Improvement of Bio-oil Production System by Using Spray Condenser: Investigation of Yields, Properties and Production Cost

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Abstract

This article presented an improvement of bio-oil production system by using the spray condenser, which was developed from previous work. Napier grasses (NG), sugarcane leaves (SL) and rubber leaves (RL) were used as raw material in order to produce as bio-oil. The direct contact heat exchanger called conventional condenser and indirect contact heat exchanger called spray condenser were employed while the bio-oil and the ethanol were also applied as absorber in the spray condenser. The circulating fluidized bed reactor was employed to produce the bio-oil by using fast pyrolysis process. The condition generating the highest yield of the bio-oil production whether the conventional condenser or the spray condenser was 60 kg/hr of feed rate and 480°C of bed temperature. From the result of the bio-oil production, it was found that the highest yields of bio-oil production from NG, SL and RL using conventional condenser were 43.73 %wt, 49.47 %wt and 37.00 %wt, respectively. The highest yield of bio-oil production from NG, SL and RL performing on spray condenser and the using of ethanol as absorber were 55.67 %wt, 62.53 %wt and 44.60 %wt, respectively while the highest yield of bio-oil production from RL performing on spray condenser and the using of bio-oil as absorber was 44.60 %wt. The using of the spray condenser and using of the ethanol as absorber can improve the properties of bio-oil such as heating value and can also increase yield of bio-oil, but the viscosity of bio-oil was increased. Besides, the using of spray condenser can increase the efficiency of energy conversion and can decrease the cost production of bio-oil production, it can also solve the problem about the dirty from the volatile or droplet in the bio-oil that was adhesive in the recirculating blower in case of the system using returned NGC to bio-oil production process.

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Tables

Table 1. Physical properties of the experimental materials.

Properties	NG	SL	RL	Sand	Units
Mean diameter (the Sauter's mean diameter)	1-3	1-3	1-3	0.249	mm
Bulk density	137.8	185.7	220.6	1,524	kg/m ³
Porosity	-	-	-	42.87	%
Heating value (ASTM D240)	15,233	15,999	14,005	-	kJ/kg
Proximate analysis (ASTM D7582-15)					
- Moisture	12.14	8.0	7.8	-	wt%
- Volatile matter	75.37	70.5	66.9	-	wt%
- Fixed Carbon*	7.33	15.0	13.8	-	wt%
- Ash	5.15	6.5	11.5	-	wt%
Elemental analysis (Perkin Elmer PE2400 Series II)					
- C	40.03	40.12	44.14	-	%
- H	6.02	6.09	6.45	-	%
- N	1.69	0.25	0.87	-	%
- S	1.08	N.D.	N.D.	-	%
- O*	51.18	53.54	48.54	-	%

*Fixed Carbon and Oxygen were calculated by difference, N.D. was not detected.

Table 2. The properties of the bio-oil.

No.	Sampling name	Heating value (kJ/kg)	Water content (%)	Viscosity (cSt)	Density (kg/m ³)	pH	Ultimate analysis (%) (Perkin Elmer PE2400 Series II)			
							C	H	N	O*
1	Bio-oil from Napier grass without spray (NG-W)	7,252	34.42	13.62	1,137	2.6	27.22	8.72	1.32	64.06
2	Bio-oil from Sugarcane leave without spray (SL-W)	9,464	39.49	14.03	1,245	3.1	31.45	8.84	0.10	59.61
3	Bio-oil from Rubber leave without spray (RL-W)	10,487	26.44	10.12	1,105	2.5	33.58	8.68	0.14	57.60
4	Bio-oil from Napier grass with spray Ethanol (NG-E)	18,855	-	1.76	1,002	5.6	39.63	10.94	0.92	48.51
5	Bio-oil from Sugarcane leave with spray Ethanol (SL-E)	17,377	-	2.04	1,107	4.4	36.39	12.03	0.08	51.50
6	Bio-oil from Rubber leave with spray Ethanol (RL-E)	22,270	-	1.92	832	6.1	44.48	12.59	0.07	42.86
7	Bio-oil from Napier grass when removed Ethanol (NG-RE)	20,970	31.09	24.92	1,180	2.4	49.52	9.66	0.39	40.43
8	Bio-oil from Sugarcane leave when removed Ethanol (SL-RE)	19,559	33.27	27.63	1,250	2.9	48.51	9.28	0.27	41.94
9	Bio-oil from Rubber leave when removed Ethanol (RL-RE)	23,358	24.48	23.24	1,125	2.4	52.56	10.48	1.18	35.78
10	Bio-oil from Napier grass with spray bio-oil (NG-B)	13,828	30.28	16.76	1,145	2.8	37.89	9.26	0.53	52.32

* Oxygen was calculated by difference.

Table 3. The chemical components of the bio-oil and the ethanol by GC-MS method.

