Supplementary Materials

Table S1. Elemental composition of Biochar Now and Pacific Biochar.

Element	Biochar Now (mg/kg)	Pacific biochar (mg/kg)
Total C	66% ± 11.3	73% -
Total N	0.56% ± 0.04	0.31% -
Al	609.4 ± 60.8	4116.2 ± 138.1
Ca	4386.1 ± 419.9	14717.7 ± 648.7
Fe	1626.5 ± 136.0	3967.5 ± 93.3
K	1612.9 ± 118.9	6144.3 ± 124.9
Mg	762.0 ± 70.7	2766.6 ± 114.8
Mn	107.0 ± 9.2	548.8 ± 27.5
Na	227.6 ± 54.3	2268.8 ± 23.66
P	196.8 ± 80.6	1103.4 ± 37.3
Zn	26.9 ± 1.0	54.7 ± 3.5

Table S2. Physicochemical properties of Biochar Now and Pacific Biochar.

Property	Biochar Now	Pacific Biochar	Unit
Bulk density	140	91	kg/m3 (dry)
EC	0.014	0.022	S/m
Liming potential	1.5	5.7	% CaCO3 equivalent
Carbon content	87.4	90.4	% by weight
Ash content	2.1	4-8	% by weight
pH	8.93	8.13	
H:C	0.48	0.4	

Table S3. Ozone concentration in DI water.[1]

Ozonation time (min)	O_3 in DI water (mg/L)	SD
5	5.54	0.78
10	11.03	1.42
20	12.57	1.65

[1] The concentration of ozone in the solution was measured using the DPD method (N,N-diethyl-p-phenylenediamine) from CHEMetrics (Ozone vacu-vials). The experiments were carried out in duplicates.

Table S4. Volume of HCl used to acidify LAD (mL HCl per L of LAD).

pH	Volume of 5 M HCl (mL/L)	Equivalent volume of concentrated HCl (ml/L)	SD
6.5	41.67	17.36	0.34
	40.00	16.67	
5.0	66.67	27.78	0.35
	65.00	27.08	

Table S5. Dissolved reactive P (DRP) concentrations on LAD before and after ozonation.

Sample	Filtered DRP (mg/L)	SD
Untreated LAD	28.94	1.49
LAD after 5 min ozonation	35.06	0.66
LAD after 10 min ozonation	47.97	1.65

Biochar dosing

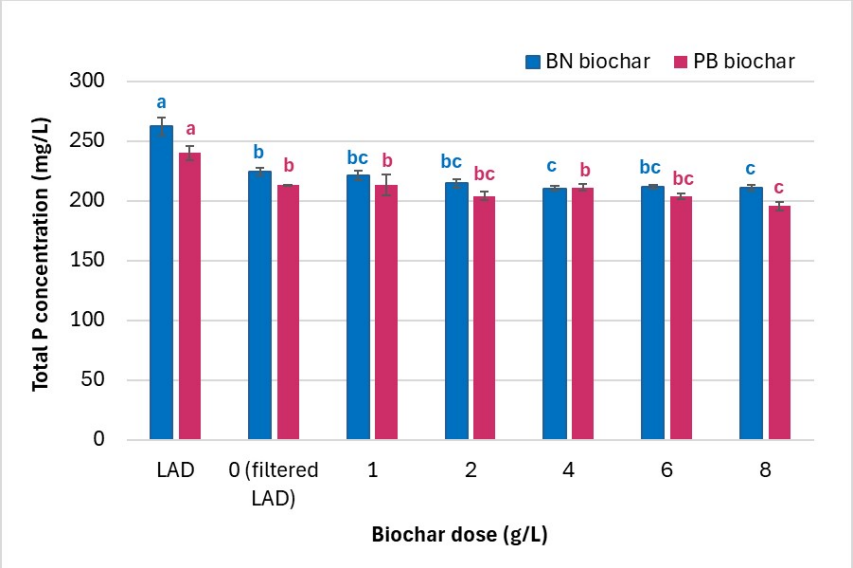


Figure S1. Total P concentration in the filtered LAD after treated with increasing doses of BN biochar or PB biochar. Different letters indicate significant differences between biochar doses within each biochar type ($p < 0.05$).

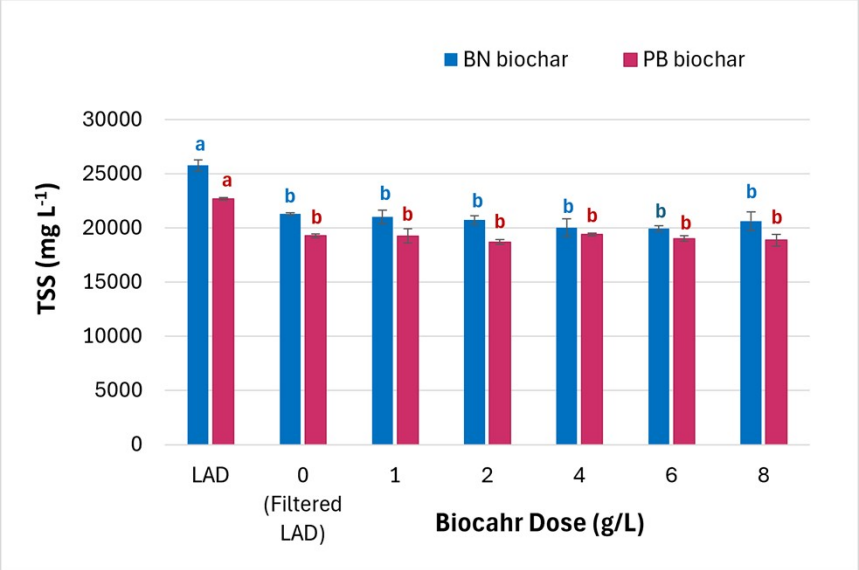


Figure S2. TSS concentration in the filtered LAD after treated with increasing doses of BN biochar or PB biochar. Different letters indicate significant differences among biochar doses within each biochar type ($p < 0.05$).

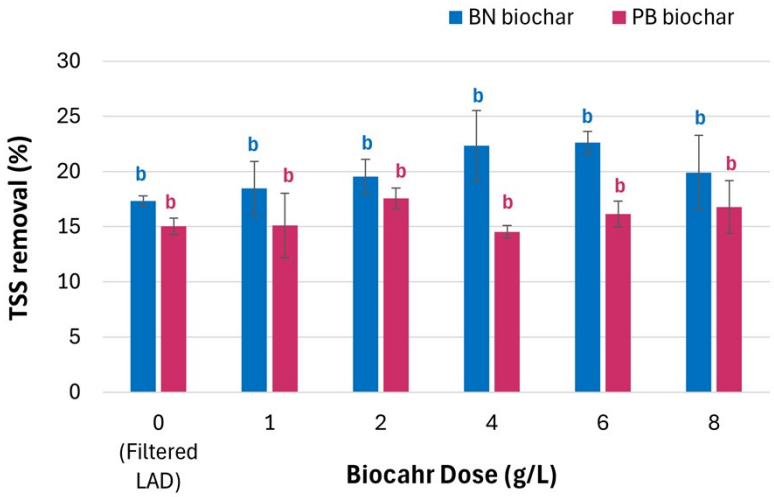


Figure S3. TSS removals from LAD after treated with increasing doses of BN biochar or PB biochar. Different letters indicate significant differences among biochar doses within each biochar type ($p < 0.05$).

