



Influence of alcohol addition on properties of bio-oil produced from fast pyrolysis of eucalyptus bark in a free-fall reactor



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ABSTRACT

Fast pyrolysis of eucalyptus bark was carried out in a free-fall pyrolysis unit at different temperatures ranging from 400 to 550 °C to produce bio-oil, char and gas. The bio-oil produced at optimum temperature was mixed with alcohols with an aim to improve its properties. The results showed that the maximum bio-oil yield of 64.65 wt% on dry biomass basis could be obtained at the pyrolysis temperature of 500 °C. The addition of a small proportion (2.5–10%) of alcohol into the bio-oil could improve its viscosity, stability and heating value. These effects were further enhanced when increasing the alcohol. © 2013 The Korean Society of Industrial and Engineering Chemistry. Published by Elsevier B.V. All rights reserved.

1. Introduction

Eucalyptus Globulus is a fast-growing tree and its wood is widely used in the pulp and paper industry, whereas its bark is removed and left as residue. The bark may be employed as a solid fuel for boilers or thermochemically converted into liquid and gaseous fuels by applying fast pyrolysis and gasification technologies, respectively. Among the three forms, liquid fuel possesses the greatest versatility in terms of usage, storage and transportation. The liquid fuel produced from fast pyrolysis processing of lignocellulosic materials such as eucalyptus bark is called “bio-oil.”

In a fast pyrolysis process, biomass is quickly heated from room temperature to approximately 400–600 °C in an oxygen-free environment where biomass instantly decomposes and vapourises, leaving char as solid residue. The vapour is rapidly cooled to room temperature and part of it is condensed into liquid bio-oil. The non-condensable part is composed mainly of permanent gases such as carbon monoxide (CO), carbon dioxide (CO₂), hydrogen (H₂), methane (CH₄), ethane (C₂H₆), ethylene (C₂H₄), propane (C₃H₈) and propylene (C₃H₆).

There are several types of pyrolysis reactors designed for bio-oil production such as fixed bed [1], bubbling fluidised-bed [2–4], circulating fluidised-bed [5], auger [6,7], vacuum [8–10], vortex

[11], rotating cone [12], ablative [13,14] and free-fall [15–17]. All of these reactors were previously used to produce bio-oil with a wide range of biomass materials and process parameters such as pyrolysis temperature, vapour residence time, biomass feed rate, type and flow rate of inert gas, condensation temperature and run duration. Most of the typical bio-oils were known to be viscous, acidic, thermally unstable and high in water and oxygen contents and low in heating value. Several attempts have been made to ameliorate the bio-oil properties by applying different techniques such as catalytic upgrading (hydrotreating, hydrolysis and catalytic vapour cracking), chemical upgrading (mild cracking and esterification) and physical upgrading (filtration, solvent addition and emulsification) [18]. Among the techniques, solvent addition can be considered as one of the simplest ways to improve the homogeneity, stability, acidity and viscosity of bio-oil. Previous works reported the effects of methanol [10,11,19–22], ethanol [11,21–25], isopropanol [22], acetone, ethyl acetate, methyl isobutyl ketone-methanol mixture and acetone-methanol mixture [11] on the improvement of bio-oil stability and viscosity. The bio-oil investigated were obtained from pyrolysis of rice husk [20], hybrid poplar wood [11], pine [22] and forestry residue [22], poultry litter [21], softwood bark [10,19] and hardwood [23] in fluidised-bed [20,21], vortex [11], vacuum [10,19] and circulating fluidised-bed [22,23] reactors.

All of the previous works reported different extent of bio-oil stability and viscosity improvement and mutually agreed that solvent could reduce the viscosity and ageing rate. Nevertheless, to

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the best of the authors' knowledge, there is no published work on the addition of solvent in eucalyptus bark bio-oil produced by a free-fall pyrolyser. Therefore, it is the purpose of the current work to investigate the production and upgrading of bio-oil produced from fast pyrolysis of eucalyptus bark in a free-fall reactor. The paper is separated into two parts. The first part focuses on the bio-oil production with an aim to investigate the effects of pyrolysis temperature on product yields and bio-oil properties so as to determine the optimum pyrolysis temperature for fast pyrolysis of eucalyptus bark in the free-fall reactor. The second part of the research work emphasises on elucidating the effect of alcohol addition on bio-oil properties.

