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Supplement of

Effects of fresh and aged biochars from pyrolysis and hydrothermal carbonization on nutrient sorption in agricultural soils

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Table S1

Fitted parameters for the Freundlich and linear isotherm. Pyro750 = pyrochar; Hydro200, Hydro250 = hydrochar produced by 200, 250°C. Carbonized feedstocks are digestates (D), *Miscanthus* (M), woodchips (W). Level of significance are indicating by *** <0.0001; ** <0.001; * <0.01, · <0.05.

Soil	Ion	Treatment	Feed-stock	Freundlich-Isotherm						Linear-Isotherm														
				K _F	±	SE	Signf. Level	n	±	SE	Signf. Level	Residual std. error	R ²	a	±	SE	Signf. Level	Intercept (Y ₀)	±	SE	Signf. Level	Residual std. error	R ²	
Sandy loam	NO ₃ ⁻	Ctrl	-										0.01	±	0.0		-0.1	±	0.7		1.6	0.06		
			Hydro200	D										0.0	±	0.0	***	-1.7	±	0.4	***	0.8	0.47	
				M										0.0	±	0.0	*	-1.3	±	0.3	***	0.6	0.23	
		W											0.0	±	0.0		-1.4	±	0.3	***	0.8	0.07		
		Hydro250	D										0.0	±	0.0	***	-0.1	±	0.3		0.7	0.51		
			M										0.0	±	0.0		-1.1	±	0.4	**	0.8	0.02		
			W										0.0	±	0.0		-0.6	±	0.5		1.3	0.06		
		Pyro750	D	0.9	±	0.4	*	1.8	±	0.4	***	1.6	0.71											
			M	1.1	±	0.3	***	1.5	±	0.1	***	1.5	0.95											
			W	2.5	±	0.3	***	1.8	±	0.1	***	1.4	0.94											
			NH ₄ ⁺	Ctrl	-	1.6	±	0.4	***	1.4	±	0.1	***	2.5	0.94									
					Hydro200	D	0.8	±	0.2	**	1.1	±	0.1	***	2.1	0.95								
M	1.4					±	0.3	***	1.3	±	0.1	***	1.8	0.96										
W	1.6			±		0.3	***	1.4	±	0.1	***	2.2	0.95											
Hydro250	D			1.2	±	0.3	***	1.3	±	0.1	***	2.1	0.95											
	M			1.6	±	0.3	***	1.4	±	0.1	***	2.1	0.95											
	W			1.6	±	0.3	***	1.4	±	0.1	***	2.2	0.94											
Pyro750	D			3.1	±	0.3	***	1.5	±	0.1	***	1.5	0.99											
	M			1.3	±	0.2	***	1.3	±	0.1	***	1.2	0.98											
	W			2.1	±	0.2	***	1.5	±	0.1	***	1.1	0.99											
	PO ₄ ³⁻			Ctrl	-										11.4	±	1.3	***	-22.3	±	4.3	***	6.0	0.82
					Hydro200	D										10.4	±	0.9	***	-33.4	±	3.8	***	4.4
		M												10.9	±	0.9	***	-26.4	±	3.4	***	4.3	0.89	
		W											10.3	±	0.9	***	-25.6	±	3.5	***	4.6	0.88		
		Hydro250	D											10.0	±	0.9	***	-31.7	±	3.7	***	4.4	0.89	
			M											10.5	±	0.9	***	-22.0	±	3.1	***	4.4	0.89	
			W											11.4	±	1.3	***	-22.0	±	4.1	***	5.7	0.82	
		Pyro750	D											-6.1	±	0.6	***	59.1	±	9.4	***	13.0	0.86	
			M											16.8	±	2.1	***	-22.5	±	5.2	***	6.9	0.78	
			W											19.2	±	2.3	***	-5.1	±	3.4	***	6.7	0.80	
			Ca ²⁺	Ctrl	-										0.0	±	0.0		-111.7	±	3.8	***	7.8	0.01
					Hydro200	D										0.2	±	0.0	***	-122.5	±	7.1	***	14.4
M														0.0	±	0.1		-119.3	±	14.6	***	29.5	0.06	
W													0.0	±	0.1		-120.1	±	10.7	***	21.6	0.06		
Hydro250	D													0.1	±	0.1		-108.2	±	9.8	***	20.1	0.03	
	M													0.1	±	0.0	*	-131.6	±	7.7	***	15.4	0.20	
	W													0.1	±	0.0	**	-140.1	±	5.8	***	11.5	0.42	
Pyro750	D			5.7	±	2.3	*	1.3	±	0.1	***	38.1	0.91											
	M													0.3	±	0.1	***	-73.5	±	8.3	***	17.8	0.67	
	W													0.1	±	0.1	·	-182.9	±	10.0	***	18.7	0.15	
	Mg ²⁺			Ctrl	-										0.0	±	0.0		-11.4	±	0.5	***	1.1	0.08
					Hydro200	D										-0.5	±	0.0	***	-17.5	±	0.9	***	1.6
		M												-0.1	±	0.1		-11.6	±	1.6	***	3.4	0.30	
		W												-0.1	±	0.1	·	-11.7	±	1.2	***	2.5	0.12	