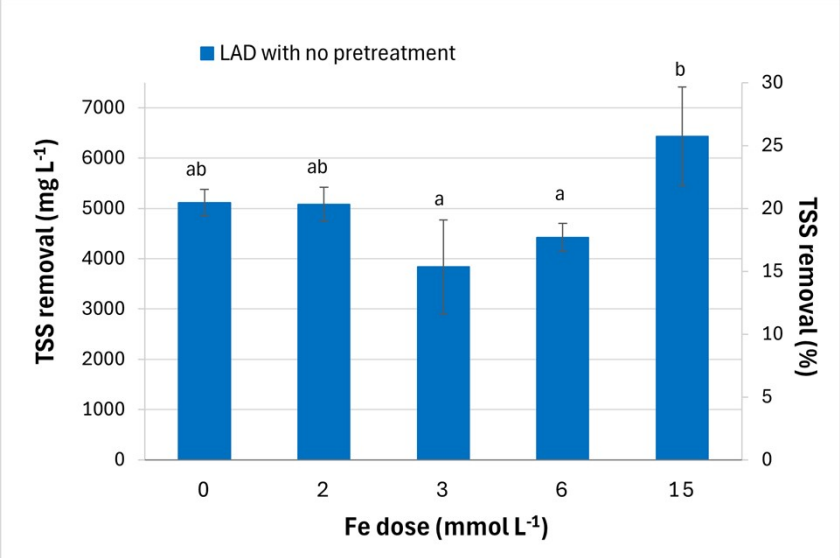


Figure S4. TSS removal for the 6 g L^{-1} biochar treatment at different Fe doses. The initial total P concentration of LAD was 262 mg L^{-1}. Different letters indicate significant differences on P recovery between Fe doses ($p < 0.05$).

Effect of pretreatment

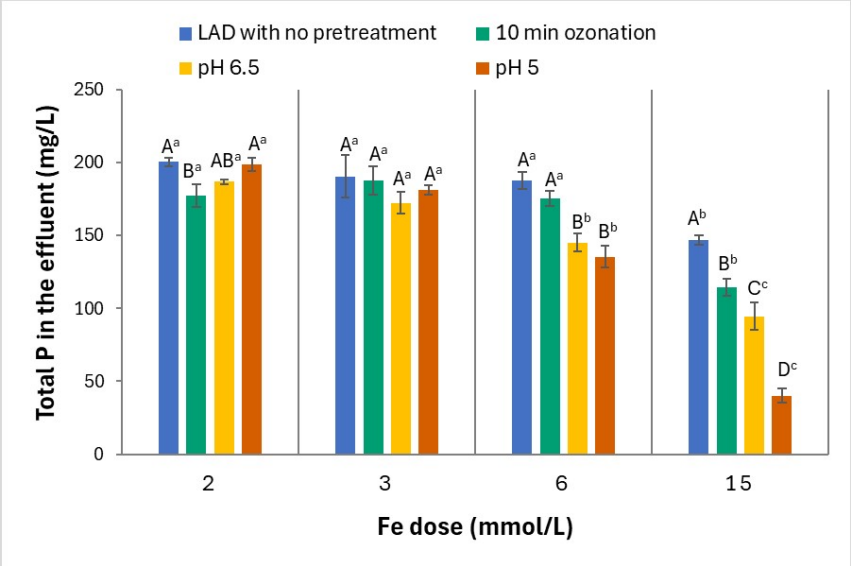


Figure S5. Total P concentration in the LAD using either no pretreatment, 10 min of ozonation, acidification to pH 6.5, and acidification to pH 5.0. Pretreatments were applied before the addition of Fe and biochar. Different uppercase letters indicate significant differences between treatments within the same Fe dose ($p < 0.05$). Different superscript letters indicate significant differences between Fe doses within the same treatment ($p < 0.05$).

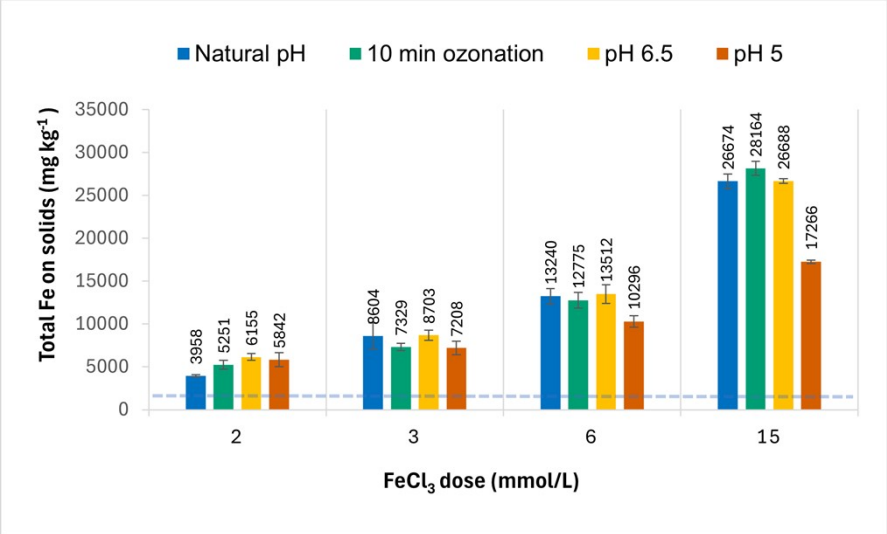


Figure S6. Total Fe concentration in the LAD using either no pretreatment, 10 min of ozonation, acidification to pH 6.5, and acidification to pH 5.0. Pretreatments were applied before the addition of Fe and biochar. Dashed line indicates the Fe concentration on LAD when 6 g L^{-1} of biochar was used with no Fe addition.

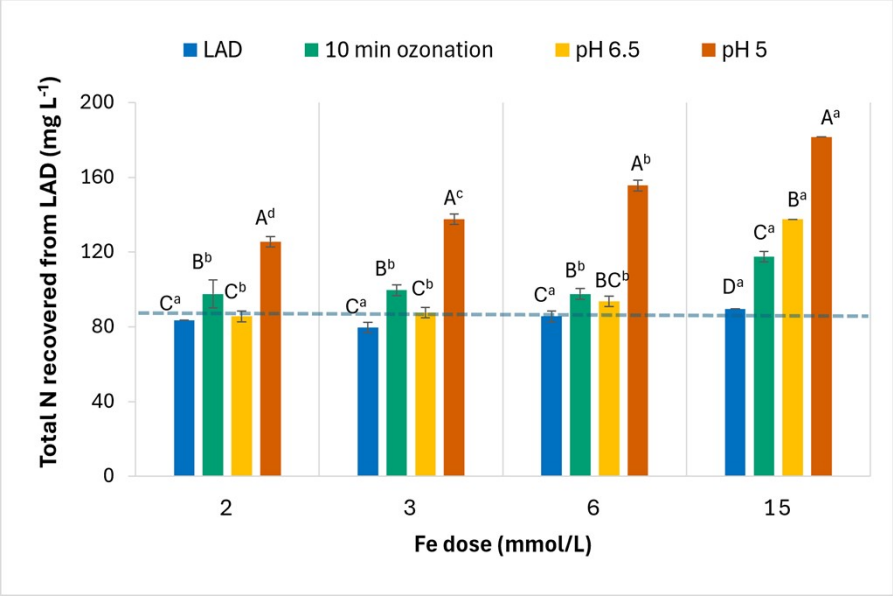


Figure S7. Estimated values for total N recovered from LAD after using either no pretreatment, 10 min of ozonation, acidification to pH 6.5, and acidification to pH 5.0. Pretreatments were applied before the addition of Fe and biochar. N removal was estimated by the differences in N concentration on recovered solids and the untreated biochar per volume of LAD. Dashed line indicates the N recovered when 6 g L^{-1} of biochar was used with no Fe addition. Different uppercase letters indicate significant differences between treatments within the same Fe dose ($p < 0.05$). Different superscript letters indicate significant differences between Fe doses within the same treatment ($p < 0.05$).

Table S6. ANOVA effect sizes (η^2) for iron dose, pretreatment, and their interaction across all response variables.

