

Supplementary Material Foliage and Grass as Fuel Pellets—Small Scale Combustion of Washed and Mechanically Leached Biomass

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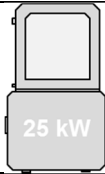
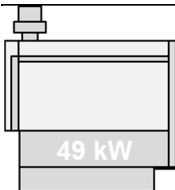
Note to Table 1: The relative change achieved by the florafuel-process (Δ_{leached}) was calculated for each parameter (if applicable) according to Equation (S1):

$$\Delta_{\text{leached}} = \left(\frac{\text{Value}_{\text{florafuel}}}{\text{Value}_{\text{original}}} \times 100 \right) - 100 \quad (\text{S1})$$

Table S1. Fuel characteristics of the two raw materials before (original) and after (leached) the application of the florafuel-process.

Raw Material		Method (DIN EN ISO)	Grass (100%)		Foliage (100%)	
			Original	Leached	Original	Leached
LHV	MJ/kg DM	18125	16.7	18.4	17.7	18.9
Ash	% DM	18122	19.1	8.1	17.5	10.5
Water	% FM	18134-1	13.3	14.6	48.3	16.2
Volatiles	% DM	18123	63.0	75.1	66.5	72.1
C	% DM	16948	44.7	48.0	48.1	51.3
H	% DM	16948	5.5	5.8	5.0	6.0
N	% DM	16948	2.0	1.4	0.9	0.8
S	% DM	16994	0.23	0.10	0.10	0.06
Cl	% DM	16994	0.33	0.02	0.18	0.01
Al	g/kg DM	16967	3.97	0.70	2.12	0.50
Pb	g/kg DM	16968	0.008	0.004	-	-
Ca	g/kg DM	16967	26.1	15.1	37.4	31.6
Fe	g/kg DM	16967	3.9	1.1	1.9	1.2
K	g/kg DM	16967	20.77	3.26	6.44	1.47
Mg	g/kg DM	16967	6.80	2.59	3.97	1.70
Na	g/kg DM	16967	0.47	0.45	0.35	-
P	g/kg DM	16967	6.44	2.03	2.20	0.60
Si	g/kg DM	16967	31.4	3.33	26.0	11.7
Ti	g/kg DM	16967	0.21	0.05	0.15	0.04
Zn	g/kg DM	16968	0.07	0.09	0.03	0.05
Ash melting behavior	SST (°C)	ox	1110	1150	1180	950
		in	830	760	1150	770
	DT (°C)	ox	1180	1180	1340	>1500
		in	1170	1160	1360	>1500
	HT (°C)	ox	1200	1210	1380	>1500
		in	1190	1200	1390	>1500
	FT (°C)	ox	1220	1220	1450	>1500
		in	1220	1230	1420	>1500

Table S2. Boiler settings used during the 4h emission measurement period given the respective fuel and the boiler. All settings refer to operation at full load.

Boiler	Parameter	Unit	Fuel		
			Grass (100%)	Foliage (100%)	Mix (50/50)
GUNTAMATIC Powercorn 30					
	Stocker	% ¹	20	17	19
	Grate movement (motor speed)	rpm	15	14	15
	Lambda setting (CO ₂ conc., λ)	%, (λ)	12, (1.7)	12, (1.7)	12, (1.7)
	Suction fan	%	70	90	90
	Primary/Secondary air setting	x ²	4	2	4
ÖKOTHERM Compact C0					
	Stocker (feeding, pause)	s	1, 8.7	1, 9	1, 8.7
	Ash pusher (one pulse per time)	min	17	17	17
	Primary air (range min-max)	%	50–65	55–70	50–65
	Secondary air (range min-max)	%	50–80	50–70	50–80
	Lambda setting (O ₂ conc., λ)	%, (λ)	7, (1.5)	7, (1.5)	7, (1.5)

¹ 100% = continuous feeding; 50% = 1.5 s feeding, 1.5 s pause; 0% = no feeding; ² Non-dimensional value of a dial on the boiler.