	Hydro250	D		17.1 ± 2.3	***	-20.1 ± 5.3	**	7.6	0.76	
		M		16.5 ± 2.4	***	-11.5 ± 4.8	*	8.1	0.73	
		W		16.9 ± 2.5	***	-11.5 ± 5.0	*	8.3	0.72	
	Pyro750	D		-7.0 ± 1.0	***	52.1 ± 9.1	***	14.8	0.74	
		M		17.7 ± 1.8	***	-20.3 ± 4.1	***	6.0	0.85	
		W		19.3 ± 2.1	***	-8.5 ± 3.5	*	6.6	0.82	
Ca ²⁺	Ctrl	-		-0.3 ± 0.1	**	-204.1 ± 18.1	***	33.5	0.33	
	Hydro200	D		-0.3 ± 0.0	***	-198.7 ± 8.3	***	15.3	0.82	
		M		-0.2 ± 0.1	***	-210.7 ± 12.5	***	22.7	0.49	
		W		-0.3 ± 0.1	***	-197.1 ± 12.7	***	23.5	0.65	
	Hydro250	D		-0.1 ± 0.1	.	-224.1 ± 18.4	***	32.8	0.11	
		M		-0.2 ± 0.1	*	-227.2 ± 16.8	***	29.9	0.18	
		W		-0.3 ± 0.1	**	-217.4 ± 18.0	***	32.3	0.35	
	Pyro750	D				NA				
		M		-0.2 ± 0.0	***	-182.4 ± 6.2	***	11.6	0.73	
		W		-0.2 ± 0.0	***	-240.6 ± 4.5	***	8.2	0.88	
	Mg ²⁺	Ctrl	-		0.537 ± 0.1	***	-11.1 ± 1.2	***	2.6	0.76
		Hydro200	D		-0.086 ± 0.1		-16.2 ± 1.4	***	2.8	0.04
M				0.421 ± 0.1	***	-12.7 ± 1.2	***	2.4	0.71	
W				0.329 ± 0.5	***	-11.8 ± 1.0	***	2.0	0.69	
Hydro250		D		0.180 ± 0.1	**	-16.0 ± 1.1	***	2.1	0.38	
		M		0.489 ± 0.1	***	-13.7 ± 1.2	***	2.5	0.73	
		W		0.464 ± 0.1	***	-12.8 ± 1.2	***	2.6	0.70	
Pyro750		D		-0.863 ± 0.1	***	-18.2 ± 3.9	***	7.4	0.67	
		M		0.354 ± 0.0	***	-11.3 ± 0.8	***	1.7	0.78	
		W		0.276 ± 0.1	*	-11.1 ± 1.8	***	3.7	0.29	
K ⁺		Ctrl	-		1.300 ± 0.1	***	-40.4 ± 4.3	***	8.9	0.91
		Hydro200	D		1.022 ± 0.1	***	-55.1 ± 4.6	***	8.9	0.88
	M			1.176 ± 0.1	***	-41.5 ± 4.6	***	9.3	0.89	
	W			1.179 ± 0.1	***	-40.0 ± 3.2	***	6.6	0.94	
	Hydro250	D		0.958 ± 0.1	***	-53.3 ± 6.0	***	11.7	0.79	
		M		1.198 ± 0.1	***	-48.0 ± 4.4	***	8.9	0.90	
		W		1.095 ± 0.1	***	-47.4 ± 5.0	***	10.0	0.86	
	Pyro750	D		-0.925 ± 0.3	**	-388.3 ± 57.4	***	44.5	0.34	
		M		-0.245 ± 0.1	*	-128.8 ± 7.2	***	11.0	0.30	
		W		0.722 ± 0.1	***	-69.1 ± 5.3	***	9.9	0.77	
	SO ₄ ²⁻	Ctrl	-		0.2 ± 0.1		-18.7 ± 2.8	***	5.7	0.06
		Hydro200	D		1.1 ± 0.7		-416.3 ± 19.2	***	38.6	0.07
M				4.2 ± 2.4	.	-387.6 ± 63.8	***	129.0	0.11	
W				3.6 ± 2.5		-374.3 ± 65.9	***	134.0	0.06	
Hydro250		D		3.8 ± 2.4		-360.9 ± 61.9	***	126.5	0.09	
		M		4.0 ± 2.2	.	-385.5 ± 58.4	***	118.2	0.12	
		W		2.6 ± 2.2		-351.1 ± 59.2	***	121.6	0.02	
Pyro750		D		5.5 ± 2.2	*	-597.3 ± 61.7	***	115.2	0.23	
		M		0.2 ± 0.7		-422.8 ± 19.7	***	39.6	0.06	
		W		-0.3 ± 0.8		-806.3 ± 26.1	***	45.3	0.68	

Table S2

pH-Values for every batch-solution concentration and treatment for the laboratory experiment.

