

Co-Pyrolysis of Rice Straw and Empty Fruit Bunch: Effects of Blending on Product Yields and Bio-Oil Composition

Mahendra Tiwari,^a Meheretu Jaleta Dirbeba,^{b*} Alessandro Ruozzi,^b Juho Lehmusto,^b Patrik Yrjas,^b Ravikrishnan Vinu^{a*}

^aDepartment of Chemical Engineering, Indian Institute of Technology Madras, Chennai, India

^bHigh-Temperature Processes and Materials, Faculty of Science and Engineering, Åbo Akademi University, Turku, Finland

*Corresponding Authors. E-mail: meheretu.dirbeba@abo.fi

E-mail: vinu@iitm.ac.in

Supplementary Information

Table S1. Pyrolysate composition in GC/MS obtained from Py-GC/MS of RS at 500 °C

Phenolics (P)	6.3
2-Methoxy-4-vinylphenol	3.6
Phenol, 2,6-dimethoxy-	0.6
3,4'-Isopropylidenediphenol	1.2
4-Tert-octylphenol	0.8
Linear oxygenates (L-O)	64
Acetaldehyde	8.7
Methyl glyoxal	8.0
2,3-Butanedione	2.5
Acetic acid	7.1
2-Propanone, 1-hydroxy-	6.1
2-Butanone, 1-(acetyloxy)-	1.5
Butanedial	2.3
2-Propanone, 1-hydroxy-	1.3
2-Propenyl n-butyl ether (cis/trans isomers)	1.2
Pentanal	4.2
Tetradecanoic acid	2.1
Pentadecanoic acid	18.0
Cis-7-hexadecenoic acid	0.9
Cyclic oxygenates (Cy-O)	25.8
1,4-Dioxane-2,5-diol	20.3
6-Oxa-bicyclo[3.1.0]hexan-3-one	2.0
1,6-Anhydro-beta-d-glucopyranose (levoglucosan)	3.4
Aromatic oxygenates (Ar-O)	1.8
Benzaldehyde, 2-methyl-	1.2
1,3-Benzenedicarboxylic acid, bis(2-ethylhexyl) ester	0.6
Furans (F)	0.7
Benzofuran, 2,3-dihydro-	0.7
Others	1.4
1,5-Diazabicyclo[3.1.0]hexane	0.4
Guanosine	0.4
Phthalic acid, octyl 2-propylpentyl ester	0.6

Table S2. Pyrolysate composition in GC/MS obtained from Py-GC/MS of 75RS at 500 °C

Phenolics (P)	11.7
Phenol	1.6
2-Methoxy-4-vinylphenol	4.1
Phenol, 2,6-dimethoxy-	1.4
Phenol, 4-ethenyl-2,6-dimethoxy-	1.3
Phenol, 2,6-dimethoxy-4-(2-propenyl)-	0.9
(E)-4-(3-hydroxyprop-1-en-1-yl)-2-methoxyphenol	1.1
Cis-sinapyl alcohol	0.9
3,4'-Isopropylidenediphenol	0.3
Linear oxygenates (L-O)	60.2
Acetaldehyde	10.1
Methyl glyoxal	9.6
2,3-Butanedione	3.0
Acetic acid	10.5
2-Propanone, 1-hydroxy-	9.3
Propanoic acid, 2-oxo-, ethyl ester	2.2
Butanedial	3.4
Pentanedial	5.4
2-Decyn-1-ol	0.4
Myristic acid	1.4
Pentadecanoic acid	4.2
9-Hexadecenoic acid	0.7
Cyclic oxygenates (Cy-O)	22.6
Glycolaldehyde dimer	16.6
6-Oxa-bicyclo[3.1.0]hexan-3-one	1.9
3-Cyclobutene-1,2-dione, 3,4-dihydroxy-	1.1
1,2-Cyclopentanedione, 3-methyl-	0.8
1,4:3,6-Dianhydro-.alpha.-d-glucopyranose	0.3
1,6-Anhydro-beta-d-glucopyranose (levoglucosan)	1.9
Aromatic oxygenates (Ar-O)	4.1
Bis(2-ethylhexyl) phthalate	0.7
1,4-Benzenedicarboxylic acid, bis(2-ethylhexyl) ester	3.4
Furans	0.8
Benzofuran, 2,3-dihydro-	0.8
Others	0.6
Guanosine	0.6