RT (min)	Compound name	Formula	Chromatographic peak area of the bio-oil and the ethanol (%)									
			NG-W	SL-W	RL-W	NG-E	SL-E	RL-E	NG-RE	SL-RE	RL-RE	NG-B
3.84	Methylamine, N,N-dimethyl-	C ₃ H ₉ N	1.09	0.15	0.21	-	-	-	0.79	0.31	0.42	0.51
3.90	Acetaldehyde	C ₂ H ₄ O	-	-	-	0.32	0.11	0.15	-	-	-	-
4.03	Methyl formate	C ₂ H ₄ O ₂	-	0.13	0.13	-	-	-	-	-	-	0.18
4.30	Ethyl formate	C ₃ H ₆ O ₂	-	-	-	0.54	0.49	0.47	-	-	0.11	-
4.33	Acetic acid, methyl ester	C ₃ H ₆ O ₂	-	-	-	-	-	-	-	-	-	0.05
4.45	Ethane, 1-ethoxy-1-methoxy-	C ₅ H ₁₂ O ₂	-	-	-	-	-	-	-	-	-	-
4.49	Methane, diethoxy-	C ₅ H ₁₂ O ₂	-	-	-	0.15	0.17	-	-	-	-	-
4.69	Ethyl Acetate	C ₄ H ₈ O ₂	-	-	-	1.12	1.78	0.45	-	-	0.12	-
4.72	Ethane, 1,1-diethoxy-	C ₆ H ₁₄ O ₂	-	-	-	1.06	0.41	1.23	-	-	-	-
4.90	2-Propanol, 2-methyl-	C ₄ H ₁₀ O	-	-	-	1.59	0.99	2.34	-	-	-	-
5.20	Ethanol	C ₂ H ₆ O	0.11	0.10	0.05	60.25	40.54	80.26	2.45	2.71	7.00	0.10
5.36	Methyl vinyl ketone	C ₄ H ₆ O	-	-	-	-	-	-	-	-	0.22	-
5.45	Propane, 1,1-diethoxy-	C ₇ H ₁₆ O ₂	-	-	-	0.22	0.24	0.29	-	-	-	-
5.61	Acetic acid ethenyl ester	C ₄ H ₆ O ₂	0.24	0.45	0.41	0.16	0.12	-	0.68	0.38	-	0.28
6.40	2-Methoxytetrahydrofuran	C ₅ H ₁₀ O ₂	-	0.12	0.16	-	-	-	-	-	-	-
6.54	1-Propanol	C ₃ H ₈ O	-	-	-	0.17	0.15	0.24	-	-	-	-
7.06	2-Ethoxytetrahydrofuran	C ₆ H ₁₂ O ₂	-	-	-	0.39	0.14	-	-	-	-	-
7.18	Butane, 1,1-diethoxy-3-methyl-	C ₉ H ₂₀ O ₂	-	-	-	-	-	-	-	-	-	-
7.44	Undecane	C ₁₁ H ₂₄	-	-	-	-	-	-	-	-	-	0.05
7.64	Dihydrocarveol	C ₁₀ H ₁₈ O	-	-	-	-	-	0.21	-	-	-	-
7.79	2-Propen-1-ol	C ₃ H ₆ O ₂	-	-	-	0.11	0.06	-	-	-	-	-
8.22	3-Penten-2-one	C ₅ H ₈ O	-	-	-	-	-	-	-	-	-	-
8.31	Butane, 1,1-diethoxy-	C ₈ H ₁₈ O ₂	-	-	-	-	-	0.13	-	-	-	-
8.32	Pentane, 1,1-diethoxy-	C ₉ H ₂₀ O ₂	-	-	-	-	-	-	-	-	-	-
8.47	Benzene, 1,4-dimethyl-	C ₁₃ H ₂₀	-	-	-	-	-	0.25	-	-	-	-
9.42	Pyridine	C ₅ H ₅ N	0.53	0.25	0.18	0.25	0.10	0.12	0.49	0.25	0.18	0.51
9.46	Cyclopentanone	C ₅ H ₈ O	-	-	-	-	-	-	-	-	-	-
9.57	Methane, (methylsulfinyl) (methylthio)-	C ₃ H ₈ OS ₂	-	0.12	0.11	0.39	0.34	-	-	-	-	-
9.59	D-Limonene	C ₁₀ H ₁₆	-	-	-	-	-	1.00	-	-	-	-
10.11	Pyridine, 2-methyl-	C ₆ H ₇ N	0.10	0.04	-	-	-	-	0.21	0.07	0.06	0.07
10.12	Hexane, 1,1-diethoxy-	C ₁₀ H ₂₂ O ₂	-	-	-	-	-	-	-	-	-	-
10.46	Furan, tetrahydro-2,5-dimethoxy-	C ₆ H ₁₂ O ₃	-	0.07	-	-	-	-	-	-	-	0.08
10.62	Styrene	C ₈ H ₈	-	-	-	-	-	-	-	-	-	-
10.71	Propanoic acid, 2-oxo-, ethyl ester	C ₅ H ₈ O ₃	-	-	-	0.27	-	0.34	0.43	0.13	0.32	-
10.91	1,4-Dioxin, 2,3-dihydro-	C ₄ H ₆ O ₂	-	0.10	0.07	-	-	-	-	-	-	-

