Supplementary online material

Biological and thermochemical conversion of human solid waste to soil amendments

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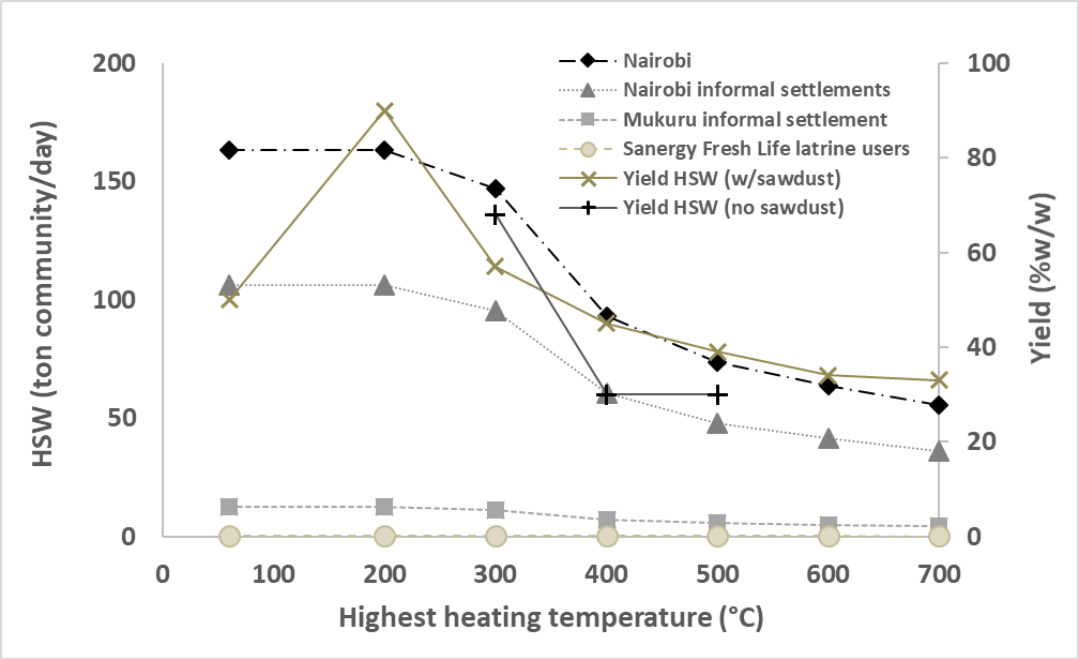


Supplementary Fig. 1. Theoretical mass recovery of human solid waste (HSW) mixed with sawdust (w/sawdust) from Nairobi and neighborhoods within Nairobi, Kenya following biological (60 °C compost) and thermochemical treatment at 200 – 700 °C, based on the measured yield recovery of torrefied and pyrolyzed Sanergy HSW (Yield; brown ×). Also included is the yield of HSW not mixed with sawdust (no sawdust) pyrolyzed at 300 °C, 400 °C, and 500 °C (Yield; black +).

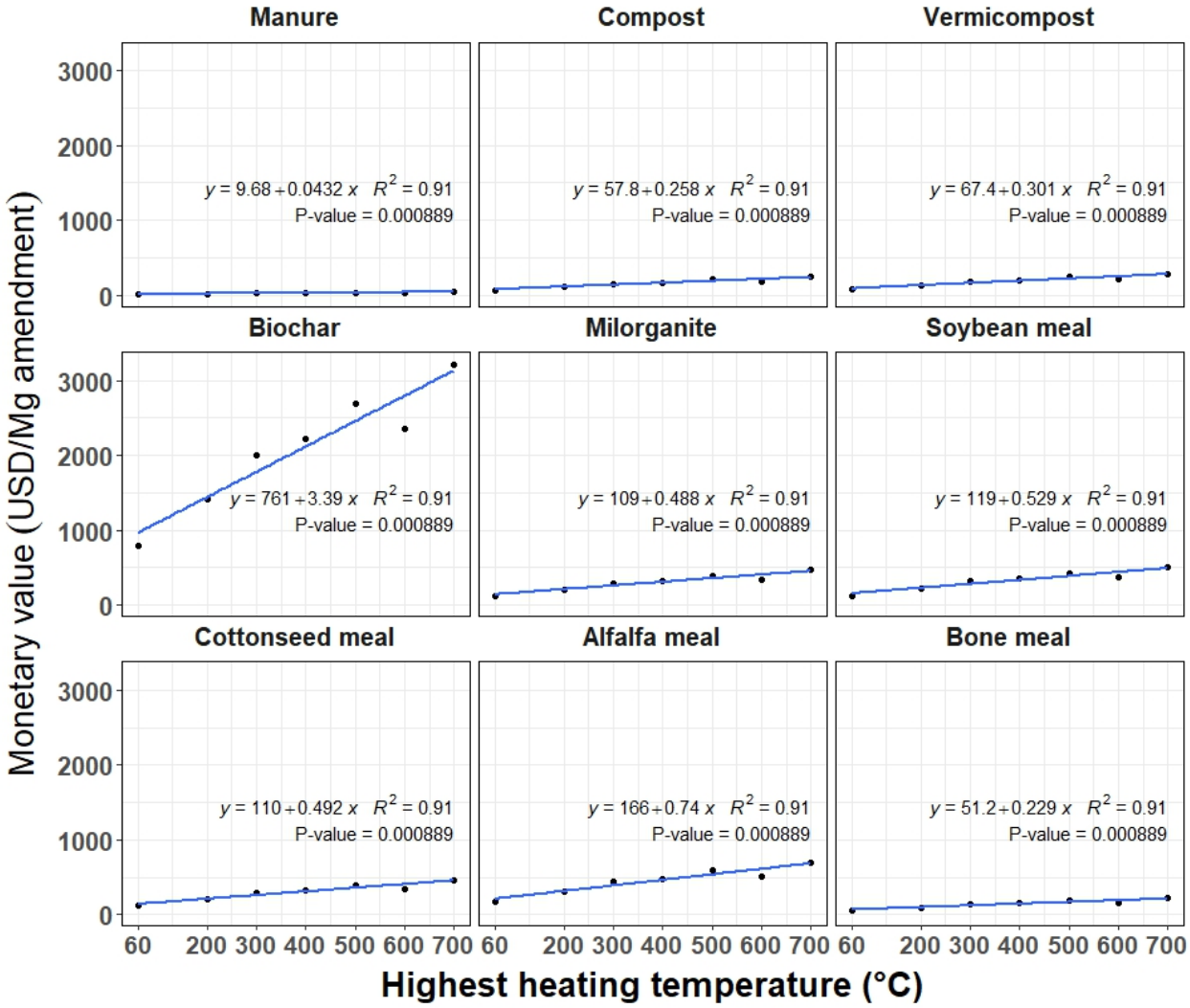
Supplementary Table 1
Concentrations of agronomically-beneficial components in HSW not mixed with sawdust, and pyrolyzed at 300 °C, 400 °C, and 500 °C. Agronomic components include plant-available N (NH_4^++ NO_3^-), P, K, Ca, Mg, S, micronutrients (B, Cu, Mn, Zn) reserve plant-available K^+, Ca^{2+}, and Mg^{2+} retained through CEC, $CaCO_3$ equivalency, and BC_{+100}. All values except $BC+_{100}$ are the average of two measurements ± standard deviation.

