

Supplementary Material

Mineral nitrogen recovery from manure slurry through multi-layer sorption of NH₃ and CO₂ onto pyrolyzed biomass

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Table S1. Avrami model parameter values describing CO₂ and NH₃ adsorption kinetics.

Count	Material	Gas	Exposure interval	K	n	Error (%)
1	ox wood biochar	CO ₂	1	0.025 ± 0.008	0.669 ± 0.117	3.57 ± 1.65
2	ox wood biochar	CO ₂	2	0.024 ± 0.005	1.137 ± 0.252	1277.45 ± 1016.20
3	ox wood biochar	CO ₂	3	0.021 ± 0.006	0.779 ± 0.073	4.88 ± 2.98
4	ox wood biochar	NH ₃	1	0.046 ± 0.035	0.500 ± 0.000	58.66 ± 80.95
5	ox wood biochar	NH ₃	2	0.013 ± 0.003	0.851 ± 0.194	3952.19 ± 859.88
6	ox wood biochar	NH ₃	3	0.006 ± 0.001	0.500 ± 0.000	37.45 ± 24.19
7	HSW biochar CO ₂ +NH ₃	CO ₂	1	0.036 ± 0.022	0.576 ± 0.210	6.758 ± 1.43
8	HSW biochar CO ₂ +NH ₃	NH ₃	1	0.004 ± 0.00	0.629 ± 0.034	4.708 ± 1.73

Table S2. The binding energy (BE) peak range assignments for the XPS C1s, N1s, and O1s core levels used for our deconvolution model.

Core level	Bond form	BE (eV)
C1s	C-C, C=C (low)	283.0-284.0
C1s	C-C, C=C	284.0-285.0
C1s	C-N	285.0-286.0
C1s	C-O	286.0-287.0
C1s	C-OH	286.0-287.0
C1s	R-C=O (R aromatic)	287.0-287.5
C1s	R-C=O	287.5-288.0
C1s	(C=O)-O	288.3-288.5
C1s	(C=O)-OH	288.5-288.8
C1s	N-C=O	288.8-290.5
N1s	N pyridine	398.0-398.9
N1s	C-NH ₂	399.0-399.5
N1s	C-O--NH ₄ ⁺	399.5-400.0
N1s	N=C-(C=O)-	400.0-400.5
N1s	N-(C=O)-	400.5-400.9
N1s	NH ₄ ⁺	401.0-403.0
O1s	R-C=O (R aromatic)	529.5-530.0
O1s	R-C=O	530.5-530.5
O1s	R-C-OH (R aromatic)	530.5-531.0
O1s	R-C-OH	531.0-531.3
O1s	C=O	531.3-532.0
O1s	C-O	532.0-533.3
O1s	H ₂ O, OH	533.5-536.0

Table S3. The proportion of C, N, and O bonds in five standard compounds, based on the binding energies (BE) and full-width at half-maximum values (FWHM) of deconvoluted curves and relative areas, as measured with XPS.

Core level	Bond form	BE range (eV)	Ammonium carbonate			Urea			Ammonium bicarbonate			Proline			Valine		
			BE (eV)	FWHM	area (%)	BE (eV)	FWHM	area (%)	BE (eV)	FWHM	area (%)	BE (eV)	FWHM	area (%)	BE (eV)	FWHM	area (%)
Cl s	C-C, C=C	284.0-285.0	284.5	1.28	57.37	248.4	1.89		284.5	1.31	57.34	284.1	1.69	37.21	284.3	1.65	45.77
Cl s	C-N	285.0-286.0	285.3	1.28	21.99	285.0	1.89	4.09	285.1	1.31	20.29	285.0	1.69	36.19	285.1	1.65	25.92
Cl s	C-O	286.0-287.0	286.3	1.28	13.01	--	--	0.00	--	--	0.00	--	--	0.00	--	--	0.00
Cl s	C-OH	286.0-287.0	--	--	0.00	--	--	0.00	286.2	1.31	13.90	286.1	1.69	11.48	286.0	1.65	10.16
Cl s	R-C=O (R...)	287.0-287.5	--	--	0.00	--	--	0.00	--	--	0.00	287.3	1.69	15.12	--	--	0.0
Cl s	R-C=O	287.5-288.0	--	--	0.00	--	--	0.00	--	--	0.00	--	--	0.00	287.7	1.65	18.16
Cl s	(C=O)-O	288.3-288.8	288.6	1.28	7.62	--	--	0.00	--	--	0.00	--	--	0.00	--	--	0.00
Cl s	(C=O)-OH	288.5-288.8	--	--	0.00	--	--	0.00	288.7	1.31	8.74	--	--	0.00	--	--	0.00
Cl s	N-C=O	288.8-290.0	--	--	0.00	289.0	1.89	89.37	--	--	0.00	--	--	0.00	--	--	0.00
N1 s	pyridinic N	398.0-398.9	398.3	1.09	7.68	398.7	1.31	21.98	398.0	1.41	2.27	--	--	0.00	--	--	0.00
N1 s	C-NH ₂	399.0-399.5	399.1	1.09	59.02	399.5	1.31	45.4	399.2	1.41	45.32	399.6	1.84	47.9	399.5	1.99	6.78
N1 s	C-O--NH ₄ ⁺	399.5-400.0	399.9	1.09	20.57	--	--	0.00	--	--	0.0	--	--	0.00	--	--	0.00
N1 s	N=C-(C=O)	400.0-400.5	--	--	0.00	--	--	0.00	--	--	0.0	400.4	1.84	52.1	--	--	0.00
N1 s	N-(C=O)	400.0-400.9	--	--	0.00	400.3	1.31	26.6	--	--	0.0	--	--	0.00	--	--	0.00
N1 s	N-C-(C=O)	400.5-400.9	400.8	1.09	7.39	--	--	0.00	400.9	1.41	34.02	--	--	0.00	400.7	1.99	93.22
N1 s	NH ₄ ⁺	401.0-403.0	401.7	1.09	5.34	401.2	1.311	6.02	401.8	1.41	18.39	--	--	0.00	--	--	0.00
O1 s	R-C=O (R...)	529.5-530.0	--	--	0.00	--	--	0.00	--	--	0.00	529.8	1.74	73.69	--	--	0.00
O1 s	R-C=O	530.5-530.5	--	--	0.00	--	--	0.00	--	--	0.00	--	--	0.00	530.4	1.69	71.51
O1 s	R-C-OH (R...)	530.5-531	--	--	0.00	--	--	0.00	--	--	0.00	530.7	1.74	26.31	--	--	0.00
O1 s	R-C-OH	531.0-531.3	--	--	0.00	--	--	0.00	--	--	0.00	--	--	0.00	531.2	1.69	28.49
O1 s	C=O	531.3-532.0	531.7	1.61	52.39	531.5	2.09	100	531.6	1.63	60.25	--	--	0.00	--	--	0.00
O1 s	C-O	532.0-533.3	533.1	1.61	47.61	--	--	0.0	533.0	1.63	39.75	--	--	0.00	--	--	0.00

Table S4. Composition of nutrient powder used for growth trial

count	reagent	amount in mixture (g)
1	$\text{CaHPO}_4 \cdot \text{H}_2\text{O}$	4.44
2	K_2CO_3	8.64
3	MgO	3.88
4	$\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$	3.89
5	NaCl	0.18
6	CaCO_3	49.48
7	K_2SO_4	1.36