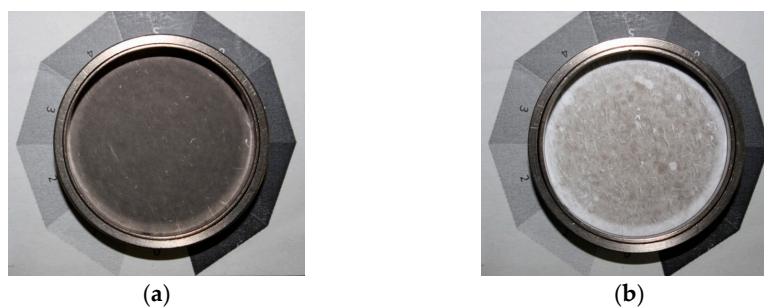


Figure S1. Picture of the PM samples that were taken: (a) before; and (b) after the PM-filter unit when the leached grass pellets were burnt in the 49 kWth pellet boiler. Samples were taken after about 2 h of steady combustion and for a duration of 30 min according to VDI 2066 [15].

Table S3. Full raw data summary and 15 min mean values of the emissions measurements across the 4 h measurement period for all three fuels in the 25 kWth boiler.

Grass (100%), Pellets (6 mm), 15 min Mean Values											Results PM Measurements			
Time	Duration	CO	NO	NO ₂	NO _x	SO ₂	HCl	THC	CO ₂	O ₂	Time	Duration	PM	
hh:mm:ss	h	mg/m ³ (13 vol% O ₂ , STP)									hh:mm	h	mg/m ³ (13 vol.% O ₂ , STP)	
09:29:38	0.00	78.9	408	3.04	629	249	15.6	29.6	12.7	9.2	Start	09:50		
09:44:45	0.25	43.0	415	2.06	638	241	16.2	29.3	12.2	9.6	End	10:20	0.5	
09:59:39	0.50	170.1	392	3.54	604	244	16.1	34.6	12.4	9.5	Start	10:25		
10:14:45	0.75	76.3	396	1.56	609	240	16.0	30.6	12.2	9.6	End	10:55	0.5	
10:29:41	1.00	31.9	400	0.85	615	242	15.6	28.3	12.3	9.5	Start	11:01		
10:44:48	1.25	165.2	368	3.58	568	239	15.7	34.3	12.6	9.2	End	11:31	0.5	
10:59:43	1.50	53.1	385	1.08	592	238	15.9	29.4	12.2	9.5	-	-	-	-
11:14:38	1.75	110.3	381	2.41	586	233	15.7	25.1	12.3	9.4	-	-	-	-
11:29:45	2.00	73.6	390	2.23	601	237	16.6	30.4	11.6	10.0	-	-	-	-
11:44:41	2.25	89.6	385	2.69	593	234	16.2	31.2	11.8	9.8	-	-	-	-
11:59:37	2.50	139.7	350	2.43	539	233	16.1	34.1	12.4	9.2	-	-	-	-
12:14:43	2.75	104.4	378	1.89	581	232	16.3	34.5	12.2	9.5	-	-	-	-
12:29:39	3.00	181.3	361	1.57	555	234	16.0	38.3	12.6	9.1	-	-	-	-
12:44:47	3.25	126.1	371	2.14	571	233	16.4	34.5	12.2	9.5	-	-	-	-
12:59:43	3.50	100.0	368	1.00	565	232	15.9	34.1	12.3	9.5	-	-	-	-
13:14:38	3.75	89.4	367	1.58	564	229	16.1	30.9	12.4	9.4	-	-	-	-
13:29:46	4.00	91.4	369	1.67	567	228	16.3	33.7	12.4	9.4	-	-	-	-
Summary of full raw data											-	-	-	-
Mean		102	381	2.08	587	236	16.0	31.9	12.3	9.5	-	-	-	-
Max		2390	661	57.3	1024	353	45.4	188	17.2	17.1	-	-	-	-
Min		4.1	149	0.00	240	96	11.9	8.6	6.1	4.5	-	-	-	-
n		1332	1332	1332	1332	1332	1332	1332	1332	1332	-	-	-	-

Table S3. Cont.