Experiment	Soil type	Feedstock	Char type	°C	pH (CaCl ₂)						
					P1	P2	P3	P4	P5	P6	
<u>Lab</u>	<u>Sandy loam</u>	Digestates	Hydrochar	200	6.3	6.1	5.8	5.6	6.0	5.7	
			Hydrochar	250	6.3	5.9	5.7	5.7	5.8	5.6	
			Pyrochar	750	7.6	7.2	6.9	6.7	7.0	6.5	
		Miscanthus	Hydrochar	200	6.1	5.8	5.8	5.5	5.7	5.5	
			Hydrochar	250	6.1	6.0	5.7	5.5	5.8	5.5	
			Pyrochar	750	6.9	6.7	6.5	6.3	6.5	6.5	
		Woodchips	Hydrochar	200	6.1	5.8	5.6	5.4	5.7	5.4	
			Hydrochar	250	6.2	5.9	5.7	5.5	5.8	5.6	
			Pyrochar	750	7.0	6.8	6.8	6.5	6.7	6.4	
	Ctrl (pure soil)	-	-	6.1	5.8	5.7	5.7	5.7	5.6		
	<u>Silty loam</u>	Digestates	Hydrochar	200	7.1	6.9	6.7	6.7	6.6	6.7	
			Hydrochar	250	7.1	7.0	6.7	6.7	6.5	6.7	
			Pyrochar	750	7.9	7.7	7.4	7.4	7.1	7.3	
			Miscanthus	Hydrochar	200	7.1	6.8	6.7	6.7	6.5	6.7
				Hydrochar	250	7.1	7.0	6.7	6.7	6.5	6.6
Pyrochar				750	7.3	7.2	7.0	7.0	6.9	6.9	
Woodchips			Hydrochar	200	7.0	6.7	6.6	6.6	6.4	6.5	
			Hydrochar	250	7.0	6.9	6.8	6.7	6.5	6.6	
			Pyrochar	750	7.3	7.3	7.0	7.0	6.9	7.0	
Ctrl (pure soil)		-	-	7	6.9	6.7	6.7	6.4	6.6		

Table S3

Adjusted p-values for statistical comparisons between feedstocks within one biochar type (e.g. d : m = char from digestates to char from *Miscanthus*); control soil to feedstock within one biochar type (e.g. Ctrl : d = control soil to char from digestates); and same feedstock to different biochar types (e.g. Pyro750-d : Hydro200-d = pyrochar from digestates to Hydro200 from digestates) for each ion. . * Statistical comparison was made with GAM (general additive model). Significant differences were assumed by $p \leq 0.05$.