Effect size from ANOVA	
Total P in the effluent	
Parameter	η^2
Iron dose	0.97
Pretreatment	0.84
Iron dose : pretreatment	0.85
Total P on solids	
Parameter	η^2
Iron dose	0.91
Pretreatment	0.63
Iron dose : pretreatment	0.55
TSS	
Parameter	η^2
Iron dose	0.98
Pretreatment	0.97
Iron dose : pretreatment	0.98
P availability	
Parameter	η^2
Iron dose	0.99
Pretreatment	0.96
Iron dose : pretreatment	0.92
Total N on solids	
Parameter	η^2
Iron dose	0.96
Pretreatment	0.98
Iron dose : pretreatment	0.88

Table S7. pH values measured after $FeCl_3$ addition.

		Pretreatment		
Fe dose (mmol L^{-1})	**LAD with no pretreatment**	**10 min ozonation**	**pH 6.5**	**pH 5**
	pH after Fe addition			
0	8.01	8.01	6.5	5
2	8.01	8.14	6.46	4.84
3	8.02	8.09	6.36	4.67
6	8.01	8.02	6.27	4.22
15	8.02	8.02	6.05	2.65

SEM images and EDS spectra of solids recovered from filtration

LAD treated with BN biochar only

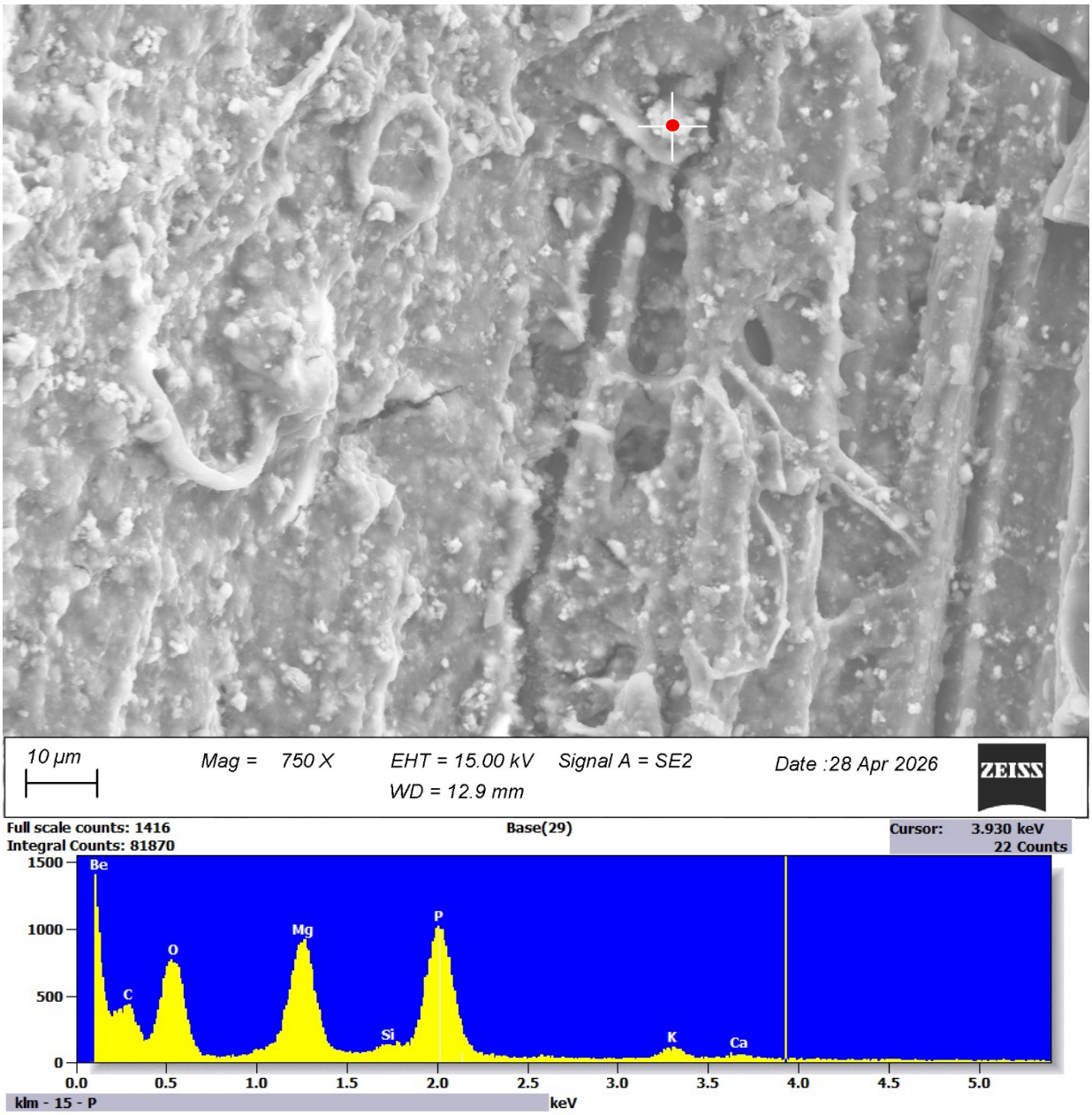


Figure S8. SEM image of solids retained during filtration of the 6 g L^{-1} biochar treatment with no Fe addition. The biochar matrix forms the darker background, while high-contrast (bright) features represent LAD-associated solids deposited on or trapped within the biochar structure. The EDS spectrum collected at the red point indicates the presence of P in these LAD solids. The Be peak is an artifact due to spectral overlapping with C.

Table S8. Quantitative Results for: Base(29). The reported Be signal is an artifact of spectral overlapping with C.

Element Line	Net Counts	Int. Cps/nA	K-Ratio	ZAF	Weight %	Weight % Error	Atom %	Atom % Error	Formula	Compnd %
Be K	10937	113.927	0.82	2.271	84.92	± 1.63	92.24	± 3.54	Be	84.92
C K	19702	205.229	0.00	0.000	---	---	---	---	(null)	---
O K	15302	159.396	0.08	2.579	10.01	± 0.25	6.12	± 0.31	O	10.01
Mg K	13556	141.208	0.03	1.186	1.52	± 0.03	0.61	± 0.02	Mg	1.52
Si K	1128	11.750	0.00	1.103	0.14	± 0.04	0.05	± 0.03	Si	0.14
Si L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
P K	17674	184.104	0.05	1.128	2.66	± 0.05	0.84	± 0.03	P	2.66
P L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
K K	1422	14.813	0.01	1.161	0.33	± 0.02	0.08	± 0.01	K	0.33
K L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
Ca K	594	6.188	0.00	1.142	0.16	± 0.02	0.04	± 0.01	Ca	0.16
Ca L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
Ta L	86	0.896	0.00	1.833	0.27	± 0.19	0.01	± 0.02	Ta	0.27
Ta M	13	0.135	0.00	0.000	---	---	---	---	(null)	---
Total					100.00		100.00			100.00