10.93	Furan, 2,5-diethoxytetrahydro-	C ₈ H ₁₆ O ₃	-	-	-	0.41	1.48	-	-	-	-	-
11.21	Acetoin	C ₄ H ₈ O ₂	0.18	0.12	0.10	0.12	0.11	-	0.25	0.17	-	0.10
11.28	Tridecane	C ₁₃ H ₂₈	-	-	-	-	-	-	-	-	-	0.18
11.33	Furan, 2,5-diethoxytetrahydro-	C ₈ H ₁₆ O ₃	-	-	-	0.77	1.52	0.52	-	-	-	-
11.35	Propane, 1,1-diethoxy-2-methyl-	C ₈ H ₁₈ O ₂	-	-	-	-	-	-	-	-	-	-
11.45	2-Propanone, 1-hydroxy-	C ₃ H ₆ O ₂	6.37	4.12	3.06	2.84	2.76	0.74	6.96	5.36	0.95	3.10
11.47	Propane, 1,1,3-triethoxy-	C ₉ H ₂₀ O ₃	-	-	-	-	-	-	-	-	-	-
11.56	Pyridine, 3-methyl-	C ₆ H ₇ N	0.15	0.07	0.06	-	-	-	0.20	0.10	0.05	0.11
11.71	Pyridine, 4-methyl-	C ₆ H ₇ N	0.09	-	-	-	-	-	0.16	-	-	0.10
12.34	Pyridine, 2,4-dimethyl-	C ₇ H ₉ N	0.04									
12.37	Phenylethyne	C ₈ H ₆	-	-	-	-	-	-	-	-	-	-
12.49	Acetic acid, (acetyloxy)-	C ₄ H ₆ O ₄	-	-	-	-	-	-	0.51	0.44	0.50	-
12.56	2-Cyclopenten-1-one	C ₅ H ₆ O	0.20	0.25	0.21	0.63	0.45	0.20	0.82	0.61	0.51	0.45
12.73	1-Hydroxy-2-butanone	C ₄ H ₈ O ₂	1.11	0.72	0.54	0.48	0.44	-	1.29	0.88	0.14	0.64
12.78	2-Cyclopenten-1-one, 2-methyl-	C ₆ H ₈ O	-	-	-	0.33	0.20	0.13	-	-	0.18	0.19
12.99	Tetradecane	C ₁₄ H ₃₀	-	-	-	-	-	-	-	-	-	0.26
13.08	Butanoic acid, hexyl ester	C ₁₀ H ₂₀ O ₂	0.13	0.08	0.06	-	-	-	0.33	0.20	-	0.41
13.26	2(5H)-Furanone, 5-methyl-	C ₅ H ₆ O ₂	0.26	1.12	0.92	-	-	-	0.39	0.48	0.10	1.11
13.50	3-Furaldehyde	C ₅ H ₄ O ₂	-	-	-	0.14	0.10	0.17	-	-	-	-
13.69	Acetic acid	C ₂ H ₄ O ₂	12.35	15.85	16.37	4.84	6.23	1.79	16.20	13.27	6.00	13.51
15.77	Cyclotetradecane	C ₁₄ H ₂₈	-	-	-	-	-	-	-	-	-	-
15.78	Benzene, 4-ethenyl-1,2-dimethyl-	C ₁₀ H ₂₄	-	-	-	-	-	-	-	-	-	-
14.04	2-Propanone, 1-(acetyloxy)-	C ₅ H ₈ O ₃	0.26	0.39	-	-	-	-	-	-	-	0.57
14.05	Ethoxyacetaldehyde diethylacetal	C ₈ H ₁₈ O ₃	-	-	0.42	3.62	5.39	0.56	2.21	2.71	1.78	-
14.15	Furfural	C ₅ H ₄ O ₂	0.08	0.51	0.49	1.42	1.34	0.59	0.78	0.92	0.73	1.14
14.67	Formic acid	CH ₂ O ₂	1.02	3.14	3.20	-	-	-	0.97	1.22	0.43	3.21
14.72	Indene	C ₉ H ₈	-	-	-	-	-	-	-	-	-	-
14.88	Pentane, 1,1-diethoxy-	C ₉ H ₂₀ O ₂	-	-	-	-	0.18	-	-	-	-	-
14.96	Ethanone, 1-(2-furanyl)-	C ₆ H ₆ O ₂	-	0.12	0.10	0.21	0.20	-	0.25	0.13	0.08	0.26
15.04	2,5-Hexanedione	C ₆ H ₁₀ O ₂	0.17	0.13	0.14	-	-	-	0.36	0.14	0.11	0.13
15.31	Propanoic acid	C ₃ H ₆ O ₂	1.11	1.14	1.11	0.37	0.40	-	1.36	0.88	0.42	1.29
15.37	Benzaldehyde	C ₇ H ₆ O	-	-	-	-	-	-	-	-	0.19	-
15.53	n-Pentadecanol	C ₁₅ H ₃₂ O	-	-	-	-	-	-	-	-	-	-
15.55	2-Cyclopenten-1-one, 3-methyl-	C ₆ H ₈ O	0.31	0.33	0.33	0.30	0.29	0.12	0.74	0.45	0.51	0.52
15.89	2-Cyclopenten-1-one, 2,3-dimethyl-	C ₇ H ₁₀ O	-	-	-	0.15	0.13	-	0.21	0.16	0.26	0.23
16.18	2-Furancarboxaldehyde, 5-methyl-	C ₆ H ₆ O ₂	-	-	-	-	-	-	0.14	0.20	0.28	0.23