		Sandy loam							Silty loam						
		NO ₃ ⁻	NH ₄ ⁺	PO ₄ ³⁻	SO ₄ ²⁻	Ca ²⁺	Mg ²⁺	K ⁺	NO ₃ ⁻	NH ₄ ⁺	PO ₄ ³⁻	SO ₄ ²⁻	Ca ²⁺	Mg ²⁺	K ⁺
Pyrochars	d : m	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	d : w	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	m : w	<0.01	0.03	<0.01	<0.01	<0.01	0.24	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.05	<0.01
	Ctrl : d	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01*	<0.01	<0.01
	Ctrl : m	<0.01	0.10	<0.01	<0.01	<0.01	0.03	<0.01	<0.01	<0.01	0.11	<0.01	<0.01*	<0.01	<0.01
	Ctrl : w	<0.01	0.02	<0.01	<0.01	<0.01	0.02	<0.01	<0.01	0.01	0.10	<0.01	<0.01*	<0.01	<0.01
	Pyro750-d : Hydro200-d	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01*	<0.01	<0.01
	Pyro750-m : Hydro200-m	<0.01	0.23	<0.01	<0.01	<0.01	0.29	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01*	0.43	<0.01
	Pyro750-w : Hydro200-w	<0.01	0.17	<0.01	<0.01	<0.01	0.74	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01*	0.90	<0.01
	Pyro750-d : Hydro250-d	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	0.09	<0.01	<0.01	<0.01*	<0.01	<0.01
	Pyro750-m : Hydro250-m	<0.01	0.18	<0.01	<0.01	0.03	0.29	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01*	0.24	<0.01
	Pyro750-w : Hydro250-w	<0.01	0.01	<0.01	<0.01	0.01	0.06	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01*	0.21	<0.01
Hydro200	d : m	0.33	0.98	<0.01	0.76	<0.01	0.00	<0.01	0.29	<0.01	0.02	<0.01	0.62	<0.01	<0.01
	d : w	0.32	0.98	0.01	0.76	<0.01	<0.01	<0.01	0.29	<0.01	0.02	<0.01	0.62	<0.01	<0.01
	m : w	0.53	0.98	0.81	0.76	0.64	0.63	0.77	0.67	0.93	0.95	0.98	0.68	0.51	0.53
	Ctrl : d	0.05	0.65	<0.01	0.32	<0.01	<0.01	<0.01	0.43	0.37	0.03	<0.01	0.14	0.51	<0.01
	Ctrl : m	0.03	0.65	0.04	0.44	<0.01	0.03	<0.01	0.43	<0.01	0.99	<0.01	0.50	0.18	0.45
	Ctrl : w	0.03	0.65	0.03	0.32	<0.01	0.02	<0.01	0.50	0.02	0.99	<0.01	0.50	<0.01	0.45
	Hydro200-d : Pyro750-d	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01*	<0.01	<0.01
	Hydro200-m : Pyro750-m	<0.01	0.23	<0.01	<0.01	<0.01	0.29	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01*	0.43	<0.01
	Hydro200-w : Pyro750-w	<0.01	0.17	<0.01	<0.01	<0.01	0.74	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01*	0.90	<0.01
	Hydro200-d : Hydro250-d	<0.01	0.61	0.02	<0.01	0.23	0.02	0.35	0.66	<0.01	0.28	<0.01	0.02	<0.01	0.83
	Hydro200-m : Hydro250-m	0.06	0.83	0.27	0.48	0.12	0.29	0.11	0.65	0.58	0.97	0.78	0.60	0.59	<0.01
	Hydro200-w : Hydro250-w	0.11	0.88	0.97	0.73	0.01	0.04	0.02	0.79	0.56	0.88	0.99	0.49	0.03	<0.01
Hydro250	d : m	0.33	0.21	<0.01	0.11	<0.01	<0.01	<0.01	0.46	0.14	0.22	0.94	0.68	<0.01	0.02
	d : w	0.33	0.21	<0.01	0.08	<0.01	<0.01	<0.01	0.46	0.40	0.22	0.94	0.68	<0.01	0.09
	m : w	0.33	0.75	0.36	0.67	0.45	0.15	0.25	0.46	0.54	0.98	0.94	0.68	0.88	0.56
	Ctrl : d	<0.01	0.15	<0.01	0.00	0.01	<0.01	<0.01	0.53	0.03	0.49	<0.01	0.78	<0.01	<0.01
	Ctrl : m	0.02	0.68	0.49	0.08	0.03	0.07	<0.01	0.53	0.03	0.99	<0.01	0.78	0.03	0.05
	Ctrl : w	0.11	0.86	0.98	0.15	0.01	0.03	<0.01	0.63	0.03	0.99	<0.01	0.78	0.04	0.01
	Hydro250-d : Hydro200-d	<0.01	0.61	0.02	<0.01	0.23	0.02	0.35	0.66	<0.01	0.28	<0.01	0.02	<0.01	0.83
	Hydro250-m : Hydro200-m	0.06	0.83	0.27	0.48	0.12	0.29	0.11	0.65	0.58	0.97	0.78	0.60	0.59	<0.01
	Hydro250-w : Hydro200-w	0.11	0.88	0.97	0.73	0.01	0.04	0.02	0.79	0.56	0.88	0.99	0.49	0.03	<0.01
	Hydro250-d : Pyro750-d	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	0.09	<0.01	<0.01	<0.01*	<0.01	<0.01
	Hydro250-m : Pyro750-m	<0.01	0.18	<0.01	<0.01	0.03	0.29	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01*	0.24	<0.01
	Hydro250-w : Pyro750-w	<0.01	0.01	<0.01	<0.01	0.01	0.06	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01*	0.21	<0.01

Table S5

Fitted parameters for the Freundlich and linear isotherm of fresh (T_0) and aged Biochars (T_1). Pyro750 = pyrochar; Hydro200 = hydrochar produced by 200°C. Carbonized feedstocks are only *Miscanthus*. Sites are: 1= Bortfeld, 2=Querenhorst, 3= Volkmarshdorf. Level of significance are indicating by *** <0.0001; ** <0.001; * <0.01, · <0.05.