Table S5. Description of growth-trial amendment treatments and irrigation amounts

potting mix	amend.	N-form	urea and biochar	TH6 (g pot ⁻¹)	biochar (g pot ⁻¹)	nutrient powder (g pot ⁻¹)	nitrogen (mg N pot ⁻¹)	urea (mg pot ⁻¹)	initial irrigation (mL pot ⁻¹)
TH6	none	none	0	41.7	0.00	0.62	0.00	0.00	150
TH6	fert 0.25x	urea	0.25-fold of wood biochar N uptake (Table 1)	41.7	0.00	0.62	8.78	18.82	150
TH6	fert 0.5x	urea	0.5-fold of wood biochar N uptake	41.7	0.00	0.62	17.55	37.64	150
TH6	fert 1x	urea	1-fold (same amount) of wood biochar N uptake	41.7	0.00	0.62	35.10	75.29	150
TH6	fert 1.5x	urea	1.5-fold of wood biochar N uptake	41.7	0.00	0.62	52.65	112.93	150
TH6	manure biochar	NH ₃ gas	equivalent on C basis to wood biochar (Table 1)	41.7	7.20		0.00	0.00	154
TH6	manure biochar+slurry	slurry	equivalent on C basis to wood biochar	41.7	7.20		0.00	0.00	154
TH6	manure biochar+1x fert	urea	equivalent on C basis to wood biochar + urea-N 1-fold of wood biochar N uptake	41.7	7.20		35.10	75.29	154
TH6	manure biochar	none	equivalent on C basis to wood biochar	41.7	7.20		0.00	0.00	154
TH6	wood biochar NH ₃ +CO ₂	NH ₃ gas	10% of pot volume	41.7	3.60	0.62	0.00	0.00	172
TH6	wood biochar+slurry	slurry	10% of pot volume	41.7	3.60	0.62	0.00	0.00	172
TH6	wood biochar+1x fert	urea	10% of pot volume + urea-N 1-fold of wood biochar N uptake	41.7	3.60	0.62	35.10	75.29	172
TH6	wood biochar	none	10% of pot volume	41.7	3.60	0.62	0.00	0.00	172

Table S6. Chemical and physical properties of wood and HSW biochars.

	ox wood biochar	HSW biochar
pH in water	5.2	10.3
SSA (m ² g ⁻¹)	275.7	74
Total N (%w w ⁻¹)	0.91	4.8
Fixed C (%w w ⁻¹)	63.9	46.2
Ash (%w w ⁻¹)	0.7	39

Table S7. Germination, mass of dry shoot and root biomass, and total carbon and nitrogen in shoot and root biomass of marigold, radish, and tomato plants. Letters indicate significant differences between amendments within plant and biomass type ($p < 0.05$; $n = 4$).

plant	amend.	germ.	shoot biomass (dry)	shoot nitrogen	shoot carbon	root biomass (dry)	root nitrogen	root carbon
		(%)	(g pot ⁻¹)	(% w w ⁻¹)	(% w w ⁻¹)	(g pot ⁻¹)	(% w w ⁻¹)	(% w w ⁻¹)
marigold	0x fert	80.0 ±	1.99 ±	1.42 ±	44.6 ±	0.82 ±	0.99 ±	43.5 ±
		23.1 a	0.26 ab	0.38 ab	1.01 a	0.14 ab	0.15 a	0.83 a
marigold	0.25x fert	55.0 ±	2.38 ±	1.30 ±	44.6 ±	1.01 ±	0.94 ±	43.0 ±
		41.2 a	0.36 ab	0.24 ab	1.33 a	0.18 ab	0.08 a	0.95 a
marigold	0.5x fert	75.0 ±	2.62 ±	1.14 ±	45.3 ±	0.97 ±	0.95 ±	43.9 ±
		34.2 a	0.41 a	0.17 ab	0.85 a	0.17 ab	0.11 a	0.62 a
marigold	1x fert	55.0 ±	2.65 ±	1.62 ±	45.2 ±	0.98 ±	1.07 ±	44.8 ±
		34.2 a	0.51 a	0.51 ab	0.97 a	0.13 ab	0.11 a	0.47 a
marigold	1.5x fert	55.0 ±	2.80 ±	1.86 ±	45.2 ±	0.86 ±	1.10 ±	43.0 ±
		19.2 a	0.39 a	0.16 a	0.33 a	0.08 ab	0.14 a	3.30 a
marigold	manure biochar	80.0 ±	1.93 ±	1.27 ±	44.5 ±	0.76 ±	1.00 ±	42.4 ±
		16.3 a	0.13 ab	0.26 ab	0.20 a	0.26 abc	0.27 a	0.81 a
marigold	manure biochar+slurry	60.0 ±	1.96 ±	1.39 ±	44.02 ±	0.97 ±	0.89 ±	42.8 ±
		43.2 a	0.42 ab	0.61 ab	1.09 a	0.14 ab	0.08 a	0.94 a
marigold	manure biochar CO ₂ +NH ₃	65.0 ±	1.24 ±	1.59 ±	33.5 ±	0.59 ±	0.86 ±	31.9 ±
		47.3 a	0.83 bc	1.16 ab	22.4 ab	0.41 bc	0.62 ab	21.3 a
marigold	dairy manure biochar+1x	30.0 ±	0.60 ±	0.47 ±	11.4 ±	0.20 ±	0.22 ±	9.04 ±
		20.0 a	1.19 c	0.94 b	22.9 b	0.41 c	0.44 b	18.1 b
marigold	wood biochar	65.0 ±	2.62 ±	0.94 ±	45.1 ±	0.94 ±	0.88 ±	42.5 ±
		19.2 a	0.13 a	0.12 ab	0.61 a	0.25 ab	0.29 a	2.41 a
marigold	wood biochar+slurry	35.0 ±	2.33 ±	1.09 ±	44.6 ±	0.81 ±	0.96 ±	43.8 ±
		34.2 a	0.29 ab	0.08 ab	0.52 a	0.15 ab	0.19 a	0.48 a
marigold	wood biochar NH ₃ +CO ₂	60.0 ±	2.70 ±	1.39 ±	45.8 ±	0.96 ±	0.94 ±	43.7 ±
		43.2 a	0.33 a	0.28 ab	0.43 a	0.14 ab	0.16 a	0.60 a
marigold	wood biochar+1x	60.0 ±	3.10 ±	1.37 ±	46.0 ±	1.20 ±	0.91 ±	43.0 ±
		28.3 a	0.17 a	0.05 ab	0.17 a	0.17 a	0.10 a	2.48 a
radish	0x fert	90.0 ±	0.77 ±	1.43 ±	41.9 ±	2.31 ±	0.81 ±	40.9 ±
		11.6 a	0.14 b	0.40 abc	1.18 ab	0.27 c	0.17 a	4.18 a
radish	0.25x fert	70.0 ±	1.05 ±	1.80 ±	42.9 ±	2.81 ±	0.78 ±	41.1 ±
		11.6 a	0.31 ab	0.33 abc	0.74 a	0.47 bc	0.25 a	2.93 a
radish	0.5x fert	80.0 ±	0.89 ±	1.86 ±	42.2 ±	3.20 ±	0.83 ±	41.7 ±
		16.3 a	0.12 ab	0.55 abc	1.18 ab	0.29 abc	0.15 a	2.30 a
radish	1x fert	65.0 ±	1.08 ±	1.96 ±	41.9 ±	3.05 ±	1.07 ±	43.1 ±
		34.2 a	0.17 ab	0.28 abc	2.10 ab	0.61 abc	0.26 a	4.45 a
radish	1.5x fert	85.0 ±	1.34 ±	2.05 ±	43.4 ±	3.04 ±	1.00 ±	39.6 ±
		19.2 a	0.34 a	0.68 ab	1.47 a	0.90 abc	0.26 a	6.99 a
radish	manure biochar	90.0 ±	0.74 ±	1.34 ±	40.4 ±	2.91 ±	0.72 ±	42.8 ±
		20.0 a	0.15 b	0.34 abc	1.92 ab	0.73 abc	0.06 a	1.53 a
radish	manure biochar+slurry	90.0 ±	1.00 ±	1.19 ±	39.1 ±	2.92 ±	0.68 ±	40.5 ±
		20.0 a	0.13 ab	0.29 bc	3.49 b	0.32 abc	0.03 a	4.27 a
radish	manure biochar CO ₂ +NH ₃	65.0 ±	0.98 ±	2.12 ±	41.8 ±	3.50 ±	1.01 ±	40.6 ±
		10.0 a	0.21 ab	0.46 a	1.34 ab	0.36 abc	0.22 a	2.39 a

