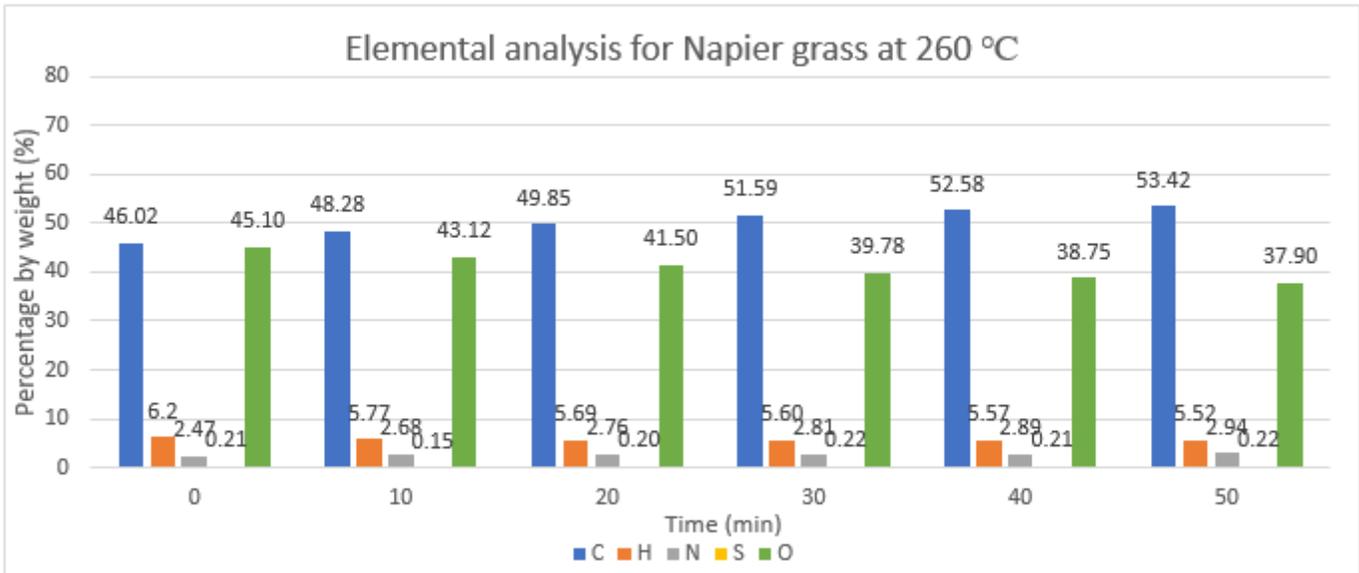
Figure 1

(a) Fixed-bed pyrolyzer used for the torrefaction process, (b) Schematic Diagram of torrefaction experiment in fixed bed drop-type pyrolyzer



**Figure 2**

Elemental analysis at reaction time of 30 minutes for (a) Napier grass and (b) oil palm petiole



**Figure 3**

Elemental analysis at reaction temperature of 260 °C of reaction time for (a) Napier grass and (b) oil palm petiole