Table S3. Pyrolysate composition in GC/MS obtained from Py-GC/MS of 50RS at 500 °C

Phenolics (P)	15.4
2-Methoxy-4-vinylphenol	4.9
Phenol, 2,6-dimethoxy-	2.8
(2,5-Dimethoxyphenyl)methanol	1.1
Phenol, 2,6-dimethoxy-4-(2-propenyl)-	1.9
(E)-4-(3-hydroxyprop-1-en-1-yl)-2-methoxyphenol	1.8
Cis-sinapyl alcohol	2.9
Linear oxygenates (L-O)	59.8
Acetaldehyde	10.8
Methyl glyoxal	7.8
2,3-Butanedione	3.5
Acetic acid	13.4
2-Propanone, 1-hydroxy-	6.4
Propanoic acid, 2-oxo-, ethyl ester	2.0
Butanedial	2.7
Oxetane, 2-propyl-	4.1
Tridecanoic acid	1.5
Pentadecanoic acid	6.1
9-Eicosenoic acid, (Z)-	0.6
9-Octadecenoic acid (Z)-	1.0
Cyclic oxygenates (Cy-O)	19.4
Glycolaldehyde dimer	15.1
Cyclohexanone	1.7
3-Cyclobutene-1,2-dione, 3,4-dihydroxy-	0.8
1,2-Cyclopentanedione, 3-methyl-	0.7
1,6-Anhydro-beta-d-glucopyranose (levoglucosan)	1.0
Aromatic oxygenates (Ar-O)	1.9
3,5-Dimethyl-4-methoxybenzoic acid	1.1
1,4-Benzenedicarboxylic acid, bis(2-ethylhexyl) ester	0.8
Furans	0.8
Benzofuran, 2,3-dihydro-	0.8
Others	3.5
Benzenesulfonic acid, 4-hydroxy-	2.8
Guanosine	0.67

Table S4. Pyrolysate composition in GC/MS obtained from Py-GC/MS of 25RS at 500 °C

Phenolics (P)	19.4
2-Methoxy-4-vinylphenol	2.6
Phenol, 2,6-dimethoxy-	2.9
2,5-Dimethoxyphenyl	0.4
Phenol, 2-methoxy-4-(2-propenyl)-	0.5
Phenol, 4-ethenyl-2,6-dimethoxy-	3.3
Phenol, 2,6-dimethoxy-4-(2-propenyl)-	2.1
(E)-4-(3-hydroxyprop-1-en-1-yl)-2-methoxyphenol	2.2
Trans-sinapyl alcohol	4.1
3,4'-Isopropylidenediphenol	1.2
Linear oxygenates (L-O)	54.4
Methyl glyoxal	6.1
2,3-Butanedione	2.9
Propanoic acid, ethenyl ester	11.4
Acetic acid	6.2
2-Propanone, 1-hydroxy-	6.9
Succindialdehyde	3.2
2-Propenyl n-butyl ether (cis/trans isomers)	1.0
Pentanedial	5.0
3,5-Dodecadiyne, 2-methyl-	0.6
Myristic acid	1.7
Pentadecanoic acid	7.8
9-Octadecenoic acid (Z)-	1.6
Cyclic oxygenates (Cy-O)	19.2
Glycolaldehyde dimer	15.4
6-Oxa-bicyclo[3.1.0]hexan-3-one	1.6
1,2-Cyclopentanedione, 3-methyl-	0.9
1,6-Anhydro-beta-d-glucopyranose (levoglucosan)	1.3
Aromatic oxygenates (Ar-O)	1.7
Benzene, (ethenyloxy)-	0.7
1,4-Benzenedicarboxylic acid, bis(2-ethylhexyl) ester	1.0
Others	5.3
Benzenesulfonic acid, 4-hydroxy-	5.3