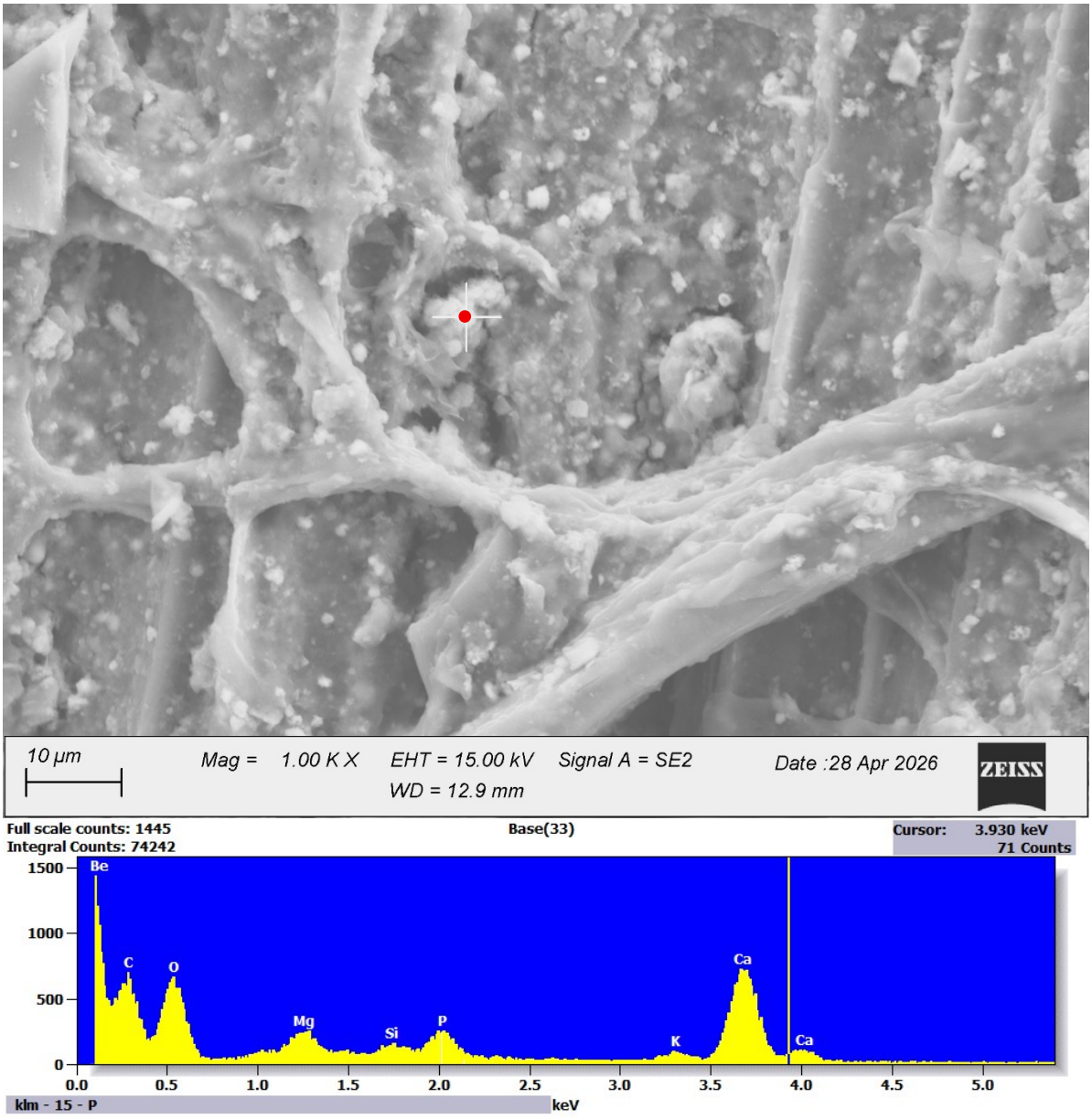


Figure S9. SEM image of solids retained during filtration of the 6 g L^{-1} biochar treatment with no Fe addition. The biochar matrix forms the darker background, while high-contrast (bright) features represent LAD-associated solids deposited on or trapped within the biochar structure. The EDS spectrum collected at the red point indicates the presence of P in these LAD solids. The Be peak is an artifact due to spectral overlapping with C.

Table S9. Quantitative Results for: Base(33). The reported Be signal is an artifact of spectral overlapping with C.

Element Line	Net Counts	Int. Cps/nA	K-Ratio	ZAF	Weight %	Weight % Error	Atom %	Atom % Error	Formula	Compnd %
Be K	11926	124.229	0.84	2.045	85.15	± 1.65	92.64	± 3.59	Be	85.15
C K	24710	257.396	0.00	0.000	---	---	---	---	(null)	---
O K	13265	138.177	0.07	2.884	9.89	± 0.28	6.06	± 0.34	O	9.89
Mg K	1916	19.958	0.00	1.219	0.23	± 0.02	0.09	± 0.02	Mg	0.23
Si K	1423	14.823	0.00	1.098	0.18	± 0.01	0.06	± 0.01	Si	0.18
Si L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
P K	3373	35.135	0.01	1.118	0.51	± 0.02	0.16	± 0.01	P	0.51
P L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
K K	1104	11.500	0.00	1.110	0.25	± 0.02	0.06	± 0.01	K	0.25
K L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
Ca K	14161	147.510	0.07	1.131	3.80	± 0.09	0.93	± 0.04	Ca	3.80
Ca L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
Total					100.00		100.00			100.00

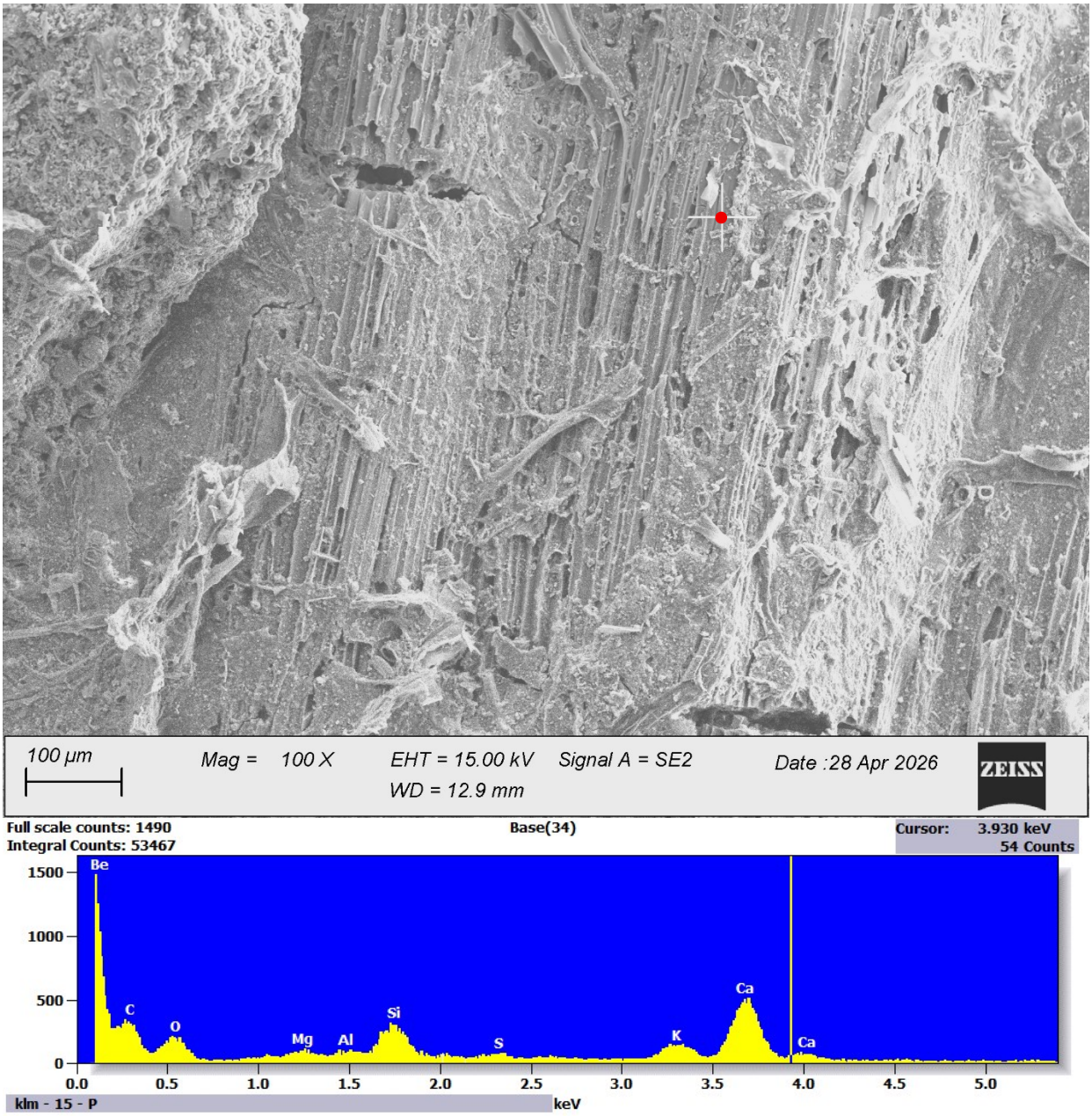


Figure S10. SEM image of solids retained during filtration of the 6 g L^{-1} biochar treatment with no Fe addition. The biochar matrix forms the darker background, while high-contrast (bright) features represent LAD-associated solids deposited on or trapped within the biochar structure. The EDS spectrum collected at the red point shows no detectable P on the biochar matrix, in contrast to the LAD-derived particles. The Be peak is an artifact due to spectral overlapping with C.