		Highest heating temperature (°C)		
Agronomic component	Unit	300 °C	400 °C	500 °C
N (NH_4^++ NO_3^-)	mg/kg feedstock	62.5 ± 1.1	3.8 ± 0.6	2.8 ± 1.9
P	mg/kg feedstock	3820 ± 60	3578 ± 89	3772 ± 306
K	mg/kg feedstock	16,923 ± 61	12,553 ± 139	11,888 ± 791
Ca	mg/kg feedstock	1274 ± 37	920 ± 25	1013 ± 49
Mg	mg/kg feedstock	2208 ± 187	2171 ± 51	2313 ± 37
S	mg/kg feedstock	439 ± 5	237 ± 7	238 ± 25
Micronutrients (B+Cu+Mn+Zn)	mg/kg feedstock	68.8 ± 3.1	56.0 ± 1.3	57.5 ± 2.6
CEC (K^++Ca^{2+}+Mg^{2+})	mg/kg feedstock	4673 ± 65	2040 ± 135	1801 ± 4
$CaCO_3$	%w/w feedstock	1.7 ± 0.8	3.3 ± 0.3	3.0 ± 0.0
BC_{+100}	%w/w feedstock	17.5 (1 rep)	22.8 (1 rep)	23.3 (1 rep)
N (NH_4^++ NO_3^-)	mg/kg amendment	92.0 ± 1.6	12.7 ± 2.1	9.2 ± 6.2
P	mg/kg amendment	5617 ± 89	11,926 ± 298	12,574 ± 1017
K	mg/kg amendment	24,886 ± 90	41,845 ± 462	39626 ± 2637
Ca	mg/kg amendment	1874 ± 54	3065 ± 82	3377 ± 164
Mg	mg/kg amendment	3248 ± 55	7238 ± 169	7710 ± 622
S	mg/kg amendment	646 ± 7	790 ± 22	793 ± 85
Micronutrients (B+Cu+Mn+Zn)	mg/kg amendment	101 ± 5	187 ± 4	192 ± 9

CEC (K^++Ca^{2+}+Mg^{2+})	mg/kg amendment	6939 ± 96	13,770 ± 448	12,864 ± 12
$CaCO_3$	%w/w amendment	2.5 ± 1.1	11.0 ± 0.9	10.2 ± 0.0
BC_{+100}	%w/w amendment	25.8 (1 rep)	76.0 (1 rep)	77.7 (1 rep)

Supplementary Table 2
Concentrations of agronomically-beneficial components in HSW amendments per unit weight of feedstock. Agronomic components include plant-available N (NH_4^++ NO_3^-), P, K, Ca, Mg, S, micronutrients (B, Cu, Mn, Zn) reserve plant-available K^+, Ca^{2+}, and Mg^{2+} retained through CEC, $CaCO_3$ equivalency, and BC_{+100}. Data are the average of two measurements ± standard deviation.

