fuels

Supplementary Materials

Table S1. ANOVA for response surface quadratic model of bulk density as affected by temperature and residence time of torrefaction treatment.

Source	Sum of Squares	df	Mean Square	F Value	p-value	
Model	572.45	5	114.49	2.34	0.15	not significant
A-Temperature (°C)	54.36	1	54.36	1.11	0.33	
B-Time (min)	134.81	1	134.81	2.76	0.14	
AB	4.16	1	4.16	0.09	0.78	
A^2	124.61	1	124.61	2.55	0.15	
B^2	110.21	1	110.21	2.25	0.18	
Residual	342.33	7	48.90			
Lack of Fit	163.95	3	54.65	1.23	0.41	not significant

Table S2. ANOVA for response surface quadratic model of particle density as affected by temperature and residence time of torrefaction treatment.

Source	Sum of Squares	df	Mean Square	F Value	p-value	
Model	5704.95	5	1140.99	4.16	0.04	significant
A-Temperature (°C)	2200.34	1	2200.34	8.02	0.03	
B-Time (min)	105.84	1	105.84	0.39	0.55	
AB	345.96	1	345.96	1.26	0.30	
A^2	3014.95	1	3014.95	11.00	0.01	
B^2	707.96	1	707.96	2.58	0.15	
Residual	1919.41	7	274.20			
Lack of Fit	708.54	3	236.18	0.78	0.56	not significant

Table S3. ANOVA for Response Surface Quadratic Model of pellet density as affected by temperature and residence time of torrefaction treatment.

Source	Sum of Squares	df	Mean Square	F Value	p-value	
Model	7424.86	5	1484.97	18.60	0.00	significant
A-Temperature	5927.70	1	5927.70	74.24	< 0.0001	
B-Time	0.03	1	0.03	0.00	0.98	
AB	287.47	1	287.47	3.60	0.10	
A^2	1115.59	1	1115.59	13.97	0.01	
B^2	470.52	1	470.52	5.89	0.05	
Residual	558.93	7	79.85			
Lack of Fit	266.27	3	88.76	1.21	0.41	not significant

Table S4. ANOVA for Response Surface Quadratic Model of tensile strength as affected by temperature and residence time of torrefaction treatment.

Source	Sum of Squares	df	Mean Square	F Value	p-value	
Model	0.02	5	0.00	8.31	0.01	significant
A-Temperature	0.01	1	0.01	32.56	0.00	
B-Time	0.00	1	0.00	0.18	0.69	
AB	0.00	1	0.00	3.28	0.11	
A^2	0.00	1	0.00	4.37	0.07	
B^2	0.00	1	0.00	3.17	0.12	
Residual	0.00	7	0.00			
Lack of Fit	0.00	3	0.00	0.84	0.54	not significant

Table S5. ANOVA for Response Surface Quadratic Model of dimensional stability as affected by temperature and residence time of torrefaction treatment.

Source	Sum of Squares	df	Mean Square	F Value	p-value	
Model	2.40	5	0.48	1.05	0.46	not significant
A-Temperature (°C)	0.69	1	0.69	1.50	0.26	
B-Time (min)	0.07	1	0.07	0.14	0.72	
AB	1.07	1	1.07	2.34	0.17	
A^2	0.28	1	0.28	0.61	0.46	
B^2	0.09	1	0.09	0.19	0.67	
Residual	3.21	7	0.46			
Lack of Fit	0.07	3	0.02	0.03	0.99	not significant

Table S6. ANOVA for Response Surface Quadratic Model of ash content as affected by temperature and residence time of torrefaction treatment.

Source	Sum of Squares	df	Mean Square	F Value	p-value	
Model	0.01	5	0.00	4.79	0.03	significant
A-Temperature	0.00	1	0.00	18.10	0.00	
B-Time	0.00	1	0.00	4.01	0.09	
AB	0.00	1	0.00	0.85	0.39	
A^2	0.00	1	0.00	0.93	0.37	
B^2	0.00	1	0.00	0.32	0.59	
Residual	0.00	7	0.00			
Lack of Fit	0.00	3	0.00	0.97	0.49	not significant

Table S7. ANOVA for response surface quadratic model of high heating value (HHV) as affected by temperature and residence time of torrefaction treatment.