Table S5. Pyrolysate composition in GC/MS obtained from Py-GC/MS of EFB at 500 °C

Phenolics (P)	23.5
Phenol	5.5
2-Methoxy-4-vinylphenol	1.7
Phenol, 2,6-dimethoxy-	3.5
Phenol, 2-methoxy-4-(2-propenyl)-	0.7
Phenol, 4-ethenyl-2,6-dimethoxy-	3.1
Phenol, 2,6-dimethoxy-4-(2-propenyl)-	2.1
(E)-4-(3-hydroxyprop-1-en-1-yl)-2-methoxyphenol	2.0
cis-Sinapyl alcohol	2.9
3,4'-Isopropylidenediphenol	1.9
Linear oxygenates (L-O)	55.2
Methyl glyoxal	4.7
2,3-Butanedione	2.1
Butanoic acid	6.4
Acetic acid	10.0
2-Propanone, 1-hydroxy-	4.9
Propanoic acid	2.2
Butanedial	2.2
Pentanal	3.3
Pentadecanoic acid	13.2
Oleic Acid	1.7
cis-11-Eicosenoic acid	2.3
Octadecanoic acid	2.3
Cyclic oxygenates (Cy-O)	15.9
Glycolaldehyde dimer	11.3
Cyclohexanone	1.5
3-Cyclobutene-1,2-dione, 3,4-dihydroxy-	0.6
1,2-Cyclopentanedione, 3-methyl-	0.9
4-Methyl-1,3-cyclohexanedione	0.6
.Beta.-d-glucopyranose, 1,6-anhydro-	1.0
Aromatic oxygenates (Ar-O)	2.0
1,2,4-Trimethoxybenzene	0.5
Benzene, 1,2,3-trimethoxy-5-methyl-	0.3
1,2-Benzenedicarboxylic acid, diisooctyl ester	0.5
1,4-Benzenedicarboxylic acid, bis(2-ethylhexyl) ester	0.8
Others	2.4
Benzenesulfonic acid, 4-hydroxy-	2.2
4-Ethoxy-3-methyl-1,2,5-oxadiazole 2-oxide	0.2

