

# Characterisation and Co-pyrolytic Degradation of the Sawdust and Waste Tyre Blends to Study the Effect of Temperature on the Yield of the Products

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## Abstract

The present study aimed to determine the effect of co-pyrolysis of sawdust biomass and scrap tyre waste employing different blending ratios of sawdust to waste tyre such as 100:0, 75:25, 50:50, 25:75, and 0:100. The thermochemical characterization of feedstocks was carried out by employing the proximate, ultimate analysis, and thermogravimetric (TGA) analyses, calorific values, and scanning electron microscope coupled with energy dispersive x-ray analysis (SEM-EDX) to select the blending ratio having better bioenergy potential amongst the studied ratios. The blending ratio of 25:75 (sawdust to waste tyre) was selected for the co-pyrolysis study in a fixed-bed pyrolysis reactor system based on its solid biofuels properties such as heating value (30.18 MJ/kg), and carbon (71.81 wt%) and volatile matter (63.82 wt%) contents. The pyrolysis temperatures were varied as 500, 600 and 700 °C while the other parameters such as heating rate and nitrogen flowrate were maintained at 30 °C/min and 0.5 L/min respectively. The bio-oil yields as 31.9, 47.1 and 61.2 wt%, bio-char yields as 34.5, 34.2 and 31.4 wt% and gaseous product yields as 33.6, 18.60 and 7.3 wt% at the pyrolysis temperatures of 500, 600 and 700 °C respectively were obtained. The blends of sawdust and waste tyres showed the improved energy characteristics which could provide the solution for the beneficial management of sawdust and scrape tyre wastes via co-pyrolysis processing.

**Keywords:** Thermochemical characterisation, Co-pyrolysis, Sawdust, Waste tyre, Blending ratio

## 1. Introduction

The high demand for energy produced from the burning of fossil fuels causes fossil fuels to be depleted[1,2]. Currently, the primary energy sources come from fossil fuels. According to the Energy Information Administration, the worldwide demand for natural resources revealed a growing trend from year to year at a stage where the petroleum needs will rise by 35% in 2025[3]. However, the combustion of fossil fuels imparts negative impacts on the environment[4]. During the combustion, carbon dioxide and other flue gases are released and these gases are considered to be the major contributors to global warming, ozone depletion and environmental pollution[5,6].

From these consequences, the researchers expanded their research to find renewable energy sources to reduce the dependency on fossil fuels and cope with environmental issues. There are various sources of renewable energy existing to substitute the fossil resources such as biomass, solar, geothermal, hydropower and tidal energy[7-10]. Over the

past three centuries, more than half of worldwide studies have focused the biomass energy, followed by the energy from solar resources, energy from tidal resources, energy from geothermal, and hydro energy [11,12]. Biomass, an abundant source is obtained from organic resources and living beings. The potential of available biomass is projected to be equivalent to the  $1.08 \times 10^{11}$  TOE per year, nearly 10 folds to the existing over-all demand of energy worldwide[13-15]. Biomass is ranked fourth with the estimated contribution of 14% of the energy requirements[16-18]. Moreover, biomass is considered to be CO<sub>2</sub> (carbon dioxide) neutral with a low sulfur content making it as an important renewable alternative energy resource[19]. Besides, the utilisation of biomass can help the countries vastly dependent on the fossil fuels to meet their needs such as it can help to meet the Brunei Vision 2035 to achieve the renewable energy goals[20].

The sawdust (SD) is a type of biomass, produced during the cutting, trimming, edging, re-sawing, and smooth out of wood, and approximately 12~25 kg of sawdust is produced through the processing of 100 kg wood in a sawmill[21]. In most of the cases, because of lack of better approaches to handle waste, the sawdust is usually thrown away into the environment without being treated[21]. Typical disposal processes for the sawdust include the direct combustion, throwing away along side the roads and water bodies and piling up at the mill

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sites[21]. Abandonment of sawdust results in aesthetic impacts and affects the air quality as the wind blows and mixes the wood dirt into the air[21]. Air pollution and respiratory problems in humans can be the consequences of this habit.

