

Chemical properties of bio-oils produced by fast pyrolysis of bamboo

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Bamboo powder was analytically pyrolyzed using pyrolysis-gas chromatography (Py-GC), and the effects of fast pyrolysis conditions on the product distribution of bio-oil were evaluated. 4-Vinylphenol (4VP) was identified as a major product of bamboo fast pyrolysis by ¹H-NMR and ¹³C-NMR spectrometry. The formation pathway of 4VP demonstrated that *p*-coumarate esters are present in bamboo lignin, and 4VP is likely to be derived from these *p*-coumarate structures. The evaluation of the effect of fast pyrolysis temperature on the product distribution of bio-oil revealed that increasing pyrolysis temperature resulted in high yields of compounds containing a furan structure and reduced yields of phenolic compounds, except catechol. The fast pyrolysis of Klason lignin produced 4VP in lower yield than that from bamboo powder, even though the yield of 4-vinylguaiacol from acid lignin was greater than that from bamboo powder. In comparison with fast pyrolysis, slow pyrolysis of bamboo produced simple phenols, such as phenol, guaiacol, methyl guaiacol, syringol, and methyl syringol, in higher yields, whereas the yield of 4VP was lower than that from fast pyrolysis. The chemical characteristics of bio-oil depend on the biomass source, pyrolysis conditions, and the type of pyrolyzer.

Key words: Bio-oil, Fast pyrolysis, Moso bamboo, Pyrolysis conditions, 4-Vinylphenol

1. INTRODUCTION

Biomass is one of the main renewable energy resources. In contrast to other renewables that provide heat and power, biomass represents the only source that provides solid, gas, and liquid fuels [1]. For fuel production from biomass, pyrolysis is a promising technique for converting organics to solid, gas, and liquid products via thermal decomposition in the absence of oxygen. Conventional pyrolysis, which may be termed slow pyrolysis, has been mainly used for carbonization to produce charcoal. Pyrolysis is also the first step in the process of gasification. A modified pyrolysis, referred to as fast pyrolysis, has been recently used for liquefaction to produce bio-oil [1, 2]. The essential features of a fast pyrolysis process are: very high heating and heat transfer rates at the reaction interface, a carefully controlled pyrolysis temperature of around 500 °C, a vapor phase temperature of 400–450 °C, short vapor residence times of typically less than 2 s, and rapid cooling of the pyrolysis vapors to give the bio-oil product [3].

Bio-oil is considered to be a new resource as a substitute for fuel oil or diesel in many static applications such as boilers, furnaces, engines, and turbines for electricity generation or chemical production [3]. Many types of biomass have been examined for bio-oil production, and pilot plants have been established worldwide [1, 4]. Switchgrass, one of the dominant tall grass species in Central North America, is thought to be a good candidate for biofuel production

because of its hardness in poor soil and climate conditions, low fertilization and herbicide requirements, and high biomass yields [5]. However, Bernhard et al. [6] showed that the direct combustion of switchgrass leads to the emission of undesirable secondary products such as components of alkali, chlorine, or sulfur, and may increase the corrosion rate of boilers. Therefore, bio-oil production as an intermediate process is important for switchgrass utilization. In addition, several other researchers have studied switchgrass pyrolysis conversion and have evaluated the product distribution [7], energy conversion efficiency in a bench-scale reactor [8], and the effect of milling of the obtained bio-oil [9]. Several studies on pyrolysis conversion have also been reported, which used crops other than switchgrass, such as wheat straw [10], rice husk [11], tobacco residue [12], orange waste [13], giant cane [14], and microalgae [15].

Bamboo is one of the fastest-growing plants, and it can usually be harvested in 1–3 years. As many as 1,000 species of bamboo are found in Asia, covering an area of more than 180,000 km². Most of the bamboo comprises natural stands of native species rather than growth on plantations or by human introduction [16]. In Japan, large volumes of bamboo have invaded forest stands and a number of them remain untouched. Therefore, researchers are considering bamboo as a feedstock for biofuel production. There has been some research on bamboo pyrolysis for bio-oil production. Bio-oil production from bamboo was performed using different

types of reactors under different pyrolytic conditions [17, 18]. In addition, the analytical pyrolysis of bamboo was conducted using pyrolysis-gas chromatography/mass spectrometry (Py-GC/MS) for the evaluation of the thermochemical characteristics of raw materials and lignin [19-21].