16.20	2-Pentanone, 5,5-diethoxy-	C ₉ H ₁₈ O ₃	-	-	-	0.42	0.52	-	-	-	-	-
16.39	Propylene Glycol	C ₃ H ₈ O ₂	0.35	0.15	0.16	-	-	-	0.30	0.15	0.14	0.17
16.49	Hexadecane	C ₁₆ H ₃₄	-	-	-	-	-	-	-	-	-	0.34
16.83	Pentanoic acid, 4-oxo-, ethyl ester	C ₇ H ₁₂ O ₃	-	-	-	-	-	-	-	-	0.11	-
16.97	Butanoic acid	C ₄ H ₈ O ₂	0.28	0.15	0.17	-	-	-	-	-	-	-
16.98	Octanoic acid	C ₈ H ₁₆ O ₂	-	-	-	-	-	-	0.25	0.35	0.27	0.45
17.09	1,2-Ethanediol	C ₂ H ₆ O ₂	0.57	0.43	0.49	-	-	-	0.63	0.48	0.18	0.50
17.15	1,2-Ethanediol, monoacetate	C ₄ H ₈ O ₃	0.37	0.80	0.95	-	-	-	0.57	0.43	0.24	1.16
17.16	Heptane, 1,1-diethoxy-	C ₉ H ₂₀ O ₂	-	-	-	-	0.17	-	-	-	-	-
17.50	Butanoic acid, 4-hydroxy-	C ₄ H ₈ O ₃	0.92	0.57	0.57	-	-	-	0.82	0.39	0.23	0.47
17.60	3-Furanmethanol	C ₅ H ₆ O ₂	0.12	0.42	0.46	0.40	0.49	-	0.51	0.70	0.37	0.34
17.78	Pentadecane, 2,6,10,14-tetramethyl-	C ₁₉ H ₄₀	-	-	-	-	-	-	-	-	-	0.48
17.80	2-Furanone, 2,5-dihydro-3,5-dimethyl	C ₆ H ₈ O ₂	0.11	0.14	0.15	-	-	-	0.23	0.18	-	-
18.31	Benzaldehyde, 2-hydroxy-	C ₇ H ₆ O ₂	-	-	-	-	-	-	-	-	-	-
18.35	2(5H)-Furanone, 5-methyl-	C ₅ H ₆ O ₂	0.15	0.27	0.25	-	0.14	-	0.42	0.29	0.29	0.26
18.41	Heptadecane	C ₁₇ H ₃₆	-	-	-	-	-	-	-	-	-	0.30
18.80	1H-Imidazole, 1-methyl-	C ₄ H ₆ N ₂	0.24	-	-	-	-	-	-	-	-	-
19.15	4-Hexen-3-one	C ₆ H ₁₀ O ₂	0.49	0.44	0.42	0.17	0.23	-	0.66	0.45	0.40	0.47
19.66	Naphthalene	C ₁₀ H ₈	-	-	-	0.10	0.14	-	-	-	-	-
19.86	2(5H)-Furanone	C ₄ H ₄ O ₂	-	1.99	1.88	0.58	0.69	0.18	3.18	2.23	1.42	1.95
19.89	Acetamide	C ₂ H ₅ NO	2.87	-	-	-	-	-	-	-	-	0.19
20.01	1,2-Cyclopentanedione	C ₅ H ₆ O ₂	-	0.19	0.14	-	-	-	-	0.27	-	-
20.33	Ethanone, 1-(4-methylphenyl)-	C ₉ H ₁₀ O	-	-	-	-	-	-	-	-	0.16	-
20.44	Octadecane	C ₁₈ H ₃₈	-	-	-	-	-	-	-	-	-	0.27
20.54	1,3-Cyclopentanedione, 2,4-dimethyl-	C ₇ H ₁₀ O ₂	0.23	0.18	0.19	-	-	-	0.29	0.20	-	0.23
20.80	Propanamide	C ₃ H ₇ NO	0.27	-	-	-	-	-	-	-	-	-
20.93	2-Furanmethanol	C ₅ H ₆ O ₂	-	0.11	0.04	-	0.18	-	0.47	0.56	0.17	-
21.30	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	C ₆ H ₈ O ₂	2.80	2.42	2.65	0.68	1.11	0.26	3.30	2.94	1.56	2.92
21.85	Phenol, 2-methoxy-	C ₇ H ₈ O ₂	0.38	1.14	1.19	1.08	1.23	0.46	1.49	1.54	2.27	3.15
22.57	Nonadecane	C ₁₉ H ₂₀	-	-	-	-	-	-	-	-	-	0.31
22.74	2-Cyclopenten-1-one, 3-ethyl-2-hydroxy-	C ₇ H ₁₀ O ₂	0.43	0.40	0.44	0.15	0.28	-	0.50	0.55	0.56	0.61
22.86	4-Methyl-5H-furan-2-one	C ₅ H ₆ O ₂	0.42	0.40	0.43	-	0.15	-	0.51	0.43	0.35	0.34
23.58	Glycerin	C ₃ H ₈ O ₃	0.17	0.30	0.11	-	-	-	0.96	0.64	-	0.31
23.94	Creosol	C ₈ H ₁₀ O ₂	-	0.26	0.32	0.30	0.71	0.25	0.39	0.72	1.20	0.96
24.39	Maltol	C ₆ H ₆ O ₃	-	0.39	0.42	-	-	-	0.20	0.29	0.32	0.46
24.74	Phenol, 2-methyl-	C ₇ H ₈ O	-	-	-	0.38	0.34	0.17	0.48	0.38	0.90	1.09