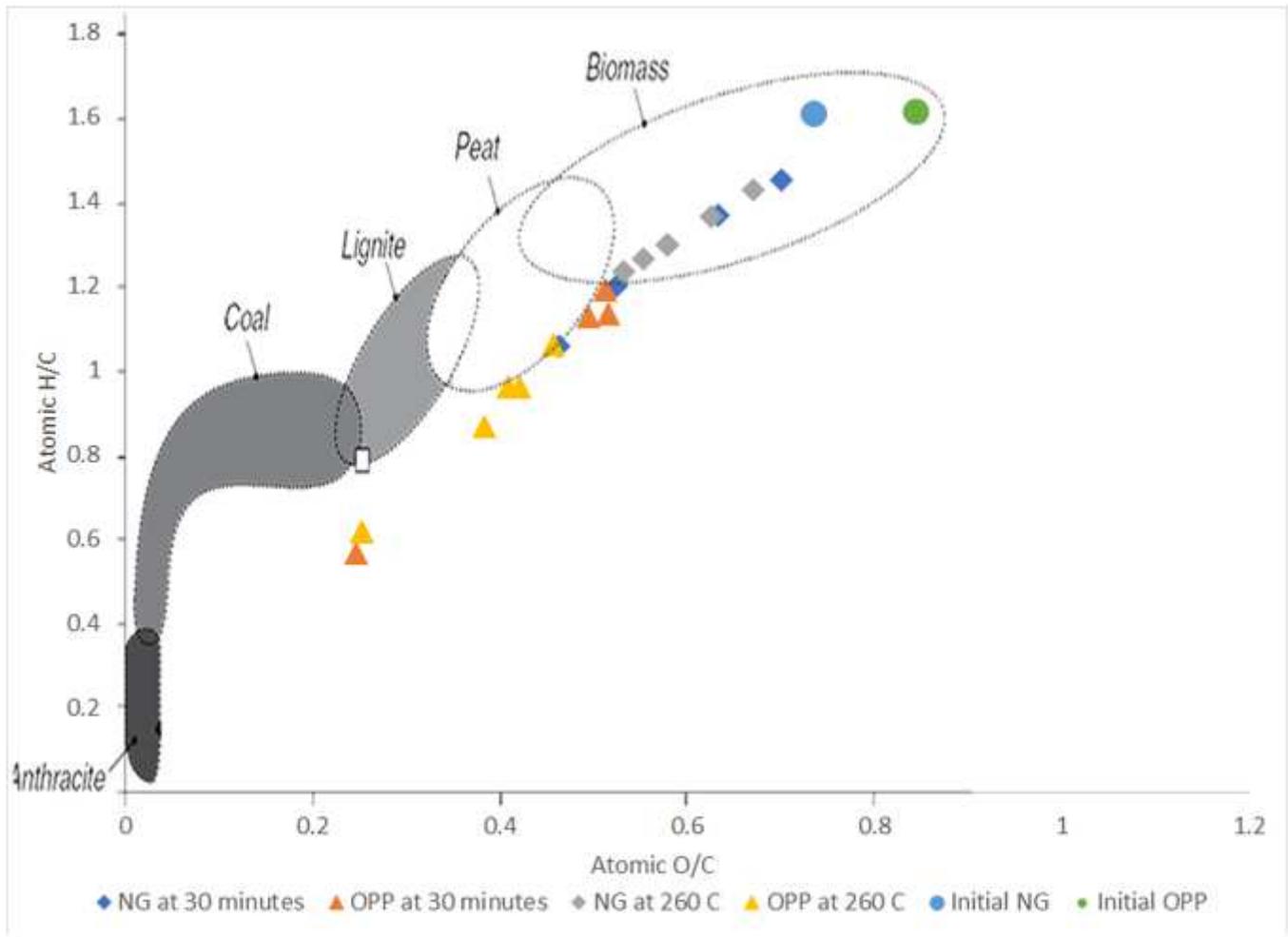