Foliage (100%), Pellets (6 mm), 15 min Mean Values											Results PM Measurements			
Time	Duration	CO	NO	NO ₂	NO _x	SO ₂	HCl	THC	CO ₂	O ₂	Time	Duration	PM	
hh:mm:ss	h	mg/m ³ (13 vol.% O ₂ , STP)									hh:mm	h	mg/m ³ (13 vol.% O ₂ , STP)	
10:09:20	0.00	93.3	277	5.39	431	88.0	41.8	29.4	11.7	10.2	Start	09:50	0.5	44
10:24:26	0.25	23.8	275	6.49	429	86.6	38.4	25.7	11.5	10.4	End	10:20		
10:39:22	0.50	19.5	295	6.48	458	92.3	33.4	25.3	10.4	11.5	Start	10:25	0.5	38
10:54:17	0.75	15.3	295	5.75	459	91.1	30.7	26.5	10.1	11.8	End	10:55		
11:09:12	1.00	14.7	296	5.41	459	91.2	27.4	26.7	10.5	11.4	Start	11:01	0.5	38
11:24:30	1.25	14.8	291	5.45	452	90.9	26.2	27.8	10.5	11.4	End	11:31		
11:39:27	1.50	14.6	298	5.10	462	92.4	24.7	27.3	10.5	11.4	-	-	-	-
11:54:35	1.75	12.4	300	5.87	466	93.7	23.8	28.5	10.1	11.8	-	-	-	-
12:09:42	2.01	12.2	297	5.07	461	91.7	22.5	29.1	10.2	11.7	-	-	-	-
12:24:37	2.25	13.2	296	5.36	459	92.8	21.6	28.6	10.4	11.5	-	-	-	-
12:39:34	2.50	11.9	297	5.48	460	92.6	21.2	29.8	10.5	11.4	-	-	-	-
12:54:31	2.75	16.9	305	6.25	473	96.0	20.3	33.7	10.2	11.7	-	-	-	-
13:09:38	3.01	14.1	306	5.20	474	94.7	19.0	33.4	10.0	11.9	-	-	-	-
13:24:35	3.25	13.1	297	5.84	461	92.9	18.0	34.4	10.1	11.7	-	-	-	-
13:39:31	3.50	11.2	303	5.96	471	94.0	18.1	34.3	10.3	11.6	-	-	-	-
13:54:27	3.75	12.3	301	5.87	467	94.1	17.6	34.9	10.2	11.7	-	-	-	-
14:09:24	4.00	12.3	292	6.40	454	100.1	16.8	55.7	10.78	11.2	-	-	-	-
Summary of full raw data											-	-	-	-
Mean		19.2	295	5.73	459	92.7	24.8	31.2	10.5	11.4	-	-	-	-
Max		1733	1308	49.9	2035	374	167	205	16.8	19.0	-	-	-	-
Min		3.8	108	0.00	168	42.0	13.7	9.2	3.1	5.4	-	-	-	-
n		1348	1348	1348	1348	1348	1348	1348	1348	1348	-	-	-	-

Table S3. Cont.