24.77	Phenol, 3-methyl-	C ₇ H ₈ O	-	-	-	-	-	-	-	-	-	-	-
24.86	Phenol	C ₆ H ₆ O	1.61	1.36	1.25	1.54	1.05	0.54	3.46	1.67	2.98	3.46	
25.13	6-Heptenoic acid	C ₇ H ₁₂ O ₂	-	-	-	-	-	-	-	-	0.31	-	
25.50	1H-Pyrrole-2-carboxaldehyde	C ₅ H ₅ NO	0.08	-	-	-	-	-	-	-	-	-	
25.55	Phenol, 4-ethyl-2-methoxy-	C ₉ H ₁₂ O ₂	-	0.15	0.19	0.15	0.27	0.14	-	0.20	0.81	0.58	
25.64	1H-Inden-1-one, 2,3-dihydro-	C ₉ H ₈ O	-	-	-	-	-	-	-	0.17	0.38	0.34	
26.21	3-Heptanone, 1,1-diethoxy-	C ₁₁ H ₂₂ O ₃	-	-	-	-	0.30	-	-	-	-	-	
26.36	2-Vinyl-9-[3-deoxy-β-d-ribofuranosyl]hypoxanthine	C ₁₂ H ₂₄ N ₄ O ₅	0.51	0.80	1.14	-	0.22	-	0.83	0.98	0.61	0.96	
26.43	2(3H)-Furanone, 5-acetyldihydro-	C ₆ H ₈ O ₃	0.22	0.14	0.13	-	-	-	0.18	0.28	0.23	0.26	
26.54	p-Cresol	C ₇ H ₈ O	0.20	0.24	0.22	0.44	0.44	0.28	0.82	0.57	1.56	1.00	
26.72	Phenol, 3-methyl-	C ₇ H ₈ O	-	-	-	0.23	0.26	0.12	0.43	0.31	0.67	0.27	
26.95	Heneicosane	C ₂₁ H ₄₄	-	-	-	-	-	-	-	-	-	-	0.19
27.21	Cyclopentanol	C ₅ H ₁₀ O	1.71	2.04	2.39	-	-	-	1.13	1.51	0.47	2.88	
27.43	7-Octenoic acid	C ₈ H ₁₄ O ₂	-	-	-	-	-	-	-	-	0.32	-	
27.69	2-Pentadecanone, 6,10,14-trimethyl-	C ₁₈ H ₃₆ O	-	-	-	-	-	-	-	-	0.50	-	
28.19	3-Methoxyacetophenone	C ₉ H ₁₀ O ₂	-	-	-	-	-	-	-	-	0.44	-	
28.41	Nonanoic acid	C ₉ H ₁₈ O ₂	0.17	-	-	-	-	-	-	-	-	-	
28.58	Phenol, 2-ethyl-	C ₈ H ₁₀ O	0.14	0.40	0.40	0.51	0.71	0.41	0.98	0.79	2.55	1.44	
28.74	2-Hydroxy-gamma-butyrolactone	C ₄ H ₆ O ₃	0.95	1.01	1.02	-	-	-	0.68	0.66	0.33	1.25	
28.79	Succinic acid, ethyl 3-heptyl ester	C ₁₃ H ₂₄ O ₄	-	-	-	-	-	-	0.86	1.59	0.38	-	
29.13	2-Methoxy-4-vinylphenol	C ₉ H ₁₀ O ₂	-	0.56	0.49	0.58	2.07	0.33	0.45	1.68	1.53	1.09	
29.61	Hexadecanoic acid, methyl ester	C ₁₇ H ₃₄ O ₂	-	-	-	-	-	-	-	-	0.39	0.86	
29.90	1H-Imidazole	C ₃ H ₄ N ₂	1.92	-	-	-	-	-	-	-	-	-	
29.96	Ethanone, 1-(4-hydroxy-3,5-dimethoxyphenyl)-	C ₁₀ H ₁₂ O ₄	-	-	-	-	0.38	-	-	-	-	-	
30.13	1H-Imidazole, 4-methyl-	C ₄ H ₆ N ₂	8.34	0.25	0.26	-	-	-	1.02	0.33	0.41	0.29	
30.42	Hexadecanoic acid, ethyl ester	C ₁₈ H ₃₆ O ₂	-	-	-	-	0.43	0.12	-	-	1.21	-	
30.65	Phenol, 2,6-dimethoxy-	C ₈ H ₁₀ O ₃	2.63	1.62	2.19	0.71	1.07	0.50	2.50	1.96	3.53	3.89	
30.91	3,4-Anhydro-d-galactosan	C ₆ H ₈ O ₄	0.32	0.49	2.11	-	-	-	0.28	0.30	0.98	0.78	
31.02	2,3-Anhydro-d-mannosan	C ₆ H ₈ O ₄	0.90	0.82	1.50	-	0.36	-	0.95	1.20	1.18	0.82	
31.35	2(1H)-Pyridinone, 3-methyl-	C ₆ H ₇ NO	0.10	-	-	-	-	-	-	-	-	-	
31.48	1H-Imidazole, 2-ethyl-	C ₅ H ₈ N ₂	1.53	-	-	-	-	-	-	-	-	-	
31.65	Butanoic acid, propyl ester	C ₇ H ₁₄ O ₂	-	-	-	0.32	0.82	-	2.02	2.61	1.79	-	
31.71	Glycerin	C ₃ H ₈ O ₃	0.87	0.65	0.81	-	-	-	-	-	-	0.87	
31.95	Pentanoic acid, 4-oxo-	C ₅ H ₈ O ₃	0.10	0.28	0.29	-	-	-	-	-	-	-	
32.38	Phenol, 2-methoxy-4-(1-propenyl)-	C ₁₂ H ₁₄ O ₃	-	-	-	0.24	0.76	-	-	0.35	0.60	-	