Table S10. Quantitative Results for: Base(34). The reported Be signal is an artifact of spectral overlapping with C.

Element Line	Net Counts	Int. Cps/nA	K-Ratio	ZAF	Weight %	Weight % Error	Atom %	Atom % Error	Formula	Compnd %
Be K	11835	123.281	0.89	1.730	89.69	± 1.52	95.49	± 3.24	Be	89.69
C K	16462	171.479	0.00	0.000	---	---	---	---	(null)	---
O K	5576	58.083	0.03	2.971	5.37	± 0.23	3.22	± 0.28	O	5.37
Mg K	757	7.885	0.00	1.167	0.11	± 0.01	0.04	± 0.01	Mg	0.11
Al K	804	8.375	0.00	1.139	0.12	± 0.01	0.04	± 0.01	Al	0.12
Si K	4169	43.427	0.01	1.078	0.64	± 0.02	0.22	± 0.01	Si	0.64
Si L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
S K	736	7.667	0.00	1.078	0.16	± 0.02	0.05	± 0.01	S	0.16
S L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
K K	2616	27.250	0.01	1.113	0.74	± 0.06	0.18	± 0.03	K	0.74
K L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
Ca K	9411	98.031	0.05	1.133	3.18	± 0.10	0.76	± 0.05	Ca	3.18
Ca L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
Total					100.00		100.00			100.00

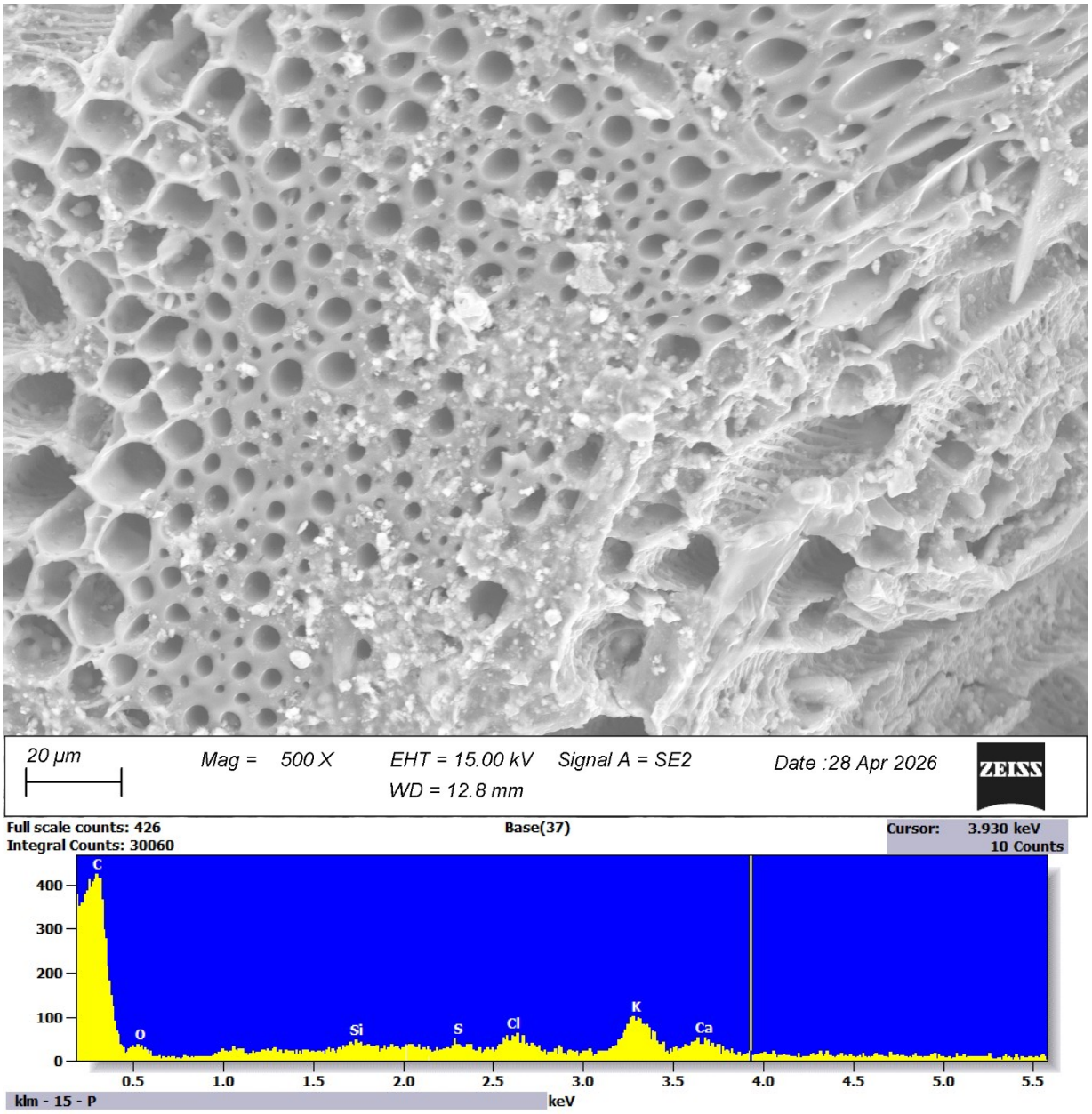


Figure S11. SEM image of solids retained during filtration of the 6 g L^{-1} biochar treatment with no Fe addition. The biochar matrix forms the darker background, while high-contrast (bright) features represent LAD-associated solids deposited on or trapped within the biochar structure. The EDS spectrum represents an area scan collected from the entire square region, encompassing both the biochar matrix and the associated solids.

Table S11. Quantitative Results for: Base(37). The reported Be signal is an artifact of spectral overlapping with C.

Element Line	Net Counts	Int. Cps/nA	K-Ratio	ZAF	Weight %	Weight % Error	Atom %	Atom % Error	Formula	Compnd %
Be K	3017	31.427	0.93	1.334	92.86	±15.36	97.40	±32.22	Be	92.86
C K	10126	105.479	0.00	0.000	---	---	---	---	(null)	---
O K	460	4.792	0.01	3.011	2.36	± 0.34	1.39	± 0.40	O	2.36
Si K	305	3.177	0.00	1.059	0.24	± 0.04	0.08	± 0.03	Si	0.24
Si L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
S K	289	3.010	0.00	1.060	0.32	± 0.07	0.09	± 0.04	S	0.32
S L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
Cl K	674	7.021	0.01	1.116	0.84	± 0.08	0.22	± 0.04	Cl	0.84
Cl L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
K K	1662	17.313	0.03	1.141	2.51	± 0.23	0.61	± 0.11	K	2.51
K L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
Ca K	493	5.135	0.01	1.144	0.88	± 0.11	0.21	± 0.05	Ca	0.88
Ca L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
Total					100.00		100.00			100.00