The present study aimed to elucidate the products of bio-oil production from moso bamboo in greater detail, and the effect of pyrolysis temperature on bio-oil composition.

2. EXPERIMENTS

Moso bamboo (*Phyllostachys pubescens*) was prepared from a forest stand in a Niigata Prefectural Forest Research Institute in Murakami City, Niigata, Japan. The culms of bamboo were air dried and milled to a particle size of less than 2 mm. 2,3-Dihydrobenzofuran and *p*-coumaric acid were purchased from Wako Pure Chemical Industries Ltd. for use as authentic samples. Acid lignin from bamboo was prepared according to the Technological Association of the Pulp and Paper Industry (TAPPI) standard method (T 222) [22].

Fast pyrolysis was performed with a Py-GC-flame ionization detector (FID): EGA/PY-3030D pyrolyzer (Frontier Lab) and Shimadzu GC-2010 Plus. 0.5 mg of samples were pyrolyzed at 400 °C, 500 °C, and 600 °C. GC was equipped with an Ultra ALLOY-5 (30 m × 0.25 mm i.d.; 0.25 μm film thickness) capillary column. The injector temperature was maintained at 300 °C, and the split injection was at a 1:100 split rate. The column oven temperature was held at 40 °C for 5 min and subsequently raised to 300 °C at a rate of 4 °C/min.

Slow pyrolysis was performed using an electric tube furnace. A sample of 30 g of bamboo powder was placed in a quartz reactor and set into the electric furnace. The furnace was heated to 600 °C at a rate of 20 °C/min and then maintained for 150 min. Bio-oil was collected from the reactor outlet. The obtained bio-oil was analyzed with a JMS T-100GCV GC-TOFMS instrument (JEOL) equipped with an Rtx-5MS capillary column (60 m × 0.25 mm i.d.; 0.25 μm film thickness). NIST mass spectral library were employed for the identification of each peak.

Separation and isolation of bio-oil products from the slow pyrolysis of bamboo were performed with column chromatography using LH20 and silica-gel C200. Isolated compounds were identified by ¹H-NMR and ¹³C-NMR spectrometry.

3. RESULTS AND DISCUSSION

3.1 Pyrolysis product analysis

The results of the chemical and proximate analysis of moso bamboo are presented in Table I. The content of the 1% NaOH soluble fraction from moso bamboo was higher compared with other wood species because of the high amount of xylan in bamboo. These results were similar to those previously reported for moso bamboo [21].

A chromatogram of the bio-oil produced from the fast pyrolysis of bamboo is shown in Fig.1. The major products in bio-oil were identified by GC/MS analysis (Table II). These products are well known as typical compounds produced by pyrolysis of many herbaceous

Table I Chemical and proximate analysis of bamboo

Item	Value
Moisture	9.41
Volatile	73.00
Fixed carbon	16.35
Ash	1.25
Hot water extractives	17.02
1% NaOH extractives	38.13
Alcohol-benzene extractives	8.70
Klason Lignin	24.37
Holocellulose	65.66
α-Cellulose	41.01

