

Alternative Fuels from Forestry Biomass Residue: Torrefaction Process of Horse Chestnuts, Oak Acorns, and Spruce Cones

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Supplementary materials

Table S1. Analysis of ash content, volatile matter content, and higher heating value with standard deviations, and coefficient of variation.

Type of biomass	Temperature	Ash Content (AC)			Volatile matter (VMC)			Higher Heating Value (HHV)		
		Value	SD*	CV**	Value	SD	CV**	Value	SD	CV**
-	°C	%			%			kJ·kg ⁻¹		
Horse chestnuts	105	2.2910	0.0755	0.0329	79.6000	0.0046	0.0058	19,077	156	0.0082
	200	2.4917	0.1653	0.0664	76.8444	0.0052	0.0067	20,648	53	0.0026
	220	2.6410	0.0364	0.0138	74.2667	0.0049	0.0066	21,716	25	0.0012
	240	3.2518	0.0728	0.0224	71.1556	0.0049	0.0068	23,495	73	0.0031
	260	3.9130	0.0388	0.0099	68.2222	0.0036	0.0052	25,602	39	0.0015
	280	4.8701	0.0149	0.0031	64.5778	0.0052	0.0080	26,832	22	0.0008
	300	6.0944	0.0516	0.0085	60.4889	0.0193	0.0319	25,860	70	0.0027
	320	5.1072	0.0361	0.0071	50.1778	0.0076	0.0152	26,516	151	0.0057
Oak acorns	105	2.1039	0.0434	0.0206	82.9667	0.0041	0.0061	18,232	48	0.0026
	200	2.2499	0.1634	0.0726	80.4778	0.0045	0.0056	19,192	92	0.0048
	220	2.1827	0.0821	0.0376	79.7667	0.0033	0.0042	19,741	122	0.0062
	240	2.3798	0.0584	0.0245	78.8778	0.0033	0.0042	20,282	87	0.0043
	260	3.0846	0.1981	0.0318	77.3667	0.0045	0.0059	22,465	121	0.0054

Spruce cones	280	4.164 2	0.052 2	0.012 5	75.944 4	0.003 3	0.004 4	24,60 4	11 5	0.004 7
	300	4.388 0	0.083 3	0.019 0	71.677 8	0.008 2	0.011 5	24,46 0	14 0	0.005 7
	320	4.693 7	0.073 3	0.015 6	59.766 7	0.009 9	0.016 6	25,62 9	61	0.002 4
	105	0.955 7	0.089 2	0.093 4	70.933 3	0.0047 3	0.006 3	19,59 0	48	0.002 5
	200	1.024 7	0.054 6	0.053 3	68.888 9	0.004 5	0.006 6	20,38 0	57	0.002 8
	220	1.095 6	0.045 5	0.041 5	68.622 2	0.005 9	0.008 6	20,85 9	85	0.004 1
	240	1.441 9	0.109 2	0.075 7	68.533 3	0.002 2	0.003 2	21,30 4	74	0.003 5
	260	1.767 5	0.019 9	0.011 2	67.200 0	0.003 6	0.005 3	22,43 2	70	0.003 1
	280	2.357 6	0.029 3	0.012 4	65.244 4	0.005 9	0.009 0	24,33 4	83	0.003 4
	300	2.402 2	0,084 0	0.035 0	62.311 1	0.012 1	0.019 5	24,17 4	12 4	0.005 1
	320	2.222 1	0.064 4	0.029 0	55.288 9	0.005 2	0.009 4	24,72 9	69	0.002 8

*Standard deviation; **Coefficient of variation.

Table S2. Analysis of fixed carbon content, and moisture content with standard deviations, and coefficient of variation.

Type of biomass	Temperature	Fixed carbon (FCC)			Moisture content in analytical state (105°C, 24 h) (MC)		
		Value	SD*	CV**	Value	SD*	CV**
-	°C		%			%	
Horse chestnuts	105	18.1090	0.0008	0.0042	30.5	6.1	0.2009
	200	20.6638	0.0048	0.0231			
	220	23.0924	0.0049	0.0211			
	240	25.5927	0.0050	0.0195			
	260	27.8648	0.0038	0.0135			
	280	30.5521	0.0051	0.0168			
	300	33.4167	0.0198	0.0591			
	320	44.7150	0.0078	0.0174			
Oak acorns	105	14.9294	0.0004	0.0029	30.6	2.1	0.0700
	200	17.2723	0.0058	0.0334			
	220	18.0506	0.0033	0.0184			
	240	18.7424	0.0032	0.0172			
	260	19.5487	0.0046	0.0235			
	280	19.8914	0.0037	0.0184			
	300	23.9342	0.0084	0.0353			
	320	35.5396	0.0101	0.0285			
Spruce cones	105	28.1110	0.0009	0.0032	10.2	0.3	0.0257
	200	30.0864	0.0047	0.0157			
	220	30.2822	0.0059	0.0194			
	240	30.0248	0.0018	0.0059			
	260	31.0325	0.0037	0.0119			
	280	32.3979	0.0057	0.0177			
	300	35.2867	0.0121	0.0343			
	320	42.4890	0.0051	0.0120			