2. Materials and methods

2.1. Biomass feedstock

Biomass used in this work was eucalyptus bark obtained from a paper factory in Udonthani province of Thailand. The biomass material was ground and sieved to a particle size range of 212–500 μm . The proximate, ultimate and heating value analyses of the biomass sample were carried out and the results in comparison with those of the eucalyptus wood [25] and pine wood [26] are given in Table 1.

The higher and lower heating values (HHV and LHV) of the biomass samples were calculated using the following equations [27].

$$\text{HHV}_{\text{dry}} \text{ (MJ/kg)} = -1.3675 + 0.3137C + 0.7009H + 0.3318O^* \quad (1)$$

where C and H are percentages on dry basis of carbon and hydrogen, respectively and O^* is 100-C-H-ash. The lower heating values (LHV) were calculated from HHV and the hydrogen content by the following equation [28].

$$\text{LHV (MJ/kg)} = \text{HHV} - 2.442 \times 8.936 \frac{H}{100} \quad (2)$$

2.2. Bio-oil production and alcohol addition

The production of bio-oil from eucalyptus bark samples was performed in a free-fall fast pyrolysis unit as shown in Fig. 1. The unit consisted mainly of a biomass hopper, a screw feeder, a tubular reactor, three char pots, two cyclone separators, a fixed-bed glass wool hot filter, a water-cooled condenser, an electrostatic precipitator (ESP), two bio-oil pots, a dry-ice/acetone condenser and a cotton wool filter. The biomass hopper was made with 304

stainless steel and had a capacity of 1.5 kg dry biomass sample. The biomass particles were conveyed to the reactor by a stainless steel screw feeder. At the top of the reactor, there was a water-cooling jacket, installed to prevent the heat from the reactor furnace from reaching the biomass. Without this cooling jacket, the biomass could be pre-pyrolysed and block the feeding. The reactor was made from a 304 stainless steel tube of 10.3 mm inside diameter and 1.2 m high. The char pots, cyclones, hot filter and the water-cooled condenser were made from 304 stainless steel. The bio-oil pots, dry-ice/acetone condenser and cotton wool filter were glassware.

The pyrolysis experiments of bio-oil production were initiated by heating the reactor to a set temperature (400, 450, 500 or 550 °C) and heating the line from the char pot to the inlet of the water-cooled condenser to a fixed temperature of 400 °C. Then two nitrogen flow meters were turned on. The first nitrogen flow was for controlling the pressure in the biomass hopper and was constant at 1 L/min. The second nitrogen flow at the side of the screw feeder was fixed at 2 L/min. The pressure of the nitrogen flow and the system was close to atmospheric pressure. Once the system temperatures reached a steady state, biomass particles were fed to the reactor at a rate of 80–150 g/h. Each experiment was carried out for approximately 1 h. The first group of experiments was to investigate the effects of pyrolysis temperature on products distribution and bio-oil properties. The second group of experiments was to investigate the effects of alcohol addition on bio-oil properties. Ethanol and methanol were added to the bio-oil at 2.5, 5 and 10 wt%. The bio-oils sample tested in this group of experiments were collected from pot 1, bio-oil from a selected experiment based on the maximum bio-oil yield.

2.3. Bio-oil analysis

The bio-oil and bio-oil/alcohol mixture samples were analysed for their water content, solids content, ash content, pH, specific gravity, viscosity, stability and heating value. The details for each analysis are summarised below.

2.3.1. Water content

The water content of the bio-oil samples was determined by volumetric Karl-Fischer titration technique. The instrument used was V20 Mettler Toledo. Hydranal composite 5 K and Working Medium K from Fluka Analytical were used as titration reagent and solvent, respectively.

2.3.2. Solids content

The solids content of bio-oil samples was measured as ethanol insolubles using a vacuum filtration technique. About 2–3 g of bio-

Table 1
Characteristics of biomass residues from eucalyptus bark.