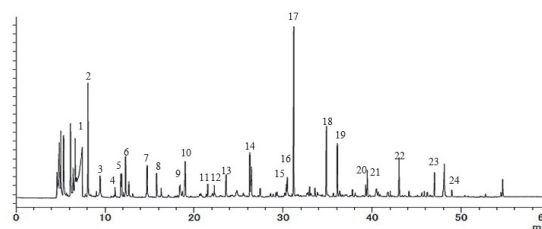


Fig.1 GC-FID chromatogram of bio-oil from fast pyrolysis of bamboo

plants as well as bamboo species [18, 21, 23-27]. All bio-oil products were derived from cellulose, hemicellulose, and lignin in the bamboo cell wall. Acetic acid was formed by the hydrolysis of acetyl groups in glucuronoxylan, known to be a typical hemicellulose in bamboo, and furans were pyrolysis products from cellulose and hemicellulose. On the other hand, phenols were produced from lignin pyrolysis, and their structures reflected the original structures of *p*-hydroxy, guaiacyl, and syringyl units in the lignin polymer. 2,3-Dihydrobenzofuran (DHBF) of peak 17 was a major product; however, the formation pathway of this compound, in particular the furan moiety, was very complex. Furthermore, the peaks around peak 17 were identified as phenols, 4-methylguaiacol (peak 15), and catechol (peak 16), as shown in Fig. 1 and Table II. These results indicated that the retention time of DHBF, which has low polarity, on the GC chromatogram should be shorter than that of peak 17. For direct identification of peak 17, authentic DHBF compound was purchased and chromatographically analyzed. A comparison of the chromatograms of the authentic compound and the bio-oil product represented by peak 17 is shown in Fig.2. The retention times of these two compounds are obviously different, which indicates that they are not the same compound. The mass spectra of these two compounds are shown in Fig.3; their spectra are very similar. This indicates that the compound corresponding

Table II Major products in bio-oil from bamboo fast pyrolysis by GC-MS analysis

Peak No	R.T.	%	Compound
1	5.906	10.953	Acetic acid
2	7.825	5.001	1-Hydroxy-2-propanone
3	9.135	0.997	Propanoic acid
4	10.822	0.506	Toluene
5	11.579	1.223	1-Hydroxy-2-butanone
6	12.129	2.114	Cyclopentanone
7	14.391	1.683	Furfural
8	15.377	1.283	2-cyclopenten-1-one
9	18.294	0.560	Furfuryl alcohol
10	18.557	2.490	Dihydrofuran-2(3H)-one
11	21.102	0.652	2(5H)Furanone
12	21.872	0.537	Phenol
13	23.008	1.314	Cyclotene
14	25.716	2.208	<i>o</i> -Guaiacol
15	29.772	0.545	4-Methylguaiacol
16	30.059	1.143	Catechol
17	30.710	9.781	2,3-Dihydrobenzofuran?
18	34.252	2.311	4-Vinylguaiacol
19	35.580	2.790	Syringol
20	38.701	0.681	4-Methylsyringol
21	38.812	1.345	<i>trans</i> -Isoeugenol
22	42.445	1.987	3',5'-Dimethoxyacetophenone
23	46.398	1.234	4-Allylsyringol
24	48.417	0.358	Acetosyringon

to peak 17 is a compound other than DHBF and that DHBF was not formed during fast pyrolysis of bamboo. Therefore, isolation and spectral analysis of this compound is required to elucidate the chemical structure of the compound represented by peak 17.

A sample of 30 g of bamboo powder (extractive free) was pyrolyzed in a quartz reactor at 600 °C, and approximately 12 g of bio-oil was obtained. The obtained bio-oil was separated using an open column packed with LH20. Low molecular fractions were recovered and separated by silica gel column chromatography using this method. A major compound of peak 17 was isolated and analyzed by ¹H-NMR and ¹³C-NMR spectrometry. The analytical results are shown in Table III. For comparison, the ¹H-NMR and ¹³C-NMR spectra of the authentic compound of DHBF

are presented in Table IV. The ¹³C-NMR spectrum of the peak 17 indicated the presence of phenol and an aliphatic conjugated structure in the molecule. From the chemical shifts of ¹H-NMR and ¹³C-NMR and coupling constant of ¹H-NMR, this major compound of peak 17 was identified to be 4-vinylphenol (4VP, Fig.4). This product is likely derived from a *p*-hydroxy unit, particularly from the *p*-coumarate structure in the bamboo lignin polymer. The results of Py-GC of *p*-coumaric acid and the formation mechanism of 4VP from *p*-coumaric acid are shown in Fig.5. Only 4VP was obtained as the major product, and no minor products were obtained. First, one proton radical is withdrawn from the γ -hydroxymethyl group by pyrolysis followed by homolytic cleavage at the β - γ bond in the side chain of lignin to release carbon dioxide. Li et al. [28] reported the formation of 4VP by the pyrolysis of herbaceous plants. They used analytical pyrolysis to evaluate the lignin structure and did not aim to produce bio-oil.