		Highest heating temperature (°C)						
Agronomic component	Unit	60 (compost)	200	300	400	500	600	700
N (NH_4^++ NO_3^-)	mg/kg feedstock	214.5 ± 0.7	701.5 ± 4.1	15.2 ± 1.1	5.2 ± 0.6	1.8 ± 1.9	0.7 ± 0.1	0.2 ± 0.0
P	mg/kg feedstock	718 ± 47	6928 ± 472	3792 ± 184	3229 ± 204	3179 ± 169	3118 ± 197	2521 ± 100
K	mg/kg feedstock	1463 ± 74	12792 ± 405	8614 ± 338	7793 ± 331	7769 ± 236	7403 ± 202	5832 ± 176
Ca	mg/kg feedstock	2560 ± 138	3350 ± 190	1632 ± 89	1468 ± 156	1367 ± 41	952 ± 57	1372 ± 48
Mg	mg/kg feedstock	685 ± 41	3807 ± 260	2305 ± 101	1946 ± 133	2209 ± 150	2185 ± 150	1413 ± 54
S	mg/kg feedstock	85 ± 6	468 ± 27	100 ± 7	99 ± 9	102 ± 8	101 ± 7	106 ± 2
Micronutrients (B+Cu+Mn+Zn)	mg/kg feedstock	177.5 ± 8.8	267.2 ± 12.4	78.4 ± 3.0	77.1 ± 4.3	80.7 ± 4.0	80.6 ± 3.7	83.2 ± 2.4
CEC (K^++Ca^{2+}+Mg^{2+})	mg/kg feedstock	4778 ± 81	4338 ± 278	5376 ± 296	3573 ± 120	2419 ± 159	1273 ± 113	1382 ± 78
$CaCO_3$	%w/w feedstock	2.0 ± 0.6	0.5 ± 0.6	1.2 ± 0.1	2.2 ± 0.3	2.8 ± 0.1	1.9 ± 0.0	3.3 ± 0.2
BC_{+100}	%w/w feedstock	1.3 ± 1.7	10.1 ± 3.4	25.1 ± 1.2	27.2 ± 0.3	30.1 ± 1.3	29.0 ± 0.3	30.7 ± 0.3



Supplementary Fig. 2. Linear regression between the monetary value of HSW amendments, calculated using the 'top-down' approach, versus the sanitization temperature. Monetary value is based on the comparative concentration of total N, P, and K in HSW (Supplementary Table 4) versus nine commercial organic amendments and their market prices (Supplementary Table 5).

Supplementary Table 3
International and East African market prices for fertilizer nutrients including N (NH_4^++ NO_3^-), P, K, Ca, Mg, S, micronutrients (B, Cu, Mn, and Zn), as well as $CaCO_3$, and carbon dioxide (CO_2) discount rates. Prices in bold were used for calculating the final value HSW presented in Fig. 3.

Source	Agronomic component	Quantile prices (USD/Mg)				
		0.1	0.25	0.5	0.75	0.9
AfricaFertilizer.org; eight East African countries; February 2016 - June 2017	NH_4^++ NO_3^--N	1051	1877	2799	4018	13,668
	P	2973	4870	7807	11,602	34,464
	K	1426	4665	6690	9097	20,985
	Ca[a]	93.2	93.2	93.2	102.5	111.8
AfricaFertilizer.org; International prices; February 2016 - June 2017	NH_4^++ NO_3^--N	383	464	512	1807	2013
	P	1385	1528	1666	3652	4612
	K	448	455	1167	2184	2424
	S	**396**	**407**	**438**	**450**	**463**
	Ca	140	157	217	336	366
AfricaFertilizer.org; eight East Africa and International prices combined; February 2016 - June 2017	NH_4^++ NO_3^--N	**384**	**1580**	**2534**	**3890**	**13,668**
	P	**1385**	**3843**	**7238**	**9893**	**34,464**
	K	**448**	**3862**	**5736**	**8423**	**20985**
	Ca	**93.2**	**143.2**	**170.9**	**332.6**	**365.5**
Kenya cement companies and Alibaba, June 2017	**$CaCO_3$**	**50**	**105**	**119**	**235**	**261**
	Mg	**207**	**359**	**406**	**460**	**663**
Alibaba, June 2017	**B**	**743**	**3235**	**3801**	**4139**	**4730**
	Zn	**1194**	**1266**	**1578**	**1860**	**2059**
	Mn	**1199**	**1269**	**1368**	**1625**	**1692**
	Cu	**5108**	**6631**	**7564**	**8291**	**10,216**
State and trends of Carbon (C) pricing 2015; World Bank Group	**CO_2**	**1.0**	**6.5**	**16.0**	**32.0**	**130.0**

[a] $CaCO_3$ was used for lime prices and Ca prices.

Supplementary Table 4
Acid-digestible total N, P, and K in sanitized HSW amendments. Data are the average of two measurements ± standard deviation.

Highest heating temperature (°C)	Total N	Total P	Total K
		(% w/w)	
60	1.6 ± 0.1	0.8 ± 0.2	0.5 ± 0.1
200	3.2 ± 0.6	1.1 ± 0.1	1.1 ± 0.2
300	4.2 ± 0.3	2.0 ± 0.0	1.1 ± 0.1
400	4.1 ± 0.1	2.6 ± 0.1	1.0 ± 0.1
500	3.5 ± 0.2	2.5 ± 0.1	2.6 ± 0.1
600	3.2 ± 0.0	3.0 ± 0.0	1.2 ± 0.1
700	2.9 ± 0.3	3.1 ± 0.0	3.5 ± 0.0

Supplementary Table 5
Literature values for the concentration of total N, P, and K in various organic amendments and their market prices.