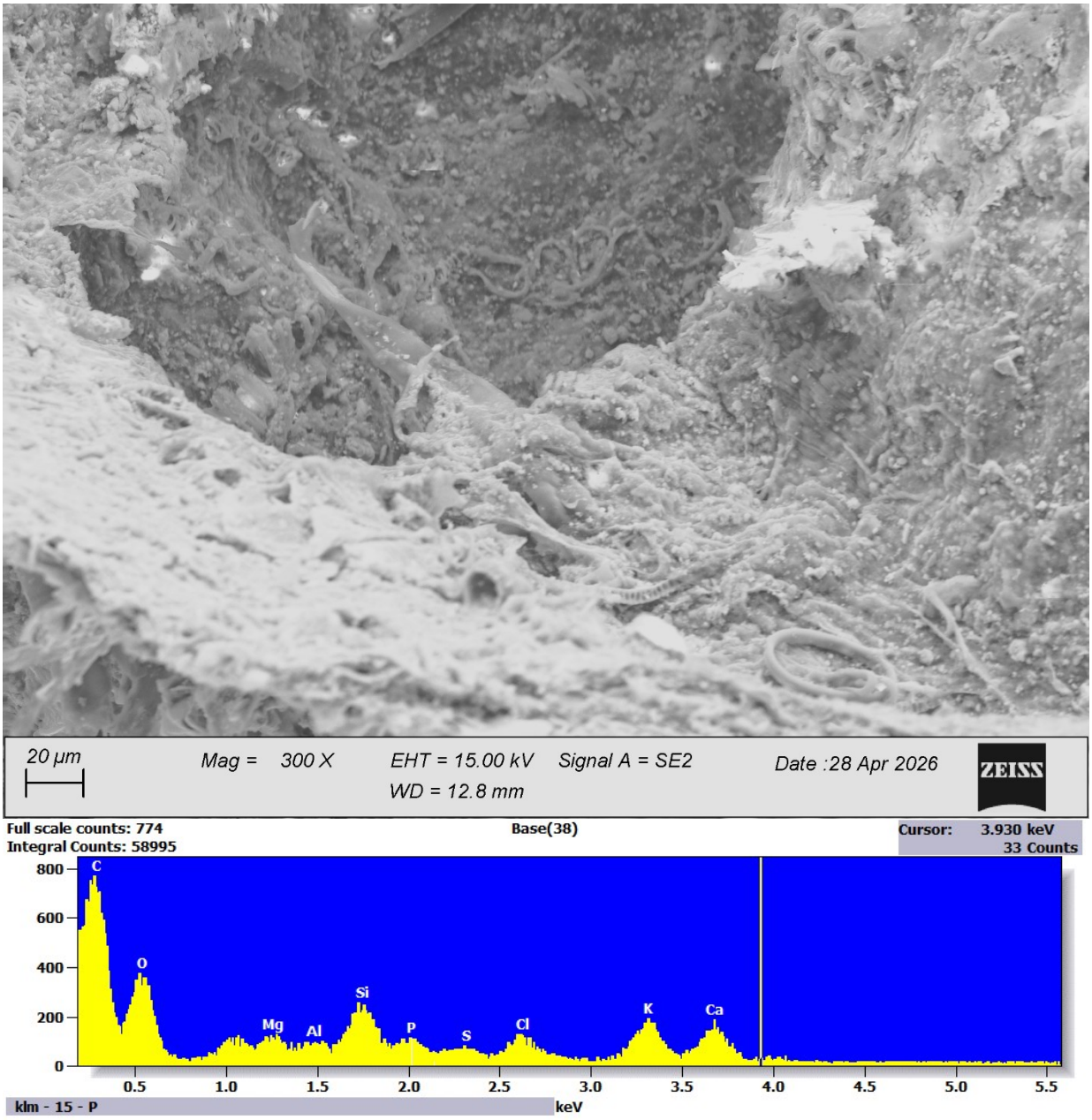


Figure S12. SEM image of solids retained during filtration of the 6 g L^{-1} biochar treatment with no Fe addition. The image shows the irregular features that represent LAD-associated solids deposited on or trapped within the biochar structure. The EDS spectrum represents an area scan collected from the entire square region and indicates the presence of P, which is associated with the LAD solids.

Table S12. Quantitative Results for: Base(38). The reported Be signal is an artifact of spectral overlapping with C.

Element Line	Net Counts	Int. Cps/nA	K-Ratio	ZAF	Weight %	Weight % Error	Atom %	Atom % Error	Formula	Compnd %
Be K	0	0.000	0.00	5.734	0.00	---	0.00	± 0.00	Be	0.00
C K	10605	110.469	0.00	0.000	---	---	---	---	(null)	---
O K	1305	13.594	0.13	5.159	39.10	± 8.87	57.89	±26.26	O	39.10
Mg K	742	7.729	0.03	1.674	2.69	± 0.33	2.62	± 0.65	Mg	2.69
Al K	540	5.625	0.02	1.461	1.88	± 0.32	1.65	± 0.57	Al	1.88
Si K	3127	32.573	0.14	1.265	10.04	± 0.37	8.46	± 0.62	Si	10.04
Si L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
P K	1046	10.896	0.06	1.302	4.16	± 0.39	3.18	± 0.60	P	4.16
P L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
S K	771	8.031	0.05	1.204	3.28	± 0.38	2.42	± 0.57	S	3.28
S L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
Cl K	1644	17.125	0.11	1.210	7.57	± 0.44	5.06	± 0.58	Cl	7.57
Cl L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
K K	3026	31.521	0.24	1.154	15.77	± 1.06	9.55	± 1.29	K	15.77
K L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
Ca K	2467	25.698	0.23	1.182	15.53	± 0.65	9.17	± 0.77	Ca	15.53
Ca L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
Total					100.00		100.00			100.00

LAD treated with biochar + 15 mmol L^{-1} Fe

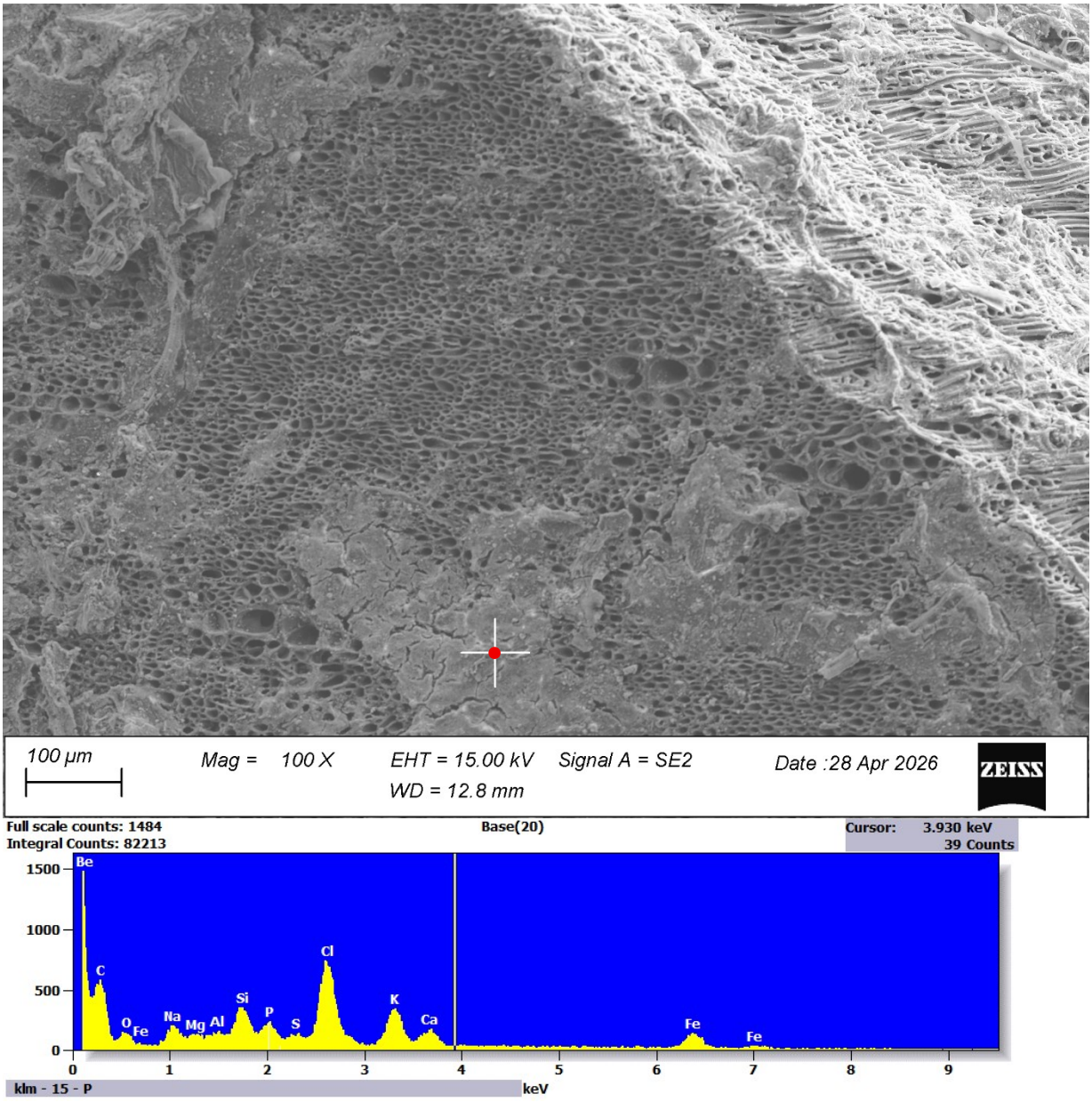
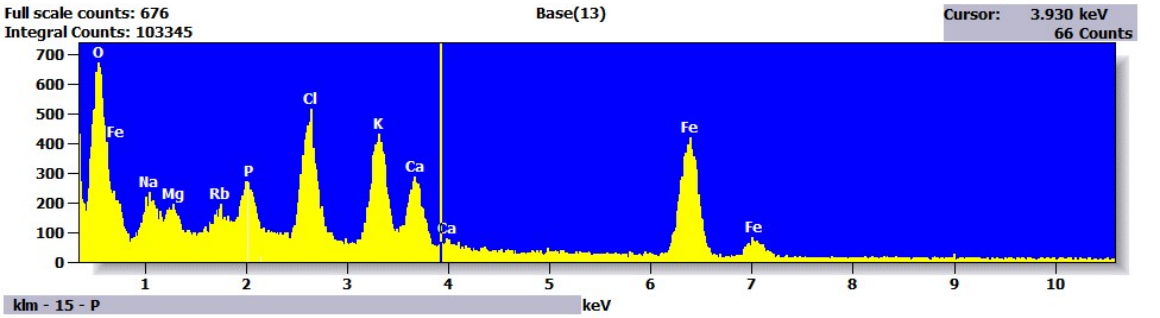