Analysis	Eucalyptus bark	Eucalyptus wood [25]	Pine wood [26]
Particle size (μm)	212–500	300–500	250–425
Proximate analysis (wt.%, dry basis)			
Volatile matter	76.1	82.6	82.3
Fixed carbon	19.7	16.4	17.6
Ash	4.2	1.0	0.1
Moisture (as-received basis)	10.7	7.7	7.5
Ultimate analysis (wt.%, dry-ash free basis)			
Carbon	38.7	48.7	52.6
Hydrogen	4.5	6.2	5.7
Nitrogen	0.3	0.3	0.9
Sulphur	<1.6	N/A	<0.1
Oxygen (by difference)	54.9	44.8	38.9
Heating value (MJ/kg, dry basis)			
HHV	15.7	18.6	20.6
LHV	14.7	17.0	19.6

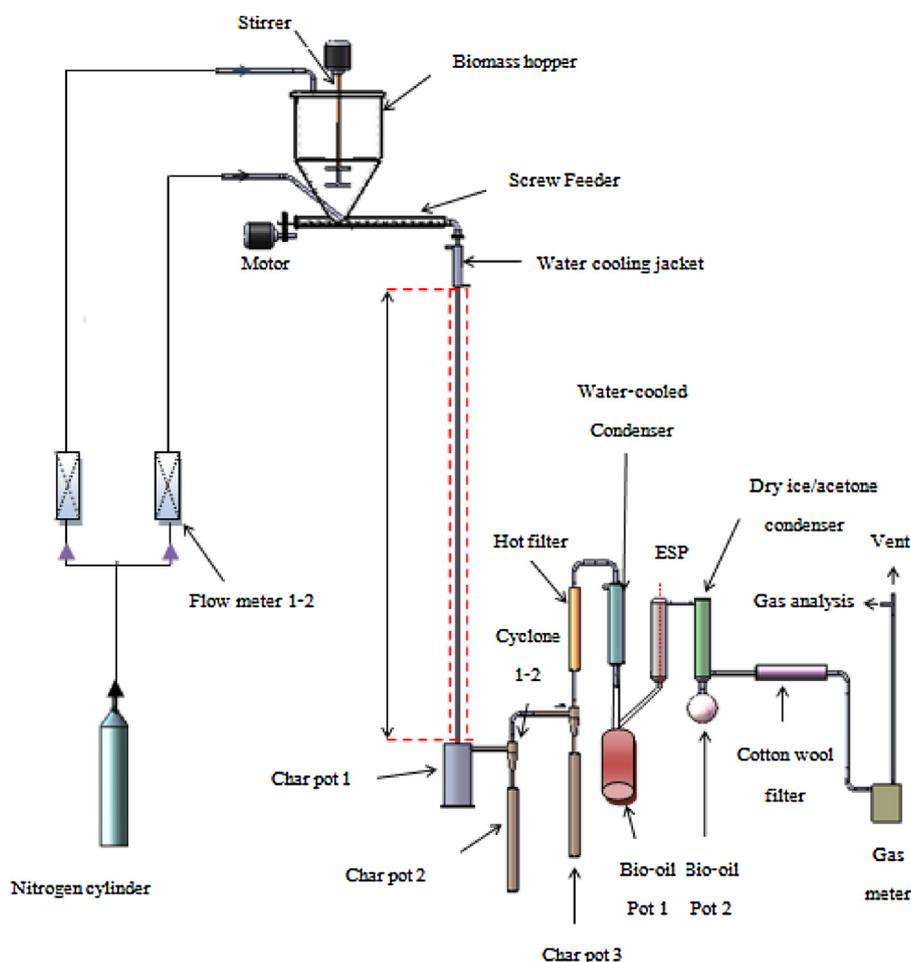


Fig. 1. Schematic diagram of the free-fall fast pyrolysis unit.

oil was mixed with approximately 50 ml of 95% ethanol. Then, the solution was filtered through a pre-dried and weighed Whatman No. 3 qualitative paper with particle retention of 6 μm . An excess amount of ethanol was supplied to the filter paper in order to remove all ethanol soluble and only solids were left over. The filter paper was then dried in ambience for 15 min and in an oven at 105 $^{\circ}\text{C}$ for 30 min. The paper was subsequently left to cool down in a desiccator before being weighed.

2.3.3. Ash content

Approximately 2–3 g of bio-oil was burned in a furnace at 775 $^{\circ}\text{C}$ for 24 h or until constant weight was reached. The residue was ash from bio-oil and was calculated as a percentage in bio-oil.