Source	Sum of Squares	df	Mean Square	F Value	p-value	
Model	3.50	5	0.70	53.75	< 0.0001	significant
A-Temperature	2.93	1	2.93	224.53	< 0.0001	
B-Time	0.10	1	0.10	7.98	0.03	
AB	0.00	1	0.00	0.19	0.67	
A^2	0.38	1	0.38	29.37	0.00	
B^2	0.00	1	0.00	0.10	0.76	
Residual	0.09	7	0.01			
Lack of Fit	0.07	3	0.02	3.46	0.13	not significant

Table S8. Optimal treatment conditions and equations for optimized response variables and values.

Variable	Value/Equation	R^2	Optimized value
Optimal conditions			
(A) Temperature (°C)			230
(B) Time (min)			45
Bulk density (kg/m^3)	330.73 -6.01A + 9.47B -2.04AB -13.43A^2 -12.63B^2	0.62	161.10 ± 6.99
Particle density (kg/m^3)	1377.88 -19.15A -4.2B + 9.3AB -33.03A^2 + 16.01B^2	0.74	1366.50 ± 16.55
Pellet density (kg/m^3)	995.47 -31.43A + 0.07B -8.47AB+ 20.09A^2 -13.05B^2	0.93	1042.50 ± 8.93
Tensile strength (MPa)	0.15 -0.04A -0.03B -0.01AB + 0.02A2 -0.02B2	0.85	0.21 ± 0.01
Dimensional stability (%)	0.99+ 0.33A + 0.1B -0.51AB -0.31A^2 + 0.17B^2	0.43	1.77 ± 0.66
Ash content (%)	0.27 + 0.02A -0.01B + 0.007AB -0.009A^2 + 0.005B^2	0.77	0.22 ± 0.01
Higher heating value (MJ/kg)	19.51 + 0.69A + 0.13B -0.02AB + 0.37A^2 + 0.02B^2	0.97	19.33 ± 0.1

Table S9. Normal distribution indicators of fibres.

Sample	Skewness	Kurtosis	Shapiro-wilk	P-value
Sawdust	1.49	1.62	0.79	0.02
Torrefied at 230 °C (IT[1])	1.76	3.14	0.76	0.01
Torrefied at 230 °C (OT[2])	2.00	4.14	0.71	0.003
Torrefied at 260 °C (OT[2])	2.21	5.19	0.67	0.001
Torrefied at 290 °C (OT[2])	2.23	5.35	0.71	0.003

[1] IT: inside temperature, [2] OT: outside temperature

Table S10. Mass and energy yield of torrefied sawdust compared to raw sawdust.

	Temperature (°C)	Time (min)	Severity factor	Mass loss (%)	HHV[3] (dry) (MJ/kg)	Mass yield (%)	Energy yield (%)
Non-treated sawdust	-	-	-	-	17.49	100	100
Torrefied (IT[1])	230	15	5.00	10	17.20	90	88.50
	230	30	5.30	13	17.30	87	86.04
	230	45	5.48	9.7	17.36	90.3	89.63
	260	15	5.89	12.5	17.39	87.5	86.98
	260	30	6.19	17.3	17.66	82.7	83.49
	260	45	6.36	16.4	17.87	83.6	85.39
	290	15	6.77	22.1	18.49	77.9	82.33
	290	30	7.07	21.2	18.59	78.8	83.73
	290	45	7.25	21.7	18.56	78.3	83.08
Torrefied (OT[2])	230	45	5.48	25.9	20.06	74.1	84.97
	260	45	6.36	35.2	20.70	64.8	76.70
	290	45	7.25	52.5	24.27	47.5	65.90

[1] IT: inside temperature, [2] OT: outside temperature, [3] HHV: higher heating value

Table S11. Thermochemical properties of raw and torrefied sawdust.

