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

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Appendix / Supplement

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.

				Freundlich-Isotherm										**Linear-Isotherm**									
Soil	Ion	Treatment	Feed-stock	K_F	±	SE	Signf. Level	n	±	SE	Signf. Level	Residual std. error	R^2	a	±	SE	Signf. Level	Inter-cept (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	0.89
			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	0.55
			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	0.91
			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											-0.3	±	0.1	***	-19.3	±	1.6	***	3.0	0.51
		M											0.0	±	0.0		-12.7	±	0.9	***	1.9	0.03
		W											0.0	±	0.0		-13.7	±	0.5	***	1.0	0.04
	Pyro750	D											-1.5	±	0.0	***	-20.8	±	1.0	***	1.9	0.99
		M											-0.2	±	0.0	**	-10.0	±	1.0	***	2.0	0.41
		W											0.0	±	0.1		-13.4	±	1.2	***	2.4	0.05
K^+	Ctrl	-											0.7	±	0.1	***	-14.7	±	2.4	***	5.6	0.91
	Hydro200	D											0.5	±	0.1	***	-30.8	±	2.6	***	5.7	0.81
		M											0.5	±	0.1	***	-17.1	±	4.3	**	9.9	0.67
		W											0.6	±	0.1	***	-16.6	±	3.5	***	8.0	0.77
	Hydro250	D											0.4	±	0.1	***	-33.7	±	3.5	***	7.5	0.70
		M											0.6	±	0.1	***	-22.4	±	2.4	***	5.3	0.89
		W											0.6	±	0.1	***	-26.8	±	2.7	***	5.9	0.86
	Pyro750	D											-1.0	±	0.2	***	-442.1	±	55.7	***	68.1	0.49
		M											-0.6	±	0.1	***	-152.7	±	9.4	***	13.3	0.74
		W											0.3	±	0.0	***	-56.3	±	3.9	***	7.7	0.53
SO_4^{2-}	Ctrl	-											0.1	±	0.0	*	-15.8	±	0.7	***	1.4	0.19
	Hydro200	D											0.0	±	0.0		-15.5	±	0.6	***	1.3	0.06
		M											0.0	±	0.0		-15.1	±	0.6	***	1.2	0.04
		W											0.0	±	0.0		-15.4	±	0.5	***	1.0	0.05
	Hydro250	D											0.0	±	0.0	***	-13.8	±	0.2	***	0.5	0.49
		M											0.0	±	0.2		-14.8	±	0.8	***	0.9	0.03
		W											0.0	±	0.0		-14.7	±	0.6	***	1.2	0.02
	Pyro750	D											-0.1	±	0.0	**	-19.8	±	0.5	***	0.9	0.44
		M											0.0	±	0.0	.	-16.1	±	0.7	***	1.4	0.14
		W											0.0	±	0.0		-35.8	±	1.5	***	2.6	0.06

				Freundlich-Isotherm										**Linear-Isotherm**									
Soil	Ion	Treatment	Feed-stock	K_F	±	SE	Signf. Level	n	±	SE	Signf. Level	Residual std. error	R^2	a	±	SE	Signf. Level	Inter-cept (Y_0)	±	SE	Signf. Level	Residual std. error	R^2
Loamy sand	NO_3^-	Ctrl	-											-0.01	±	0.0		-11.5	±	0.8	***	1.8	0.06
		Hydro200	D											0.073	±	0.0	**	-13.1	±	0.8	***	1.8	0.36
			M											0.050	±	0.0	*	-13.5	±	0.6	***	1.4	0.29
			W											0.028	±	0.0		-13.1	±	0.8	***	1.7	0.04
		Hydro250	D											0.052	±	0.0	.	-12.6	±	1.1	***	2.3	0.11
			M											0.056	±	0.0	*	-13.8	±	0.9	***	1.9	0.21
			W											0.019	±	0.0		-12.5	±	0.7	***	1.5	0.00
		Pyro750	D											0.133	±	0.0	***	-10.5	±	0.7	***	1.6	0.72
			M											0.256	±	0.0	***	-11.3	±	0.9	***	2.0	0.85
			W											0.308	±	0.0	***	-7.9	±	1.1	***	2.4	0.84
	NH_4^+	Ctrl	-	7.8	±	0.6	***	1.6	±	0.1	***	2.8	0.99										
		Hydro200	D	6.4	±	0.4	***	1.5	±	0.0	***	2.2	0.99										
			M	8.5	±	1.0	***	1.6	±	0.1	***	4.6	0.97										
			W	8.4	±	1.1	***	1.6	±	0.1	***	4.5	0.96										
		Hydro250	D	8.2	±	0.8	***	1.6	±	0.1	***	3.5	0.98										
			M	9.2	±	0.9	***	1.6	±	0.1	***	3.9	0.98										
			W	9.0	±	0.8	***	1.6	±	0.1	***	3.6	0.98										
		Pyro750	D	5.3	±	0.9	***	1.3	±	0.1	***	5.5	0.96										
			M	5.0	±	0.3	***	1.4	±	0.0	***	1.6	1.00										
			W	6.7	±	0.3	***	1.5	±	0.0	***	1.6	1.00										
	PO_4^{3-}	Ctrl	-											16.6	±	2.5	***	-11.8	±	5.0	*	8.4	0.72
		Hydro200	D											16.9	±	1.3	***	-20.5	±	3.1	***	4.4	0.91
			M											16.7	±	2.7	***	-11.6	±	5.5	.	8.7	0.69
			W											15.8	±	2.7	***	-10.9	±	5.6	.	9.0	0.67

	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
Lab	Sandy loam	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
	Silty loam	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 char type (e.g. d : m = char from digestates to char from *Miscanthus*); control soil to feedstock within one char type (e.g. Ctrl : d = control soil to char from digestates); and same feedstock to different char 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 S4

Adjusted p-values for statistical comparisons of same char type and same feedstock between sandy and loamy soil for each ion. * Statistical comparison was made with GAM (general additive model). Significant differences were assumed by $p \leq 0.05$.

	Sandy loam vs. Silty loam						
	NO_3^-	NH_4^+	PO_4^{3-}	SO_4^{2-}	Ca^{2+}	Mg^{2+}	K^+
Ctrl	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Pyro750-D	<0.01	<0.01	0.11	<0.01	<0.01*	<0.01	0.03
Pyro750-M	<0.01	<0.01	0.34	<0.01	<0.01	<0.01	<0.01
Pyro750-W	<0.01	<0.01	0.55	<0.01	<0.01	<0.01	<0.01
Hydro250-D	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Hydro250-M	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Hydro250-W	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Hydro200-D	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Hydro200-M	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Hydro200-W	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

Table S5

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

				Freundlich-Isotherm										**Linear-Isotherm**									
Sampling Time	Ion	Treat-ment	Site	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

				Freundlich-Isotherm										Linear-Isotherm									
Sampling Time	Ion	Treatment	Site	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 Volkmarsdorf (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 Volkmarsdorf (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 char type (Pyro750 vs. Hydro200) and char type to control (Ctrl) for each ion and sampling time (T_0 & T_1).

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 Volkmarsdorf (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 chars. Comparisions are for same char 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 Volkmarsdorf (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