Likewise, scrape tyre (WT) is the other waste being produced at large quantities. In 2012, approximately 17 million tons of tyre (2.8 million tyres) were manufactured worldwide[22,23]. Around 64% of the waste tyres are abandoned to the landfills where only 13% of these tyres are recycled[24,25]. Tyres are made up of several rubbers (60–65 wt%), classified as the synthetic rubber, natural rubber, and carbon black (25–35 wt%) including the additives and fillers[26]. A high amount of rubber in the tyre made it to be resistant to wear and corrosion because tyres are needed to be non-biodegradable, consist of non-melting thermoset polymer[27]. Hence, waste tyres occupying landfill space and are difficult to be recycled[28]. The stockpiles tyres create a breeding place for vermin and mosquitoes which results in diseases that can affect human health, such as dengue and may provoke uncontrollable burning that eventually results in air pollution[28].

Pyrolysis process has been recognised as a promising technology to recover energy from biomass and wastes resources. Co-pyrolysis is carried out in a similar way to the pyrolysis, but in co-pyrolysis, it involves the use of two or more materials to be mixed as feedstock. The problems imminent from the sawdust and waste tyre can be tackled by employing the co-pyrolysis process. This process is considered as advantageous and effective waste management tool which has the potential to considerably utilise the wastes as feedstock to produce biofuels and value-added products. Various environmental issues can also be solved by employing this technology and it can help in achieving energy security for the future[29-33].

Previous studies have focused the co-pyrolysis of various feedstock in fixed-bed reactors, micro-reactors and thermos-balances[34-41]. Shah *et al.*[42], studied the effect of adding waste tyre to cotton stalk in a fixed bed reactor with different blending ratios and concluded that the gas yields decreased from 35.4 to 18.4 wt% as the amount of waste tyre was increased. Moreover, adding the waste tyre in the blends increased the liquid yield from 35 to 48.1 wt% for the CS/WT (4 : 1) to CS/WT (2 : 3). Cao *et al.*[34], studied the co-pyrolysis of wood biomass and waste tyre using SBA-15, MCM-41 and HZSM-5 catalysts. Farooq *et al.*[35], investigated the effects of adding waste tyre to wheat straw at various blending ratios. When waste tyre addition was 20, 40, 60 and 100%, the liquid yields increased from 35 to 44 wt% and char yields also increased from 31.8 to 37.6 wt% respectively. However, the gas yields were decreased from 33.2 to 18.4 wt% after the waste tyre was added. Hossain *et al.*[36], reported the co-pyrolysis of rice husk with waste tyre and concluded that as the waste tyre in the blend increased, the liquid yield also increased. Uçar and Karagöz[43], studied the co-pyrolysis of pine nut-shells with scrap tyres at a temperature of 500 °C. As a result, the yields of gas and bio-oil increased when the ratio of scrap tyres was increased in the feedstock. The present study aimed at the investigation of detailed thermochemical characterization of the different sawdust and waste tyre blends to analyse the effect of blending on the thermochemical properties and to select the blend hav-

ing the optimum properties to use as the feedstock of co-pyrolysis study in a fixed bed reactor. The pyrolytic and oxidative degradation behavior of all the sawdust and waste tyre blends was studied with the help of thermogravimetric analyses (TGA and DTG) analysis. The fixed bed reactor was selected because of its economical design and ease of operation to study the effects of the pyrolysis temperatures on the yields of products. The study is expected provide a beneficial management solution to the sawdust and scrape tyres wastes to contribute for the renewable energy production.

## 2. Methodology

### 2.1. Samples collections and preparations

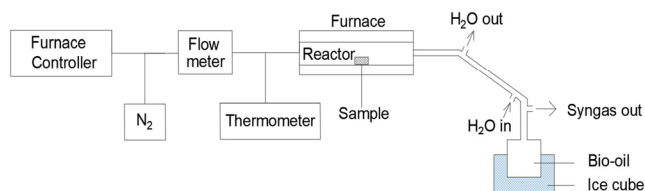
The biomass used in this study was sawdust (SD) collected from the furniture making facility, Masnor Sawmill, Lamunin, Tutong, Brunei. The scrape tyre (WT) waste samples were collected from the Bukit Udal Recovery Centre, Tutong. The samples were crushed and sieved through the 60 mesh no screen (250 µm) before conducting the analysis and both the samples were reduced to the size of less than 1 cm for the pyrolysis experiment. Both the sawdust and waste tyre were dried for 1h at the temperature of 55 °C before pyrolysis experiments to remove the free moisture. Then, these samples were divided into 5 different blends based on the ratio of SD/WT by keeping the blending ratios of 100/0, 75/25, 50/50, 25/75 and 0/100. These samples were then packed separately and sealed tightly in the plastic bags to avoid the contamination and mixing of the samples.