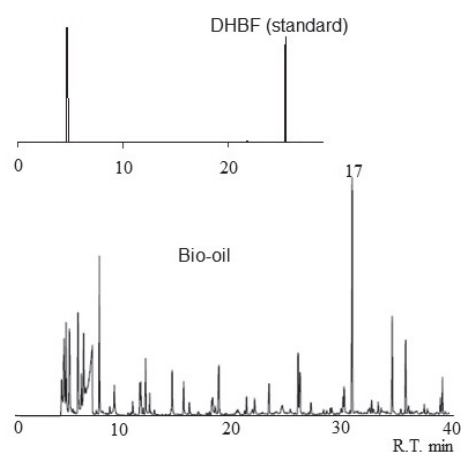


Fig.2 GC chromatograms between authentic DHBF (upper part) and bio-oil (bottom part)

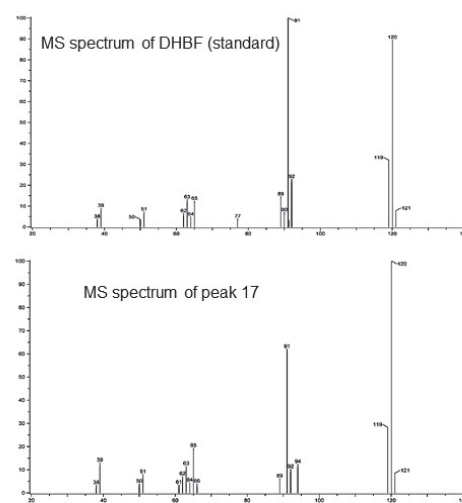


Fig.3 Comparison of MS spectra between authentic DHBF (upper part) and peak 17 (bottom part)

The presence of *p*-coumarate in the bamboo lignin polymer has been proposed by several researchers [29-31]. Higuchi et al. [32] elucidated the characteristic structure of bamboo lignin by acidolysis and proposed that the polymeric system of bamboo lignin is composed of about 10:68:22 of *p*-coumaryl alcohol, coniferyl alcohol, and sinapyl alcohol via similar linkages found in spruce lignin, and that *p*-coumaric acid (0.07/C6-C3) is esterified at the terminal γ -carbons of the side chains of the polymeric system. Tanahashi et al. [33] also analyzed the bamboo lignin structure using acidolysis and mild ozonolysis methods and proposed that many *p*-hydroxyphenyl units are contained in the acidolysis residue, whereas the low molecular weight acidolysis products contain many syringyl units. In other words, bamboo lignin might be composed of both condensed and uncondensed parts; the former mainly includes *p*-hydroxyphenyl units, and the latter mainly includes syringyl and guaiacyl units. Several studies have reported that grass lignins are acylated at the γ -position by *p*-coumarates; primarily syringyl units are acylated in maize, bamboo, and bromegrass as follows. There is convincing evidence that the biochemical process involved, from three possible pathways, is the incorporation into normal lignification of preacylated

monolignols [34-36]. Lu and Ralph [37] proposed three possible pathways for the incorporation of *p*-coumarates into lignins (shown in Fig.6) by acylation at the γ -position by *p*-coumarates. In the analysis of the biosynthesis of the monolignol conjugates, Withers et al. [38] identified the transferase enzyme OsPMT from *O. sativa* and confirmed that the enzyme produced primary monolignol *p*-coumarates. This fact should reflect the properties of bio-oil obtained from herbaceous plants and contribute to the different bio-oil characteristics from woody biomass. The formation of 4VP from these structures can be explained by the reaction mechanism shown in Fig.7.