32.44	1,2,4-Trimethoxybenzene	C ₉ H ₁₂ O ₃	0.18	0.17	0.30	-	-	-	0.24	0.32	1.33	0.50
33.15	Benzofuran, 2,3-dihydro-	C ₈ H ₈ O	0.12	0.87	0.76	1.55	3.91	0.58	1.36	3.34	3.23	2.51
33.61	1,4:3,6-Dianhydro-α-d-glucopyranose	C ₆ H ₈ O ₄	1.51	1.36	1.82	0.24	0.52	0.24	1.63	1.68	1.65	2.01
33.90	3-Pyridinol	C ₅ H ₅ NO	0.49	0.90	0.93	-	0.29	-	0.76	1.24	0.57	0.97
34.18	2(1H)-Pyridinone, 3-methyl-	C ₆ H ₇ NO	0.24	-	-	-	-	-	-	-	-	-
34.41	1-Cyclohexene-1-acetaldehyde, 2,6,6-trimethyl-	C ₁₁ H ₁₈ O	-	-	-	-	-	-	-	-	0.52	-
34.42	t-Butylhydroquinone	C ₁₀ H ₁₄ O	-	-	-	0.29	0.69	-	-	-	-	-
34.46	11-Octadecenoic acid, methyl ester	C ₁₉ H ₃₆ O ₂	-	-	-	-	-	-	-	-	-	0.43
34.94	Carbamic acid, methyl ester	C ₂ H ₅ NO ₂	0.21	-	-	-	-	-	-	-	-	-
35.04	Succinimide	C ₄ H ₅ NO ₂	0.27	-	-	-	-	-	-	-	-	-
35.36	5-Hydroxymethyldihydrofuran-2-one	C ₅ H ₈ O ₃	2.83	1.62	2.09	0.22	0.40	-	1.45	1.42	0.62	2.51
35.50	5-Hydroxymethylfurfural	C ₆ H ₆ O ₃	-	0.65	0.53	0.22	0.68	-	1.17	1.88	1.13	0.88
35.67	1,2-Benzenediol, 3-methoxy-	C ₇ H ₈ O ₃	0.33	0.17	0.24	-	0.27	-	-	0.73	-	-
36.29	Phenol, 2,6-dimethoxy-4-(2-propenyl)-	C ₁₁ H ₁₄ O ₃	-	-	-	-	0.19	-	-	-	0.60	0.19
36.89	Vanillin	C ₈ H ₈ O ₃	0.92	2.26	2.31	0.62	1.56	0.69	2.71	2.99	4.97	3.51
37.08	Sucrose	C ₁₂ H ₂₂ O ₁₁	1.03	0.22	0.51	0.36	1.01	0.35	2.57	3.75	2.41	0.41
37.48	2(3H)-Furanone, dihydro-4-hydroxy-	C ₄ H ₆ O ₃	0.16	0.40	0.47	-	-	-	-	-	-	-
38.41	Apocynin	C ₉ H ₁₀ O ₃	0.53	0.49	0.53	-	0.33	-	0.64	0.59	1.49	0.75
38.58	1,2,4-Cyclopentanetriol	C ₅ H ₁₀ O ₃	0.13	0.33	0.39	-	-	-	-	-	-	-
38.74	2-Propanone, 1-(4-hydroxy-3-methoxyphenyl)-	C ₁₀ H ₁₂ O ₃	0.72	0.84	1.07	-	0.37	-	0.57	0.86	0.43	0.56
39.25	Tetradecanoic acid	C ₁₄ H ₂₈ O ₂	-	-	-	-	-	-	-	-	0.63	-
39.36	Catechol	C ₆ H ₆ O ₂	3.02	4.02	4.01	0.66	1.69	0.37	3.68	4.63	4.32	5.02
40.05	2-Cyclohexen-1-one, 4-(3-hydroxybutyl)-3,5,5-trimethyl-	C ₁₃ H ₂₂ O ₂	-	-	-	-	-	-	-	-	0.41	-
40.38	Lidocaine	C ₁₄ H ₂₂ N ₂ O	-	-	-	-	-	-	-	-	0.24	-
40.47	1,2-Benzenediol, 4-methyl-	C ₇ H ₈ O ₂	0.26	0.29	0.37	-	0.35	-	0.53	0.84	0.50	0.36
43.11	Sucrose	C ₁₂ H ₂₂ O ₁₁	0.50	-	-	0.48	1.07	0.18	2.75	4.12	1.86	-
43.80	n-Hexadecanoic acid	C ₁₆ H ₃₂ O ₂	7.83	8.05	5.04	0.52	0.89	0.62	1.65	1.08	5.90	1.81
44.95	Benzaldehyde, 4-hydroxy-3,5-dimethoxy-	C ₉ H ₁₀ O ₄	-	-	-	-	-	-	0.67	0.52	1.98	0.64
45.05	Benzaldehyde, 4-hydroxy-	C ₇ H ₆ O ₂	0.50	1.02	0.90	-	-	-	1.00	0.91	1.30	1.64
45.95	Homovanillic acid	C ₉ H ₁₀ O ₄	-	-	-	-	-	-	-	-	0.48	-
46.21	Orcinol	C ₇ H ₈ O ₂	0.86	0.53	0.55	-	-	-	0.54	0.66	-	0.62
46.47	Ethanone, 1-(4-hydroxy-3,5-dimethoxyphenyl)-	C ₁₀ H ₁₂ O ₄	0.31	0.25	0.31	-	-	-	0.34	0.34	1.07	0.53
47.02	Hydroquinone	C ₆ H ₆ O ₂	2.36	2.73	2.99	0.40	0.64	-	2.24	2.54	-	3.20
48.44	Squalene	C ₃₀ H ₅₀	-	-	-	-	-	-	-	-	0.59	-