Sample	HHV[3] (dry) (MJ/kg)	Proximate analysis (% wt., dry)			Ultimate analysis (% wt., dry)						
		Fixed carbon	Volatile	Ash	N[4]	C[5]	H[6]	S[7]	O[8]	O/C	H/C
Sawdust	17.49	17.4	77.80	0.23	0.06	49.25	6.27	0.02	44.39	0.90	0.13
Torrefied at 230 °C (IT[1])	17.36	18.16	77.17	0.22	0.07	49.67	6.40	0.08	43.79	0.88	0.13
Torrefied at 230 °C (OT[2])	20.06	26.63	69.31	0.37	0.11	53.92	6.16	0.25	39.56	0.73	0.11
Torrefied at 260 °C (OT[2])	20.7	32.50	62.83	0.36	0.09	54.21	5.74	0.05	39.91	0.74	0.11
Torrefied at 290 °C (OT[2])	24.27	52.22	41.76	0.55	0.16	66.57	5.51	0.02	27.74	0.42	0.08

[1] IT: inside temperature, [2] OT: outside temperature, [3] HHV: higher heating value, [4] N: nitrogen, [5] C: carbon, [6] H: hydrogen, [7] S: sulphur, [8] O: oxygen.

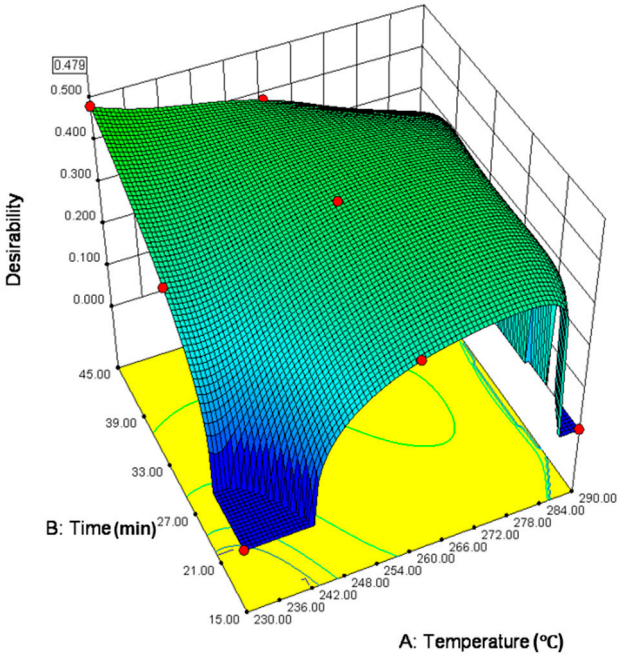

Figure S1. The desirability of collective responses for torrefaction treatment factors.

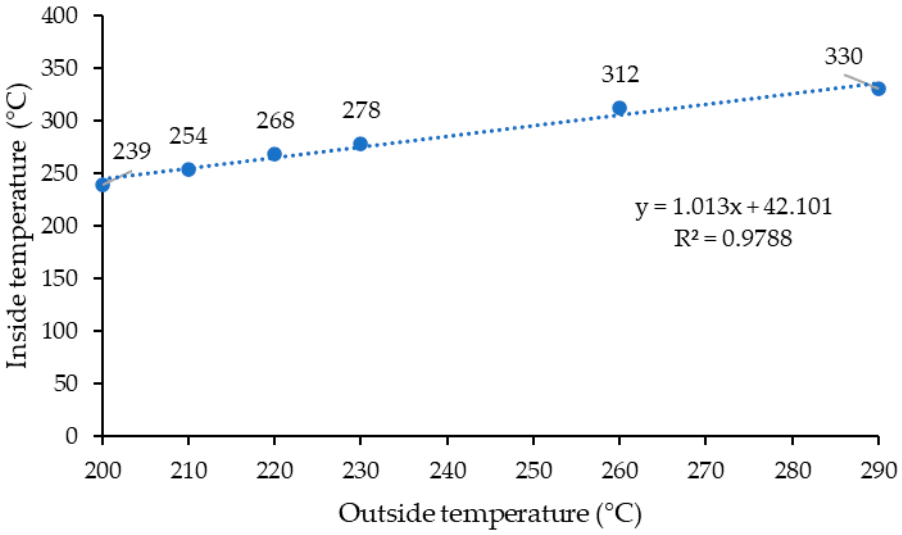

Figure S2. Relationship between inside and outside temperature of the batch torrefaction unit during torrefaction process.