### 2.2. Characterisation of samples

The characterisation of samples is a very important step to determine their suitability for pyrolysis and to understand the properties of the samples. The proximate analysis included to find the moisture, volatile matter, fixed carbon and ash content in the SD and WT samples. The moisture content, volatile matter and ash content were analyzed following the standard procedures while the fixed carbon content was calculated by subtracting the sum of moisture contents, volatile matter and ash with 100. The Flash 2000-Ultimate analyzer from Thermo Quest Scientific, Italy was used to determine the percentage of C, H, N and S contents while the O content was calculated by subtracting the sum of C, H, N and S from 100. A bomb calorimeter by P. A. Hilton (UK) was employed to find the calorific values of both of the samples. TGA7 TGA analyzer from Perkin Elmer, USA was employed to test the TGA and DTG analyses of the samples. To ensure the inert atmosphere, continuous supply of nitrogen gas was maintained. The analysis was conducted by ramping the heating at 30 °C/min and the samples were heated from 50 to 900 °C. The feedstock degradation curves were investigated further to obtain the thermal degradation patterns of samples under pyrolysis process and determine the suitable temperature windows to conduct experimental co-pyrolysis of the SD and WT were established. The Schottky Field Emission (JSM-7610F) SEM from the Japan Electron-Optics Lab, was employed to conduct the SEM-EDX analysis of the samples. This Electron Microscope was set up at the AV (accelerating-voltage) of 5 kV at different magnifications to study

**Table 1. Properties of Various Blending Ratios of Sawdust and Waste Tyre**

Parameter	SD/WT					
	100/0	75/25	50/50	25/75	0/100	
Proximate analysis (wt. %)	Moisture content	6.06	5.55	3.67	1.59	0.38
	Ash content	1.72	2.45	4.82	4.03	8.29
	Volatile content	74.30	72.30	69.25	63.82	59.86
	Fixed carbon	17.90	19.70	22.27	30.55	31.47
Ultimate analysis (wt. %)	C	47.70	55.74	63.77	71.81	79.84
	H	6.06	6.16	6.25	6.35	6.44
	N	0.134	-	-	-	0.49
	S	0.00	-	-	-	1.28
	O	44.20	36.14	28.08	20.01	11.95
Molar ratio	O/H	0.69	0.49	0.33	0.21	0.11
	H/C	1.52	1.33	1.18	1.06	0.97
	Calorific value (dry basic, MJ/kg)					
	HHV	20.10	23.60	26.41	30.18	32.99

**Figure 1. Schematic diagram of the pyrolysis system used.**

the surface morphology and detect the presence of the elements in samples.

### 2.3. Experimental procedure

The schematic diagram of the pyrolysis reactor system used in the study is shown in Figure 1. The experiment was performed the fixed-bed reactor system fabricated from the stainless steel with the reactor dimensions of 70 cm length and 25.4 mm of diameter. Glass wool was used to cover each side of the reactor to minimize the heat losses to the surroundings during each run. To guarantee the pyrolysis atmosphere inside the reactor, continuous supply of nitrogen gas was maintained for the sweeping purposes, the gas cylinder was connected to the reactor to supply constant nitrogen gas at the flow rate of 0.1~0.5 L/min. For each batch run, 10 g of the sample was introduced into the reactor. The pyrolysis experiments were conducted at three different temperatures maintained as 500, 600 and 700 °C where the heating rate was kept as 30 °C/min and the pyrolysis time was maintained as 60 min for all experiments. The electrically-heated furnace was used to heat the pyrolysis reactor and to sustain the desired pyrolysis temperature, an E-type thermocouple (automatic temperature controller) was used. The vapors and gases formed from the decomposition of feedstock were directed to pass through the sequence of condensers to collect the bio-oil from each experimental run. The biochar produced was obtained in the reactor and was collected once the temperature conditions of the system had reached the ambient temperature. A very

precise and careful mass balance for each experimental run was obtained by measuring the difference in the mass of the system components to calculate the yields of bio-oil yield and biochar. While the gas products yield was calculated by deducting the total yields of bio-oil and bio-char from 100. Each experiment was repeated to ensure the repeatability and integrity of the results. For every single run, the sample was dried before starting the co-pyrolysis experiment while for every single run of pyrolysis, the system was cleaned completely to prevent mixing and contamination of samples and products.