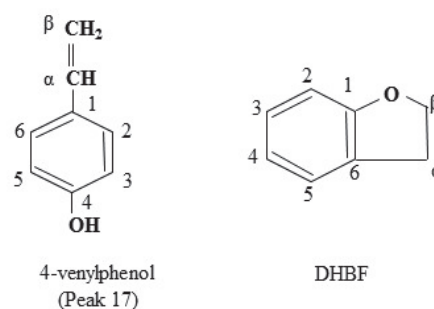


Fig.4 Chemical structure of peak 17 and DHBF

Table III Chemical shift of $^1\text{H-NMR}$ and $^{13}\text{C-NMR}$ of peak 17

	^1H	^{13}C
C1	-	129.6
C2	6.75 (d)	127.5
C3	7.01 (d)	115.4
C4	-	156.8
C5	7.01 (d)	115.4
C6	6.75 (d)	127.5
α	6.73 (t)	136.5
β	5.51 (cis,d) 5.01 (trans,d)	110.8

*Refer to the number of $^1\text{H-NMR}$ and $^{13}\text{C-NMR}$ of DHBF

Table IV Chemical shift of $^1\text{H-NMR}$ and $^{13}\text{C-NMR}$ of DHBF

	^1H	^{13}C
C1	-	
C2	6.69 (d)	109.0
C3	7.01 (t)	124.8
C4	6.78 (t)	120.3
C5	7.09 (d)	127.7
C6	-	127.1
α	4.37 (t)	29.4
β	3.01 (t)	70.8

*Refer to the number of $^1\text{H-NMR}$ and $^{13}\text{C-NMR}$ of DHBF

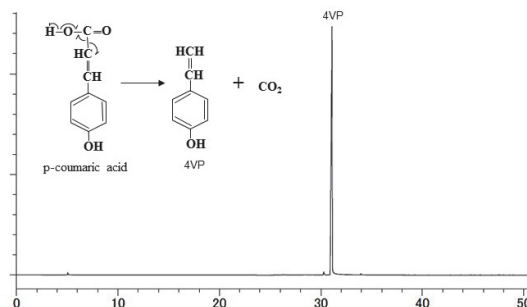


Fig.5 Py-GC chromatogram of *p*-coumaric acid and formation mechanism of 4VP

On the other hand, Hosoya et al. [39] and Asmadi et al. [40] reported that the pyrolysis of guaiacol at 600 °C for 80 s produces 2,3-benzofuran in a very small yield (0.95%). They assumed that 2-ethoxy phenol should be formed as an important intermediate by intermolecular rearrangement at the *o*-methoxyl position. However, they did not obtain DHBF in the pyrolytic products.

3.2 Effect of pyrolysis conditions on bio-oil composition

The chemical properties of bio-oil produced by fast pyrolysis depend on the reaction temperature and residence time of pyrolysis products in a pyrolyzer. In general, the optimum temperature of fast pyrolysis is determined by bio-oil yield and considered to be 450–600 °C. This optimum temperature range differs according to the chemical properties and moisture content of the raw materials [41]. For the evaluation of this temperature effect on the composition of bamboo bio-oil, 60–80 mesh bamboo powder was pyrolyzed at