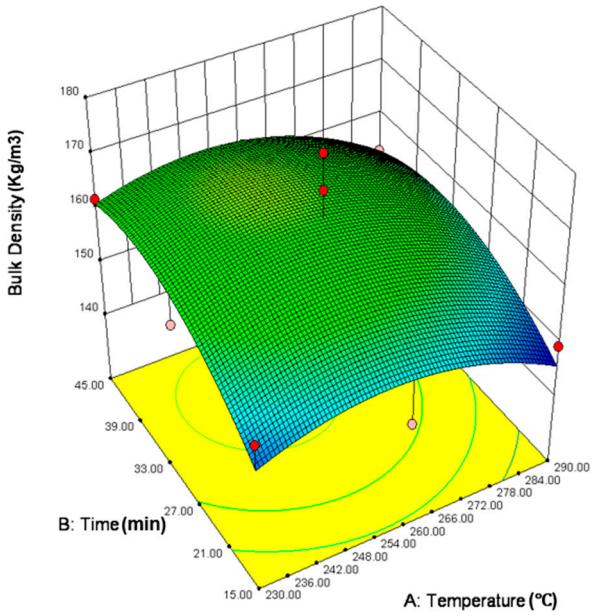

Figure S3. Response surface chart for bulk density of torrefied sawdust as affected by temperature and residence time of torrefaction treatment.

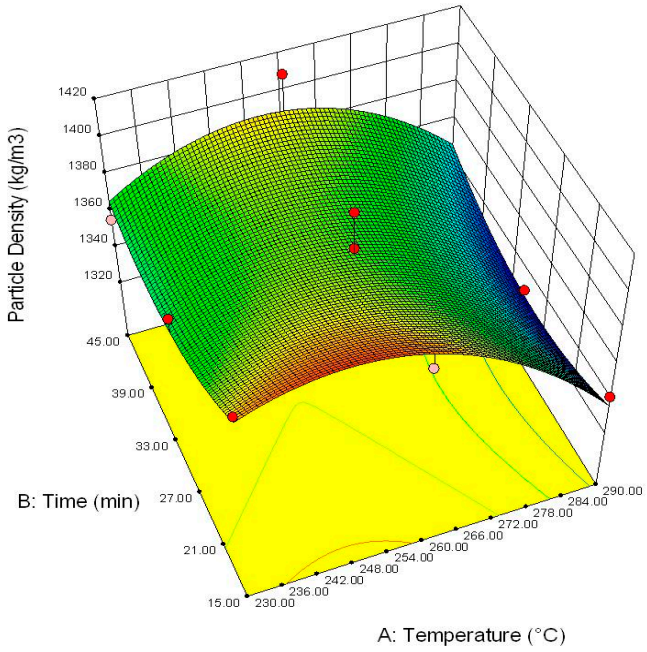

Figure S4. Response surface chart for particle density of torrefied sawdust as affected by temperature and residence time of torrefaction treatment.

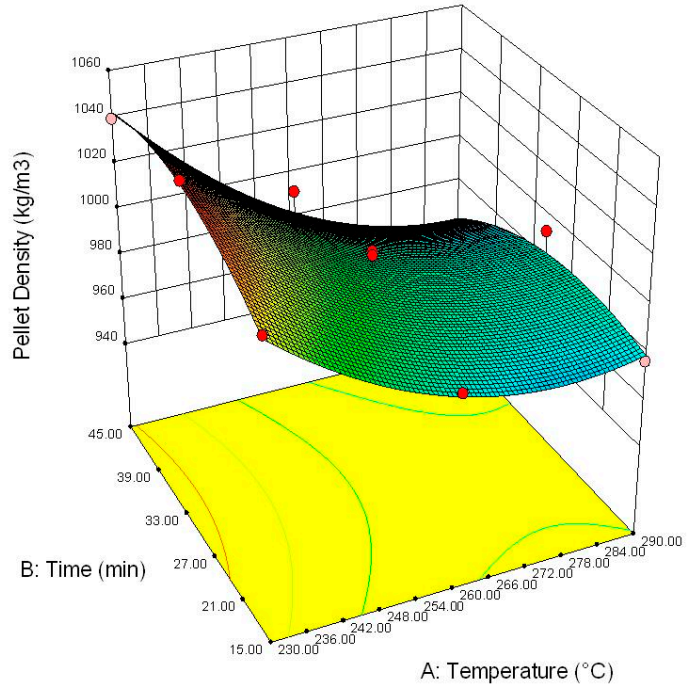

Figure S5. Response Surface chart for pellet density of torrefied pellets as affected by temperature and residence time of torrefaction treatment.