Description	N	P (%w/w)	K	Source	Material	Country	Cost (USD/Mg)	Source
Manure								
Zero grazed cattle manure	1.7	1.85	2.05	Njenga et al., 2010	Farmyard manure	Kenya	10	Kirigia et al., 2013
Average of composted and biodynamic FYM	2.2	4.60	2.16	Zaller and Koepke, 2004	Farmyard manure	Kenya	30	Otinga et al., 2013
Dairy manure and bedding	1.5	0.04	0.76	Carpenter-Boggs et al., 2000	Cattle manure	USA	35	MSU, 2008
Cattle manure	1.0	0.22	0.44	Penhallegon, 2003	Farmyard manure	Kenya	50	Wango et al., 2015, 2016
Dairy manure	1.0	0.17	0.44	Penhallegon, 2003	Farmyard manure	Kenya	100	Nekesa et al., 2007
Compost								
MSW compost	2.0	0.58	0.39	Hargreaves et al., 2009a,b	Compost	Kenya	3	Wango et al., 2015, 2016
Garden compost	1.0	0.16	0.5	Chan et al., 2007a	Compost	USA	28	Home Depot amendments
Urban waste compost	1.2	0.45	0.6	Njenga et al., 2010	Compost	USA	70	Ideal compost co.
Greenwaste	2.3	0.33	0.65	Penhallegon, 2003	Compost	USA	50	Hargreaves et al., 2009a,b
Composted farmyard manure	1.2	0.38	0.44	Chan et al., 2007a	Compost	Kenya	90	Nekesa et al., 2007
Composted farmyard manure	1.9	0.65	0.67	Hargreaves et al., 2009a,b				
Vermicompost								
Straw, manure, food waste	2.6	0.9	2.4	Suthar, 2007	Vermicompost	Kenya	350	Ndung'u, 2016

Paper waste	1.0	2.7	6.2	Arancon et al., 2004	Vermicompost	Kenya	500	Strathmore University, 2017
Food waste	1.3	2.7	9.2	Arancon et al., 2004	Vermicompost	Vietnam	100	Viet D.E.L.T.A Industrial Co., LTD; Alibaba
Worm castings	1.5	1.1	1.08	Penhallegon, R., 2003	Vermicompost	India	31.11	Vermico company
Worm castings	3.2	0.5	1.25	Traunfeld and Nibali, 2013	Vermicompost	China	225	Shijiazhuang Hanhao Trade Co., Ltd; Alibaba
Biochar								
Poultry litter	5.2	0.58	2.5	Singh et al., 2010	Biochar (70% derived from plant biomass)	Global mean	2650	Jirka and Tomlinson, 2014
Cow manure	1.4	0.44	2.6	Singh et al., 2010	Biochar	Philippines	90	Jirka and Tomlinson, 2014
E. Saligna wood	1.4	0.01	0.18	Singh et al., 2010	Biochar	UK	8850	Jirka and Tomlinson, 2014
HSW 500 °C	3.0	2.5	2.6	Krounbi et al. (2018)	Biochar (woody feedstock)	USA	525	Wakefield Biochar
Miscellaneous organic amendments								
Biosolids (Milorganite)	6.0	1.75	0	Wallmart	Biosolids	USA	257.94	Wallmart
Alfalfa meal	2.5	0.22	1.66	Penhallegon, 2003	Alfalfa meal	USA	264.75	USDA market news, 6/20/2017
Alfalfa meal	3.0	0.44	1.66	Traunfeld and Nibali, 2013				
Cottonseed meal	5.0	0.87	0.44	Penhallegon, 2003	Cottonseed meal	USA	212.5	USDA market news, 6/20/2017
Cottonseed meal	6.0	0.87	0.44	Traunfeld and Nibali, 2013				
Soy meal	6.5	0.65	1.99	Penhallegon, 2003	Soy meal	USA	307.86	USDA market news, 6/20/2017
Soy meal	7.0	0.87	0.83	Traunfeld and Nibali, 2013				

Bone meal	1.0	4.8	0	Traunfeld and Nibali, 2013	Bone meal	USA	247.1	USDA market news, 6/20/2017
Feather meal	15.0	0	0	Penhallegon, 2003				

Supplementary Table 6
R software packages used for data organization, analysis, and presentation.

Count	R package	Authors
1	broom	Robinson (2017)
2	cowplot	Wilke (2017)
3	data.table	Dowle and Srinivasan (2017)
4	devtools	Wickham and Chang (2017)
5	dplyr	Wickham et al. (2017)
6	ggplot2	Wickham (2009)
7	ggpmisc	Aphalo. (2016)
8	grid	R Core Team (2017)
9	lattice	Sarkar (2008)
10	lsmeans	Lenth (2016)
11	multcompView	Graves et al. (2015)
12	plotly	Sievert et al. (2017)
13	plyr	Wickham (2011)
14	quantreg	Koenker (2018)
15	reshape2	Wickham (2007)
16	stringr	Wickham (2017)
17	tidyverse	Wickham (2017)
18	xlsx	Dragulescu (2014)
19	xlsxjars	Dragulescu (2014)

Supplementary Table 7
Fecal pathogens in HSW sanitized through various methods at different highest heating temperatures (HHT).

Treatment	HHT (°C)	Intestinal ova and parasites	*Salmonella* species	*Shigella* species	*Aeromonas* species	*E. coli* serotype 157	*Yersinia enterocolitica*
Raw	25	Entamoeba histolytica, Giardia lamblia	ND[a]	ND	ND	ND	ND
Sun-dried	40	ND	ND	ND	ND	ND	ND
Autoclaved	105	ND	ND	ND	ND	ND	ND
Composted	60	ND	ND	ND	ND	ND	ND
Torrefied	200	ND	ND	ND	ND	ND	ND
Pyrolyzed	300	ND	ND	ND	ND	ND	ND
Pyrolyzed	400	ND	ND	ND	ND	ND	ND
Pyrolyzed	500	ND	ND	ND	ND	ND	ND
Pyrolyzed	600	ND	ND	ND	ND	ND	ND

[a]ND = not detected

Supplementary Table 8
Total polyaromatic hydrocarbons (PAHs) in HSW amendments.