2.3.4. pH value

The pH value of the liquid samples was measured using a UB-10 Denver Instrument pH meter. Prior to the analysis, the instrument was calibrated with buffer solutions of pH 4, 7 and 10.

2.3.5. Specific gravity

The specific gravity of bio-oil was measured by weighing a constant volume of bio-oil in a density bottle of 25 ml. The weight and volume were used to calculate the bio-oil density and specific gravity.

2.3.6. Viscosity

The kinematic viscosity of the bio-oil samples was determined by a Cannon-Fenske opaque viscometer. Approximately 10–11 g of bio-oil was put into the viscometer maintained at 40 $^{\circ}\text{C}$ and

allowed to flow freely. The time spent in the tube was recorded and the viscosity was calculated by a constant factor obtained from calibration with liquid standard.

2.3.7. Stability

Stability indicates how much the bio-oil changes over a period of time in terms of viscosity. Generally, the viscosity of bio-oil freshly produced is compared with that stored for about one year. Researchers [29] reported that the viscosity of bio-oil stored at 80 $^{\circ}\text{C}$ for 24 h is equivalent to that stored at room temperature for 1 year. Therefore, the process of simulating the storage of bio-oil for 1 year by this high temperature storage technique is called accelerated ageing. The parameter used to explain the bio-oil stability is stability index (SI) and is calculated by the following equation:

$$SI = \frac{V_{\text{aged}} - V_{\text{fresh}}}{V_{\text{fresh}}} \quad (3)$$

where V_{aged} and V_{fresh} are the kinematic viscosity in cSt of the aged and the fresh bio-oil, respectively. The bio-oil of high SI indicates low stability and vice versa.

2.3.8. Heating value

The higher heating value (HHV) of bio-oil was determined by an IKA-C200 Toledo bomb calorimeter. Approximately 1 g of bio-oil was filled in a cup and put in a bomb. The HHV was calculated based on the bio-oil weight, the changes of temperature and the specific heat capacity of the bomb, which was obtained by

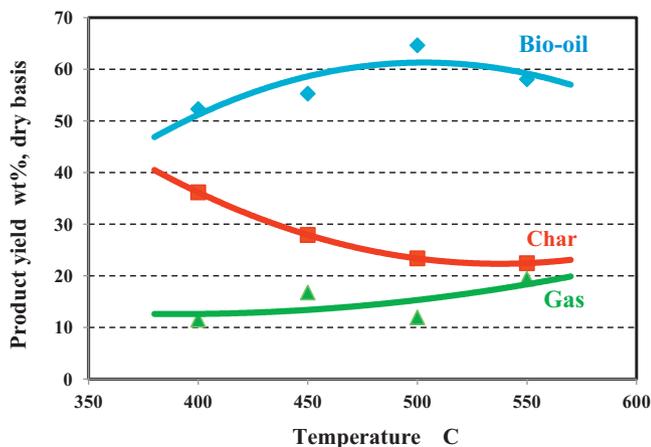


Fig. 2. Effects of pyrolysis temperature on product yields.

employing benzoic acid as a standard. The HHV determination was performed according to the ASTM D 4809 standard method.

3. Results and discussion

3.1. Effect of pyrolysis temperature on bio-oil production

The effects of pyrolysis temperature on the yields of bio-oil, char and gas from fast pyrolysis of eucalyptus bark in the free-fall reactor are illustrated in Fig. 2. Under the temperature range of 400–550 °C, the yields of bio-oil, char and gas were in the ranges of 52.3–64.7, 22.5–36.2 and 11.5–19.5 wt% on dry biomass basis, respectively. It was found that the bio-oil yield reached its maximum of 64.7 wt% at a pyrolysis temperature of 500 °C. This yield is comparable to the previous findings using linseed [30], rapeseed [31], red oak [15], legume straw and apricot [32], sugarcane leaves, sugarcane tops, cassava stalk and cassava rhizome [16] as raw materials in free-fall reactors, which gave maximum bio-oil yields of 68.8, 75, 72, 55, 57, 53.3, 44.1, 52.3 and 50.3 wt%, respectively.