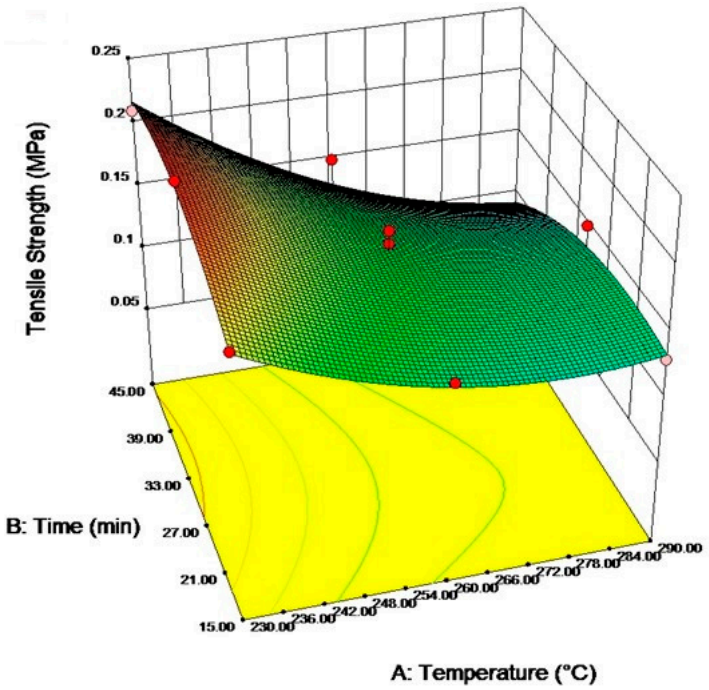

Figure S6. Response Surface chart for tensile strength of torrefied pellets as affected by temperature and residence time of torrefaction treatment.

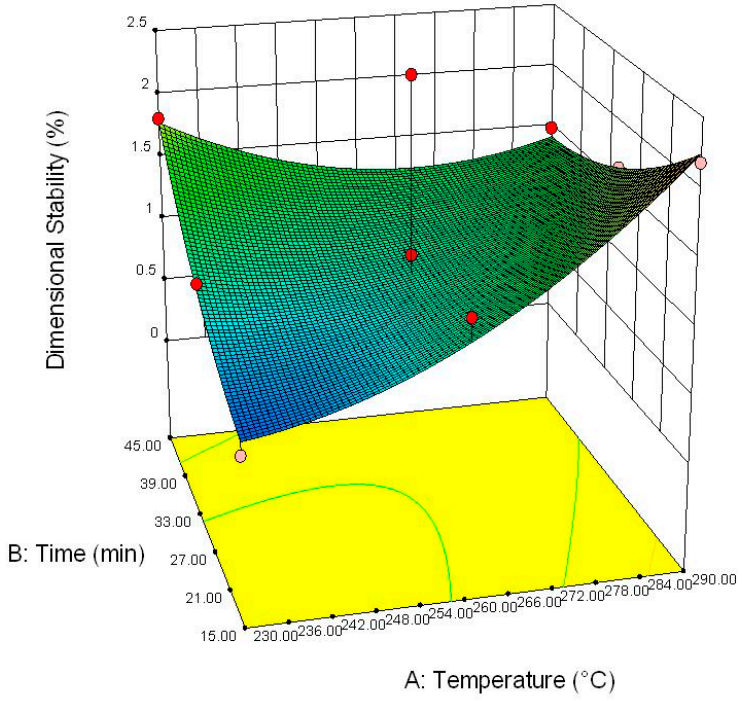

Figure S7. Response Surface chart for dimensional stability of torrefied pellets as affected by temperature and residence time of torrefaction treatment.