	Highest heating temperature (°C)			
	60 (compost)	300	500	700
Congener	(µg/kg)			
Acenaphthene	ND[a]	ND	8.2	4.56
Acenaphthylene	ND	373	2.56	ND
Anthracene	ND	ND	26.2	ND
Benzo(a)anthracene	6.7	ND	9.63	ND
Benzo(a)pyrene	6.7	ND	3.22	ND
Benzo(b)fluoranthene	6	ND	3.51	ND
Benzo(g,h,i)perylene	ND	ND	2.26	ND
Benzo(k)fluoranthene	6	ND	2.88	ND
Chrysene	6.7	ND	19.9	ND
Dibenzo(a,h)anthracene	ND	ND	ND	ND
Fluoranthene	7.3	ND	18.1	ND
Fluorene	ND	186	20.4	4.26
Indeno(1,2,3-cd)pyrene	ND	ND	1.84	ND
2-Methylnaphthalene	ND	261	205	14.9
Naphthalene	ND	122	1160	21.6
Phenanthrene	8	ND	129	8.85
Pyrene	8.7	ND	19.8	ND
Total PAHs	56.1	942	1632.5	54.17

[a] ND = not detected

Supplementary Table 9
Concentrations of polychlorinated bi-phenyls (PCBs) in HSW amendments.

	Highest heating temperature (°C)			
	60 (compost)	300	500	700
Congener type	(µg/kg)			
Monochlorobiphenyls	0.119	0.107	0.174	0.256
Dichlorobiphenyls	0.186	0.522	0.656	1.170
Trichlorobiphenyls	0.205	0.205	0.387	0.626
Tetrachlorobiphenyls	0.138	ND[a]	ND	0.292
Pentachlorobiphenyls	0.748	0.077	ND	0.243
Hexachlorobiphenyls	0.564	ND	ND	ND
Heptachlorobiphenyls	ND	ND	ND	ND
Octachlorobiphenyls	ND	ND	ND	ND
Nonachlorobiphenyls	ND	ND	ND	ND
Decachlorobiphenyls	ND	ND	ND	ND
Total PCBs	**1.96**	**0.91**	**1.22**	**2.59**

[a] ND = not detected

Supplementary Table 10
Concentrations of PCCD/Fs found in HSW amendments and associated TEFs for each congener.

		Highest heating temperature (°C)			
	TEF	60 (compost)	300	500	700
Congener type			(µg/kg)		
2,3,7,8 TCDF	0.1	2	ND[a]	ND	ND
Total TCDF		63	ND	ND	ND
2,3,7,8 TCDD	1		ND	ND	ND
Total TCDD		26	ND	ND	ND
1,2,3,7,8 PeCDF	0.03		ND	ND	ND
2,3,4,7,8 PeCDF	0.3		ND	ND	ND
Total PeCDF		17	ND	ND	ND
1,2,3,7,8 PeCDD	1		ND	ND	ND
Total PeCDD		8	ND	ND	ND
1,2,3,4,7,8 HxCDF	0.1		ND	ND	ND
1,2,3,6,7,8 HxCDF	0.1		ND	ND	ND
2,3,4,6,7,8 HxCDF	0.1		ND	ND	ND
1,2,3,7,8,9 HxCDF	0.1		ND	ND	ND
Total HxCDF		6.4	ND	ND	ND
1,2,3,4,7,8 HxCDD	0.1		ND	ND	ND
1,2,3,6,7,8 HxCDD	0.1		ND	ND	ND
1,2,3,7,8,9 HxCDD	0.1		ND	ND	ND
Total HxCDD		17	ND	ND	ND
1,2,3,4,6,7,8 HpCDF	0.01	10	ND	ND	ND
1,2,3,4,7,8,9 HpCDF	0.01		ND	ND	ND
Total HpCDF		19	ND	ND	ND
1,2,3,4,6,7,8 HpCDD	0.01	42	ND	ND	ND
Total HpCDD		80	ND	ND	ND
OCDF	0.0003	27	ND	ND	ND
OCDD	0.0003	820	ND	ND	ND
Total TEQ		**0.97**	**0**	**0**	**0**

[a] ND = not detected

Supplementary Table 11
Median quantile value (p = 0.5) of agronomically-beneficial components in HSW amendments per megagram (Mg) of dry, unsanitized HSW (feedstock) and sanitized HSW (amendment). Agronomic components include plant-available N (NH_4^++ NO_3^-), P, K, Ca, Mg, S, micronutrients (B, Cu, Mn, Zn) the contribution of the CEC toward retention of K^+, Ca^{2+}, and Mg^{2+}, $CaCO_3$ equivalency, and BC_{+100}.