radish	manure biochar+1x	75.0 ±	0.94 ±	1.51 ±	41.1 ±	4.10 ±	0.80 ±	42.7 ±
		19.2 a	0.12 ab	0.33 abc	0.40 ab	0.20 a	0.06 a	0.78 a
radish	wood biochar	90.0 ±	0.84 ±	1.10 ±	42.8 ±	3.13 ±	0.72 ±	42.6 ±
		20.0 a	0.12 ab	0.12 c	0.91 ab	0.27 abc	0.15 a	1.48 a
radish	wood biochar+slurry	90.0 ±	0.91 ±	1.17 ±	42.3 ±	2.82 ±	0.78 ±	42.3 ±
		11.6 a	0.26 ab	0.20 bc	0.49 ab	0.24 bc	0.07 a	1.30 a
radish	wood biochar NH ₃ +CO ₂	80.0 ±	1.23 ±	1.52 ±	42.9 ±	3.81 ±	0.83 ±	42.8 ±
		16.3 a	0.26 ab	0.19 abc	0.68 a	0.44 ab	0.11 a	1.03 a
radish	wood biochar+1x	90.0 ±	1.15 ±	1.39 ±	42.3 ±	3.88 ±	0.84 ±	43.6 ±
		11.6 a	0.11 ab	0.19 abc	1.07 ab	0.61 ab	0.08 a	0.29 a
tomato	0x fert	85.0 ±	3.04 ±	1.13 ±	42.1 ±	0.47 ±	1.18 ±	42.4 ±
		19.2 a	0.37 bcd	0.12 c	0.54 abcd	0.09 bc	0.08 c	0.47 abcde
tomato	0.25x fert	85.0 ±	3.37 ±	1.19 ±	42.3 ±	0.56 ±	1.26 ±	42.8 ±
		19.2 a	0.57 abcd	0.17 bc	0.73 abcd	0.10 abc	0.11 bc	0.29 ab
tomato	0.5x fert	55.0 ±	3.65 ±	1.27 ±	42.6 ±	0.55 ±	1.24 ±	43.3 ±
		37.9 a	0.27 abcd	0.15 bc	0.45 abcd	0.13 bc	0.16 bc	0.58 a
tomato	1x fert	65.0 ±	3.31 ±	1.68 ±	42.8 ±	0.52 ±	1.53 ±	43.6 ±
		44.4 a	0.67 abcd	0.52 c	0.74 abc	0.11 bc	0.30 ab	0.39 a
tomato	1.5x fert	100 ± 0.0	2.77 ±	2.41 ±	43.3 ±	0.34 ±	1.76 ±	42.6 ±
		a	0.51 d	0.38 a	0.69 ab	0.13 c	0.14 a	0.66 abc
tomato	manure biochar	85.0 ±	2.84 ±	1.01 ±	41.2 ±	0.52 ±	1.09 ±	41.2 ±
		19.15 a	0.26 cd	0.11 c	0.34 d	0.05 bc	0.06 c	0.35 e
tomato	manure biochar+slurry	85.0 ±	3.06 ±	1.00 ±	41.1 ±	0.56 ±	1.21 ±	41.3 ±
		30.0 a	0.36 bcd	0.13 c	0.50 d	0.09 abc	0.11 c	0.53 de
tomato	manure biochar CO ₂ +NH ₃	70.0 ±	3.99 ±	1.12 ±	41.6 ±	0.56 ±	1.29 ±	42.4 ±
		25.8 a	0.21 ab	0.12 c	0.22 cd	0.03 bc	0.07 bc	0.90 abcde
tomato	manure biochar+1x	55.0 ±	3.77 ±	1.14 ±	42.2 ±	0.63 ±	1.13 ±	41.5 ±
		37.9 a	0.38 abc	0.17 c	0.63 abcd	0.11 ab	0.07 c	0.83 cde
tomato	wood biochar	100 ±	3.09 ±	0.96 ±	42.0 ±	0.59 ±	1.02 ±	42.5 ±
		0.00 a	0.23 abcd	0.06 c	0.42 abcd	0.08 ab	0.07 c	0.42 abcd
tomato	wood biochar+slurry	90.0 ±	3.21 ±	1.07 ±	41.8 ±	0.56 ±	1.09 ±	41.8 ±
		11.6 a	0.34 abcd	0.12 c	0.85 bcd	0.16 bc	0.06 c	0.27 bcde
tomato	wood biochar NH ₃ +CO ₂	90.0 ±	3.69 ±	1.21 ±	43.4 ±	0.64 ±	1.14 ±	43.1 ±
		11.6 a	0.26 abcd	0.10 bc	0.82 a	0.07 ab	0.04 c	0.18 a
tomato	wood biochar+1x	85.0 ±	4.06 ±	1.18 ±	43.5 ±	0.80 ±	1.18 ±	43.17 ±
		10.0 a	0.42 a	0.06 bc	0.80 a	0.03 a	0.07 c	0.11 a

Table S8. Total aluminum (Al), sodium (Na), macronutrients (Ca, K, Mg, P, S), micronutrients (Micros; B, Cu, Mn, Mo, Zn), and heavy metals (H. metal; Cd, Cr, Pb) in plant shoots. Letters indicate significant differences between amendments within plant and biomass type ($p < 0.05$; $n = 4$).