Table S6. Pyrolysate composition in GC/MS obtained from FBR of RS at 500 °C

Phenolics (P)	13.2
Phenol	4.9
Phenol, 2-methyl-	2.3
Phenol, 2-methoxy-	1.2
Phenol, 4-ethyl-	1.3
Catechol	2.8
2-Isopropoxyphenol	0.7
Linear oxygenates (L-O)	20.0
2,3-Pentanedione	0.4
1-Hydroxy-2-butanone	10.4
Pentanal	3.3
1-Butoxy-2-methyl-2-butene	1.0
1-Propene, 3-methoxy-	2.7
2-Butanone, 3,3-dimethyl-	0.5
Butanoic acid, 2-propenyl ester	1.7
Cyclic oxygenates (Cy-O)	54.0
Cyclopentanone	1.5
3-Cyclopentene-1-acetaldehyde, 2-oxo-	20.9
Cyclopentanone, 2-methyl-	0.6
Cyclopentanone, 3-methyl-	0.5
2-Cyclopenten-1-one, 3-methyl-	0.6
2-cyclopenten-1-one, 2-methyl-	5.3
2H-pyran, 3,4-dihydro-	2.3
2-Cyclopenten-1-one, 3-methyl-	5.5
3,4-Dimethyl-2-cyclopenten-1-one	1.0
2-Cyclopenten-1-one, 2,3-dimethyl-	0.6
2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	7.2
2-Cyclopenten-1-one, 2,3-dimethyl-	2.0
1,3-Cyclopentadien, 5-trimethylsilyl-	0.9
3,5-Dimethyl cyclopentenolone	0.9
2-Cyclopenten-1-one, 3-ethyl-	0.4
2-Cyclopenten-1-one, 3-ethyl-2-hydroxy-	1.0
1,4:3,6-Dianhydro-.alpha.-d-glucopyranose	2.6
Cyclohexanecarboxylic acid, phenyl ester	0.4
Aromatic oxygenates (Ar-O)	3.7
Oxirane, 2,2'-[oxybis(methylene)]bis-	1.2
Benzenemethanol	2.6
Furans (F)	5.8
2-Methoxytetrahydrofuran	1.3
3-Furaldehyde	1.3
Ethanone, 1-(2-furanyl)-	1.5
2(5H)-furanone, 5-methyl-	0.8
2(5h)-furanone, 3-methyl-	0.4
3,5-Dimethyl-2(5h)-furanone	0.6
Others	3.3
Hydrazine, 1,2-diethyl-	0.5
3-Amino-2,4-dimethylpentane	1.6
Carbamic acid, phenyl ester	0.4
2-Ethyl-3-methyl-n-phenyl-2-butenamide	0.8

Table S7. Pyrolysate composition in GC/MS obtained from FBR of 50RS at 500 °C

Phenolics (P)	45.7
Phenol	18.9
Phenol, 2-methyl-	3.9
Phenol, 4-methyl-	4.2
Phenol, 2-methoxy-	2.4
Phenol, 2,6-dimethyl-	0.7
Phenol, 2-ethyl-	0.3
Phenol, 2,4-dimethyl-	0.7
Phenol, 4-ethyl-	1.4
Catechol	6.1
2-Isopropoxyphenol	1.2
1,2-Benzenediol, 3-methoxy-	0.6
1,2-Benzenediol, 3-methyl-	1.4
Ethanone, 1-(2,5-dihydroxyphenyl)-	0.3
1,2-Benzenediol, 4-methyl-	0.8
Phenol, 2,6-dimethoxy-	1.0
1,3-Benzenediol, 4-ethyl-	0.9
Vanillin	0.7
Ethanone, 1-(4-hydroxy-3,5-dimethoxyphenyl)-	0.2
Linear oxygenates (L-O)	14.4
2,3-Pentanedione	0.3
3-Penten-2-one	0.7
2-Butenal, 2-methyl-, (e)-	0.2
Propanoic acid	1.1
Ethyl-1-propenyl ether	2.6
1-Hydroxy-2-butanone	4.2
Propanal	2.4
2-Hexenal	0.4
2,5-Hexanedione	0.3
3-Methyl-3-butene-1,2-diol	0.3
Benzaldehyde, 2-hydroxy-	0.6
Butanoic acid, 2-propenyl ester	0.8
N-Hexadecanoic acid	0.3
Cyclic oxygenates (Cy-O)	20.4
Cyclopentanone	1.3
4-Cyclopentene-1,3-dione	0.2
2-Cyclopenten-1-one, 2-methyl-	3.5
Cyclopentanone	1.2
2-Cyclohexen-1-one	0.4
2-Cyclopenten-1-one, 3-methyl-	0.9
2-Cyclopenten-1-one, 3,4-dimethyl-	1.1
2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	8.5
2-Cyclopenten-1-one, 2,3-dimethyl-	1.3
Cyclohexane, (1-methylethylidene)-	0.4
2-Cyclopenten-1-one, 3-ethyl-2-hydroxy-	1.6
Aromatic oxygenates (Ar-O)	5.1
Benzene, [(3-methyl-2-butenyl)oxy]-	5.1
Benzene, 1,4-dimethoxy-	0.2
1H-Inden-1-one, 2,3-dihydro-	0.4
Furans	11.8
2-Methoxytetrahydrofuran	1.3
3-Furaldehyde	0.8
Furan, tetrahydro-2-(methoxymethyl)-	0.9
2-Furanmethanol, tetrahydro-	1.3
Furan, tetrahydro-2,5-dimethoxy-	0.8
Ethanone, 1-(2-furanyl)-	2.1
2-Furancarboxaldehyde, 5-methyl-	1.1
2-Furancarboxaldehyde, 5-methyl-	2.7
3,5-Dimethyl-2(5h)-furanone	0.5
2(5h)-Furanone, 5-methyl	0.3
Others	2.2
Hydrazine, 1,2-diethyl-	0.6
3-Amino-2,4-dimethylpentane	0.2
N-(4-pentenyl)-n-propylamine	0.7
4-Methylspiro[2.5]octane-1,1-dicarbonitrile	0.3
Benzenesulfonic acid, 4-hydroxy-	0.4