Agronomic component[a]	HSW highest heating temperature (°C)						
	60 (compost)	200	300	400	500	600	700
	(USD/Mg feedstock)						
NH_4^++ NO_3^--N	0.5 ± 0.0	1.8 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
P	5.2 ± 0.3	50.2 ± 3.4	27.5 ± 1.3	23.4 ± 1.5	23.0 ± 1.2	22.6 ± 1.4	18.3 ± 0.7
K	8.4 ± 0.4	73.4 ± 2.3	49.4 ± 1.9	44.7 ± 1.9	44.6 ± 1.4	42.5 ± 1.2	33.5 ± 1.0
Ca	0.4 ± 0.0	0.6 ± 0.0	0.3 ± 0.0	0.3 ± 0.0	0.2 ± 0.0	0.2 ± 0.0	0.2 ± 0.0
Mg	0.3 ± 0.0	1.6 ± 0.1	0.9 ± 0.0	0.8 ± 0.1	0.9 ± 0.1	0.9 ± 0.1	0.6 ± 0.0
S	1.2 ± 0.1	6.3 ± 0.4	1.4 ± 0.1	1.3 ± 0.1	1.4 ± 0.1	1.4 ± 0.1	1.4 ± 0.0
B	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Cu	0.0 ± 0.0	0.1 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.0	0.2 ± 0.0
Mn	0.2 ± 0.0	0.2 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.0 ± 0.0
Zn	0.1 ± 0.0	0.2 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.0
Micronutrients (B+Cu+Zn+Mn)	0.3 ± 0.0	0.4 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.2 ± 0.0	0.3 ± 0.0
K^+ (CEC)	8.4 ± 0.3	15.0 ± 1.0	20.4 ± 1.3	13.8 ± 0.5	9.4 ± 0.7	5.0 ± 0.4	5.2 ± 0.3
Ca^{2+} (CEC)	0.3 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Mg^{2+} (CEC)	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
CEC (K^++Ca^{2+}+Mg^{2+})	8.8 ± 0.3	15.1 ± 1.0	20.6 ± 1.3	13.9 ± 0.5	9.5 ± 0.7	5.0 ± 0.4	5.3 ± 0.3
$CaCO_3$	2.4 ± 0.8	0.5 ± 0.8	1.4 ± 0.1	2.6 ± 0.3	3.4 ± 0.1	2.3 ± 0.0	3.9 ± 0.2
BC_{+100}	0.1 ± 0.1	0.4 ± 0.2	1.1 ± 0.1	1.2 ± 0.0	1.3 ± 0.1	1.3 ± 0.0	1.3 ± 0.0

Sum	26.4 ± 2.4	144.2 ± 5.9	101.4 ± 3.7	87.0 ± 3.2	83.1 ± 2.6	74.8 ± 2.4	63.4 ± 2.0
				(USD/Mg amendment)			
NH_4^++ NO_3^--N	1.1 ± 0.0	2.0 ± 0.0	0.1 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
P	10.4 ± 0.7	55.7 ± 3.8	48.2± 2.3	51.9 ± 3.3	59 ± 3.2	66.4 ± 4.2	55.3 ± 2.2
K	16.8 ± 0.9	81.5 ± 2.6	86.7 ± 3.4	99.3 ± 4.2	114.3 ± 3.5	124.9 ± 3.4	101.4 ± 3.1
Ca	0.9 ± 0.1	0.6 ± 0.0	0.5 ± 0.0	0.6 ± 0.1	0.6 ± 0.0	0.5 ± 0.0	0.7 ± 0.0
Mg	0.6 ± 0.0	1.7 ± 0.1	1.6 ± 0.1	1.8 ± 0.1	2.3 ± 0.2	2.6 ± 0.2	1.7 ± 0.1
S	0.1 ± 0.0	0.2 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0
Cu	0.0 ± 0.0	0.1 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.0	0.2 ± 0.0	0.6 ± 0.1
B	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Mn	0.4 ± 0.0	0.2 ± 0.0	0.1 ± 0.0	0.2 ± 0.0	0.2 ± 0.0	0.2 ± 0.0	0.1 ± 0.0
Zn	0.1 ± 0.0	0.3 ± 0.0	0.0 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0
Micronutrients (B+Cu+Mn+Zn)	0.5 ± 0.0	0.5 ± 0.0	0.2 ± 0.0	0.3 ± 0.0	0.4 ± 0.0	0.5 ± 0.0	0.9 ± 0.1
K^+ (CEC)	16.8 ± 0.6	16.6 ± 1.1	35.9 ± 2.2	30.7 ± 1.1	24.1 ± 1.7	14.6 ± 1.3	15.8 ± 1.0
Ca^{2+} (CEC)	0.6 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.0 ± 0.0	0.1 ± 0.0
Mg^{2+} (CEC)	0.2 ± 0.0	0.1 ± 0.0	0.2 ± 0.0	0.2 ± 0.0	0.2 ± 0.0	0.1 ± 0.0	0.1 ± 0.0
CEC (K^++Ca^{2+}+Mg^{2+})	17.6 ± 0.6	16.8 ± 1.1	36.2 ± 2.2	31.0 ± 1.1	24.3 ± 1.7	14.7 ± 1.3	15.9 ± 1.0
$CaCO_3$	4.7 ± 1.5	0.6 ± 0.8	2.4 ± 0.2	5.8 ± 0.8	8.6 ± 0.2	6.6 ± 0.0	11.9 ± 0.7
BC_{+100}	0.1 ± 0.2	0.5 ± 0.2	1.92 ± 0.09	2.6 ± 0.0	3.4 ± 0.2	3.7 ± 0.0	4.1 ± 0.0
Sum	52.7 ± 4.9	160.2 ± 6.5	177.8 ± 6.5	193.4 ± 7.2	212.9 ± 6.7	220.0 ± 7.2	192.0 ± 6.0

[a] Prices for N (NH_4^++ NO_3^-), P, K, Ca, and $CaCO_3$ include products from both African and international markets. International prices were used for Mg, S, and micronutrients, while prices for BC_{+100} refer to CO_2 discount rates across 30 countries. Median (0.5 quantile) price values have been used for calculations ± standard deviation.

Supplementary Table 12
Coefficients of regression, slope (β) and intercept (α), of quantiles of the monetary value of agronomic components in HSW versus highest heating temperature (HHT).