Sampling Time	Ion	Treatment	Site	Freundlich-Isotherm						Linear-Isotherm														
				KF	±	SE	Signif. Level	n	±	SE	Signif. Level	Residual std. error	R ²	a	±	SE	Signif. Level	Intercept (Y ₀)	±	SE	Signif. Level	Residual std. error	R ²	
T ₀	NO ₃ ⁻	Ctrl	1		±			±								-0.58 ± 0.1		-24.22 ± 3.3	***	6.57	<0.01			
			2		±			±									-0.28 ± 0.0	**	-7.98 ± 1.0	***	2.34	0.44		
			3		±			±									-0.65 ± 0.1		-21.95 ± 5.0	***	10.17	0.09		
		Pyro750	1		±			±									-0.24 ± 0.1	*	-11.58 ± 2.3	*	1.12	0.25		
			2		±			±									-0.25 ± 0.0	***	-3.58 ± 2.3	***	1.14	0.85		
			3		±			±									-0.36 ± 0.1		-15.84 ± 2.4	**	1.05	0.09		
		Hydro200	1		±			±									0.06 ± 0.0		-11.58 ± 2.2	***	4.99	0.03		
			2		±			±									-0.20 ± 0.0		-3.58 ± 2.3		5.47	0.31		
			3		±			±									0.02 ± 0.1		-15.84 ± 2.4	***	5.09	0.01		
	NH ₄ ⁺	Ctrl	1	3.49	± 0.4	***	1.40	± 0.1	***	1.71	0.96													
			2	5.42	± 0.8	***	2.02	± 0.2	***	2.78	0.93													
			3	4.16	± 0.5	***	1.85	± 0.1	***	1.91	0.96													
		Pyro750	1	7.99	± 0.6	***	2.24	± 0.1	***	1.96	0.97													
			2	5.63	± 0.5	***	2.06	± 0.1	***	1.76	0.97													
			3	8.30	± 1.1	***	2.29	± 0.2	***	1.74	0.97													
		Hydro200	1	4.15	± 0.4	***	1.70	± 0.1	***	1.92	0.97													
			2	6.64	± 0.5	***	2.28	± 0.1	***	1.82	0.97													
			3	4.10	± 0.4	***	1.73	± 0.1	***	3.66	0.92													
	PO ₄ ³⁻	Ctrl	1		±			±								21.15 ± 1.8	***	-18.70 ± 3.5	***	5.07	0.89			
			2		±			±								18.45 ± 2.7	***	-27.36 ± 6.9	**	8.52	0.74			
			3		±			±								23.31 ± 2.3	***	-14.37 ± 3.7	**	5.84	0.86			
		Pyro750	1		±			±									25.01 ± 4.6	***	-31.24 ± 9.4	***	4.72	0.91		
			2		±			±									9.14 ± 2.1	***	-7.08 ± 6.0	*	6.77	0.81		
			3		±			±									27.03 ± 2.6	***	-25.33 ± 4.5	***	4.48	0.91		
		Hydro200	1		±			±									23.33 ± 1.8	***	-23.46 ± 3.5	**	9.75	0.65		
			2		±			±									12.27 ± 1.5	***	-10.25 ± 3.8		10.55	0.54		
			3		±			±									19.73 ± 1.5	***	-11.21 ± 2.6	***	5.71	0.87		
	Ca ²⁺	Ctrl	1		±			±								-0.24 ± 0.1		-41.22 ± 15.2	*	33.60	<0.01			
			2		±			±								-0.09 ± 0.0	**	-45.54 ± 6.2	***	13.74	0.48			
			3		±			±								-0.40 ± 0.1		-56.70 ± 14.5	**	31.60	0.13			