In addition, when the pyrolysis temperature was increased from 400 to 550 °C, the yield of char decreased, whereas that of gas increased, accordingly. The decrease in char yield indicated higher thermal decomposition of biomass at elevated temperature. The increase of gas with temperature from 400 to 500 °C may be predominantly due to the char thermal decomposition. When the temperature was increased from 500 to 550 °C, the increase of the gas yield could be mainly owing to the secondary cracking of the condensable pyrolysis vapour, which would otherwise become bio-oil, rather than the char decomposition since the char yield was hardly affected by this temperature increase. These trends of bio-oil, char and gas yields with temperature were in accordance with previous studies [2,16,30,33] even though different biomass and reactor types were applied.

The effects of temperature on the properties of bio-oil produced from fast pyrolysis of eucalyptus bark in the free-fall reactor are summarised in Table 2. It is apparent that most of the properties monitored except for water content hardly relied on the pyrolysis temperature. The pH value, specific gravity, solids content, ash content, viscosity, stability and heating values were in the ranges of 2.38–3.87, 1.10–1.15, 0.07–0.47 wt%, 0.02–0.23 wt%, 7.56–16.28 cSt, 0.87–1.45 and 12.45–13.89 MJ/kg, respectively. The water content of eucalyptus bark bio-oil tended to increase with temperature. It was 26.07 wt% at 400 °C and 29.89 wt% at 550 °C. The increase in the water content of bio-oil may be related to the secondary cracking of pyrolysis vapour and the secondary

Table 2

Properties of bio-oil produced at different pyrolysis temperatures.

Properties	Pyrolysis temperatures (°C)			
	400	450	500	550
pH value	2.78	2.76	2.87	2.38
Specific gravity	1.13	1.15	1.14	1.14
Ash content (wt%)	0.02	0.04	0.23	0.15
Water content (wt%)	26.07	27.98	32.86	29.89
Solids content (wt%)	0.18	0.07	0.45	0.47
Viscosity at 40 °C (cSt)				
Fresh bio-oil	10.56	15.24	16.28	13.08
Aged bio-oil	14.14	24.81	39.89	27.50
Stability index	0.87	0.63	1.45	1.10
HHV (MJ/kg)	12.45	13.89	12.23	12.77

decomposition of the char or lignin. This finding is consistent with that reported by Amutio et al. [34] when sawdust was pyrolysed in a conical spouted bed reactor at 400–600 °C and the water content of the bio-oil was increased from 23.33 wt% to 27.17 wt%.

3.2. Effects of alcohol addition on bio-oil properties

The bio-oil produced from fast pyrolysis of eucalyptus bark in the free-fall pyrolyser at 500 °C was mixed with 2.5–10.0 wt% methanol or ethanol. The alcohol/bio-oil mixtures were subjected to property analyses, which included viscosity, stability, heating value, pH, specific gravity, ash, water and solids contents.

3.2.1. Viscosity

Fig. 3 shows the effects of alcohol addition on the viscosity of fresh and aged bio-oils. It is apparent from the graph that the pure bio-oil (without alcohol addition) had significantly higher viscosity than the alcohol/bio-oil mixture. In other words, the addition of alcohol could improve the bio-oil viscosity. The viscosity change of the fresh bio-oil (ageing time = 0 h) showed that when adding 2.5–10% of either methanol or ethanol, the bio-oil viscosity was decreased from 16.8 cSt to about 6 cSt. The difference among the viscosities of the fresh alcohol/bio-oil mixtures was negligible. Nevertheless, when the time for ageing the bio-oil at 80 °C was increased, the difference among the mixtures was clearer. It can be seen that the higher the concentration of alcohol, the lower the