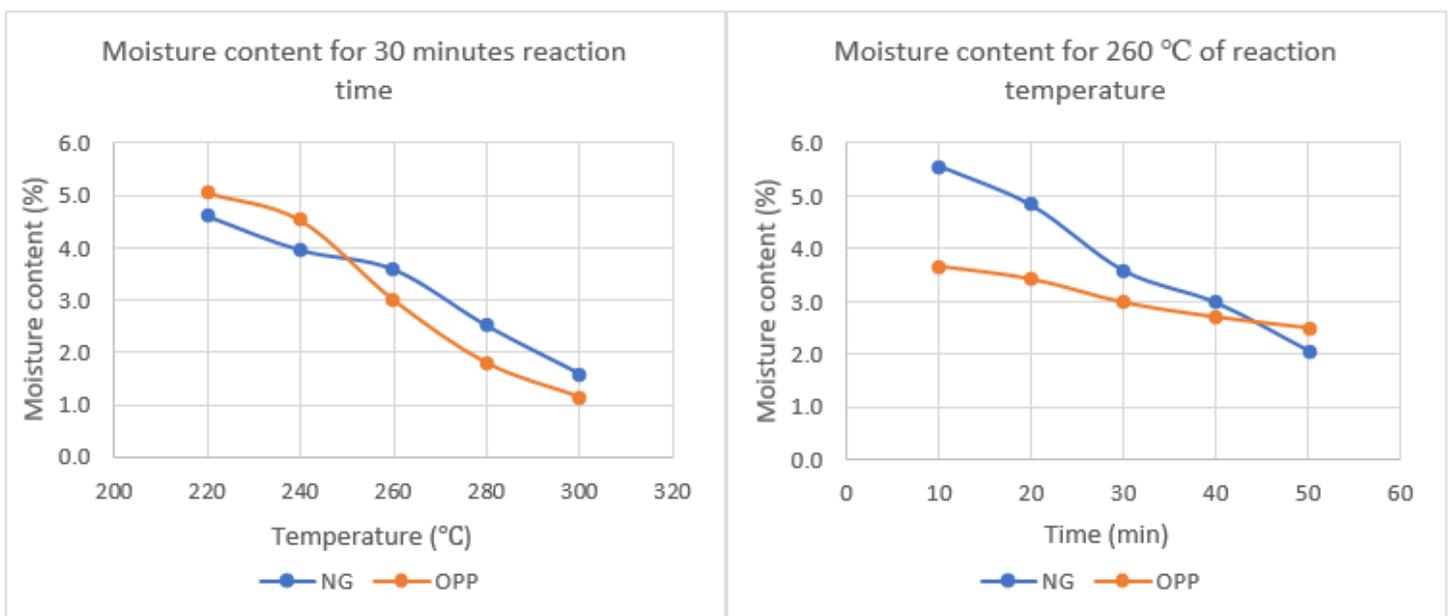