*Standard deviation; **Coefficient of variation.

Table S3. Analysis of bulk density, specific density, and porosity with standard deviations, and coefficient of variation.

Type of biomass	Temperature	Bulk Density (ρ_B)			Specific Density (ρ_s)			Porosity (ϵ)		
		Value	SD*	CV**	Value	SD*	CV**	Value	SD*	CV**
-	°C	g·cm ⁻³			g·cm ⁻³			%		
Horse chestnuts	105	0.5814	0.0183	0.0315	1.4426	0.0476	0.0330	59.6298	2.3496	0.0394
	200	0.5818	0.0271	0.0465	1.4166	0.0381	0.0269	58.8953	2.3294	0.0396
	220	0.5840	0.0114	0.0195	1.4993	0.0918	0.0613	60.8799	2.7841	0.0457
	240	0.5416	0.0267	0.0492	1.4606	0.4156	0.0284	62.8741	2.3932	0.0381
	260	0.4802	0.0098	0.0205	1.4283	0.1036	0.0726	66.1456	3.2483	0.0491

	280	0.463 6	0.176	0.038 0	1.375 0	0.058 0	0.042 2	66.276 7	0.358 0	0.005 4
	300	0.475 8	0.020 9	0.043 9	1.410 4	0.070 3	0.049 8	66.181 1	2.241 2	0.033 9
	320	0.365 3	0.100 7	0.275 7	1.960 8	0.081 6	0.041 6	81.205 6	5.619 9	0.069 2
Oak acorns	105	0.543 5	0.007 8	0.014 4	1.604 3	0.059 9	0.037 3	66.089 8	0.789 7	0.011 9
	200	0.573 9	0.026 0	0.045 3	1.473 8	0.050 2	0.034 0	60.994 8	2.472 4	0.040 5
	220	0.562 3	0.027 6	0.049 0	1.553 8	0.038 3	0.024 6	63.743 6	2.625 4	0.041 2
	240	0.543 7	0.006 5	0.012 0	1.465 4	0.077 5	0.052 9	62.793 1	2.036 5	0.032 4
	260	0.476 5	0.027 8	0.058 3	1.439 0	0.125 6	0.087 3	66.641 5	3.342 6	0.050 2
	280	0.386 4	0.014 5	0.037 5	1.383 5	0.099 5	0.071 9	71.968 9	1.675 5	0.023 3
	300	0.399 0	0.008 7	0.021 7	1.386 3	0.048 3	0.034 8	71.164 5	1.540 5	0.021 6
	320	0.369 0	0.019 1	0.051 6	2.283 9	0.074 8	0.032 7	83.797 1	1.379 2	0.016 5
Spruce cones	105	0.482 7	0.052 7	0.109 1	1.521 8	0.081 9	0.053 8	68.038 4	4.873 0	0.071 6
	200	0.485 2	0.009 3	0.019 1	1.465 3	0.025 3	0.017 3	66.883 8	0.305 1	0.004 6
	220	0.462 5	0.014 3	0.030 9	1.492 8	0.078 1	0.052 3	68.954 6	1.483 4	0.021 5
	240	0.417 1	0.024 8	0.059 5	1.593 5	0.146 1	0.091 7	73.747 1	0.898 6	0.012 2
	260	0.376 3	0.033 8	0.089 8	1.631 6	0.247 9	0.151 9	76.255 2	4.805 0	0.063 0
	280	0.351 6	0.002 8	0.008 0	1.867 4	0.068 8	0.036 8	81.149 8	0.628 8	0.007 7
	300	0.365 7	0.008 8	0.024 0	1.674 7	0.098 4	0.058 8	78.103 6	1.147 9	0.014 7
	320	0.326 9	0.005 3	0.016 1	2.199 5	0.023 9	0.010 9	85.136 6	0.080 5	0.000 9

*Standard deviation; **Coefficient of variation.