Table S8. Pyrolysate composition in GC/MS obtained from FBR of EFB at 500 °C

Phenolics (P)	54.3
Phenol	25.0
Phenol, 2-methyl-	4.6
Ethanone, 1-phenyl-	0.5
P-Cresol	4.0
Phenol, 2-methoxy-	1.6
Phenol, 2,6-dimethyl-	0.8
Phenol, 2-ethyl-	0.4
Phenol, 2,4-dimethyl-	1.0
Phenol, 4-ethyl-	1.2
Phenol, 3,4-dimethyl-	0.5
Catechol	5.8
Phenol, 2-propoxy-	1.1
1,2-Benzenediol, 3-methoxy-	1.3
1,2-Benzenediol, 3-methyl-	1.8
Guaiacol, 4-ethyl-	0.7
Ethanone, 1-(2,5-dihydroxyphenyl)-	0.4
1,2-Benzenediol, 4-methyl-	0.8
Phenol, 2,6-dimethoxy-	1.0
1-Hydroxy-2-methoxy-4-methylbenzene	0.6
1,3-Benzenediol, 4-ethyl-	0.9
4-Hydroxy-3-methoxy-benzaldehyde	0.3
Linear oxygenates (L-O)	12.34
2,3-Pentanedione	0.41
Ethylidene acetone	0.66
2-Butenal, 2-methyl-, (e)-	0.47
1-Hydroxy-2-butanone	4.88
Pentanal	1.67
Butanoic acid	0.62
3-Pentenal, 4-methyl-	0.32
2-Hexanone, 3-methyl-	1.62
3-Oxo-1-butenyl 2-methylpropanoate	0.7
2-Hydroxyisocaproic acid, methyl ether, methyl ester	0.3
N-Hexadecanoic acid	0.69
Cyclic oxygenates (Cy-O)	12.65
Cyclopentanone	0.99
2-Cyclopenten-1-one, 2-methyl-	2.05
1,2-Cyclooctanedione	0.83
2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	5.57
2-Cyclopenten-1-one, 2,3-dimethyl-	1.12
2-Cyclopenten-1-one, 3-ethyl-2-hydroxy-	0.27
6,6-Dimethyl-spiro[2.3]hexan-4-one	0.38
2-Cyclopenten-1-one, 3-ethyl-2-hydroxy-	1.15
1,4:3,6-Dianhydro-.alpha.-d-glucopyranose	0.29
Aromatic oxygenates (Ar-O)	6.52
Benzene, [(3-methyl-2-butenyl)oxy]-	5.17
Benzaldehyde, 2-hydroxy-	0.83
Benzoic acid	0.52
Furans	5.59
2-Methoxytetrahydrofuran	1.89
Furfural	0.39
Furan, tetrahydro-2,5-dimethoxy-	1.31
Ethanone, 1-(2-furanyl)-	1.15
2-Furancarboxaldehyde, 5-methyl-	0.85
Others	8.55
Hydrazine, 2-ethyl-1,1-dimethyl-	0.26
Pyrazole, 1,4-dimethyl-	7.43
Ethanone, 1-(1h-imidazol-4-yl)-	0.86