		Pyro750	1		±			±									0.29 ± 0.1		17.12 ± 13.9	*	27.00	0.04		
			2		±			±									0.12 ± 0.0	**	-9.80 ± 10.2	***	10.44	0.36		
			3		±			±									-0.01 ± 0.0		-13.02 ± 10.6	***	28.84	0.08		
		Hydro200	1		±			±									-0.12 ± 0.0	.	-33.89 ± 12.1		33.25	0.21		
			2		±			±									-0.11 ± 0.0	*	-37.98 ± 4.6		23.69	0.31		
			3		±			±									-0.40 ± 0.1		-64.74 ± 13.4		24.49	0.05		
	Mg ²⁺	Ctrl	1		±			±								-0.05 ± 0.1		-5.24 ± 2.3	***	3.15	<0.01			
			2		±			±								-0.08 ± 0.1		-7.26 ± 1.5	***	3.17	0.07			
			3		±			±								-0.01 ± 0.1		-6.72 ± 1.4	***	3.15	0.03			
		Pyro750	1		±			±									-0.18 ± 0.1	*	-2.75 ± 1.5	.	3.49	0.24		
			2		±			±									0.04 ± 0.1		-2.79 ± 1.0	*	2.24	0.03		
			3		±			±									-0.08 ± 0.1		-4.46 ± 1.1	***	2.37	0.13		
		Hydro200	1		±			±									-0.04 ± 0.1		-4.99 ± 2.2	*	4.82	0.01		
			2		±			±									-0.20 ± 0.1	.	-6.88 ± 2.0	**	4.41	0.21		
			3		±			±									0.07 ± 0.1		-6.40 ± 1.1	**	3.92	0.04		
	K ⁺	Ctrl	1		±			±								-0.45 ± 0.1	**	-49.12 ± 4.8	***	9.31	0.45			
			2		±			±								-0.93 ± 0.2	.	-45.84 ± 23.3		44.34	0.06			
			3		±			±								-0.16 ± 0.1	.	-25.72 ± 13.5		27.77	0.06			
		Pyro750	1		±			±									-2.13 ± 0.1	***	-172.96 ± 16.5	***	16.46	0.58		
			2		±			±									-1.03 ± 0.1		-82.88 ± 10.4	***	18.16	<0.01		
			3		±			±									-1.84 ± 0.1	***	-158.92 ± 7.2	***	9.71	0.51		
		Hydro200	1		±			±									0.25 ± 0.1	*	-52.39 ± 5.7	***	10.82	0.30		
			2		±			±									-0.01 ± 0.2		-59.17 ± 13.7	***	25.87	<0.01		
			3		±			±									0.60 ± 0.0	***	-26.92 ± 2.2	***	4.61	0.92		
	SO ₄ ²⁻	Ctrl	1		±			±								-0.03 ± 0.0	.	-1.47 ± 0.3	***	0.78	0.16			
			2		±			±									0.10 ± 0.1		-10.91 ± 3.5	**	7.35	0.03		
			3		±			±									-0.05 ± 0.0	.	-0.78 ± 0.6		1.29	0.21		
		Pyro750	1		±			±									-0.03 ± 0.0		-4.09 ± 0.5	***	1.16	0.13		
			2		±			±									0.19 ± 0.1	**	-6.10 ± 1.4	***	3.19	0.39		
			3		±			±									-0.02 ± 0.0		-3.28 ± 0.4	***	0.97	0.05		
		Hydro200	1		±			±									0.03 ± 0.0		-0.45 ± 0.4		0.94	0.16		
			2		±			±									0.19 ± 0.0	***	-5.90 ± 0.7	***	1.48	0.73		
			3		±			±									-0.01 ± 0.0		0.14 ± 0.3		0.77	0.06		