Plant	Amendment	Al	Ca	K	Mg	Na	P	S	Micros	H. metal
shoot		g kg ⁻¹	g kg ⁻¹	g kg ⁻¹	g kg ⁻¹	g kg ⁻¹	g kg ⁻¹	g kg ⁻¹	g kg ⁻¹	mg kg ⁻¹
marigold	0x fert	4.67 ± 1.25 a	8.36 ± 0.68 a	8.07 ± 0.85 a	5.17 ± 0.47 a	0.6 ± 0.29 a	4.4 ± 0.92 a	3.17 ± 0.63 a	0.23 ± 0.03 a	0.45 ± 0.28 a
marigold	0.25x fert	4.66 ± 2.1 a	8.22 ± 0.37 a	6.84 ± 0.97 a	5.19 ± 0.45 a	0.62 ± 0.12 a	3.85 ± 0.66 a	2.71 ± 0.55 a	0.21 ± 0.03 a	0.28 ± 0.09 a
marigold	0.5x fert	4.49 ± 1.17 a	7.83 ± 0.88 a	6.37 ± 0.4 a	5.07 ± 0.83 a	0.36 ± 0.26 a	3.28 ± 0.75 a	2.41 ± 0.45 a	0.20 ± 0.03 a	0.40 ± 0.22 a
marigold	1x fert	5.5 ± 1.55 a	8.39 ± 2.08 a	6.38 ± 0.82 a	5.64 ± 1.73 a	0.43 ± 0.34 a	3.67 ± 0.86 a	2.53 ± 0.44 a	0.23 ± 0.04 a	0.26 ± 0.06 a
marigold	1.5x fert	5.61 ± 1.29 a	7.33 ± 1.12 a	6.63 ± 0.45 a	4.80 ± 0.7 a	0.49 ± 0.26 a	3.49 ± 0.41 a	2.62 ± 0.32 a	0.21 ± 0.03 a	0.59 ± 0.59 a
marigold	manure biochar	4.66 ± 2.53 a	9.24 ± 1.15 a	7.64 ± 1.12 a	5.07 ± 0.58 a	0.27 ± 0.22 a	4.40 ± 0.56 a	3.07 ± 0.24 a	0.20 ± 0.03 a	0.26 ± 0.02 a
marigold	manure biochar+slurry	6.63 ± 2.54 a	8.78 ± 2.03 a	9.65 ± 2.76 a	4.95 ± 1.46 a	0.64 ± 0.38 a	4.93 ± 1.75 a	3.50 ± 1.58 a	0.19 ± 0.04 a	0.32 ± 0.11 a
marigold	manure biochar CO ₂ +NH ₃	2.57 ± 2.3 a	6.65 ± 4.56 a	6.96 ± 4.77 a	3.96 ± 2.80 a	0.60 ± 0.48 a	4.06 ± 2.96 a	2.87 ± 2.06 a	0.16 ± 0.12 a	0.20 ± 0.15 a
marigold	manure biochar+1x	5.65 ± 0.00 a	7.12 ± 0.00 a	10.3 ± 0.00 a	4.13 ± 0.00 a	0.97 ± 0.00 a	4.35 ± 0.00 a	3.16 ± 0.00 a	0.18 ± 0.00 a	0.20 ± 0.00 a
marigold	wood biochar	3.75 ± 0.75 a	7.24 ± 0.52 a	7.56 ± 0.34 a	3.9 ± 0.21 a	0.16 ± 0.02 a	3.19 ± 0.15 a	2.15 ± 0.08 a	0.21 ± 0.02 a	0.17 ± 0.04 a
marigold	wood biochar+slurry	5.10 ± 0.33 a	6.94 ± 1.11 a	8.76 ± 1.12 a	3.95 ± 0.59 a	0.48 ± 0.24 a	4.16 ± 0.53 a	2.67 ± 0.43 a	0.21 ± 0.03 a	0.24 ± 0.11 a
marigold	wood biochar NH ₃ +CO ₂	6.54 ± 3.73 a	7.61 ± 0.86 a	7.96 ± 2.31 a	4.30 ± 0.44 a	0.28 ± 0.28 a	3.44 ± 0.64 a	2.52 ± 0.68 a	0.22 ± 0.04 a	0.42 ± 0.33 a
marigold	wood biochar+1x	4.69 ± 2.01 a	7.96 ± 0.84 a	7.28 ± 0.68 a	4.68 ± 0.49 a	0.52 ± 0.24 a	3.01 ± 0.37 a	2.23 ± 0.26 a	0.19 ± 0.05 a	0.33 ± 0.17 a
radish	0x fert	43.0 ± 60.93 a	23.7 ± 3.85 a	17.83 ± 4.28 a	8.78 ± 1.54 a	7.01 ± 2.19 ab	2.41 ± 0.30 a	2.47 ± 0.52 a	0.44 ± 0.10 a	0.58 ± 0.12 a
radish	0.25x fert	10.6 ± 3.91 a	22.6 ± 5.53 a	17.3 ± 5.34 a	7.52 ± 1.99 a	7.28 ± 1.70 ab	2.59 ± 0.77 a	2.69 ± 0.63 a	0.41 ± 0.08 a	0.29 ± 0.12 a
radish	0.5x fert	13.1 ± 6.42 a	22.5 ± 6.00 a	18.28 ± 4.72 a	8.62 ± 1.93 a	9.49 ± 1.20 a	2.35 ± 0.40 a	2.58 ± 0.62 a	0.45 ± 0.04 a	0.44 ± 0.19 a
radish	1x fert	11.5 ± 4.27 a	24.7 ± 4.50 a	18.0 ± 4.23 a	8.77 ± 1.41 a	9.50 ± 1.88 a	2.59 ± 0.22 a	2.29 ± 0.31 a	0.45 ± 0.03 a	0.33 ± 0.10 a
radish	1.5x fert	20.1 ± 24.15 a	22.9 ± 5.33 a	17.6 ± 6.76 a	7.83 ± 1.57 a	7.93 ± 2.27 ab	2.80 ± 1.18 a	2.96 ± 1.90 a	0.51 ± 0.17 a	4.46 ± 7.41 a

radish	manure biochar	7.08 ± 1.60 a	25.5 ± 6.28 a	20.2 ± 5.05 a	7.69 ± 1.73 a	3.72 ± 1.92 b	2.84 ± 0.68 a	3.07 ± 1.18 a	0.46 ± 0.08 a	0.20 ± 0.05 a
radish	manure biochar+slurry	7.53 ± 2.79 a	26.7 ± 9.82 a	19.6 ± 4.77 a	7.56 ± 2.08 a	3.77 ± 1.18 b	2.76 ± 0.34 a	2.75 ± 0.45 a	0.45 ± 0.11 a	0.33 ± 0.12 a
radish	manure biochar CO ₂ +NH ₃	10.86 ± 3.06 a	26.0 ± 4.87 a	18.5 ± 2.30 a	8.63 ± 1.57 a	7.41 ± 4.38 ab	2.89 ± 0.40 a	2.58 ± 0.30 a	0.51 ± 0.08 a	0.67 ± 0.64 a
radish	manure biochar+1x	10.47 ± 2.45 a	26.8 ± 4.56 a	17.4 ± 3.31 a	8.67 ± 1.22 a	6.89 ± 2.04 ab	2.56 ± 0.47 a	2.06 ± 0.25 a	0.48 ± 0.03 a	0.33 ± 0.12 a
radish	wood biochar	8.50 ± 4.75 a	21.3 ± 6.27 a	16.3 ± 4.21 a	6.27 ± 1.86 a	4.46 ± 2.54 ab	2.38 ± 0.45 a	2.46 ± 0.40 a	0.41 ± 0.08 a	0.40 ± 0.32 a
radish	wood biochar+slurry	7.89 ± 4.00 a	18.2 ± 1.38 a	19.0 ± 3.42 a	5.90 ± 0.81 a	5.09 ± 3.02 ab	2.37 ± 0.57 a	2.59 ± 0.68 a	0.40 ± 0.03 a	0.25 ± 0.16 a
radish	wood biochar NH ₃ +CO ₂	20.6 ± 24.53 a	20.6 ± 2.61 a	18.2 ± 3.05 a	6.29 ± 1.23 a	4.76 ± 0.94 ab	2.10 ± 0.39 a	1.90 ± 0.45 a	0.43 ± 0.04 a	0.41 ± 0.18 a
radish	wood biochar+1x	13.3 ± 6.78 a	23.7 ± 2.80 a	20.2 ± 6.06 a	7.59 ± 0.88 a	6.40 ± 2.15 ab	2.40 ± 0.56 a	2.18 ± 0.49 a	0.44 ± 0.06 a	0.59 ± 0.35 a
tomato	0x fert	4.53 ± 1.52 a	12.8 ± 1.27 bc	12.48 ± 0.49 a	5.06 ± 0.47 a	2.48 ± 0.52 ab	3.39 ± 0.57 abcd	3.81 ± 0.89 ab	0.19 ± 0.02 a	0.10 ± 0.02 a
tomato	0.25x fert	4.90 ± 0.37 a	12.3 ± 0.48 bc	12.88 ± 0.99 a	5.08 ± 0.52 a	2.53 ± 0.33 ab	3.04 ± 0.22 cd	3.10 ± 0.35 abc	0.18 ± 0.01 a	0.08 ± 0.01 a
tomato	0.5x fert	4.78 ± 1.94 a	10.65 ± 0.87 c	12.51 ± 1.39 a	4.42 ± 0.20 a	2.51 ± 0.49 ab	2.87 ± 0.28 cd	3.02 ± 0.47 abc	0.17 ± 0.02 a	0.08 ± 0.02 a
tomato	1x fert	5.00 ± 0.70 a	10.2 ± 0.86 c	12.16 ± 0.08 a	4.54 ± 0.15 a	3.08 ± 0.73 ab	3.11 ± 0.55 cd	3.58 ± 0.59 abc	0.16 ± 0.01 a	0.11 ± 0.04 a
tomato	1.5x fert	4.90 ± 2.31 a	10.15 ± 1.16 c	12.8 ± 0.49 a	4.69 ± 0.50 a	4.33 ± 1.10 a	3.76 ± 0.71 abc	3.91 ± 0.92 ab	0.18 ± 0.02 a	0.16 ± 0.05 a
tomato	manure biochar	6.53 ± 1.42 a	16.8 ± 1.77 a	13.29 ± 0.55 a	5.08 ± 0.50 a	2.44 ± 0.88 b	4.36 ± 0.33 a	4.12 ± 0.52 a	0.22 ± 0.04 a	0.14 ± 0.03 a
tomato	manure biochar+slurry	5.90 ± 2.33 a	14.9 ± 1.60 ab	13.93 ± 1.23 a	4.51 ± 0.37 a	3.41 ± 1.90 ab	4.22 ± 0.36 ab	3.95 ± 0.51 a	0.41 ± 0.46 a	1.99 ± 3.79 a
tomato	manure biochar CO ₂ +NH ₃	5.15 ± 1.33 a	12.2 ± 0.60 bc	13.6 ± 0.74 a	4.27 ± 0.23 a	2.67 ± 0.31 ab	3.75 ± 0.51 abc	3.24 ± 0.33 abc	0.16 ± 0.01 a	0.1 ± 0.01 a
tomato	manure biochar+1x	4.67 ± 1.33 a	12.8 ± 1.60 bc	12.9 ± 0.97 a	4.23 ± 0.68 a	1.95 ± 0.50 b	3.57 ± 0.47 abcd	3.18 ± 0.58 abc	0.15 ± 0.02 a	0.1 ± 0.02 a
tomato	wood biochar	5.85 ± 1.67 a	12.1 ± 1.04 bc	13.8 ± 0.55 a	4.22 ± 0.10 a	2.14 ± 0.22 b	3.17 ± 0.06 bcd	3.04 ± 0.38 abc	0.22 ± 0.01 a	0.08 ± 0.00 a
tomato	wood biochar+slurry	5.47 ± 2.59 a	12.0 ± 2.14 bc	14.0 ± 0.61 a	4.32 ± 0.60 a	2.84 ± 0.26 ab	3.69 ± 0.32 abc	3.56 ± 0.55 abc	0.22 ± 0.03 a	0.23 ± 0.32 a
tomato	wood biochar NH ₃ +CO ₂	5.88 ± 2.44 a	10.6 ± 0.58 c	12.1 ± 1.42 a	4.21 ± 0.50 a	2.29 ± 0.44 b	2.82 ± 0.31 cd	2.60 ± 0.06 bc	0.19 ± 0.01 a	0.11 ± 0.06 a
tomato	wood biochar+1x	5.45 ± 0.59 a	11.3 ± 1.34 c	12.6 ± 0.44 a	4.24 ± 0.50 a	1.92 ± 0.23 b	2.59 ± 0.40 d	2.36 ± 0.24 c	0.19 ± 0.02 a	0.08 ± 0.01 a