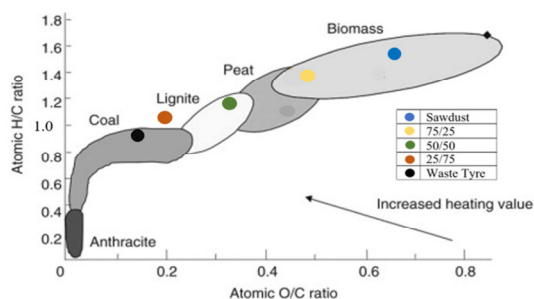
## 3. Results and Discussions

### 3.1. Characterisation of samples

Table 1 summarizes the properties of the different blends of the sawdust and waste tyre formed in this study. Proximate analysis is a fundamental test to check the properties including the volatile matter, moisture content, fixed carbon and ash content in the samples. When choosing samples for the pyrolysis process, moisture content plays an essential role[44]. As the fraction of moisture in feedstock increases, heating values decreases and the quality of pyrolysis products is deteriorated especially the properties of bio-oil produced[44,45]. Volatile matter is also considered to be a vital property of samples as a higher percentage of volatile matter demonstrates its ease of combustion and decomposition during thermal conversion[44]. Usually, greater yields of bio-oil are obtained because of the higher percentage of volatiles removal from biomass which is condensed to get bio-oil, whereas a higher percentage of biochar is produced because of lower volatile matter and higher ash and fixed carbon contents in the samples. Moisture content, volatile matter, fixed carbon and ash contents in SD/WT blending ratios of 100/0, 75/25, 50/50, 25/75 and 0/100 were found to be in the range of 6.06~0.38, 59.86~74.30, 17.90~31.47 and 1.72~8.29 wt% respectively. The carbon, hydrogen and oxygen concentrations in SD/WT blending ratios of 100/0, 75/25, 50/50, 25/75 and

**Table 2. Result of TGA and DTG of the Blends**

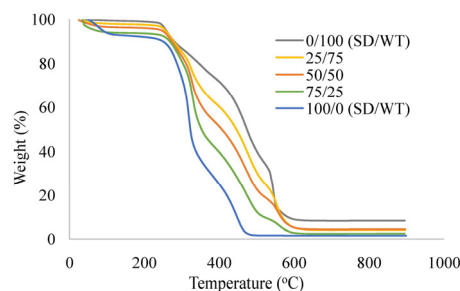
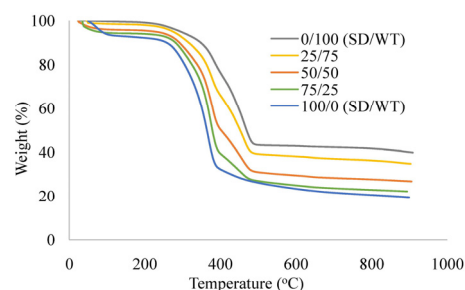
		SD/WT				
		100/0	75/25	50/50	25/75	100/0
Pyrolysis	Main peak temperature (°C)	367.97	374.97	377.02	376.64	461.65
	Max degradation rate (wt%/min)	8.61	8.90	7.46	4.76	5.04
	Shoulder peak (°C)	Not visible	450.76	457.46	376.64	384.35
Combustion	Main peak temperature (°C)	319.09	329.56	327.64	551.88	544.06
	Max degradation rate (wt%/min)	15.45	9.29	6.46	4.99	15.28
	Shoulder peak/s (°C)	448.92	560.14, 472.64	556.64, 463.62	475.15, 326.71, 267.76	468.61, 353.28, 257.41

**Figure 2. Van Krevelen diagram of various blending ratios of sawdust and waste tyre.**

0/100 were reported in the range of 47.70~79.84, 6.06~6.44 and 11.95~44.20 wt% respectively. The concentrations of nitrogen in sawdust and waste tyre were reported as 0.134 and 0.49 wt% respectively. There was no sulfur content present in sawdust, whereas there was 1.28 wt% sulfur present in waste tyre.