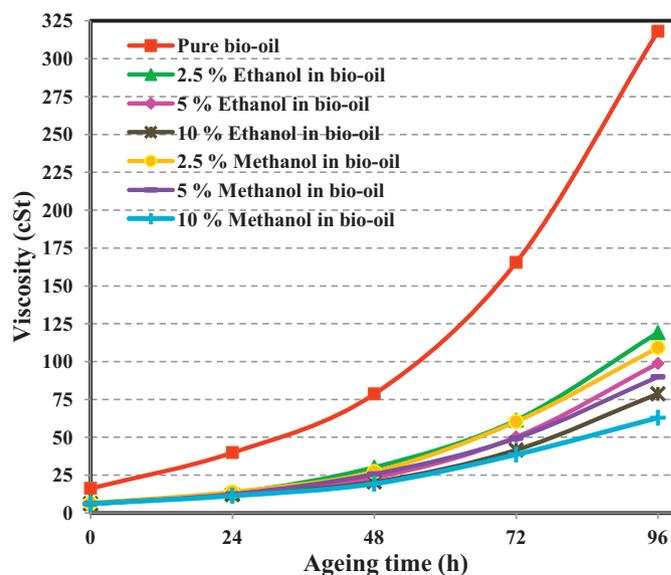


Fig. 3. Effects of alcohol addition on bio-oil viscosity measured at 40 °C.

Table 3
Bio-oils stability evaluation.

Data source	Reactor	Biomass	Sample	Ageing temperature (°C)	Ageing time (h)	Measurement temperature (°C)	Ageing rate (AR) (cSt/h)	Ageing rate decrease factor (ARDF)	Stability index (SI)	Ranking					
										AR	ARDF	SI			
This work	Free-fall	bark	Pure bio-oil	80	96	40	3.14	1.0	17.9	7	7	7			
			2.5% Ethanol				1.17	2.7	17.3	6	6	6			
			5% Ethanol				0.96	3.3	14.9	4	4	4			
			10% Ethanol				0.75	4.2	11.5	2	2	2			
			2.5% Methanol				1.07	2.9	16.1	5	5	5			
			5% Methanol				0.87	3.6	13.7	3	3	3			
			10% Methanol				0.59	5.3	9.5	1	1	1			
Diebold and Czernik [11]	Vortex	Hybrid poplar	Pure bio-oil	90	24	40	2.08	1.0	2.0	3	3	3			
			10% Ethanol				0.18	11	1.0	2	2	2			
			10% Methanol				0.12	18	0.9	1	1	1			
Lu et al. [20]	Fluidised-bed	Rice husk	Pure bio-oil	80	48	40	0.24	1.0	0.85	4	4	3			
			5% Methanol				72	0.13	1.8	0.90	3	3	4		
			10% Methanol				120	0.04	6.0	0.63	2	2	1		
			15% Methanol				120	0.03	8.0	0.67	1	1	2		
Boucher et al. [10]	Vacuum	Softwood bark	Pure bio-oil	80 ^a	17.1	30	4.14	1.0	0.7	3	3	2			
			10% Methanol				1.74	2.4	1.4	2	2	3			
			15% Methanol				0.23	18.0	0.2	1	1	1			
			Pure bio-oil				Room temperature	260 days	30	0.011	1.0	0.7	3	3	2
			10% Methanol				0.005	2.2	1.4	2	2	3			
Mante and Agblevor [21]	Fluidised-bed	50% Poultry litter in pine	Pure bio-oil	80 ^a	11.8	60	91.81	1.0	4.3	3	3	1			
			10% Ethanol				23.64	3.9	5.7	1	1	2			
			10% Methanol				24.46	3.8	7.4	2	2	3			
			Pure bio-oil				Room temperature	180 days	60	0.25	1.0	4.3	3	3	1
			10% Ethanol				0.06	4.2	5.7	1	1	2			
Oasmaa et al. [23]	CFB	Hardwood (oak-maple)	Pure bio-oil	50	168	50	0.50	1.0	0.5	2	2	2			
			5% Ethanol				0.07	7.1	0.1	1	1	1			
			Pure bio-oil				Room temperature	12 months	40	0.004	1.0	1.3	2	2	2
Oasmaa et al. [22]	CFB	Pinewood	Pure bio-oil	80 ^a	24	40	1.63	1.0	1.3	2	2	2			
			5% Ethanol				0.67	2.4	0.8	1	1	1			
			Pure bio-oil				Room temperature	12 months	40	0.004	1.0	1.3	2	2	2
			5% Ethanol				0.002	2.0	0.8	1	1	1			

^a Equivalent ageing temperature based on the room temperature data and an assumption that ageing at 80 °C for 24 h would lead to the viscosity increase similar to ageing at room temperature for 1 year.