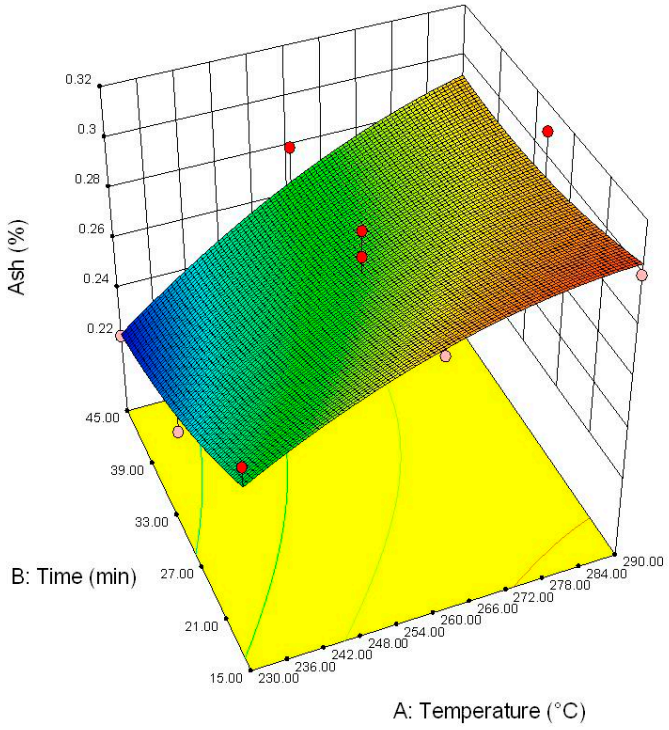

Figure S8. Response Surface chart for ash content of torrefied sawdust as affected by temperature and residence time of torrefaction treatment.

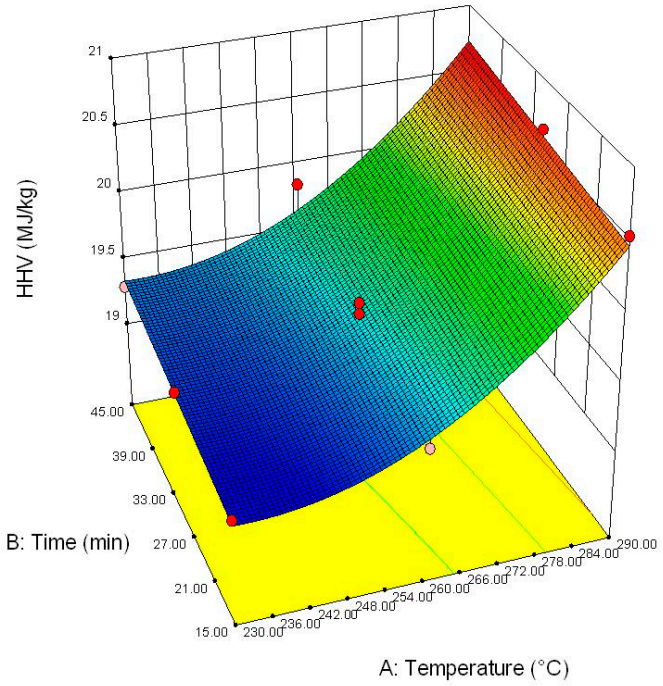

Figure S9. Response Surface chart for High Heating Value (HHV) of torrefied sawdust as affected by temperature and residence time of torrefaction treatment.

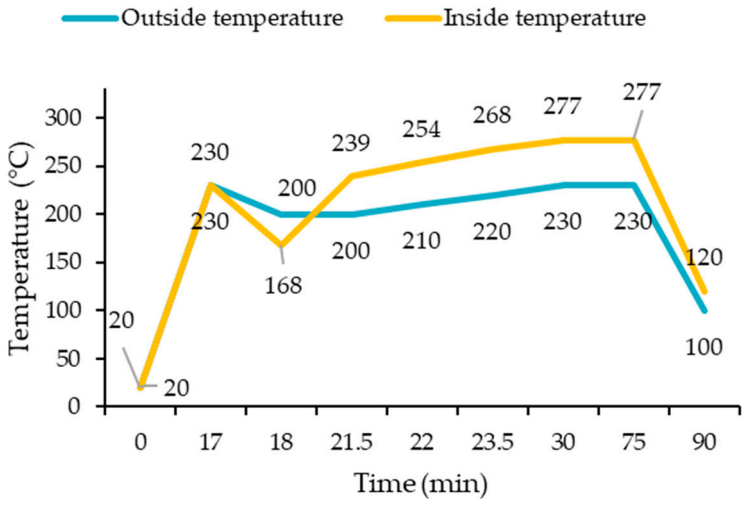

Figure S10. Temperature profile recorded from external and internal thermometers in BTU during sawdust torrefaction (230 °C and 45 min).