Figure S13. SEM image of solids retained during filtration of the 6 g L^{-1} biochar with 15 mmol L^{-1} Fe treatment. The biochar matrix forms a porous carbon framework in the background, while the irregular deposits represent LAD-associated solids attached to or trapped within the biochar structure. The EDS spectrum collected at the red point indicates the presence of Fe and P in these LAD solids. The Be peak is an artifact due to spectral overlapping with C.

Table S13. Quantitative Results for: Base(20). The reported Be signal is an artifact of spectral overlapping with C.

Element Line	Net Counts	Int. Cps/nA	K-Ratio	ZAF	Weight %	Weight % Error	Atom %	Atom % Error	Formula	Compnd %
Be K	3917	40.802	0.65	2.400	77.64	± 6.50	92.51	±15.49	Be	77.64
C K	9090	94.688	0.00	0.000	---	---	---	---	(null)	---
O K	1295	13.490	0.02	3.377	2.67	± 0.23	1.79	± 0.31	O	2.67
Na K	2236	23.292	0.01	1.528	1.13	± 0.05	0.53	± 0.05	Na	1.13
Mg K	832	8.667	0.00	1.295	0.25	± 0.03	0.11	± 0.03	Mg	0.25
Al K	934	9.729	0.00	1.212	0.28	± 0.03	0.11	± 0.03	Al	0.28
Si K	4398	45.813	0.02	1.114	1.31	± 0.04	0.50	± 0.03	Si	1.31
Si L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
P K	2341	24.385	0.02	1.130	0.85	± 0.05	0.29	± 0.03	P	0.85
P L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
S K	1023	10.656	0.01	1.082	0.41	± 0.05	0.14	± 0.03	S	0.41
S L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
Cl K	13382	139.396	0.11	1.130	6.06	± 0.14	1.83	± 0.09	Cl	6.06
Cl L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
K K	6172	64.292	0.06	1.155	3.39	± 0.14	0.93	± 0.08	K	3.39
K L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
Ca K	2013	20.969	0.02	1.143	1.29	± 0.07	0.35	± 0.04	Ca	1.29
Ca L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
Fe K	2661	27.719	0.07	1.272	4.72	± 0.20	0.91	± 0.08	Fe	4.72
Fe L	74	0.771	0.00	0.000	---	---	---	---	(null)	---
Total					100.00		100.00			100.00


Full scale counts: 676
Integral Counts: 103345
Base(13)
Cursor: 3.930 keV
66 Counts
700
600
500
400
300
200
100
0
O
Fe
Na
Mg
Rb
P
Cl
K
Ca
Ca
Fe
Fe
1
2
3
4
5
6
7
8
9
10
klm - 15 - P
keV

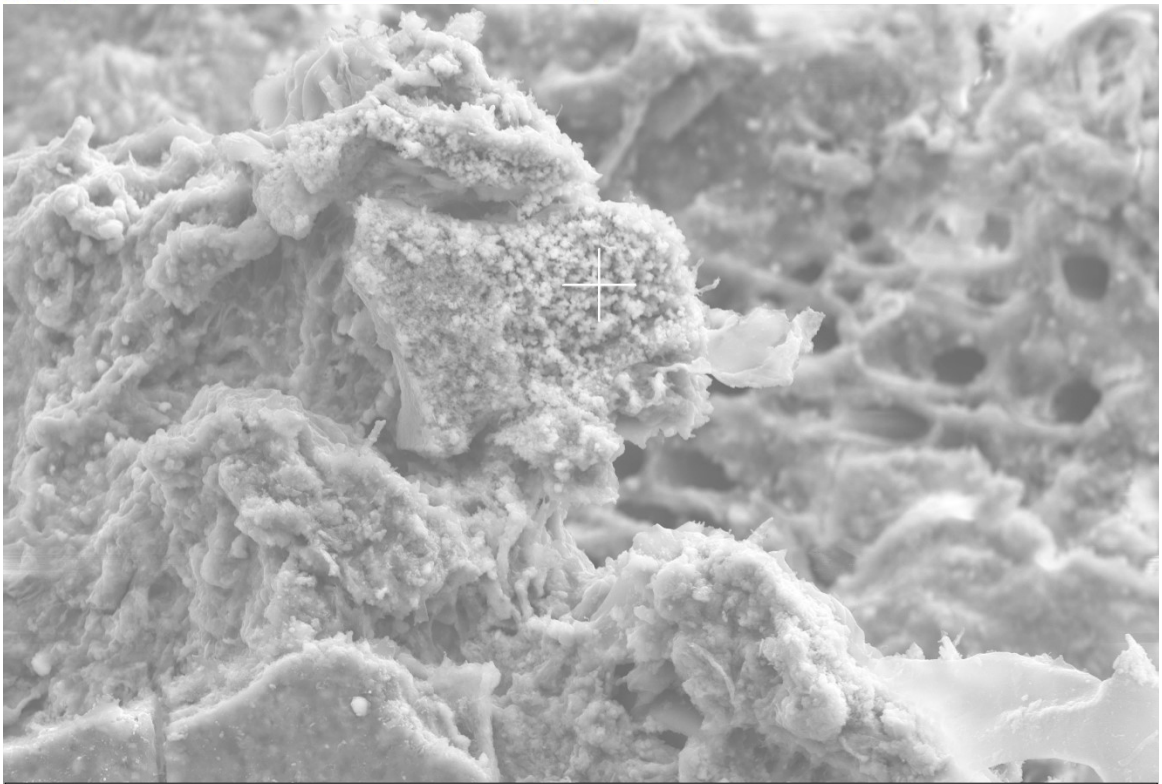

10 µm
Mag = 700 X
EHT = 15.00 kV
Signal A = SE2
Date :28 Apr 2026

Figure S14. SEM image of solids retained during filtration of the 6 g L^{-1} biochar with 15 mmol L^{-1} Fe treatment. The image corresponds to the irregular deposits from LAD-associated solids attached to or trapped within the biochar structure. The EDS spectrum collected at the red point indicates the presence of Fe and P in these LAD solids.