Mixture (50/50), Pellets (6 mm), 15 min Mean Values											Results PM Measurements			
Time	Duration	CO	NO	NO ₂	NO _x	SO ₂	HCl	THC	CO ₂	O ₂	Time	Duration	PM	
hh:mm:ss	h	mg/m ³ (13 vol.% O ₂ , STP)									hh:mm	h	mg/m ³ (13 vol.% O ₂ , STP)	
09:56:16	0.00	109	334	4.58	516	150	7.11	23.9	12.9	9.13	Start	09:50	0.5	59
10:11:23	0.25	145	344	5.29	533	148	7.31	30.3	12.6	9.24	End	10:20		
10:26:17	0.50	116	350	3.99	540	151	7.57	27.3	12.5	9.42	Start	10:25	0.5	48
10:41:24	0.75	95	341	3.39	527	150	8.41	22.1	13.0	9.06	End	10:55		
10:56:20	1.00	118	331	3.56	512	148	8.18	24.9	12.9	9.09	Start	11:01	0.5	44
11:11:16	1.25	137	330	3.50	510	149	8.16	26.9	12.8	9.08	End	11:31		
11:26:22	1.50	47	347	1.87	533	151	8.24	22.7	12.8	9.20	-	-	-	-
11:41:19	1.75	79	345	2.29	531	152	8.83	26.0	12.7	9.26	-	-	-	-
11:56:15	2.00	133	322	2.98	497	150	7.72	26.4	13.3	8.67	-	-	-	-
12:11:23	2.25	36	353	1.67	543	153	8.24	26.7	12.3	9.60	-	-	-	-
12:26:19	2.50	96	338	2.30	520	151	8.40	26.1	13.0	9.02	-	-	-	-
12:41:16	2.75	55	332	1.02	510	151	8.66	23.3	12.9	9.04	-	-	-	-
12:56:24	3.00	48	337	1.35	517	153	8.99	24.1	12.8	9.22	-	-	-	-
13:11:21	3.25	18	337	4.73	522	153	8.96	48.5	12.1	9.65	-	-	-	-
13:26:18	3.50	13	204	5.14	318	191	8.04	135.1	11.7	9.00	-	-	-	-
13:56:17	4.00	85	306	2.81	472	141	8.59	32.1	13.8	8.07	-	-	-	-
Summary of full raw data											-	-	-	-
Mean		84	331	3.13	510	152	8.22	32.9	12.8	9.12	-	-	-	-
Max		2232	1047	39.6	1605	379	27.6	309	17.9	17.6	-	-	-	-
Min		1	41	0.00	63	65	5.39	8.8	4.2	3.90	-	-	-	-
n		1263	1263	1263	1263	1263	1263	1263	1263	1263	-	-	-	-

Table S4. Full raw data summary and 15 min mean values of the emissions measurements across the 4 h measurement period for all three fuels in the 49 kWth boiler.