Table S9. Total aluminum (Al), sodium (Na), macronutrients (Ca, K, Mg, P, S), micronutrients (Micros; B, Cu, Mn, Mo, Zn), and heavy metals (H. metal; Cd, Cr, Pb) in plant roots. Letters indicate significant differences between amendments within plant and biomass type ($p < 0.05$; $n = 4$).

Plant	Amendment	Al	Ca	K	Mg	Na	P	S	Micros	H. metal
root		g kg ⁻¹	g kg ⁻¹	g kg ⁻¹	g kg ⁻¹	g kg ⁻¹	g kg ⁻¹	g kg ⁻¹	g kg ⁻¹	mg kg ⁻¹
marigold	0x fert	101 ± 125 a	4.21 ± 0.43 a	13.9 ± 3.3 abcd	2.97 ± 0.63 ab	22.7 ± 6.41 a	1.85 ± 0.35 ab	3.01 ± 0.87 ab	0.39 ± 0.16 a	1.66 ± 0.56 a
marigold	0.25x fert	59.4 ± 52.5 a	3.75 ± 0.2 a	11.1 ± 3.42 abcd	3.05 ± 1.22 ab	18.9 ± 3.35 a	1.43 ± 0.31 abcde	2.31 ± 0.28 b	0.30 ± 0.07 a	1.27 ± 0.33 a
marigold	0.5x fert	34.9 ± 16.5 a	4.01 ± 0.38 a	9.00 ± 1.84 cd	3.14 ± 0.57 ab	17.9 ± 1.76 a	1.18 ± 0.20 de	2.04 ± 0.35 b	0.25 ± 0.05 a	1.03 ± 0.16 a
marigold	1x fert	71.6 ± 75.8 a	3.97 ± 0.78 a	8.18 ± 2.76 d	3.41 ± 1.25 a	19.9 ± 8.44 a	1.27 ± 0.30 bcde	2.10 ± 0.46 b	0.32 ± 0.16 a	1.53 ± 1.10 a
marigold	1.5x fert	33.9 ± 15.0 a	3.83 ± 0.22 a	9.36 ± 1.04 bcd	2.81 ± 0.47 ab	19.2 ± 3.40 a	1.30 ± 0.15 abcde	2.16 ± 0.14 b	0.27 ± 0.06 a	1.11 ± 0.24 a
marigold	manure biochar	31.2 ± 14.9 a	3.96 ± 0.22 a	17.23 ± 2.44 a	2.28 ± 0.44 ab	19.2 ± 4.64 a	1.76 ± 0.37 abcd	3.25 ± 0.64 ab	0.20 ± 0.03 a	0.59 ± 0.48 a
marigold	manure biochar+slurry	26.8 ± 13.3 a	3.45 ± 0.38 a	15.4 ± 3.00 ab	1.71 ± 0.44 ab	14.8 ± 2.98 a	1.48 ± 0.15 abcde	2.31 ± 0.44 b	0.19 ± 0.07 a	0.57 ± 0.41 a
marigold	manure biochar CO ₂ +NH ₃	38.5 ± 13.8 a	3.98 ± 0.44 a	15.6 ± 2.44 abc	2.44 ± 0.16 ab	18.5 ± 2.04 a	1.93 ± 0.27 a	3.25 ± 0.65 ab	0.24 ± 0.07 a	0.69 ± 0.53 a
marigold	manure biochar+1x	28.3 ± 0.00 a	4.81 ± 0.00 a	18.2 ± 0.00 a	2.86 ± 0.00 ab	26.1 ± 0.00 a	1.94 ± 0.00 abc	3.95 ± 0.00 a	0.28 ± 0.00 a	0.07 ± 0.00 a
marigold	wood biochar	19.2 ± 3.17 a	3.51 ± 0.70 a	15.1 ± 2.35 abc	1.72 ± 0.44 ab	14.9 ± 4.21 a	1.4 ± 0.16 abcde	2.26 ± 0.48 b	0.34 ± 0.31 a	0.55 ± 0.20 a
marigold	wood biochar+slurry	31.8 ± 15.5 a	3.63 ± 0.23 a	16.4 ± 2.48 a	1.45 ± 0.47 b	14.0 ± 2.10 a	1.75 ± 0.06 abcd	2.68 ± 0.4 ab	0.21 ± 0.04 a	0.54 ± 0.40 a
marigold	wood biochar NH ₃ +CO ₂	53.5 ± 44.3 a	3.65 ± 0.57 a	13.8 ± 3.01 abcd	2.22 ± 0.94 ab	17.4 ± 4.92 a	1.22 ± 0.24 cde	2.49 ± 0.64 ab	0.26 ± 0.11 a	0.83 ± 0.81 a
marigold	wood biochar+1x	34.2 ± 13.8 a	4.10 ± 0.56 a	11.2 ± 1.43 abcd	2.85 ± 0.54 ab	18.4 ± 2.48 a	1.12 ± 0.15 e	2.04 ± 0.42 b	0.24 ± 0.04 a	0.65 ± 0.43 a
radish	0x fert	26.7 ± 8.19 a	4.95 ± 0.79 a	8.87 ± 2.17 bcd	4.16 ± 0.43 abcd	17.2 ± 1.76 a	2.53 ± 0.29 abcde	1.46 ± 0.07 ab	0.20 ± 0.02 a	0.00 ± 0.00 a
radish	0.25x fert	36.8 ± 4.06 a	4.47 ± 0.29 a	6.63 ± 1.35 cd	3.75 ± 0.33 bcde	14.9 ± 1.58 a	1.96 ± 0.19 de	1.41 ± 0.16 ab	0.23 ± 0.01 a	0.00 ± 0.00 a
radish	0.5x fert	38.1 ± 15.1 a	4.64 ± 0.46 a	7.90 ± 2.14 bcd	3.68 ± 0.32 bcde	14.9 ± 2.66 a	1.90 ± 0.41 de	1.46 ± 0.29 ab	0.23 ± 0.03 a	0.00 ± 0.00 a