The molar ratios of O/C and H/C demonstrated energy contents contained in the samples depending on hydrogen-carbon and oxygen-carbon bonds[52]. The H/C and O/C molar ratios of SD/WT blending ratios of 100/0, 75/25, 50/50, 25/75 and 0/100 were reported as 0.69, 0.49, 0.33, 0.21 and 0.11 respectively and 1.52, 1.33, 1.18, 1.06 and 0.97 respectively. Figure 2 showed the Van Krevelen diagram of SD/WT blending ratios of 100/0, 75/25, 50/50 and 0/100, biomass, lignite and coal respectively. For the thermochemical conversion, low molar ratios of O/C and higher ratios of H/C were usually recommended because they had more energy potential[31].

The calorific value of samples indicated the amount of energy contained in each sample. The calorific values of SD/WT blending ratios of 100/0, 75/25, 50/50, 25/75 and 0/100 were reported as 20.10, 23.60, 26.41, 30.18 and 32.99 MJ/kg respectively. Hence, as more waste tyre was added in blending ratios, the calorific value increased. Moreover, the difference in the calorific value of each material is due to the different concentrations of the main elements such as carbon, oxygen and hydrogen in the samples. The higher the concentration of oxygen, the lower the calorific value. Oasama and Czernik[46], high oxygenated compounds (35~60 wt%) produced low calorific value and decreased combustion efficiency. The contents of C and H, and H/C ratio could significantly change the calorific value. The calorific values of the waste tyre and SD/WT blending ratio of 25/75 used in this study were higher

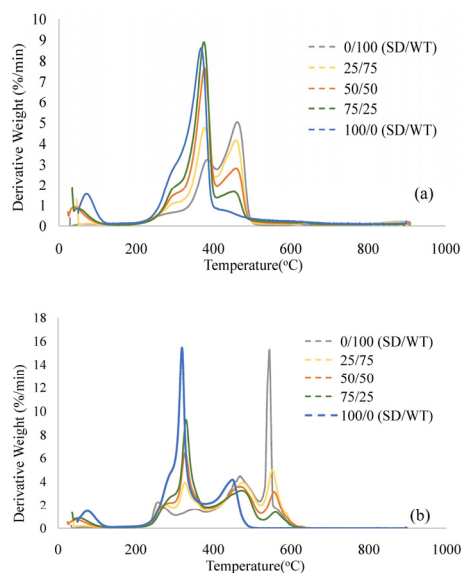
**Figure 3. TGA under (a) a nitrogen atmosphere (pyrolysis) (b) an oxygen atmosphere (combustion) at 10 °C/min.**

than coal, charcoal, and coke but within the range with semi anthracite. Energy recovery from the valorization had a large potential as waste tyre and SD/WT blending ratio of 25/75 consisted of a higher calorific value than the conventional fuel such as coal. Hence, both could be used as a feedstock to generate energy.

### 3.1.1. Thermogravimetric analysis of the samples under pyrolytic atmosphere

The curves acquired from the thermogravimetric analysis of various blending ratios of SW/WT in used in this study are shown in Figure 3(a) and (b) while the loss in the weight during the analysis is given in Table 2. These curves could be used to recognize the thermal decomposition patterns of the feedstocks and the reaction kinetics of the process[47]. The components degradation could be explained into three steps: moisture elimination, main de-volatilisation and incessant small degradation for pyrolysis.

Figure 3 shows the weight loss characteristics under a nitrogen atmosphere using TGA at 30 °C/min for various blending ratios while Figure 4(a) shows the derivative weight loss characteristics under nitro-



**Figure 4.** DTG under (a) a nitrogen atmosphere (pyrolysis) (b) an oxygen atmosphere (combustion) at 10 °C/min.

gen atmosphere for various blending ratios. It can be observed that both materials were volatilized at the same range of temperature between 150–600 °C, whereas, at the temperature of 250–500 °C, their pyrolysis temperatures overlapped.