Grass (100%), Pellets (6 mm), 15 min Mean Values											Results PM Measurements				
Time	Duration	CO	NO	NO ₂	NO _x	SO ₂	HCl	THC	CO ₂	O ₂	Time	Duration	PM		
hh:mm:ss	h	mg/m ³ (13 vol.% O ₂ , STP)											Before ESP	After ESP	
											hh:mm	h	mg/m ³ (13 vol.% O ₂ , STP)		
08:49:19	0.00	11.54	409	1.33	629	154	39.0	1.17	12.6	10.2					
09:04:19	0.25	8.20	392	0.15	601	146	43.2	0.96	13.0	10.0	Start	09:50			
09:19:20	0.50	7.79	391	2.70	602	146	45.4	0.52	12.8	10.0	End	10:20	0.5	71	3
09:34:11	0.75	10.91	387	2.62	597	149	39.9	0.25	12.8	10.1	Start	10:25			
09:49:12	1.00	10.54	407	1.27	626	147	47.9	0.31	12.8	10.0	End	10:55	0.5	24	2
10:04:21	1.25	9.91	395	2.64	609	149	44.3	0.35	13.1	9.7	Start	11:01			
10:19:12	1.50	12.21	376	0.89	577	143	46.9	0.22	13.0	9.8	End	11:31	0.5	26	3
10:34:13	1.75	5.46	379	1.49	582	149	40.1	0.20	12.9	10.1	-	-	-	-	-
10:49:13	2.00	2.77	365	1.54	562	147	38.1	0.13	13.0	10.0	-	-	-	-	-
11:04:13	2.25	2.97	347	1.24	533	152	38.1	0.17	13.4	9.7	-	-	-	-	-
11:19:14	2.50	2.49	367	1.31	564	144	40.0	0.27	13.5	9.6	-	-	-	-	-
11:34:14	2.75	2.04	341	1.37	525	140	37.9	0.20	13.2	9.7	-	-	-	-	-
11:49:14	3.00	2.81	350	2.02	538	139	37.1	0.19	12.9	10.0	-	-	-	-	-
12:04:15	3.25	1.67	355	2.67	548	144	38.3	0.22	13.1	9.8	-	-	-	-	-
12:19:15	3.50	2.30	357	2.85	550	152	35.0	0.17	13.0	10.0	-	-	-	-	-
12:34:15	3.75	2.14	397	3.09	612	166	39.8	0.17	13.2	9.6	-	-	-	-	-
12:49:16	4.00	1.27	359	3.41	554	166	42.7	0.21	14.0	9.0	-	-	-	-	-
Summary of full raw data											-	-	-	-	-
Mean		5.70	375	1.84	577	149	40.8	0.34	13.1	9.9	-	-	-	-	-
Max		67.4	685	95.0	1072	253	67.0	5.62	16.3	12.5	-	-	-	-	-
Min		0.00	278	0.00	426	99	31.2	0.04	9.6	6.6	-	-	-	-	-
n		1750	1750	1750	1750	1750	1750	1750	1750	1750	-	-	-	-	-

Table S4. Cont.

Foliage (100%), Pellets (6 mm), 15 min Mean Values											Results PM Measurements				
Time	Duration	CO	NO	NO ₂	NO _x	SO ₂	HCl	THC	CO ₂	O ₂	Time	Duration	PM		
hh:mm:ss	h	mg/m ³ (13 vol.% O ₂ , STP)									hh:mm	h	Before ESP	After ESP	
10:08:46	0.00	10.20	275	5.08	427	83.9	24.2	0.31	14.3	8.60					
10:23:47	0.25	13.65	267	3.12	413	86.7	25.7	0.25	14.2	8.60	Start	09:50	0.5	16	3
10:38:47	0.50	10.97	279	3.92	432	79.0	25.1	0.26	13.0	9.75	End	10:20			
10:53:47	0.75	14.17	275	3.07	424	79.1	26.4	0.33	13.8	8.90	Start	10:25	0.5	13	2
11:08:48	1.00	13.45	265	1.83	409	81.1	24.7	0.20	13.5	9.24	End	10:55			
11:23:57	1.25	9.74	268	1.97	413	79.7	23.8	0.24	13.7	9.02	Start	11:01	0.5	14	2
11:38:57	1.50	7.53	276	2.75	426	78.4	23.3	0.25	13.2	9.55	End	11:31			
11:53:57	1.75	8.14	283	3.84	438	78.8	22.9	0.27	13.0	9.67	-	-	-	-	-
12:08:58	2.00	7.31	273	3.06	421	74.6	22.9	0.22	13.3	9.41	-	-	-	-	-
12:23:58	2.25	8.50	279	4.17	432	74.1	20.6	0.25	13.0	9.73	-	-	-	-	-
12:38:58	2.50	8.32	271	4.09	419	75.5	21.3	0.30	13.2	9.52	-	-	-	-	-
12:53:59	2.75	9.64	276	2.87	426	76.3	20.7	0.22	13.3	9.34	-	-	-	-	-
13:08:59	3.00	11.80	264	2.03	407	80.1	21.5	0.27	13.8	8.96	-	-	-	-	-
13:23:48	3.25	8.20	265	1.52	408	78.0	21.8	0.28	13.6	9.07	-	-	-	-	-
13:38:50	3.50	8.08	255	0.46	392	85.3	21.5	0.26	14.2	8.54	-	-	-	-	-
13:53:53	3.75	5.28	260	1.18	400	77.8	21.9	0.31	13.6	9.07	-	-	-	-	-
14:08:56	4.00	6.60	257	1.34	396	82.3	22.0	0.29	13.8	8.90	-	-	-	-	-
Summary of full raw data											-	-	-	-	-
Mean		9.51	270	2.73	417	79.4	23.0	0.27	13.6	9.17	-	-	-	-	-
Max		196	369	32.2	570	184	31.3	2.14	17.0	11.8	-	-	-	-	-
Min		0.00	187	0.00	286	52.9	17.7	0.03	10.1	5.45	-	-	-	-	-
n		1740	1740	1740	1740	1740	1740	1740	1740	1740	-	-	-	-	-