radish	1x fert	50.2 ± 8.43 a	4.51 ± 0.57 a	6.13 ± 0.86 d	3.62 ± 0.56 bcde	16.2 ± 1.30 a	1.75 ± 0.46 de	1.75 ± 0.26 ab	0.24 ± 0.03 a	0.00 ± 0.00 a
radish	1.5x fert	47.7 ± 29.2 a	4.43 ± 0.51 a	9.61 ± 3.64 bcd	3.70 ± 0.78 bcde	17.8 ± 3.91 a	2.46 ± 0.42 bcde	2.08 ± 0.67 a	0.25 ± 0.08 a	0.00 ± 0.00 a
radish	manure biochar	32.8 ± 6.55 a	5.61 ± 0.82 a	13.8 ± 0.95 abc	4.86 ± 0.90 ab	14.15 ± 1.82 a	3.59 ± 0.36 a	1.47 ± 0.09 ab	0.20 ± 0.02 a	0.00 ± 0.00 a
radish	dairy manure biochar+slurry	30.4 ± 7.02 a	5.12 ± 0.23 a	15.0 ± 4.6 ab	4.62 ± 0.62 abc	15.7 ± 3.02 a	3.46 ± 0.45 ab	1.69 ± 0.35 ab	0.18 ± 0.01 a	0.00 ± 0.00 a
radish	manure biochar CO ₂ +NH ₃	37.2 ± 11.08 a	4.98 ± 0.46 a	8.95 ± 1.74 bcd	3.95 ± 0.76 abcde	16.0 ± 3.75 a	2.35 ± 0.42 cde	1.30 ± 0.15 b	0.20 ± 0.01 a	0.00 ± 0.00 a
radish	manure biochar+1x	39.6 ± 19.0 a	5.75 ± 1.02 a	10.5 ± 5.66 abcd	5.24 ± 0.81 a	17.5 ± 2.23 a	3.32 ± 0.91 abc	1.74 ± 0.48 ab	0.21 ± 0.05 a	0.00 ± 0.00 a
radish	wood biochar	46.1 ± 22.4 a	5.24 ± 1.05 a	13.2 ± 3.39 abcd	3.19 ± 0.51 cde	13.2 ± 2.35 a	2.15 ± 0.39 de	1.33 ± 0.26 b	0.27 ± 0.09 a	1.36 ± 2.73 a
radish	wood biochar+slurry	27.8 ± 15.0 a	4.64 ± 0.63 a	17.56 ± 3.63 a	3.03 ± 0.55 de	13.4 ± 3.76 a	2.84 ± 0.43 abcd	1.51 ± 0.23 ab	0.19 ± 0.04 a	0.00 ± 0.00 a
radish	wood biochar NH ₃ +CO ₂	37.3 ± 8.83 a	4.59 ± 0.82 a	8.17 ± 0.47 bcd	2.91 ± 0.49 de	16.2 ± 4.48 a	1.74 ± 0.10 e	1.25 ± 0.19 b	0.22 ± 0.03 a	0.00 ± 0.00 a
radish	wood biochar+1x	29.1 ± 9.27 a	4.69 ± 0.45 a	7.91 ± 2.47 bcd	2.49 ± 0.19 e	12.9 ± 2.99 a	1.60 ± 0.05 e	1.15 ± 0.17 b	0.20 ± 0.04 a	0.00 ± 0.00 a
tomato	0x fert	26.7 ± 8.19 a	4.95 ± 0.79 a	8.87 ± 2.17 bcd	4.16 ± 0.43 abcd	17.2 ± 1.76 a	2.53 ± 0.29 abcde	1.46 ± 0.07 ab	0.20 ± 0.02 a	0.00 ± 0.00 a
tomato	0.25x fert	36.8 ± 4.06 a	4.47 ± 0.29 a	6.63 ± 1.35 cd	3.75 ± 0.33 bcde	14.94 ± 1.58 a	1.96 ± 0.19 de	1.41 ± 0.16 ab	0.23 ± 0.01 a	0.00 ± 0.00 a
tomato	0.5x fert	38.1 ± 15.1 a	4.64 ± 0.46 a	7.9 ± 2.14 bcd	3.68 ± 0.32 bcde	14.88 ± 2.66 a	1.90 ± 0.41 de	1.46 ± 0.29 ab	0.23 ± 0.03 a	0.00 ± 0.00 a
tomato	1x fert	50.2 ± 8.43 a	4.51 ± 0.57 a	6.13 ± 0.86 d	3.62 ± 0.56 bcde	16.2 ± 1.30 a	1.75 ± 0.46 e	1.75 ± 0.26 ab	0.24 ± 0.03 a	0.00 ± 0.00 a
tomato	1.5x fert	47.7 ± 29.2 a	4.43 ± 0.51 a	9.61 ± 3.64 bcd	3.70 ± 0.78 bcde	17.8 ± 3.91 a	2.46 ± 0.42 bcde	2.08 ± 0.67 a	0.25 ± 0.08 a	0.00 ± 0.0 a
tomato	manure biochar	32.8 ± 6.55 a	5.61 ± 0.82 a	13.8 ± 0.95 abc	4.86 ± 0.90 ab	14.2 ± 1.82 a	3.59 ± 0.36 a	1.47 ± 0.09 ab	0.2 ± 0.02 a	0.00 ± 0.00 a
tomato	slurry	30.4 ± 7.02 a	5.12 ± 0.23 a	14.5 ± 4.6 ab	4.62 ± 0.62 abc	15.7 ± 3.02 a	3.46 ± 0.45 ab	1.69 ± 0.35 ab	0.18 ± 0.01 a	0.00 ± 0.00 a
tomato	manure biochar CO ₂ +NH ₃	37.2 ± 11.1 a	4.98 ± 0.46 a	8.95 ± 1.74 bcd	3.95 ± 0.76 abcde	16.0 ± 3.75 a	2.35 ± 0.42 cde	1.30 ± 0.15 b	0.20 ± 0.01 a	0.00 ± 0.00 a
tomato	manure biochar+1x	39.6 ± 19.0 a	5.75 ± 1.02 a	10.5 ± 5.66 abcd	5.24 ± 0.81 a	17.5 ± 2.23 a	3.32 ± 0.91 abc	1.74 ± 0.48 ab	0.21 ± 0.05 a	0.00 ± 0.00 a