Sawdust sample decomposed in three stages: first weight loss took place at a temperature of 5–200 °C due to the removal of moisture and light volatile content of the sample. Second weight loss was due to the main devolatilisation that occurred between 220–315 °C related to the decomposition of hemicellulose. The final weight loss was recorded between 315–400 °C due to the decomposition of cellulose[48]. After the temperature of 400 °C, the lignin content began to decompose. Hence, the main peak of sawdust decomposition appeared at 367.97 °C and at maximum degradation rate of 8.61 wt%/min, which was linked to the cellulose components, with the earlier shoulder being related with the hemicellulose decomposition. The last shoulder appeared at upper temperatures was associated with the lignin decomposition ranged from 180–600 °C.

Various authors had examined the thermal degradation of different types of rubbers where the typical method used had been TG and DTG measurements[49]. From Figure 3(a), two peaks observed from this study were the same with the peaks observed by other studies[50,51], the first peak at 380 °C referred to natural rubber and the succeeding peak at 430 °C referred to styrene-butadiene rubber[52]. Hence, the main peak of the waste tyre was found at 461.65 °C and at the maximum degradation was 5.04 wt%/min, which contributed to styrene-butadiene rubber degradation. The shoulder peak observed at the temperature of 384.35 °C was related to natural rubber degradation. For the preceding shoulder the main weight loss was reported between 150–320 °C, correlated to the decomposition of volatile additives present in the tyre, for example, phenolic resins or aromatic oil[53].

As for the remaining blending ratios for SD/WT of 25/75, 50/50 and 75/50, their main peaks were found at 374.97, 377.02 and 376.64 °C

with a maximum degradation rate of 8.90, 7.46 and 4.76 wt%/min respectively, which were correlated to cellulose and natural rubber degradation. Their shoulder peaks appeared at the temperatures of 450.76, 457.46 and 461.65 °C which contributed to the degradation of styrene-butadiene and lignin. Their preceding shoulders were correlated to the degradation of hemicellulose and volatile additives in the tyre, for example, phenolic resins or aromatic oils.

### 3.1.2. Thermogravimetric analysis of samples under oxidation atmosphere

Figure 4(a) shows the weight loss reported under the oxidation environment while Figure 4(b) shows the derivative weight loss characteristics for various blending ratios used in the study. The combustion curves are essential tools in understanding the combustibility of fuels for the application in combustion facilities[54]. With respects to the combustion mechanisms of the feedstock used in this study, three patterns of components degradation were observed including the drying of feedstock, oxidative pyrolysis of the components and the char combustions. The drying area was primarily because of the moisture and lower boiling point organic matter removal in the samples observed around the temperature range of 50–250 °C. The oxidative pyrolysis region primarily occurred because of the exiting of volatile matters present in the samples which produced the char around the temperature of 250–350 °C. The final stage, which was a slow process, primarily occurred because of the oxidation of char around 350–900 °C.

For all the lignocellulosic-based materials, the first components degradation stage occurred in the temperature range 200–380 °C, which was associated to the degradation of hemicelluloses and cellulose up to 300 °C. The degradation of lignin was observed in the second combustion degradation stage at a temperature of 370–550 °C due to the oxidation of char. Hence, the main peak of sawdust appeared at a temperature of 319.09 °C and at maximum degradation rate of 15.45 wt%/min which corresponded to the degradation of cellulose and hemicellulose. The shoulder peak observed at the temperature of 448.2 °C contributed to the degradation of lignin. The degradation of lignin in combustion could be seen compared to pyrolysis due to the oxidation of char.

Castaldi and Kwon[55] concluded that the major degradation process took place between the temperatures range of 350–400 °C was very likely related to the combustion of the butadiene backbone. The minor process took place between temperatures of 410–550 °C and was associated to aromatic rings from the styrene. Galiani *et al.*[56] explained that the first stage of degradation of the rubber samples began at a temperature of 260–400 °C corresponding to natural rubber. The second stage of degradation at the temperature up to 385 °C was associated with the final degradation of the natural rubber. The third stage of degradation between 430–600 °C was correlated to the carbonaceous residues. Hence, the main peak of waste tyre appeared at a temperature of 544.06 °C and at the maximum degradation of 15.28 wt%/min which was attributed to the carbonaceous residues. There were three shoulder peaks observed at temperatures of 468.61, 353.28 and 257.41 °C which could be attributed to the degradation of aromatic rings from styrene, butadiene and natural rubber respectively.