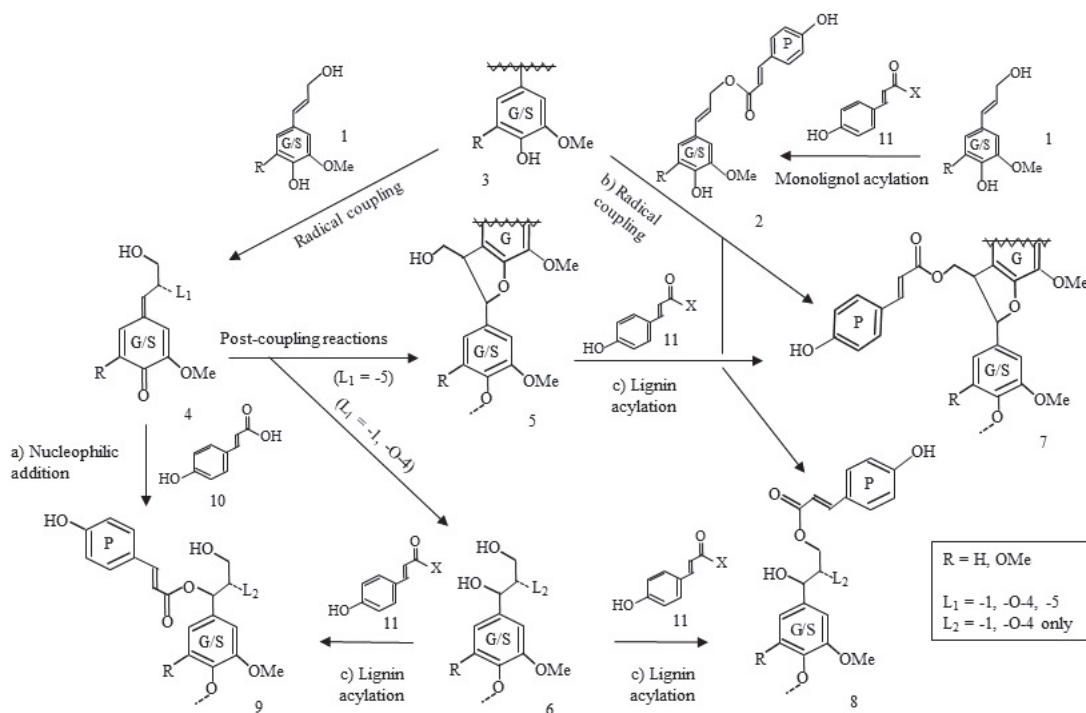


Fig.6 Three possible pathways for incorporation of p-coumarates into lignins proposed by Lu and Ralph [37]

400 °C, 500 °C, and 600 °C using Py-GC. The bamboo pyrolysis products obtained at various temperatures are listed in Table V. In the case of pyrolysis at 400 °C, bio-oil yield (total peak area) was very low and only 4VP was obtained as the major compound. This result indicates that the p-coumarate structures in the bamboo lignin polymer have higher reactivity to thermal treatment compared with other lignin structures. In fact, p-coumaric acid decomposed in an injection port of GC at 300 °C during the GC analysis procedure. The yields of products containing a furan structure, such as furfural, furfuryl alcohol, dihydrofuran-2(3H)-one, and 2(5H)-furanone, increased with pyrolysis temperature. On the other hand, yields of phenolic compounds decreased with pyrolysis temperature, except for catechol. Catechol was derived from a guaiacyl unit by the demethylation of aromatic methoxyl groups from produced phenolic compounds. This reaction required higher activation energy.

Xiao et al. [42] evaluated the pyrolytic property of bamboo by analyzing the obtained gas, char, and tar. They concluded that when the temperature was increased from 400 °C to 700 °C, the percentage of moisture in tar increased from approximately 13% to 20%, whereas the higher heating value (HHV) of the bamboo tar decreased from approximately 28 MJ/kg to 21 MJ/kg. Lira et al. [43] reported the influence of pyrolysis temperature on the energy balance of pyrolysis products using Amazon tucumã seeds. They indicated that the HHV of bio-oil increased with temperatures up to 550 °C (32 MJ/kg) and decreased with increasing pyrolysis temperature. In addition, they estimated that the maximum bio-oil yield occurred at 500 °C and the

minimum water content in bio-oil was obtained at 550 °C. Lou et al. [18] assessed the effect of ash content in bamboo and rice straw on bio-oil yield; the ash content of bamboo and rice straw was 0.62% and 13.53%, respectively. They indicated that the bio-oil yield from bamboo and rice straw reached maximum values at 500 °C and 450 °C, respectively, as pyrolysis temperature increased and the secondary reaction intensified, causing the bio-oil yield to decline. Liu et al. [44] reported that high yields of furfural and simple phenols, such as phenol, 4-methylphenol, and 4-ethyl phenol, were obtained from tobacco pyrolysis at 600 °C. On the other hand, moso bamboo pyrolysis resulted in a high yield of 4VP at 600 °C (Table V). These results indicate that pyrolysis temperature, feedstock ash content, and lignin structure may influence the pyrolytic behavior of moso bamboo.