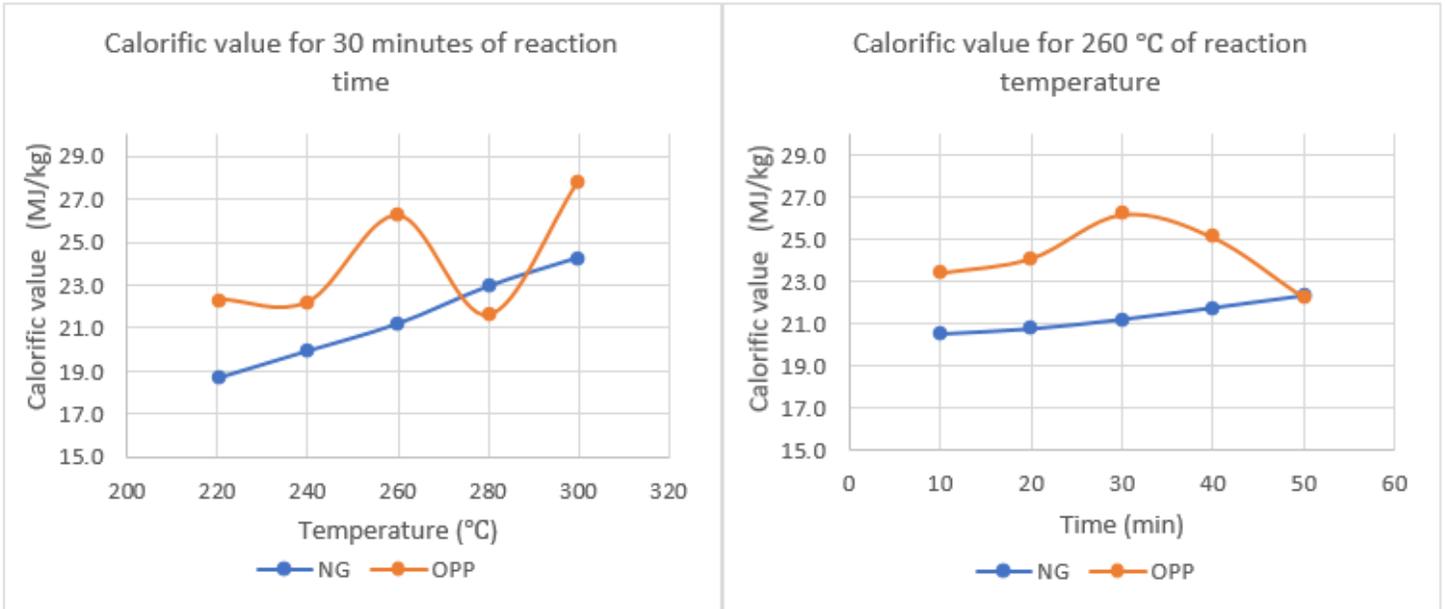
Figure 4

Van Krevelen diagram of the torrefied biomass



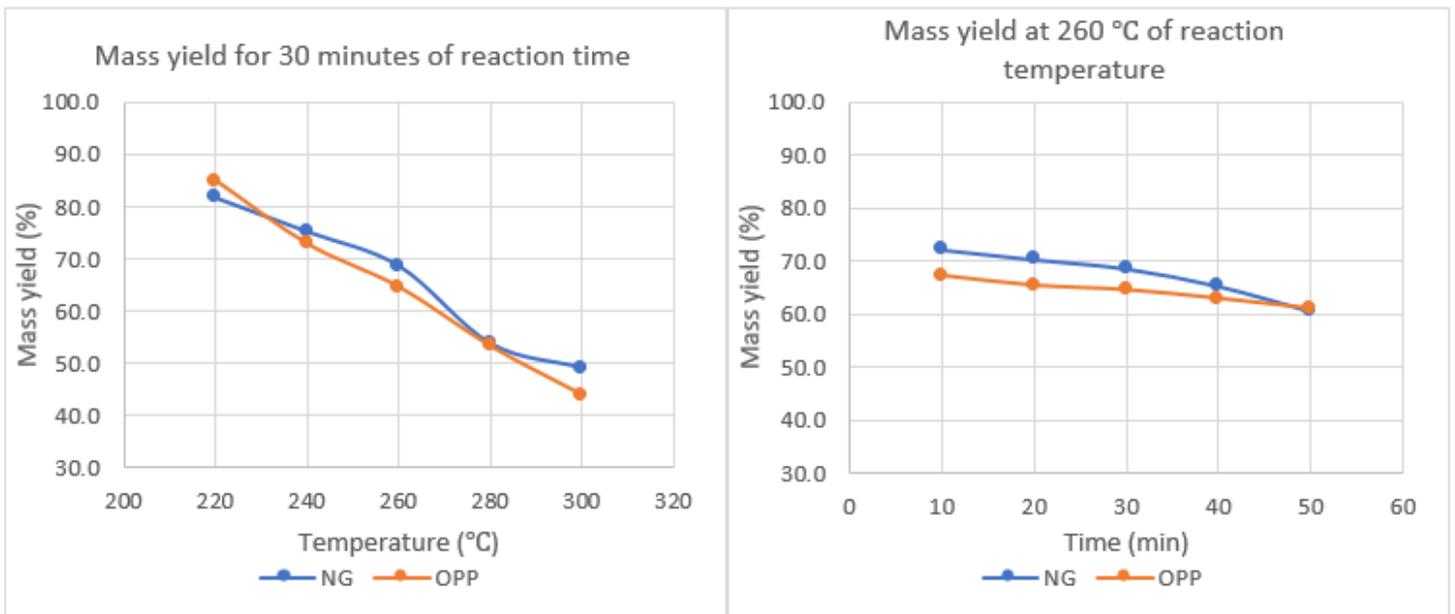
**Figure 5**

Moisture content (a) against temperature at constant reaction time of 30 minutes and (b) against reaction time at constant temperature of 260 °C