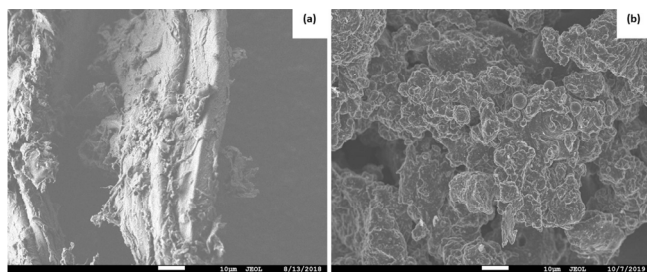


Figure 5. The SEM images of the (a) sawdust biomass, (b) waste tyre.

As for the SD/WT blending ratios of 75/25 and 50/50, their main peaks appeared at 329.56 and 327.64 °C with a maximum degradation rate of 9.29 and 6.46 wt%/min respectively, which could be correlated to the degradation of cellulose, hemicellulose, and butadiene. Their second shoulder peaks were observed at the temperature of 560.14 and 556.64 °C which was correlated to the degradation of carbonaceous residue. Whereas, their third shoulder peaks were observed at the temperature of 472.64 and 463.62 °C respectively and were associated with the degradation of aromatic rings and lignin. For SD/WT blending ratio of 25/75, its main peak was observed at a temperature of 551.88 °C and at the maximum degradation rate of 4.99 wt%/min, which was associated with the carbonaceous residue. There were three shoulder peaks observed at temperatures of 475.15, 326.71 and 267.76 °C. The first shoulder peak at a temperature of 475.15 °C was associated with the degradation of lignin and aromatic ring whereas the second shoulder peak at the temperature of 326.71 °C was associated with the cellulose, hemicellulose and butadiene. The final shoulder peak at temperature 267.76 °C was attributed to the degradation of natural rubber.

### 3.2. SEM-EDX analysis

SEM and EDX spectroscopy was used to examine the surface characteristics, morphology and the elemental composition of the sawdust and waste tyre blends. Figure 5(a) and (b) presents the SEM images of sawdust and waste tyre respectively. For SEM of sawdust, the presence of the elongated fibers and vessels which consisted of fibers could be seen in Figure 5(a). Whereas for SEM of the waste tyre, spherical particles present were the predominant morphology; only a small sum of them displayed a hollow or irregular shape as showed in Figure 5(b). The surface of the particles appeared to be rough, probably as a result of the chemical compositions[57]. Figure 6(a) and (b) shows the EDX of sawdust and waste tyre respectively. Elements present in the sawdust were carbon, oxygen, aluminium, silicon, calcium and potassium with a weight percentage of 32.27, 66.65, 0.02, 0.02 and 0.02 wt% respectively. Whereas, carbon, oxygen, aluminium, sulfur and zinc with a weight percentage of 32.30, 87.97, 0.08, 0.42 and 0.06 wt% respectively were present in the waste tyre. Both EDX of sawdust and waste tyre determined that the highest element was carbon and the second-highest element was oxygen.

Table 3. Pyrolysis Products Yields Reported at 500, 600 and 700 °C Respectively

Yield of (wt.%)	500 °C	600 °C	700 °C
Bio-oil	31.9	47.1	61.2
Bio-char	34.5	34.2	31.4
Syngas	33.6	18.6	7.3

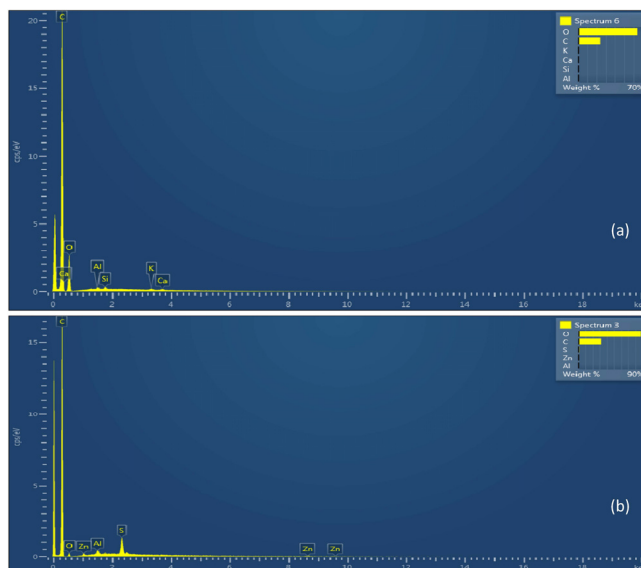


Figure 6. EDX of (a) sawdust, (b) waste tyre.