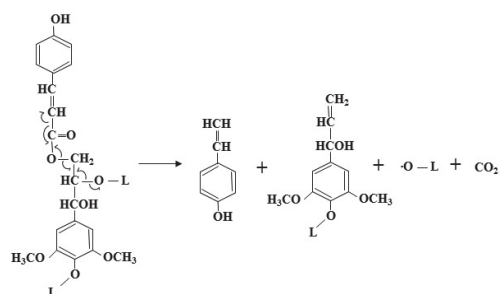


Fig.7 Possible formation pathways of 4VP from p-coumarates structure in lignins

Table V Major products and peak area in in bio-oil from different temperature pyrolysis

Peak No	Compound	R.T.	Peak area (%)		
			673	773	873
1	Acetic acid	5.906	19.247	10.953	5.113
2	1-Hydroxy-2-propanone	7.825	3.984	5.001	9.623
3	Propanoic acid	9.135	0.969	0.997	0.704
4	Toluene	10.822	-	0.506	0.798
5	1-Hydroxy-2-butanone	11.579	1.468	1.223	2.130
6	Cyclopentanone	12.129	0.835	2.114	0.648
7	Furfural	14.391	1.318	1.683	1.798
8	2-cyclopenten-1-one	15.377	1.529	1.283	1.099
9	Furfuryl alcohol	18.294	0.165	0.560	0.411
10	Dihydrofuran-2(3H)-one	18.557	1.823	2.490	2.299
11	2(5H)Furanone	21.102	0.503	0.652	1.647
12	Phenol	21.872	0.463	0.537	0.288
13	Cyclotene	23.008	0.446	1.314	1.279
14	<i>o</i> -Guaiacol	25.716	1.964	2.208	1.169
15	4-Methyl guaiacol	29.772	-	0.545	0.401
16	Catechol	30.059	-	1.143	2.375
17	4-Vinylphenol	30.710	14.968	9.781	9.573
18	4-Vinylguaiacol	34.252	4.102	2.311	1.094
19	Syringol	35.580	1.351	2.790	0.440
20	4-Methyl syringol	38.701	-	0.681	0.559
21	<i>trans</i> -Isoeugenol	38.812	1.505	1.345	0.215
22	3',5'-dimethoxyacetophenone	42.445	1.197	1.987	0.299
23	4-Allyl syringol	46.398	4.712	1.234	-
24	Acetosyringon	48.417	0.228	0.358	0.252

The residence time of pyrolysis products in a reactor is also an important factor, which affects bio-oil composition. In general, fast or flash pyrolysis is achieved in a reaction time of less than 2 s. Additional reaction time leads to secondary reactions in the pyrolyzer and makes bio-oil composition more complex. To evaluate the effect of residence time on bio-oil composition, bio-oil produced by slow pyrolysis was analyzed by GC and the result was compared with a Py-GC chromatogram (residence time was set to less than 2 s in a pyrolyzer heating zone at 500 °C). The analytical results are listed in Table VI. In comparison with fast pyrolysis, slow pyrolysis produced simple phenols such as phenol, guaiacol, methyl guaiacol, syringol, and methyl syringol in higher yields. These compounds were produced from complex phenols by secondary reactions and were considered to be heat stable.

Acid lignin prepared from bamboo powder was subjected to Py-GC at 500 °C. The results are listed in Table VI together with the data from fast pyrolysis of bamboo powder at 500 °C. The yields of 4-methylguaiacol and 4-methylsyringol from bamboo

acid lignin were significantly greater than those from bamboo powder and were beyond the theoretical amounts (the lignin content of bamboo is 24.3%). On the other hand, the yield of 4VP from acid lignin was lower than that from bamboo powder, despite the yield of 4-vinylguaiacol from acid lignin being greater than that from bamboo powder. This fact indicates that different yields of phenols with unsaturated side chains likely result from differences in the bonding mode of the lignin polymer. As mentioned above, 4VP was derived from *p*-coumarate esters at the γ -position of the lignin side chain, and cleavage of the ester bond by acid treatment formed soluble *p*-coumaric acid. Therefore, the *p*-coumarate content in acid lignin should be decreased, and 4VP should be produced by Py-GC in low yield. In addition, 4-vinylguaiacol should be derived from the lignin complex with higher resistance to acid, such as an aryl ether structure.