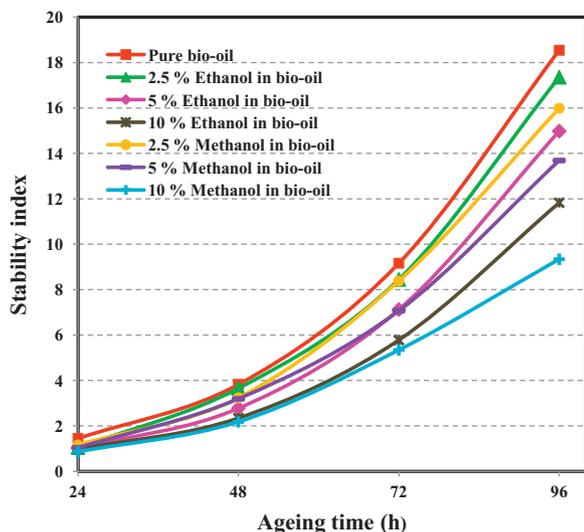


Fig. 4. Effect of alcohol addition on stability index of bio-oil.

viscosity of bio-oil. Also, methanol appeared to be slightly more effective than ethanol. Previous studies using different pyrolysis reactors such as vortex [11], fluidised-bed [20,21], CFB [22,23] and vacuum [10] with different biomass feedstock such as hybrid poplar [11], rice husk [20], softwood [10], poultry litter mixed with pinewood [21] and pinewood [22] also found that the addition of alcohol could reduce the bio-oil viscosity to a certain degree. Most of the previous work [11,21,22] reported that methanol was superior to ethanol in terms of the reduction of bio-oil viscosity. Thus, the current results utilising eucalyptus bark in a free-reactor support this finding.

3.2.2. Stability

Stability of bio-oil can be monitored from the changes of viscosity after storage for a period of time at a specific temperature. In this work, bio-oil samples were subjected to accelerated ageing in which they were stored at an elevated temperature, which was 80 °C, for 24 h. This was reported to be equivalent to storing bio-oil at room temperature for one year based on the viscosity increase [22,23]. The changes of viscosity in comparison to the initial viscosity, or stability indices, were calculated and the results are plotted in Fig. 4. It can be seen that the stability index increased with the ageing time. The bio-oil without alcohol addition had the

highest viscosity index, which reflected that when alcohol was added to bio-oil, the stability could be enhanced. Fig. 4 also shows that the higher the percentage of the alcohol, the better the stability of the bio-oil. Additionally, methanol appeared to be more effective than ethanol.

Apart from the stability index (SI), ageing rate (AR), calculated as the change of the viscosity over storage time and ageing rate decrease factor (ARDF), calculated as the ratio of the ageing rate of the pure bio-oil to that of the alcohol/bio-oil mixture could be used to compare the bio-oil stability.

Table 3 shows that the ageing rate of the bio-oil produced in this work decreased from 3.14 cSt/h to 0.59–1.17 cSt/h when 2.5–10% of alcohol was added. This corresponds to the ageing rate decrease factor of 2.7–5.3. It can be noticed that the higher the amount of alcohol added, the higher the ARDF. At the same amount of alcohol addition, methanol was superior to ethanol in terms of AR and ARDF. Table 3 also demonstrates the ranking of the stability improvement with alcohol addition based on the AR, ARDF and SI. It is apparent that the ranking order of bio-oil produced in this work was the same regardless of the three parameters.

To compare the current findings with literature data, the AR, ARDF and SI calculated from the viscosity of fresh and aged bio-oil, together with the ageing time data, extracted from references [10,11,20–23] are also given in Table 3. When similar ageing temperatures were applied, AR of 10% methanol/bio-oil mixture from pyrolysis of hybrid poplar in a vortex reactor [11] and rice husk in a fluidised-bed reactor [20] could be as low as 0.12 cSt/h and 0.03 cSt/h, respectively. These are much lower than the bio-oil from eucalyptus bark in a free-fall reactor. The ARDF of 10% methanol/bio-oil mixture from the references [11,20] were also higher than the current finding. This may be explained by the use of a highly efficient hot filter in the vortex pyrolysis system [11] and possibly the higher amount of low molecular weight compounds of rice-husk bio-oil, since the rice husk contained higher ash content than the eucalyptus bark [20]. Some previous studies [10,21–23] applied different ageing temperatures, either at 50 °C [23] or at room temperature [10,21,22]. The data from room temperature ageing were re-calculated to storage at 80 °C with an assumption that the viscosity change at room temperature for 1 year was equivalent to that at 80 °C for 24 h. It can be seen from Table 3 that the AR and ARDF of bio-oil and its mixtures with alcohol for all data were ranked in the same order, whereas some of the SI ranking deviated from the AR and ARDF trend. Therefore, the SI may not be used as the only parameter for bio-oil stability evaluation.