Sampling Time	Ion	Treatment	Site	Freundlich-Isotherm							Linear-Isotherm												
				KF	±	SE	Signif. Level	n	±	SE	Signif. Level	Residual std. error	R ²	a	±	SE	Signif. Level	Intercept (Y ₀)	±	SE	Signif. Level	Residual std. error	adj R ²
T ₁	NO ₃ ⁻	Ctrl	1													-0.28 ± 0.0	***	-4.37 ± 1.1	**	2.66	0.68		
			2														-0.66 ± 0.1		-23.61 ± 4.1	***	8.28	0.08	
			3														-0.37 ± 0.0	**	-9.05 ± 2.2	***	5.02	0.35	
		Pyro750	1														-0.36 ± 0.1		-11.78 ± 2.2	***	4.86	0.14	
			2														-0.43 ± 0.1		-16.04 ± 4.2	**	8.89	0.01	
			3														-0.40 ± 0.1		-13.17 ± 2.7	***	6.15	0.13	
	Hydro200	1														-0.30 ± 0.0	***	-5.38 ± 0.8	***	1.80	0.82		
		2														-0.01 ± 0.0		1.69 ± 0.4	**	1.01	0.07		
		3														-0.18 ± 0.0	***	-5.45 ± 0.8	***	1.93	0.80		
	NH ₄ ⁺	Ctrl	1	5.15 ± 0.6	***	1.95 ± 0.1	***	2.30	0.95														
			2	6.26 ± 0.7	***	1.72 ± 0.1	***	3.22	0.96														
			3	7.61 ± 0.4	***	1.86 ± 0.1	***	1.46	0.99														
Pyro750		1	3.57 ± 0.3	***	1.58 ± 0.1	***	1.53	0.98															
		2	5.87 ± 0.5	***	1.64 ± 0.1	***	2.42	0.98															
		3	8.13 ± 0.4	***	1.88 ± 0.1	***	1.48	0.99															
Hydro200		1	4.70 ± 0.4	***	1.89 ± 0.1	***	1.62	0.98															
		2	8.15 ± 0.4	***	1.80 ± 0.1	***	1.75	0.99															
		3	8.65 ± 0.4	***	1.87 ± 0.0	***	1.54	0.99															
PO ₄ ³⁻	Ctrl	1	8.85 ± 2.0	***	0.94 ± 0.9	***	8.35	0.73															
		2	19.27 ± 0.9	***	0.63 ± 0.6	***	3.10	0.96															
		3	17.79 ± 1.8	***	0.84 ± 0.8	***	6.51	0.86															
	Pyro750	1	4.82 ± 1.4	**	0.61 ± 0.6	***	7.35	0.79															
		2	11.02 ± 1.5	***	0.51 ± 0.5	***	5.20	0.90															
		3	14.88 ± 1.8	***	0.76 ± 0.8	***	6.76	0.84															
	Hydro200	1	8.99 ± 1.9	***	0.86 ± 0.9	***	7.65	0.76															
		2	17.93 ± 1.1	***	0.67 ± 0.7	***	3.47	0.95															
		3	21.13 ± 1.7	***	0.86 ± 0.9	***	6.32	0.87															
Ca ²⁺	Ctrl	1													0.05 ± 0.1		-63.16 ± 11.8	***	25.70	0.33			
		2													-0.05 ± 0.0		-91.15 ± 8.1	***	16.93	0.08			
		3													0.00 ± 0.0		-72.50 ± 5.2	***	11.26	<0.01			
	Pyro750	1													-0.01 ± 0.0		-97.45 ± 7.6	***	15.80	<0.01			
		2													0.01 ± 0.0		-46.66 ± 8.5	***	18.77	<0.01			
		3													-0.05 ± 0.0	*	-66.36 ± 3.8	***	8.30	0.24			
	Hydro200	1													0.04 ± 0.1		-61.33 ± 10.7	***	23.27	0.03			
		2													-0.05 ± 0.0		-77.71 ± 6.0	***	12.69	0.11			
		3													-0.06 ± 0.0		-59.91 ± 6.4	***	14.00	0.15			
Mg ²⁺	Ctrl	1													0.13 ± 0.1	.	-4.17 ± 1.2	**	2.72	0.18			
		2													-0.56 ± 0.1	***	-13.12 ± 2.9	***	5.84	0.57			
		3													-0.42 ± 0.0	***	-10.80 ± 0.7	***	1.43	0.92			
	Pyro750	1													-0.09 ± 0.1		-9.26 ± 2.1	***	4.44	0.04			
		2													-0.48 ± 0.0	***	-9.89 ± 0.9	***	1.84	0.91			
		3													-0.48 ± 0.1	***	-10.20 ± 2.1	***	4.42	0.63			
	Hydro200	1													0.00 ± 0.1		-5.71 ± 1.3	***	2.83	<0.01			
		2													-0.56 ± 0.1	***	-13.80 ± 1.8	***	3.64	0.78			
		3													-0.55 ± 0.0	***	-10.40 ± 0.7	***	1.55	0.95			
K ⁺	Ctrl	1													-0.11 ± 0.3		-24.06 ± 19.9		41.60	<0.01			
		2													0.68 ± 0.2	*	-28.87 ± 12.1	*	24.69	0.33			
		3													0.58 ± 0.2	*	-41.89 ± 11.2	**	22.51	0.33			
	Pyro750	1													-0.39 ± 0.4		-10.45 ± 26.8		56.52	0.05			
		2													-1.29 ± 0.4	**	-64.78 ± 39.7		62.76	0.39			
		3													0.46 ± 0.3		-32.39 ± 15.3	.	31.61	0.14			
	Hydro200	1													-0.74 ± 0.4		-7.57 ± 27.9		59.06	0.16			
		2													0.59 ± 0.2	*	-32.47 ± 10.8	**	21.98	0.33			
		3													0.65 ± 0.2	**	-43.18 ± 10.3	***	20.71	0.41			
SO ₄ ²⁻	Ctrl	1													0.17 ± 0.0	***	-4.44 ± 0.3	***	0.72	0.91			
		2													-0.08 ± 0.1		-7.56 ± 1.8	***	3.83	0.07			
		3													0.16 ± 0.0	***	-6.63 ± 0.5	***	1.19	0.76			
	Pyro750	1													0.14 ± 0.1	*	-7.88 ± 1.5	***	3.41	0.24			
		2													-0.11 ± 0.1		-8.96 ± 3.0	**	6.27	0.06			
		3													0.20 ± 0.0	***	-7.45 ± 1.0	***	2.29	0.56			
	Hydro200	1													0.13 ± 0.0	***	-4.41 ± 0.7	***	1.68	0.53			
		2													-0.03 ± 0.1		-7.86 ± 1.8	***	3.88	<0.01			
		3													0.12 ± 0.0	**	-7.10 ± 0.8	***	1.69	0.49			