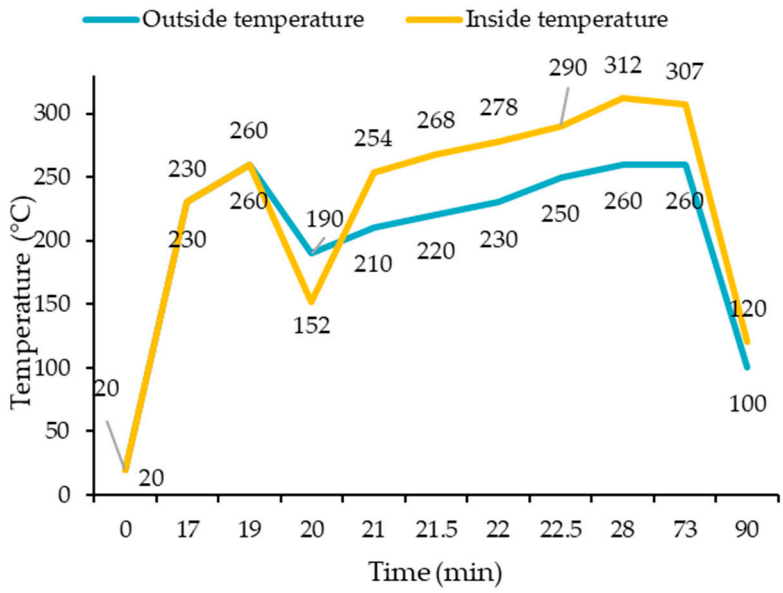

Figure S11. Temperature profile recorded from external and internal thermometers in BTU during sawdust torrefaction (260 °C and 45 min).

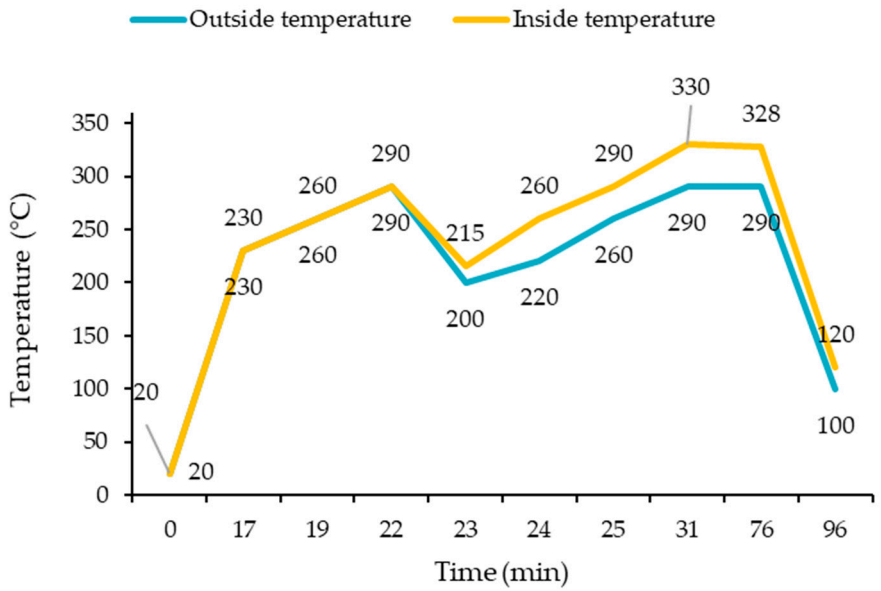

Figure S12. Temperature profile recorded from external and internal thermometers in BTU during sawdust torrefaction (290 °C and 45 min).