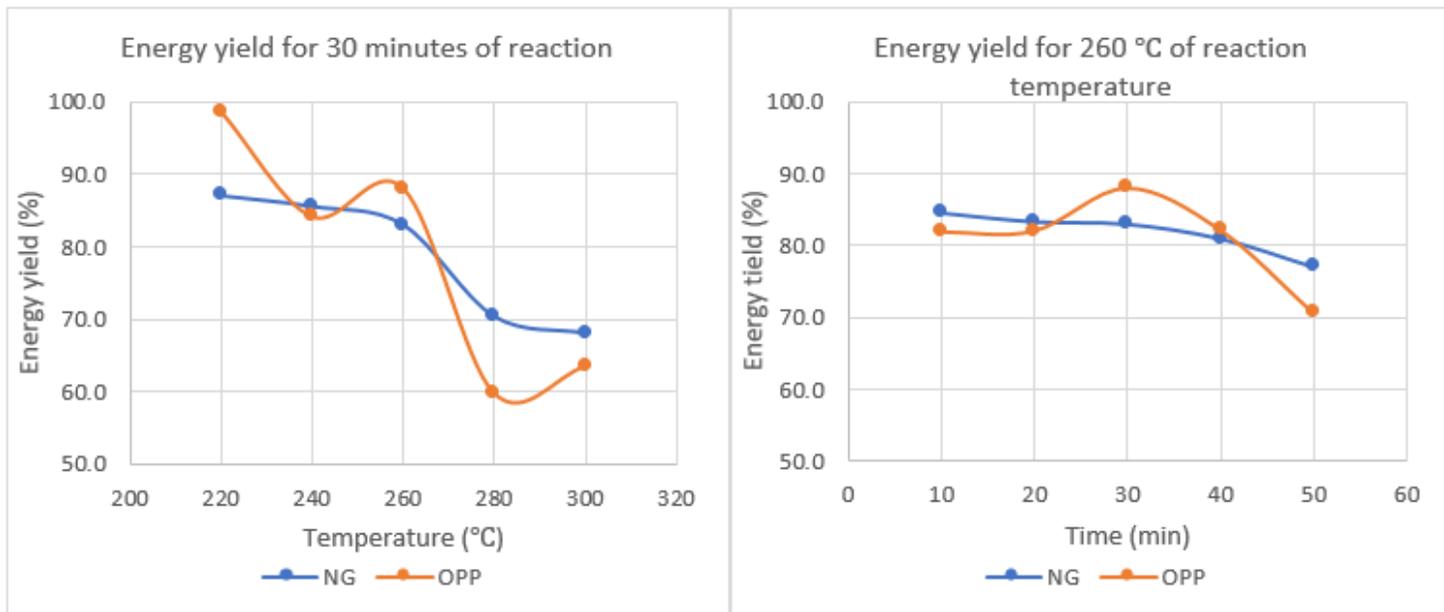
**Figure 6**

Calorific value of torrefied biomasses (a) against temperature at constant reaction time of 30 minutes and (b) against reaction time at constant temperature of 260 °C



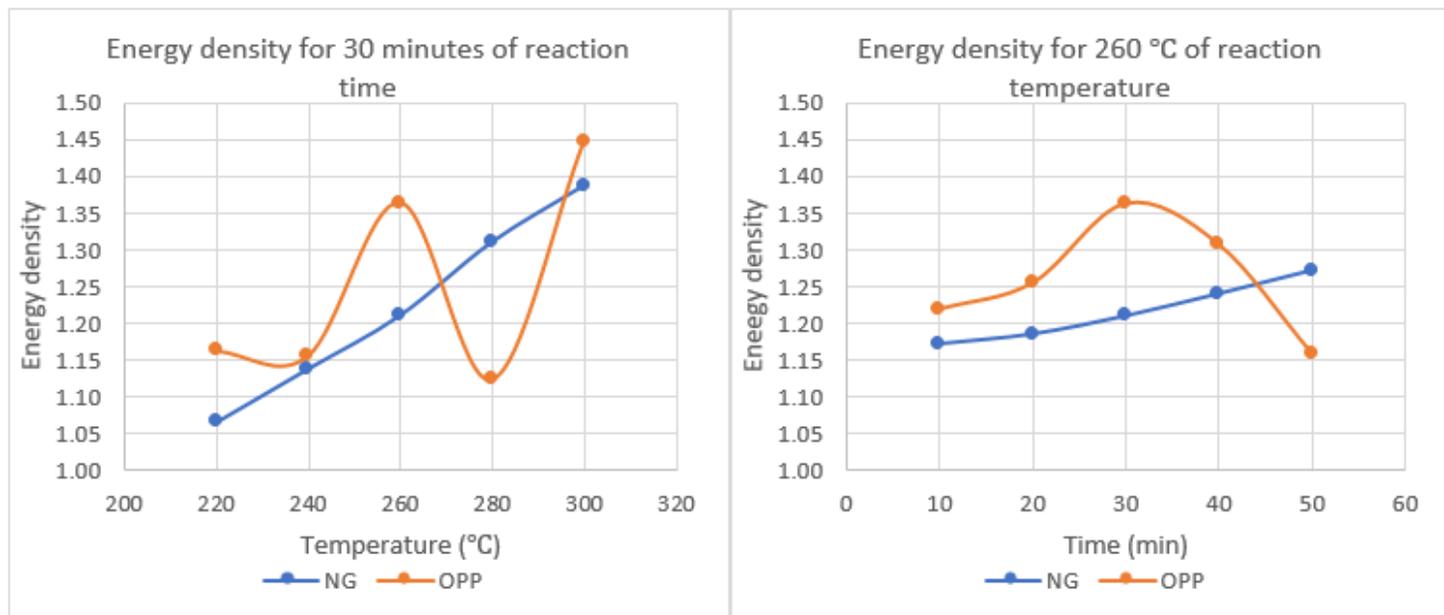
**Figure 7**

Mass yield (a) against temperature at constant reaction time of 30 minutes and (b) against reaction time at constant temperature of 260 °C



**Figure 8**

Energy yield (a) against temperature at constant reaction time of 30 minutes and (b) against reaction time at constant temperature of 260 °C



**Figure 9**

Energy density (a) against temperature at constant reaction time of 30 minutes and (b) against reaction time at constant temperature of 260 °C

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