Table S6

pH-Values for every batch-solution concentration and treatment for the field experiment. Carbonized feedstocks are only *Miscanthus*.

Sampling Time	Site	Char type	°C	pH (CaCl ₂)					
				P1	P2	P3	P4	P5	P6
T ₀	1 Bortfeld (sandy loam)	Hydrochar	200	6.0	6.4	6.3	6.2	6.1	6.1
		Pyrochar	750	6.7	6.9	6.9	6.7	6.7	6.6
		Ctrl (pure soil)		6.1	6.5	6.4	6.3	6.3	6.2
	2 Querenhorst (loamy sand)	Hydrochar	200	6.3	6.6	6.6	6.4	6.4	6.3
		Pyrochar	750	6.8	6.7	7.1	6.9	6.9	6.8
		Ctrl (pure soil)		6.4	6.8	6.8	6.6	6.6	6.5
	3 Volkmarisdorf (sandy loam)	Hydrochar	200	6.6	6.7	6.7	6.6	6.5	6.5
		Pyrochar	750	6.4	7.3	7.3	7.2	7.1	7.1
		Ctrl (pure soil)		7.0	6.9	7.0	6.7	6.7	6.7
T ₁	1 Bortfeld (sandy loam)	Hydrochar	200	6.5	6.4	6.3	6.1	6.1	6.0
		Pyrochar	750	6.5	6.2	6.2	6.0	6.0	5.9
		Ctrl (pure soil)		6.7	6.6	6.6	6.4	6.0	6.3
	2 Querenhorst (loamy sand)	Hydrochar	200	6.7	6.6	6.5	6.4	6.3	6.3
		Pyrochar	750	6.9	6.8	6.8	6.6	6.5	6.5
		Ctrl (pure soil)		6.6	6.5	6.5	6.3	6.5	6.3
	3 Volkmarisdorf (sandy loam)	Hydrochar	200	6.6	6.6	6.5	6.4	6.4	6.3
		Pyrochar	750	6.9	6.8	6.8	6.5	6.6	6.6
		Ctrl (pure soil)		6.7	6.6	6.6	6.5	6.6	6.4

Table S7

Adjusted p-values for statistical comparisons of the field incubation between biochar type (Pyro750 vs. Hydro200) and biochar type to control (Ctrl) for each ion and sampling time (T₀ & T₁).

Site		T ₀							T ₁						
		NO ₃ ⁻	NH ₄ ⁺	PO ₄ ³⁻	SO ₄ ²⁻	Ca ²⁺	Mg ²⁺	K ⁺	NO ₃ ⁻	NH ₄ ⁺	PO ₄ ³⁻	SO ₄ ²⁻	Ca ²⁺	Mg ²⁺	K ⁺
1 Bortfeld (sandy loam)	Pyro750 : Hydro200	<0.01	<0.01	0.14	<0.01	<0.01	1	<0.01	<0.01	0.04	1	<0.05	<0.01	<0.05	1
	Ctrl : Pyro750	<0.01	<0.01	0.15	<0.01	<0.01	1	<0.01	<0.05	0.13	0.88	<0.01	<0.01	<0.01	1
	Ctrl : Hydro200	<0.01	<0.01	1	<0.01	0.70	1	1	0.91	1	1	0.05	1	0.08	0.92
2 Querenhorst (loamy sand)	Pyro750 : Hydro200	<0.01	1	0.49	0.26	<0.01	<0.01	0.24	<0.01	<0.01	<0.05	0.45	<0.01	<0.01	<0.01
	Ctrl : Pyro750	0.06	0.73	0.38	<0.01	<0.01	<0.01	0.06	0.14	1	<0.01	0.67	<0.01	<0.01	<0.01
	Ctrl : Hydro200	<0.01	1	0.61	<0.01	1	0.91	0.68	<0.01	<0.01	0.46	1	0.24	1	1
3 Volkmarisdorf (sandy loam)	Pyro750 : Hydro200	<0.01	<0.01	0.30	<0.01	<0.01	0.49	<0.01	<0.01	<0.01	0.22	0.53	0.61	<0.05	1
	Ctrl : Pyro750	<0.01	<0.05	0.41	0.12	<0.01	1	<0.01	1	0.27	1	0.43	1	<0.05	1
	Ctrl : Hydro200	<0.01	<0.01	0.87	<0.01	1	1	<0.01	<0.05	<0.01	1	0.27	1	<0.05	1

Table S8

Adjusted p-values for statistical comparisons of two sampling times (T_0 & T_1) of field incubated biochars. Comparisons are for same biochar type or control each ion. * Statistical comparison was made with GAM (general additive model). Significant differences were assumed by $p \leq 0.05$.

Site		T_0 vs. T_1						
		NO_3^-	NH_4^+	PO_4^{3-}	SO_4^{2-}	Ca^{2+}	Mg^{2+}	K^+
1 Bortfeld (sandy loam)	Ctrl	<0.01	<0.01	<0.01*	<0.01	0.48	<0.05	<0.01
	Pyro750	<0.01	0.52	<0.01*	<0.01	<0.01	<0.05	<0.01
	Hydro200	0.09	<0.01	<0.01*	<0.01	<0.05	0.28	<0.01
2 Querenhorst (loamy sand)	Ctrl	<0.01	<0.01	<0.01*	0.11	<0.01	<0.01	<0.01
	Pyro750	<0.01	<0.01	<0.01*	<0.01	<0.01	<0.01	<0.01
	Hydro200	<0.05	<0.01	<0.01*	<0.01	<0.01	<0.01	<0.01
3 Volkmarisdorf (sandy loam)	Ctrl	<0.01	<0.01	<0.01*	<0.01	<0.01	<0.01	0.61
	Pyro750	<0.01	<0.01	<0.01*	<0.01	<0.01	<0.01	<0.01
	Hydro200	0.45	<0.01	<0.01*	<0.01	0.07	<0.01	<0.01