Table S4. Cont.

Mixture (100%), Pellets (6 mm), 15 min Mean Values											Results PM Measurements				
Time	Duration	CO	NO	NO ₂	NO _x	SO ₂	HCl	THC	CO ₂	O ₂	Time	Duration	PM		
hh:mm:ss	h	mg/m ³ (13 vol.% O ₂ , STP)									hh:mm	h	mg/m ³ (13 vol.% O ₂ , STP)		
													Before ESP	After ESP	
10:42:33	2.50	9.52	388	12.18	607	148	19.0	0.15	12.1	10.49					
10:57:33	2.75	15.42	333	2.89	513	170	19.5	0.18	14.9	8.20	Start	09:50	0.5	18	4
11:12:33	3.00	4.58	352	4.66	544	156	24.9	0.15	14.7	8.36	End	10:20			
11:27:34	3.25	4.34	354	3.85	546	151	22.1	0.17	13.4	9.49	Start	10:25	0.5	29	7
11:42:34	3.50	12.05	338	2.87	522	162	20.5	0.18	14.3	8.68	End	10:55			
11:57:34	3.75	6.30	333	4.36	515	151	23.0	0.19	14.0	8.96	Start	11:01	0.5	17	4
12:12:35	4.00	6.43	348	2.02	535	155	20.2	0.11	13.5	9.41	End	11:31			
12:27:35	4.25	3.52	333	1.82	513	177	23.7	0.18	14.9	8.15	-	-	-	-	-
12:42:35	4.50	4.07	337	2.44	519	150	20.9	0.11	13.6	9.27	-	-	-	-	-
12:57:45	4.75	6.48	323	2.85	499	155	22.5	0.17	14.1	8.88	-	-	-	-	-
13:12:54	5.01	2.31	322	1.74	495	152	22.5	0.12	14.2	8.66	-	-	-	-	-
13:27:54	5.26	2.16	335	2.11	516	151	21.7	0.19	13.7	9.17	-	-	-	-	-
13:42:37	5.50	6.70	320	2.52	493	167	21.5	0.23	14.4	8.61	-	-	-	-	-
13:57:37	5.75	1.86	318	1.30	489	148	23.1	0.23	14.1	8.80	-	-	-	-	-
14:12:39	6.00	2.02	305	0.92	469	154	23.3	0.33	14.4	8.54	-	-	-	-	-
14:27:35	6.25	0.96	329	2.27	506	149	22.9	0.28	13.4	9.39	-	-	-	-	-
14:42:55	6.51	1.49	307	1.13	472	162	24.4	0.32	14.7	8.20	-	-	-	-	-
Summary of full raw data											-	-	-	-	-
Mean		5.31	334	3.07	515	156	22.1	0.19	14.0	8.91	-	-	-	-	-
Max		378	544	80.3	855	322	29.1	3.36	18.1	12.2	-	-	-	-	-
Min		0.00	225	0.00	345	102	14.8	0.03	10.2	4.87	-	-	-	-	-
n		1745	1745	1745	1745	1745	1745	1745	1745	1745	-	-	-	-	-