Element		Quantile	Value ± std error	t value	p value
NH_4^++ NO_3^-	α	0.1	849.5 ± 32.5	26.16	0.00
	β		-1.6 ± 0.1	-23.09	0.00
	α	0.25	1719.6 ± 98.5	17.46	0.00
	β		-3.2 ± 0.2	-15.32	0.00
	α	0.5	6364.8 ± 380.8	16.71	0.00
	β		-10.6 ± 0.6	-16.66	0.00
	α	0.75	18153.4 ± 450.3	40.31	0.00
	β		-25.9 ± 0.6	-40.31	0.00
	α	0.9	32871.2 ± 1409.2	23.33	0.00
	β		-46.9 ± 2.0	-23.31	0.00
P	α	0.1	31602.2 ± 1730.4	18.26	0.00
	β		339.5 ± 9.2	36.94	0.00
	α	0.25	74950.3 ± 5720.1	13.1	0.00
	β		464.8 ± 21.09	22.04	0.00
	α	0.5	142790.4 ± 19655.0	7.26	0.00
	β		799.3 ± 48.3	16.54	0.00
	α	0.75	394929.9 ± 21629.7	18.26	0.00
	β		834.4 ± 87.0	9.59	0.00
	α	0.9	425794.2 ± 152072.4	2.8	0.00
	β		2829.1 ± 269.7	10.49	0.00
K	α	0.1	27184.3 ± 14632.8	1.86	0.06
	β		457.3 ± 58.7	7.79	0.00
	α	0.25	72871.1 ± 9430.3	7.73	0.00
	β		1021.8 ± 81.5	12.54	0.00
	α	0.5	274118.23 ± 64141.0	4.27	0.00
	β		1505.9 ± 159.3	9.45	0.00
	α	0.75	333486.3 ± 59122.8	5.64	0.00
	β		2796.4 ± 257.7	10.85	0.00
	α	0.9	1476473.7 ± 192463.7	7.67	0.00
	β		3318.7 ± 436.8	7.6	0.00
Ca	α	0.1	0.3 ± 0.1	3.05	0.00

	β		0.0 ± 0.0	0	1.00
	α	0.25	0.6 ± 0.1	7.21	0.00
	β		0.0 ± 0.0	-1.47	0.15
	α	0.5	0.7 ± 0.1	5.27	0.00
	β		0.0 ± 0.0	-0.78	0.44
	α	0.75	1.3 ± 0.3	5.27	0.00
	β		0.0 ± 0.0	-0.88	0.38
	α	0.9	1.6 ± 0.2	7.73	0.00
	β		0.0 ± 0.0	-1.38	0.17
Mg	α	0.1	0.3 ± 0.1	3.44	0.00
	β		0.0 ± 0.0	5.55	0.00
	α	0.25	0.5 ± 0.1	4.03	0.00
	β		0.0 ± 0.0	7.13	0.00
	α	0.5	0.6 ± 0.3	1.91	0.06
	β		0.0 ± 0.0	3.51	0.00
	α	0.75	1.0 ± 0.3	3.43	0.00
	β		0.0 ± 0.0	4.35	0.00
	α	0.9	1.5 ± 0.4	3.45	0.00
	β		0.0 ± 0.0	2.18	0.03
S	α	0.1	0.1 ± 0.0	1.2E+16	0.00
	β		0.0 ± 0.0	-0.72	0.48
	α	0.25	0.1 ± 0.0	5.82E+15	0.00
	β		0.0 ± 0.0	-0.31	0.75
	α	0.5	0.1 ± 0.0	1.14E+16	0.00
	β		0.0 ± 0.0	0	1.00
	α	0.75	0.1 ± 0.1	1.43	0.16
	β		0.0 ± 0.0	0	1.00
	α	0.9	0.2 ± 0.0	1.23E+16	0.00
	β		0.0 ± 0.0	-1.1E+15	0.00
Micronutrients (B+Cu+Mn+Zn)	α	0.1	1.6 ± 0.5	2.99	0.00
	β		0.0 ± 0.0	0.56	0.57
	α	0.25	1.9 ± 0.7	2.74	0.01
	β		0.0 ± 0.0	0.87	0.39
	α	0.5	4.0 ± 0.6	6.98	0.00
	β		0.0 ± 0.0	-1.43	0.16
	α	0.75	5.0 ± 0.4	14.48	0.00

	β		0.0 ± 0.0	-3.21	0.00
	α	0.9	5.8 ± 0.3	17.99	0.00
	β		0.0 ± 0.0	-4.36	0.00
K^+ (CEC)	α	0.1	50219.1 ± 4211.5	11.92	0.00
	β		-10.8 ± 8.8	-1.24	0.22
	α	0.25	128810.2 ± 6938.7	18.56	0.00
	β		-27.4 ± 16.4	-1.67	0.10
	α	0.5	225458.0 ± 12759.2	17.67	0.00
	β		-50.7 ± 23.5	-2.16	0.03
	α	0.75	453749.0 ± 34420.3	13.18	0.00
	β		-158.5 ± 91.2	-1.74	0.08
	α	0.9	616957.9 ± 88275.1	6.99	0.00
	β		-110.5 ± 142.8	-0.77	0.44
Ca^{2+} (CEC)	α	0.1	0.2 ± 0.1	2.02	0.05
	β		0.0 ± 0.0	-1.97	0.05
	α	0.25	0.2 ± 0.0	7.0	0.00
	β		0.0 ± 0.0	-3.77	0.00
	α	0.5	0.3 ± 0.1	2.76	0.01
	β		0.0 ± 0.0	-1.88	0.06
	α	0.75	0.4 ± 0.1	3.66	0.00
	β		0.0 ± 0.0	-2.63	0.01
	α	0.9	1.0 ± 0.3	3.26	0.00
	β		0.0 ± 0.0	-2.93	0.00
Mg^{2+} (CEC)	α	0.1	0.1 ± 0.0	8.5	0.00
	β		0.0 ± 0.0	0	1.00
	α	0.25	0.1 ± 0.0	3.62	0.00
	β		0.0 ± 0.0	0	1.00
	α	0.5	0.2 ± 0.0	6.41	0.00
	β		0.0 ± 0.0	-3.32	0.00
	α	0.75	0.3 ± 0.0	8.22	0.00
	β		0.1 ± 0.1	-3.25	0.00
	α	0.9	0.3 ± 0.1	4.96	0.00
	β		0.0 ± 0.0	-1.82	0.07
$CaCO_3$	α	0.1	-1.3 ± 0.4	-3.20	0.00
	β		0.0 ± 0.1	5.81	0.00
	α	0.25	-1.7 ± 0.7	-2.53	0.01