50.31	Octadecanoic acid	C ₁₈ H ₃₆ O ₂	1.98	3.26	2.36	-	-	-	0.64	0.47	1.24	0.72
51.55	Oleic Acid	C ₁₈ H ₃₄ O ₂	13.32	17.99	17.23	1.84	2.73	0.90	0.97	1.53	3.57	1.71
Total			100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 4. Temperature distribution of condensing unit.

Position of measurement	Result of temperature measuring (°C)		
	Without spray	Spray with the bio-oil	Spray with the ethanol
Pyrolysis gas temperature before entering to gas pre-heater	481.71	482.09	485.28
Pyrolysis gas temperature before entering to 8 kW of condenser	248.79	240.08	248.83
Pyrolysis gas temperature before entering to 3 kW of spray condenser	85.53	75.58	88.27
Exit temperature of NCG from 3 kW of spray condenser	36.84	35.41	36.31
NCG temperature before entering to filter packing column	36.02	35.01	35.51
Exit temperature of NCG from filter packing column	35.14	31.95	34.76
Temperature of liquid absorber	-	37.71	30.92
Temperature of cooling water from 10 RT cooling tower	23.25	23.53	23.04
Exit temperature of cooling water from 8 kW of condenser	24.67	24.76	24.47
Exit temperature of cooling water from 3 kW of spray condenser	24.28	24.49	24.11

Table 5. Energy consumption, efficiency of energy conversion and cost production of bio-oils at 60 kg/hr of feed rate and 480 °C of bed temperature.