### 3.3. Co-pyrolysis experiments

The SD/WT blending ratio of 25/75 was selected to be co-pyrolysed at three different temperatures because it had better characteristics among the blends studies as discussed in the above sections. The selection was made on the moisture content and calorific value of the blends. SD/WT blending ratio of 25/75 had lower moisture content which led to high heating values, which will also result in the better quality of bio-oil as the high moisture content in feedstock deteriorates the quality of pyrolysis products, particularly the properties of liquid bio-oil. Moreover, SD/WT blending ratio of 25/75 had higher calorific value as it contained the maximum ratio of the waste tyre.

#### 3.3.1. Pyrolysis products yield distribution

Table 3 presents the percentage yields of the products produced by co-pyrolysing SD/WT blending ratio of 25/75. At the temperatures of 500, 600 and 700 °C, bio-oil yields produced were reported as 31.9, 47.1 and 61.2 wt% respectively, bio-char yields produced were reported as 34.5, 34.2 and 31.4 wt% respectively and syngas yields were 33.6, 18.6 and 7.3 wt% respectively. The increase in pyrolysis temperature caused the percentage of bio-oil yield to increase drastically, percentage of bio-char to decrease and the percentage of syngas to decrease drastically. Hence, the temperature of 700 °C was selected as the more bio-oil yield was produced compared to other temperatures. Yang *et al.*[58] and Abnisa and Wan Daud[59] concluded that an increase in bio-oil yield was due to the decomposition of lignin at a

**Table 4. Bio-oil Yields Produced from Co-pyrolysis of Waste Tyre and Different Biomass**

Biomass	Temperature (°C)	Bio-oil Yield (wt.%)
Rice husk	450	67[36]
Wheat straw		44[43]
Pine nutshells	500	47[34]
Palm shells		48.1[59]

higher temperature. Besides, according to Laresgoiti *et al.*[60], the pyrolysis of tyre that occurred at higher temperature produced more bio-oil. Hence, these might be the reasons why bio-oil yield increased at a higher temperature. Table 4 shows the other co-pyrolysis studies from the literature. The maximum bio-oil yields of 44, 47 and 48.1 wt% were attained in the fixed-bed co-pyrolysis of waste tyre with wheat straw, pine nutshells and palm shells at 500 °C, and 67 wt% was the highest liquid yield reported using rice husk at 450 °C. When comparing the bio-oil yield produced at temperatures of 450 and 500 °C from previous studies and this study, this study concluded that maximum bio-oil yield could be obtained at the higher temperature (700 °C). This probably could be because of the extended temperatures of co-pyrolysis up to 700 °C with the same blending ratio whereas the previous studies only conducted the co-pyrolysis between the temperature ranges of 450–500 °C using different blending ratio. The bio-oil produced at different temperature has been reported to have different properties but the major challenge with regards to the utilisation of bio-oil in the internal combustion engines is its strongly acidic nature with a higher percentage of oxygenated compounds which further require the up-gradation of its properties through the applications different processing technologies[61-63].

#### 4. Conclusion

This study aimed at the valorization of sawdust waste from the processing of wood from the furniture industry and the waste tyres which are being excreted at higher rates globally and posing serious disposal threats. Co-pyrolysis is an effective processing technology applied to recycle wastes to produce biofuels. The thermochemical characterisation of various blending ratios of the sawdust and waste tyres was carried out to conclude their suitability before co-pyrolysing. Based on the comprehensive characterisation results the blending ratio of 25/75 (SD/WT) was selected to be co-pyrolysed at 500, 600 and 700 °C. The yields of pyrolysis products; bio-oil, bio-char and syngas were reported in the range of 31.9–61.2, 31.4–34.5 and 33.6–7.3 wt% respectively. Future research work can be conducted to study the co-pyrolysis of the other blending ratios along with carrying out the comprehensive characterisation of the products to study the effects of temperature on the yields and properties of the co-pyrolysis products. This study is expected to provide a useful data set for the utilisation of sawdust and waste tyres to produce energy to meet the global needs which are heavily dependent on the fossil resources.

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