Table S4. Analysis of mass yield, energy densification ratio, and energy yield with standard deviations, and coefficient of variation.

Type of biomass	Temperature	Mass Yield (MY)			Energy densification ratio (EDR)			Energy Yield (EY)		
		Value	SD*	CV**	Value	SD*	CV**	Value	SD*	CV**
-	°C		%		-				%	
Horse chestnuts	105	100.00	0.0000	0.0000	1.00	0.0000	0.0000	100.00	0.0000	0.0000
	200	97.24	0.5183	0.0053	1.08	0.0111	0.0102	105.26	1.3028	0.0124
	220	94.67	0.4869	0.0051	1.14	0.0082	0.0072	107.77	1.1390	0.0106
	240	91.56	0.4869	0.0053	1.23	0.0099	0.0080	112.77	0.7984	0.0071
	260	88.62	0.3556	0.0040	1.34	0.0114	0.0085	118.95	1.4552	0.0122
	280	84.98	0.5183	0.0061	1.41	0.0107	0.0076	119.54	1.4037	0.0117
	300	80.89	1.9271	0.0238	1.36	0.0124	0.0091	109.68	3.3625	0.0307
	320	70.58	0.7647	0.0108	1.39	0.0113	0.0081	98.10	1.0849	0.0111
Oak acorns	105	100.00	0.0000	0.0000	1.00	0.0000	0.0000	100.00	0.0000	0.0000
	200	97.51	0.4532	0.0046	1.05	0.0049	0.0046	102.64	0.9310	0.0091
	220	96.80	0.3326	0.0034	1.08	0.0072	0.0067	104.81	0.7054	0.0067
	240	95.91	0.3326	0.0035	1.11	0.0042	0.0038	106.69	0.6704	0.0063
	260	94.40	0.4532	0.0048	1.23	0.0072	0.0058	116.31	0.3357	0.0029
	280	92.98	0.3326	0.0036	1.35	0.0083	0.0062	125.47	1.2071	0.0096
	300	88.71	0.8243	0.0093	1.34	0.0071	0.0053	119.01	1.1929	0.0100
	320	76.80	0.9898	0.0129	1.41	0.0067	0.0047	107.95	1.0899	0.0101
Spruce cones	105	100.00	0.0000	0.0000	1.00	0.0000	0.0000	100.00	0.0000	0.0000
	200	97.96	0.4532	0.0046	1.04	0.0010	0.0011	101.91	0.4317	0.0042
	220	97.69	0.5896	0.0060	1.06	0.0045	0.0042	104.02	0.6285	0.0060
	240	97.60	0.2177	0.0022	1.09	0.0036	0.0033	106.14	0.4927	0.0046
	260	96.27	0.3556	0.0037	1.15	0.0034	0.0030	110.23	0.3799	0.0034

280	94.31	0.589 6	0.006 3	1.24	0.004 4	0.003 6	117.1 5	0.176 2	0.006 1
300	91.38	1.212 3	0.013 3	1.23	0.006 3	0.005 1	112.7 6	1.395 5	0.012 4
320	84.36	0.518 3	0.006 1	1.26	0.005 2	0.004 1	106.4 9	1.049 3	0.009 9

*Standard deviation; **Coefficient of variation.

Table S5. Analysis of hydrophobicity properties with standard deviation, and coefficient of variation.

Type of biomass	Temperature	Hydrophobicity test (WDPT Test)		
		Value	SD*	CV**
-	°C		s	
Horse chestnuts	105	0.0	0	0.0000
	200	60.0	0	0.0000
	220	60.0	0	0.0000
	240	80.0	28.3	0.3536
	260	23720.0	890.4	0.0375
	280	40660.0	657.9	0.0162
	300	42480.0	636.9	0.0150
	320	52400.0	1298.3	0.0248
Oak acorns	105	0.0	0.0	0.0000
	200	980.0	679.4	0.6933
	220	4440.0	2131.9	0.7054
	240	6140.0	4339.2	0.7067
	260	50820.0	602.0	0.0118
	280	52900.0	490.7	0.0093
	300	54540.0	3282.3	0.0602
	320	82700.0	1113.2	0.0135
Spruce cones	105	6360.0	342.9	0.0539
	200	17860.0	2627.4	0.1471
	220	29000.0	3088.4	0.1065
	240	29740.0	3333.2	0.1121
	260	31380.0	2575.1	0.0821
	280	53440.0	541.8	0.0101
	300	78540.0	1267.1	0.0161
	320	83760.0	1753.2	0.0209

*Standard deviation; ** Coefficient of variation.