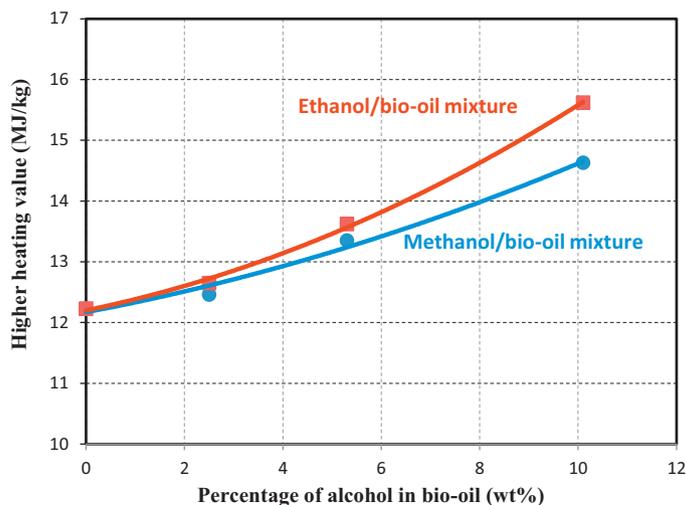


Fig. 5. Effects of alcohol addition on the heating value of bio-oil.

Table 4

Properties of bio-oil-alcohol mixtures.

Sample	pH value	Specific gravity	Ash content (wt%)	Water content (wt%)	Solids content (wt%)
Pure bio-oil	2.87	1.14	0.23	32.86	0.45
2.5% Ethanol	2.50	1.13	0.23	32.61	0.53
5% Ethanol	2.53	1.13	0.10	32.76	0.17
10% Ethanol	2.55	1.12	0.11	31.25	0.19
2.5% Methanol	2.47	1.13	0.22	32.31	0.26
5% Methanol	2.54	1.12	0.21	31.21	0.24
10% Methanol	2.57	1.12	0.19	27.48	0.22
Typical bio-oil ^a	2.5	1.2	n/a	25	0.1

^a Typical bio-oil reported by Bridgwater [18].

3.2.3. Heating value

The effects of alcohol addition on the higher heating value (HHV) of bio-oil are illustrated in Fig. 5. When 2.5–10 wt% of ethanol and methanol was added, the HHV increased from 12.23 MJ/kg to 12.65–15.62 MJ/kg and 12.46–14.63 MJ/kg, respectively. The increase of the heating value by ethanol addition was larger than that by methanol addition because the heating value of ethanol is higher than that of methanol. Oasmaa et al. [22] also reported that when 5 wt% of ethanol and methanol was added, the LHV increased from 15.15 MJ/kg to 16.5 and 15.8 MJ/kg, respectively. The increase of the heating value was due to the higher heating value of the alcohols compared to that of the bio-oil.

3.2.4. Other properties

Additional properties of bio-oil and its mixtures with alcohol were also tested, in terms of pH, specific gravity, ash, water and solids contents. The results are shown in Table 4. It can be seen that all bio-oil samples had properties similar to typical bio-oil. In other works, the effects of alcohol addition on these properties of bio-oil produced from pyrolysis of eucalyptus bark in a free-fall reactor were insignificant.

4. Conclusions

Eucalyptus bark was pyrolysed in a bench-scale free fall reactor at 400–550 °C to produce bio-oil, char and gas. It was found that the maximum bio-oil yield, which occurred at a pyrolysis temperature of 500 °C was 64.65 wt%, whereas the corresponding char and gas yields were 23.39 and 11.69 wt%, respectively. When ethanol and methanol were added to bio-oil, the initial viscosity, stability and heating value could be improved to a certain extent. The higher the alcohol content, the higher the improvement. Moreover, in this case, methanol was found to be superior to ethanol.

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