No.	Description	Energy consumption at each of bio-oil						
		NG-W	SL-W	RL-W	NG-RE	SL-RE	RL-RE	NG-B
- Energy input to system (MJ/hr)								
1	Feedstock	913.98	959.94	840.30	913.98	959.94	840.30	913.98
2	Air blower 1	7.02	7.02	7.02	7.02	7.02	7.02	7.02
3	Air blower 2	6.30	6.30	6.30	6.30	6.30	6.30	6.30
4	Re-circulating blower	4.32	4.32	4.32	4.32	4.32	4.32	4.32
5	Feed motor	0.79	0.79	0.79	0.79	0.79	0.79	0.79
6	Water pump	5.22	5.22	5.22	5.22	5.22	5.22	5.22
7	Cooling tower motor	1.26	1.26	1.26	1.26	1.26	1.26	1.26
8	Re-circulating pump	0.00	0.00	0.00	2.01	2.02	2.02	2.65
9	Spark ignition	0.05	0.05	0.05	0.05	0.05	0.05	0.05
10	LPG	211.34	208.58	214.11	206.74	205.82	211.80	210.88
- Energy from bio-oil (MJ/hr)								
11	Bio-oil	124.79	169.97	171.26	482.64	489.70	472.05	257.99
Cold efficiency (%)		13.65	17.71	20.38	52.81	51.01	56.18	28.23
Total energy conversion to bio-oil (%)		10.85	14.24	15.87	42.05	41.06	43.74	22.39
Operating cost (\$/hr)		4.64	4.60	4.69	5.50	5.58	5.26	4.74
Bio-oil production cost (\$/lite)		0.237	0.205	0.259	0.202	0.178	0.231	0.221
Energy production cost (\$/GJ)		37.21	27.04	27.40	11.40	11.39	11.15	18.38

Table 6. A comparison of energy conversion efficiency to the literatures.

Pyrolysis oil production from the literature	Cold efficiency (%)	Total energy conversion to pyrolysis oil (%)
Present study		
- Napier grasses	52.81	42.05
- Sugarcane leaves	51.01	41.06
- Rubber leaves	56.18	43.74
Treedet and Suntivarakorn [6]	46.06	32.94
Lu [7]	73.01	48.19
Lu, et al. [9]	61.12	42.00
Cai, et al. [11-12]	53.17	20.86
Treedet and Suntivarakorn [20]	24.88	19.77
Mei, et al. [35]	46.70	-
Treedet and Suntivarakorn [36]	27.05	3.77

Table 7. A comparison of costs for bio-oil production to the literatures.

Study	Bio-oil cost		Feed capacity (tons/day)	Year
	\$/liter	\$/GJ		
Solantausta, et al. [37]	0.156	7.30	1000	1992
Cottam and Bridgwater [38]	0.108	5.00	1000	1994
Gregoire and Bain [39]	0.132	6.10	1000	1994
Islam and Ani [40]	0.458	21.20	2.4	2000
Islam and Ani [40]	0.217	10.10	2.4	2000
Mullaney, et al. [41]	0.320	14.50	100	2002
Mullaney, et al. [41]	0.235	10.60	400	2002
Peacocke, et al. (Wellman plant) [42]	0.204	9.50	48	2004
Peacocke, et al. (BTG plant) [42]	0.172	8.00	48	2004
Marker, et al. [43]	0.114	5.10	2000	2005
Marker, et al. [43]	0.146	6.77	500	2005
Ringer, et al. [44]	0.164	7.62	550	2006
Uslu, et al. [45]	0.177	6.00	132	2008
Velden, et al. [46]	0.241	11.63	-	2008
Dynamotive [47]	0.196	4.04	200	2009
Badger, et al. [48]	0.249	11.54	100	2010
Czernik, et al. [49]	0.127	6.00	-	2010
Wright, et al. [50]	0.220	10.19	2000	2010
Rogers and Brammer [51]	0.242	11.25	400	2012
Jones and Male [52]	0.156	7.24	2000	2012
Brown, et al. [53]	0.466	21.73	15	2013
Czernik and French [54]	0.206	9.57	-	2014
Mirkouei, et al. [55]	0.304	14.11	13.6	2016
Singbua, et al. [56]	2.357	146.54	0.54	2017
Treedet and Suntivarakorn [6]	0.353	9.56	1.08	2018
Suntivarakorn, et al. [20]	0.481	19.06	1.8	2018
Present study				
- NG-W	0.237	31.21	1.8	2020
- SL-W	0.205	27.04	1.8	2020
- RL-W	0.259	27.40	1.8	2020
- NG-RE	0.202	11.40	1.8	2020
- SL-RE	0.178	11.39	1.8	2020
- RL-RE	0.231	11.15	1.8	2020
- NG-B	0.221	18.38	1.8	2020

Figures

Figure 1

The experimental devices of this work.

a) Bio-oil production at feed rate of 45 kg/hr.

b) Bio-oil production at feed rate of 60 kg/hr.

c) Bio-oil production at feed rate of 75 kg/hr.

Figure 2

Bio-oil production by using a conventional condenser.

a) Prediction of bio-oil production from Napier grass (NG)

b) Prediction of bio-oil production from Sugarcane leave (SL).

c) Prediction of bio-oil production from Rubber leave (RL).

Figure 3

Prediction of bio-oil production by using Respond Surface Model.

Figure 4

Comparison of bio-oil production in different condenser.

(a)

(b)

Figure 5

The re-circulating blower after 40 hours of usability: (a) without spray mode (b) with spray mode by using the ethanol.