Yi et al. [45] applied bamboo bio-oil as a source for resin with phenol and formaldehyde. The performance of the plywood specimen bonded with bio-oil-phenol-formaldehyde resin was able to achieve the demands of the Chinese National Standard for

Plywood (GB/T 9846-2004). Hong et al. [46] demonstrated that bio-oil from bamboo has protective effects against N-methyl-D-aspartate-induced cell death in primary cultured cortical neurons and has anti-plasmin effects as determined using a fibrin and fibrinogen degradation products assay. Bio-oil has potential demand not only as a fuel but also for chemicals used in the wood and pharmaceutical industries. For utilization of bio-oil in various fields, estimation and control of its properties are becoming increasingly important. Technologies for reforming bio-oil have also been studied [47], and these technologies are expected to lead to an expanded demand for bio-oil.

4. CONCLUSION

Bamboo powder was pyrolyzed using Py-GC, and the effect of pyrolysis conditions on the product distribution of bio-oil was evaluated. Although a major product in bamboo bio-oil was previously assumed to be DHBFB

comparison with a GC/MS database, this compound was identified to be 4VP by isolation and NMR analysis in this study. The formation pathway of 4VP demonstrated that p-coumarate esters are present in bamboo lignins as well as herbaceous plants by acylation at the γ -position at the side chain in lignin polymer, and that 4VP should be derived from this p-coumarates structure. The evaluation of the effect of pyrolysis temperature on the product distribution of bio-oil revealed that increasing pyrolysis temperature resulted in high yields of compounds containing a furan structure, such as furfural, furfuryl alcohol, dihydrofuran-2(3H)-one, and 2(5H)-furanone, and the yields of phenolic compounds decreased, except that of catechol. Compared with fast pyrolysis, slow pyrolysis produced simple phenols, such as phenol, guaiacol, methyl guaiacol, syringol, and methyl syringol, in high yields. These compounds were formed from complex phenols by secondary reactions and considered to be heat stable. In acid lignin pyrolysis, the high yields of 4-methylguaiacol and

Table VI Major products of fast pyrolysis from bamboo powder and bamboo acid lignin and from slow pyrolysis

Peak No	Compound	R.T.	Peak area (%)		
			Fast pyrolysis		Slow pyrolysis
			Bamboo powder	Acid lignin	Bamboo powder
1	Acetic acid	5.906	10.953		8.465
2	Acetol	7.825	5.001	0.626	4.844
3	Propanoic acid	9.135	0.997		1.162
4	Toluene	10.822	0.506		-
5	1-Hydroxy-2-butanone	11.579	1.223		2.453
6	Cyclopentanone	12.129	2.114		0.392
7	Furfural	14.391	1.683		0.388
8	2-cyclopenten-1-one	15.377	1.283		0.473
9	Furfuryl alcohol	18.294	0.560		3.086
10	Dihydrofuran-2(3H)-one	18.557	2.490		0.473
11	2(5H)Furanone	21.102	0.652		0.522
12	Phenol	21.872	0.537	2.079	6.114
13	Cyclotene	23.008	1.314		0.222
14	<i>o</i> -Guaiacol	25.716	2.208	5.078	8.221
15	4-Methylguaiacol	29.772	0.545	7.633	3.033
16	Catechol	30.059	1.143	0.442	-
17	4-Vinylphenol	30.710	9.781	6.006	9.829
18	4-Vinylguaiacol	34.252	2.311	4.681	3.985
19	Syringol	35.580	2.790	3.577	6.958
20	4-Methylsyringol	38.701	0.681	5.775	1.638
21	<i>trans</i> -Isoeugenol	38.812	1.345	1.929	2.108
22	3',5'-dimethoxyacetophenone	42.445	1.987	2.065	1.726
23	4-Allylsyringol	46.398	1.234	2.026	2.172
24	Acetosyringon	48.417	0.358	2.590	0.239

4-methylsyringol from bamboo acid lignin were significantly greater compared with bamboo powder, even beyond the theoretical amounts. The yield of 4VP from acid lignin was lower than that from bamboo powder, even though the yield of 4-vinylguaiacol from acid lignin was greater. In conclusion, the chemical characteristics of bio-oil are influenced by the biomass source, pyrolysis conditions, and the type of pyrolyzer.

5. REFERENCES

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