tomato	wood biochar	46.1 ± 22.4 a	5.24 ± 1.05 a	13.2 ± 3.39 abcd	3.19 ± 0.51 cde	13.2 ± 2.35 a	2.15 ± 0.39 de	1.33 ± 0.26 b	0.27 ± 0.09 a	1.36 ± 2.73 a
tomato	wood biochar+slurry	27.8 ± 15.0 a	4.64 ± 0.63 a	17.6 ± 3.63 a	3.03 ± 0.55 de	13.4 ± 3.76 a	2.84 ± 0.43 abcd	1.51 ± 0.23 ab	0.19 ± 0.04 a	0.00 ± 0.00 a
tomato	wood biochar NH ₃ +CO ₂	37.3 ± 8.83 a	4.59 ± 0.82 a	8.17 ± 0.47 bcd	2.91 ± 0.49 de	16.2 ± 4.48 a	1.74 ± 0.10 e	1.25 ± 0.19 b	0.22 ± 0.03 a	0.00 ± 0.00 a
tomato	wood biochar+1x	29.1 ± 9.27 a	4.69 ± 0.45 a	7.91 ± 2.47 bcd	2.49 ± 0.19 e	12.9 ± 2.99 a	1.60 ± 0.05 e	1.15 ± 0.17 b	0.20 ± 0.04 a	0.00 ± 0.00 a

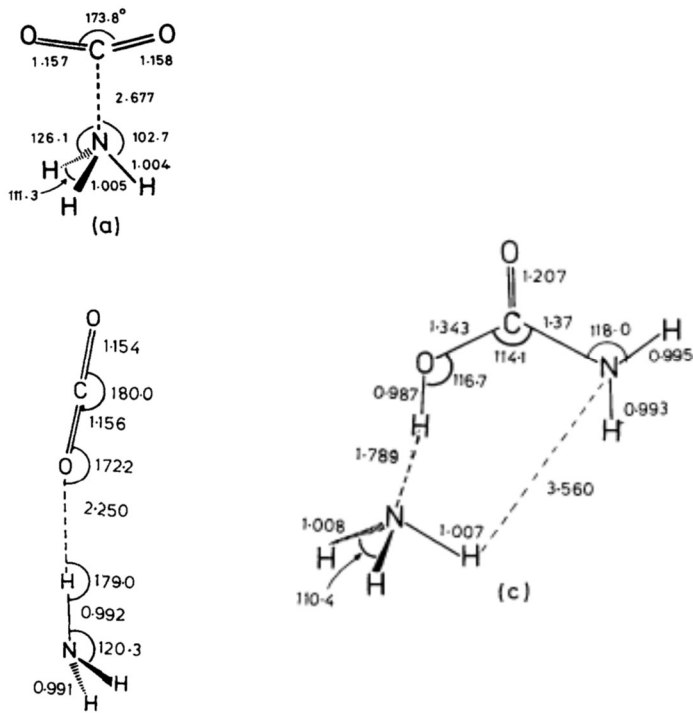


Figure S1. Van der Waals interactions between NH_3 and CO_2 . (A) chemisorption (B) H-bonding (C) Van der Waals complex Error! Reference source not found.

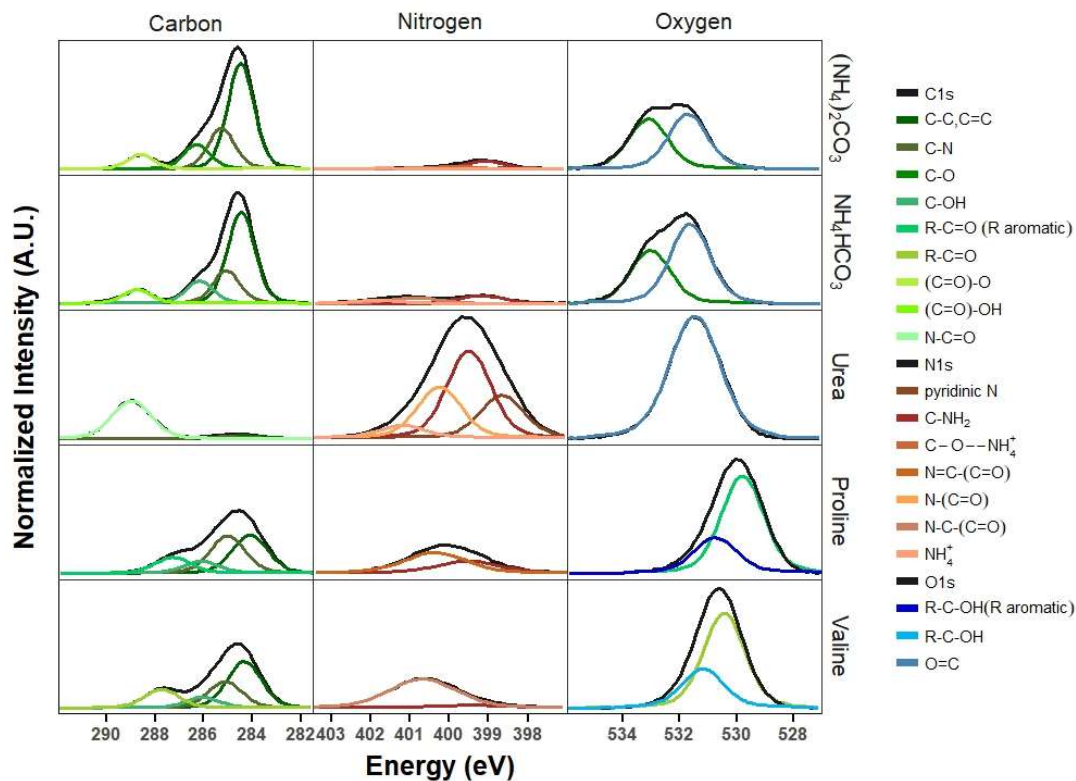


Figure S2. Normalized XPS spectra for C1s, N1s, and O1s core-level electron excitations of five standard compounds. Spectral deconvolution is also displayed in the fitting of multiple Lorentzian-Gaussian curves to each spectrum. Assigned peak positions of C, N, and O bonds and the relative peak areas associated with those bonds is outlined in Tables S2 and S3.