	β		0.0 ± 0	5.34	0.00
	α	0.5	-0.2 ± 1.8	-0.11	0.91
	β		0.0 ± 0	3.97	0.00
	α	0.75	3.4 ± 1.7	2.02	0.05
	β		0.0 ± 0	3.91	0.00
	α	0.9	7.8 ± 2.1	3.68	0.00
	β		0.0 ± 0	4.76	0.00
BC_{+100}	α	0.1	-0.1 ± 0.1	-1.24	0.22
	β		0.0 ± 0.0	3.67	0.00
	α	0.25	-0.2 ± 0.1	-2.53	0.01
	β		0.0 ± 0.0	6.06	0.00
	α	0.5	-0.3 ± 0.1	-2.52	0.01
	β		0.0 ± 0.0	5.1	0.00
	α	0.75	-0.6 ± 0.2	-2.54	0.01
	β		0.1 ± 0.0	4.11	0.00
	α	0.9	-1.1 ± 0.3	-3.96	0.00
	β		0.0 ± 0.0	7.87	0.00

Supplementary Table 13
Value of total N, P, and K in HSW sanitized at different HHTs benchmarked against the median market price of nine commercial organic amendments according to respective concentrations of total N, P, and K (Supplementary Table 4, Supplementary Table 5). The average value of HSW amendments, shown at the bottom of the table, does not include the value benchmarked against biochar.

		Highest heating temperature (°C)						
	Nutrient	60 (compost)	200	300	400	500	600	700
		(USD/Mg amendment)						
Manure	N	3.1	6.5	8.6	8.5	7.2	6.7	6
	P	4.6	6.7	11.9	15.1	14.7	17.6	18.4
	K	2.3	4.9	5	4.6	12.4	5.6	16.6
	Sum N+P+K	10	18.1	25.6	28.2	34.3	29.9	41
Compost	N	18.7	38.7	51.5	50.6	42.9	40	35.7
	P	27.6	39.7	71.2	90.4	87.6	105.1	110
	K	13.6	29.4	29.9	27.7	74	33.7	99.1
	Sum N+P+K	59.9	107.9	152.7	168.6	204.6	178.7	244.7
Vermicompost	N	21.8	45.2	60.1	59	50	46.7	41.6
	P	32.2	46.4	83.1	105.5	102.2	122.6	128.3
	K	15.9	34.3	34.9	32.3	86.4	39.3	115.6
	Sum N+P+K	69.8	125.8	178.1	196.7	238.6	208.5	285.5
Milorganite	N	35.3	73.3	97.4	95.6	81.1	75.7	67.5
	P	52.1	75.2	134.7	171	165.7	198.7	207.9
	K	25.8	55.6	56.6	52.3	140	63.6	187.4
	Sum N+P+K	113.2	204	288.7	318.9	386.8	338	462.8
Soybean meal	N	38.3	79.4	105.6	103.6	87.9	82	73.1
	P	56.5	81.5	145.9	185.3	179.6	215.3	225.4
	K	27.9	60.2	61.4	56.7	151.7	69	203.1
	Sum N+P+K	122.7	221.1	312.9	345.6	419.2	366.3	501.6
Cottonseed meal	N	35.7	73.9	98.3	96.5	81.9	76.4	68.1
	P	52.6	75.8	135.9	172.5	167.2	200.4	209.8
	K	26	56.1	57.1	52.8	141.2	64.2	189.1
	Sum N+P+K	114.2	205.8	291.3	321.7	390.3	341	467
Alfalfa meal	N	53.5	111	147.6	144.9	122.9	114.7	102.2
	P	79	113.9	204	259.1	251.1	301	315.1
	K	39.1	84.2	85.8	79.2	212.1	96.4	284
	Sum N+P+K	171.6	309.1	437.4	483.2	586.2	512.1	701.3
Bone meal	N	16.6	34.3	45.6	44.8	38	35.4	31.6
	P	24.4	35.2	63.1	80.1	77.6	93.1	97.4
	K	12.1	26	26.5	24.5	65.6	29.8	87.8
	Sum N+P+K	53	95.5	135.2	149.3	181.2	158.3	216.8
*Biochar (Poultry and cattle manure, wood, HSW 500 °C)	N	245.8	509.6	677.6	665	564.3	526.3	469.2
	P	362.5	522.8	936.5	1189.2	1152.6	1381.8	1446.3
	K	179.3	386.4	393.8	363.6	973.6	442.6	1303.5
	Sum N+P+K	787.5	1418.8	2007.9	2217.8	2690.5	2350.7	3219.1
AVERAGE HSW value (excluding biochar)		**79.4**	**143.0**	**202.4**	**223.6**	**271.2**	**237.0**	**324.5**

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