Table S14. Quantitative Results for: Base(13). The reported Be signal is an artifact of spectral overlapping with C.

Element Line	Net Counts	Int. Cps/nA	K-Ratio	ZAF	Weight %	Weight % Error	Atom %	Atom % Error	Formula	Compnd %
Be K	4298	44.771	0.56	3.062	71.45	± 5.88	88.40	±14.56	Be	71.45
C K	10172	105.958	0.00	0.000	---	---	---	---	(null)	---
O K	8759	91.240	0.08	2.855	9.88	± 0.22	6.89	± 0.31	O	9.88
Na K	2028	21.125	0.01	1.884	0.81	± 0.05	0.40	± 0.05	Na	0.81
Mg K	1493	15.552	0.01	1.491	0.33	± 0.05	0.15	± 0.05	Mg	0.33
P K	2039	21.240	0.01	1.169	0.49	± 0.06	0.18	± 0.04	P	0.49
P L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
Cl K	7892	82.208	0.05	1.135	2.31	± 0.08	0.73	± 0.05	Cl	2.31
Cl L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
K K	7372	76.792	0.05	1.125	2.53	± 0.10	0.72	± 0.06	K	2.53
K L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
Ca K	3793	39.510	0.03	1.115	1.52	± 0.05	0.42	± 0.03	Ca	1.52
Ca L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
Fe K	9251	96.365	0.20	1.259	10.43	± 0.28	2.08	± 0.11	Fe	10.43
Fe L	2664	27.750	0.00	0.000	---	---	---	---	(null)	---
Rb K	13	0.135	0.00	0.000	---	---	---	---	(null)	---
Rb L	831	8.656	0.00	1.285	0.24	± 0.04	0.03	± 0.01	Rb	0.24

Total	100.00	100.00	100.00

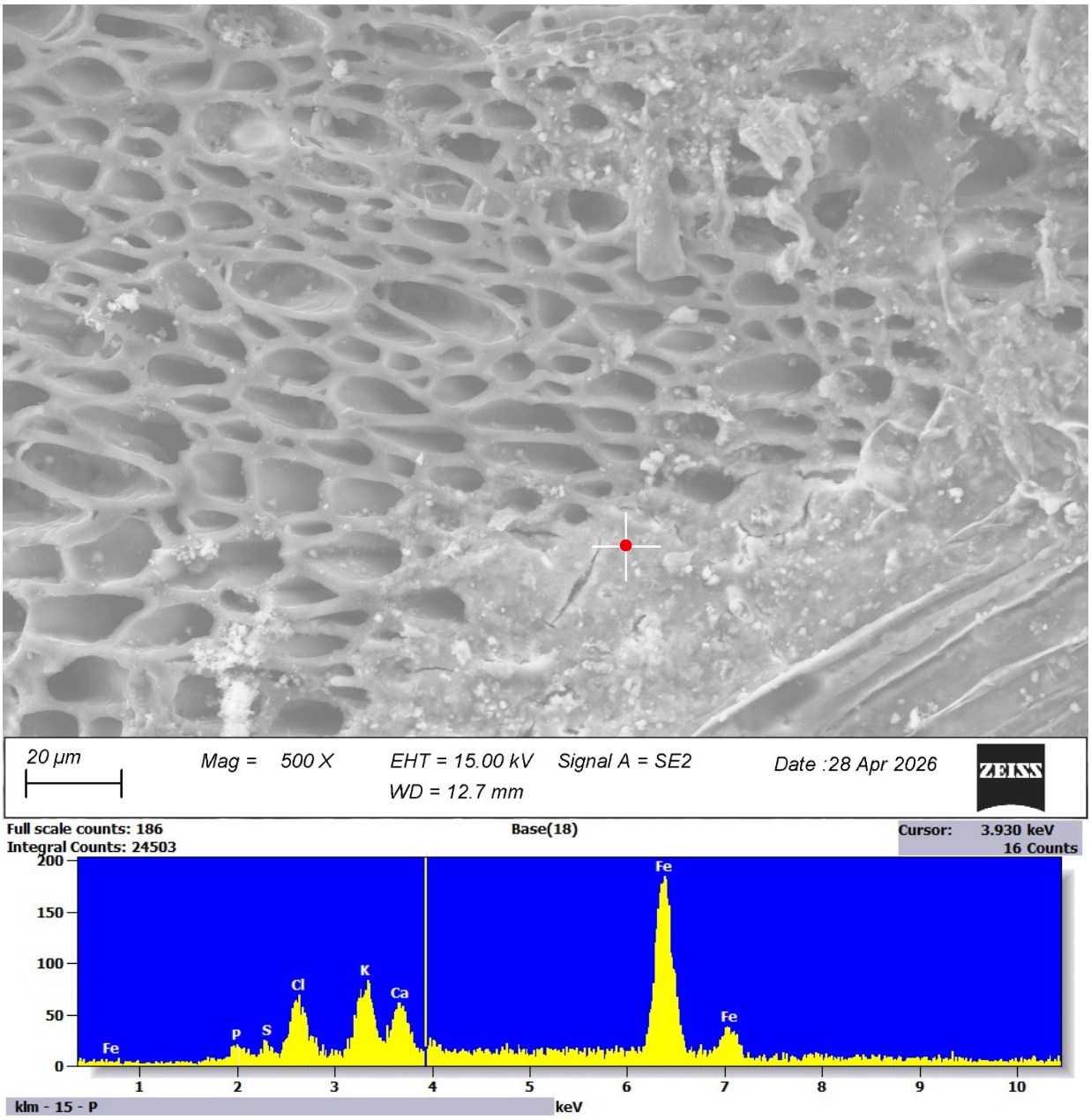


Figure S15. SEM image of solids retained during filtration of the 6 g L^{-1} biochar with 15 mmol L^{-1} Fe treatment. The biochar matrix forms a porous carbon framework in the background, while the irregular deposits represent LAD-associated solids attached to or trapped within the biochar structure. The EDS spectrum collected at the red point indicates the presence of Fe and P in these LAD solids.

Element Line	Net Counts	Int. Cps/nA	K-Ratio	ZAF	Weight %	Weight % Error	Atom %	Atom % Error	Formula	Compnd %
Be K	2427	25.281	0.73	2.160	82.73	± 7.77	96.39	±18.11	Be	82.73
P K	225	2.344	0.00	1.147	0.16	± 0.02	0.05	± 0.02	P	0.16
P L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
S K	234	2.438	0.00	1.090	0.18	± 0.03	0.06	± 0.02	S	0.18
S L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
Cl K	1210	12.604	0.02	1.125	1.04	± 0.09	0.31	± 0.05	Cl	1.04
Cl L	2159	22.490	0.00	0.000	---	---	---	---	(null)	---
K K	1433	14.927	0.02	1.114	1.44	± 0.13	0.39	± 0.07	K	1.44
K L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
Ca K	963	10.031	0.02	1.096	1.12	± 0.16	0.29	± 0.08	Ca	1.12
Ca L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
Fe K	3996	41.625	0.20	1.259	13.34	± 0.58	2.51	± 0.22	Fe	13.34
Fe L	0	0.000	0.00	0.000	---	---	---	---	(null)	---
Total					100.00		100.00			100.00

Table 15. Quantitative Results for: Base(18). The reported Be signal is an artifact of spectral overlapping with C.