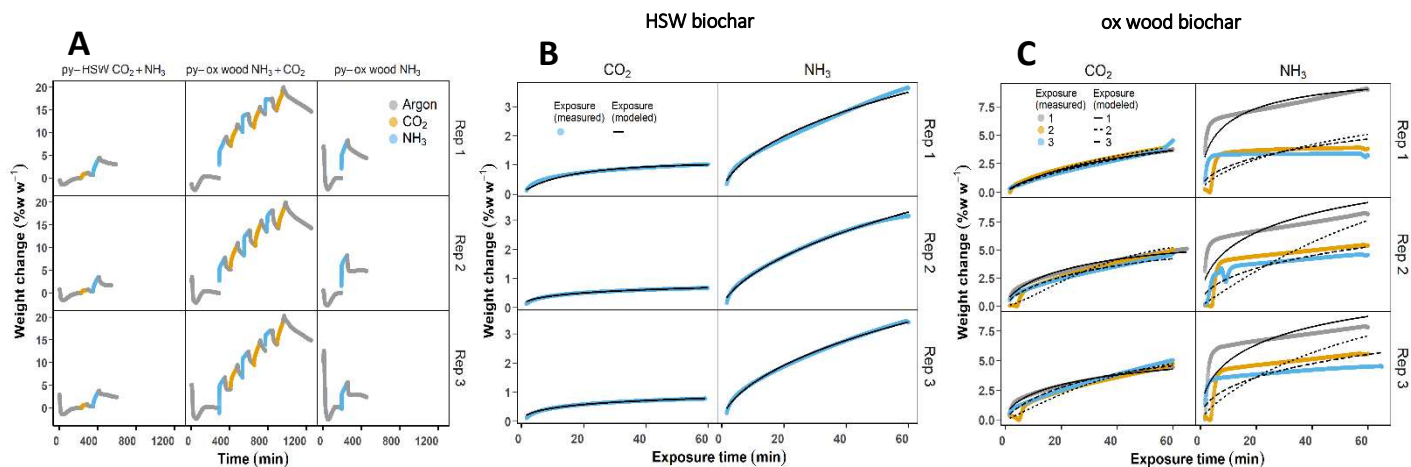


Figure S3. (A) Three replicate thermograms depicting the weight of change with exposure to CO₂ (orange) followed by NH₃ (blue), separated an argon purge (gray). (B) Three replicates of gravimetrically-measured CO₂ and NH₃ adsorption onto HSW biochar (blue) overlaid with modeled adsorption curves using the Avrami fractional order model (black line). (C) Three replicates of gravimetrically-measured CO₂ and NH₃ adsorption at three sequential exposure intervals (1,2,3) onto ox wood biochar (colors) overlaid with modeled adsorption curves using the Avrami fractional order model.

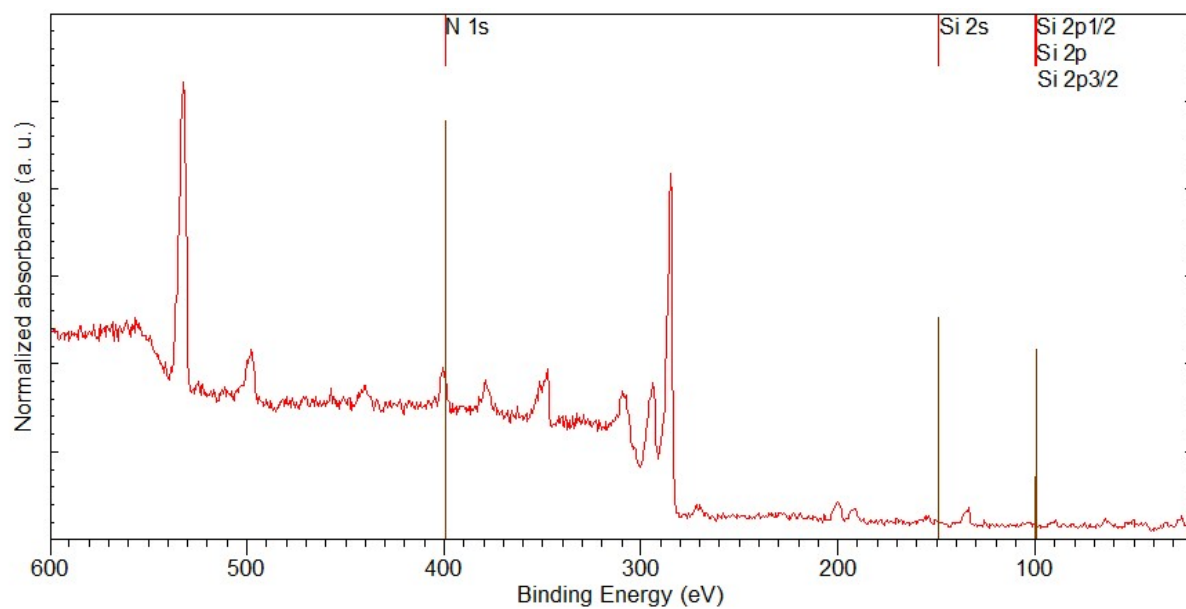


Figure S2. Wide-scan XPS spectra for unexposed HSW biochar depicting a prominent peak for nitrogen (N1s) and no peak features for silicon (Si 2s, Si 2p, Si 2p1/2, Si 2p3/2).

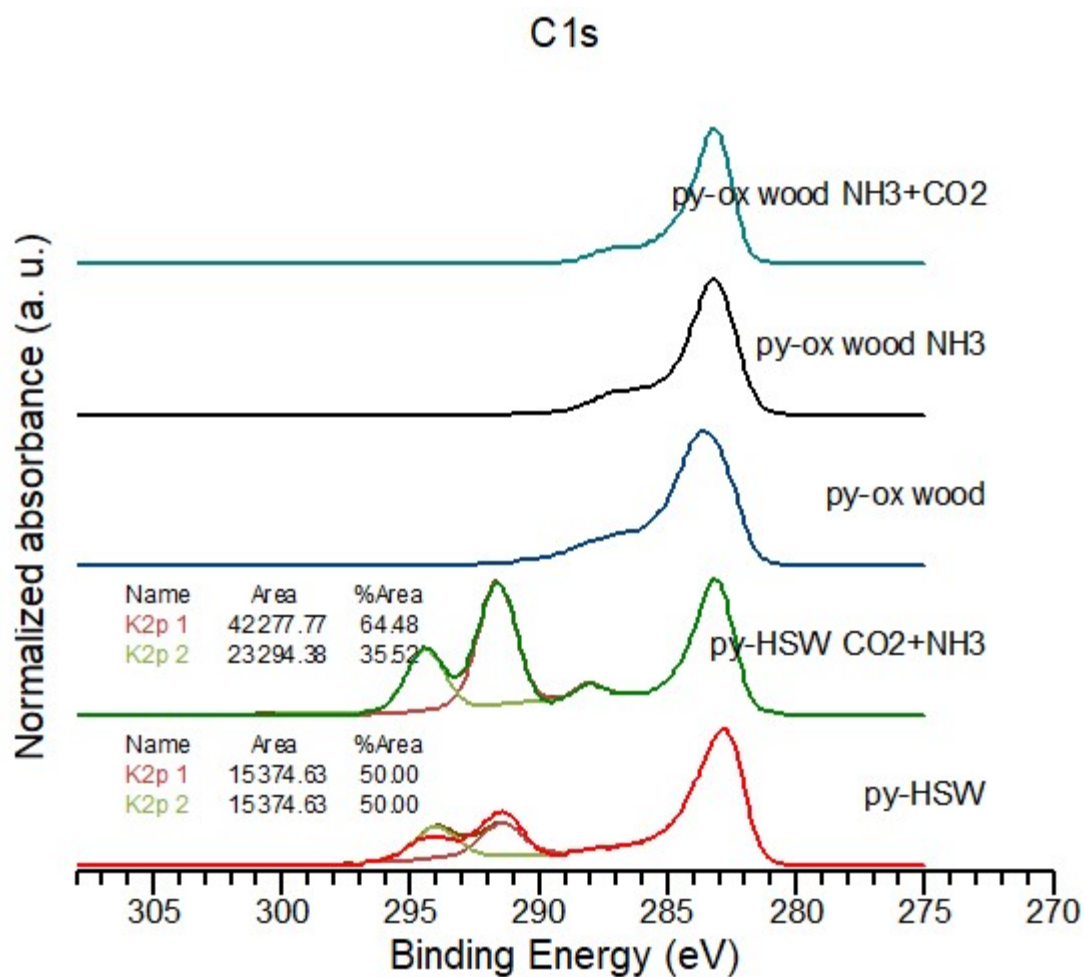


Figure S3. Narrow scan XPS spectra in the C1s region showing peaks for the K2p region for potassium between 296-290 eV, highlighted with black arrows. The K2p 1 peak between 293-290 eV increases in area by 2.7-fold in HSW biochar CO₂+NH₃ compared to HSW biochar.