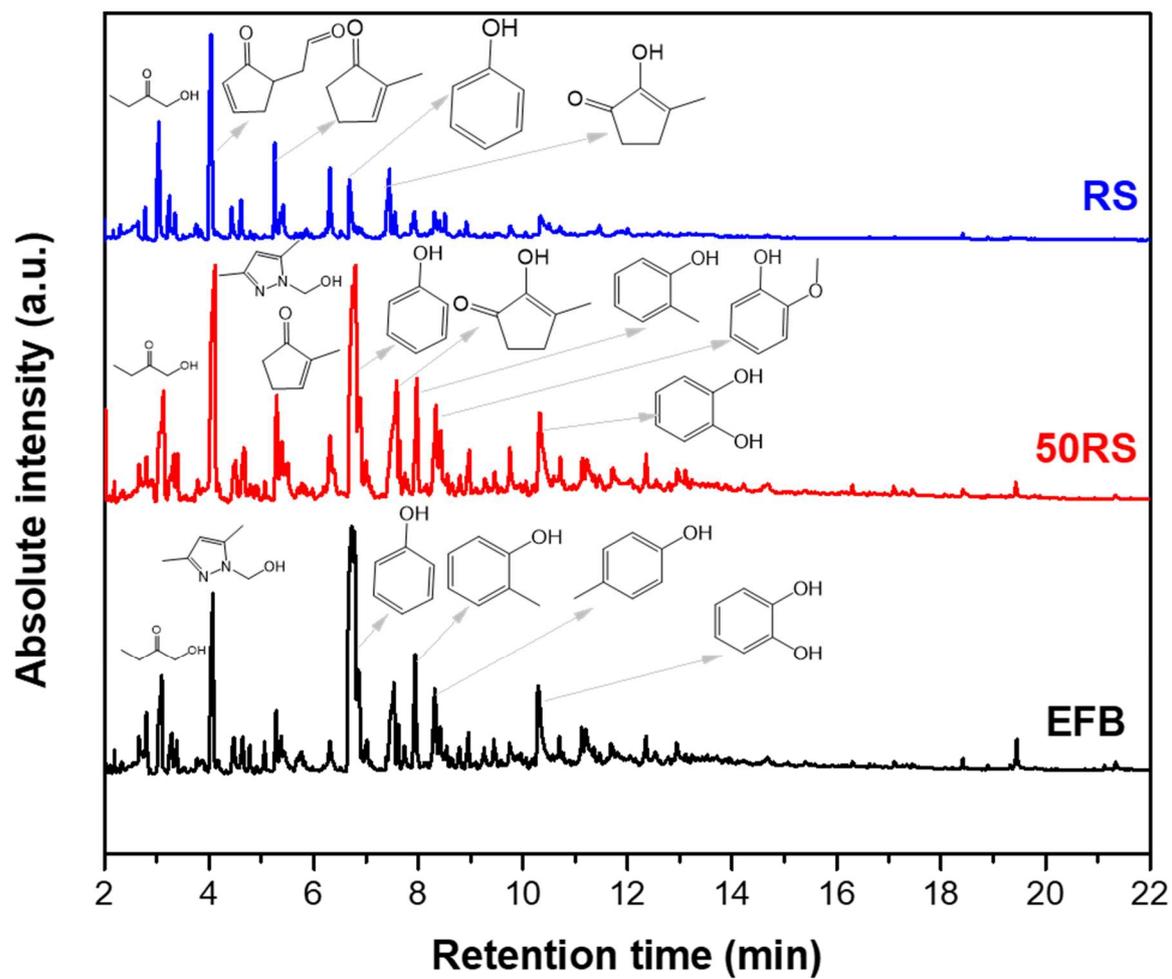


Fig. S2. Total ion chromatogram from fluidized bed pyrolysis of RS, EFB, and their blend at 500 °C.

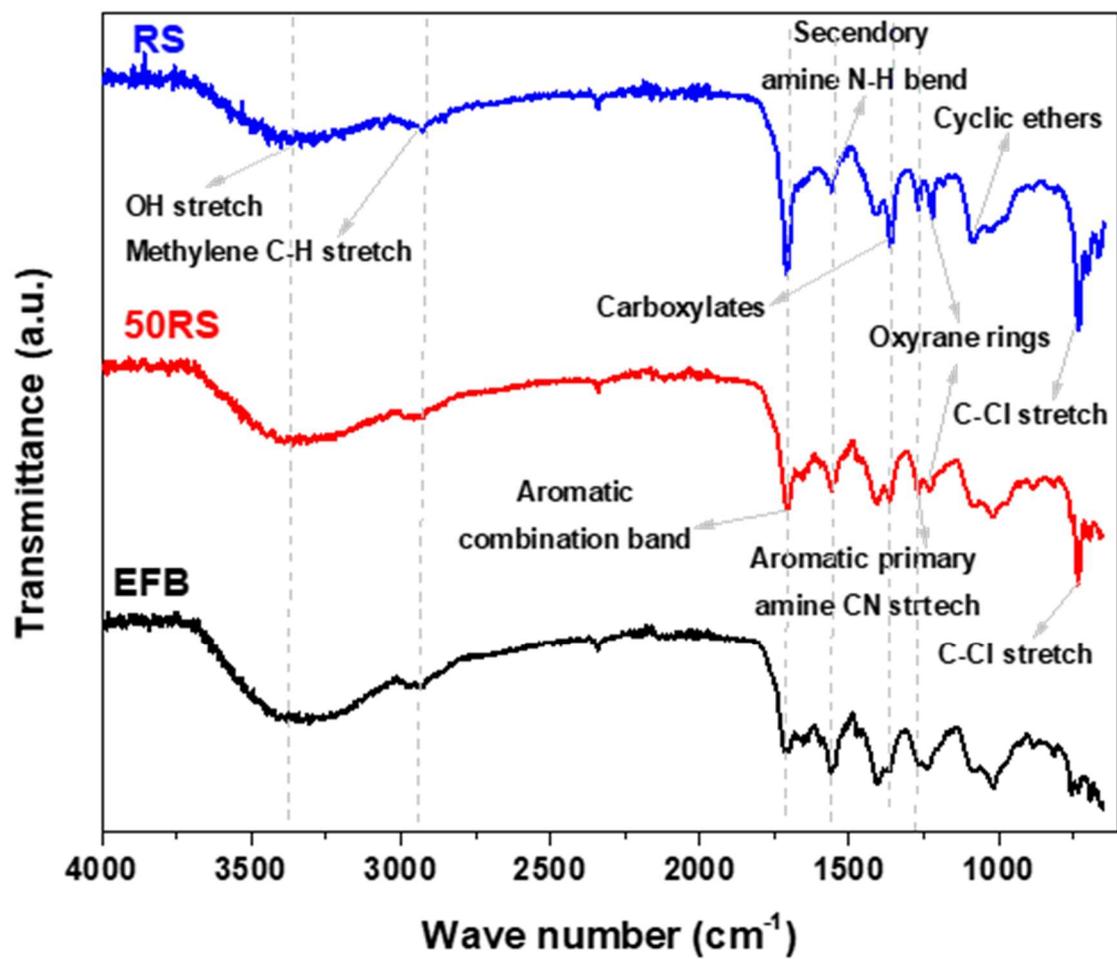


Fig. S3 FTIR spectra for the oil from fluidized bed pyrolysis of RS, EFB, and their blend at 500 °C.