

Experimental and Machine Learning Studies on Chitosan-Polyacrylamide Copolymers for Selective Separation of Metal Sulfides in Froth Flotation Process

Supplementary Information

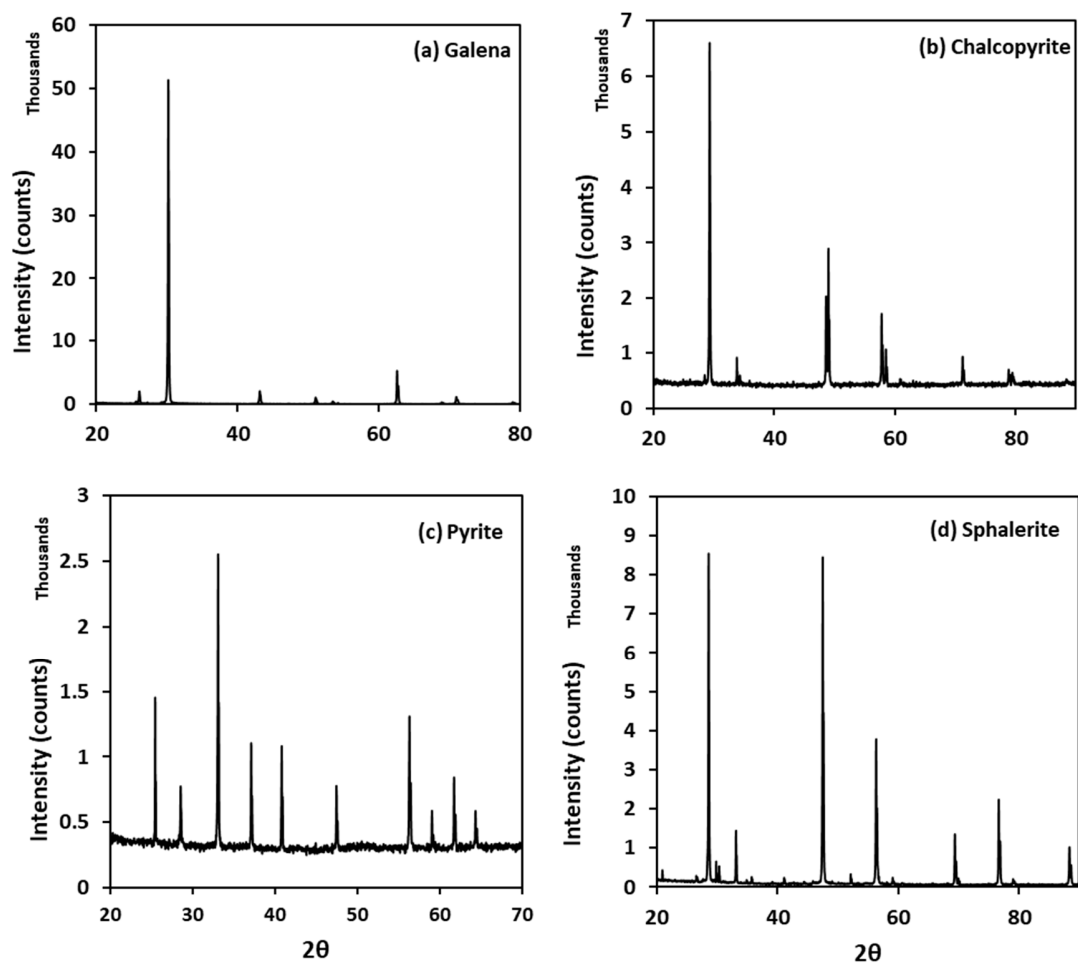


Figure S1. X-Ray Diffraction spectra of model sulfide minerals to illustrate purity of (a) galena; (b) chalcopyrite; (c) pyrite and (d) sphalerite.

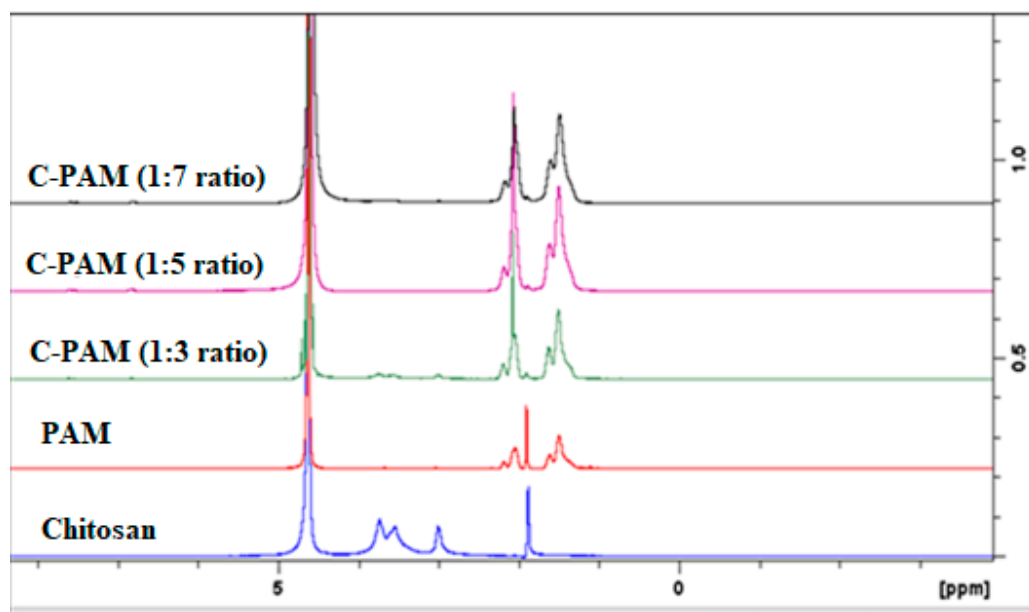


Figure S2. ^1H NMR spectra of chitosan, PAM and C-PAMs synthesized from chitosan of 85% DD at different weight ratios of chitosan: AM.

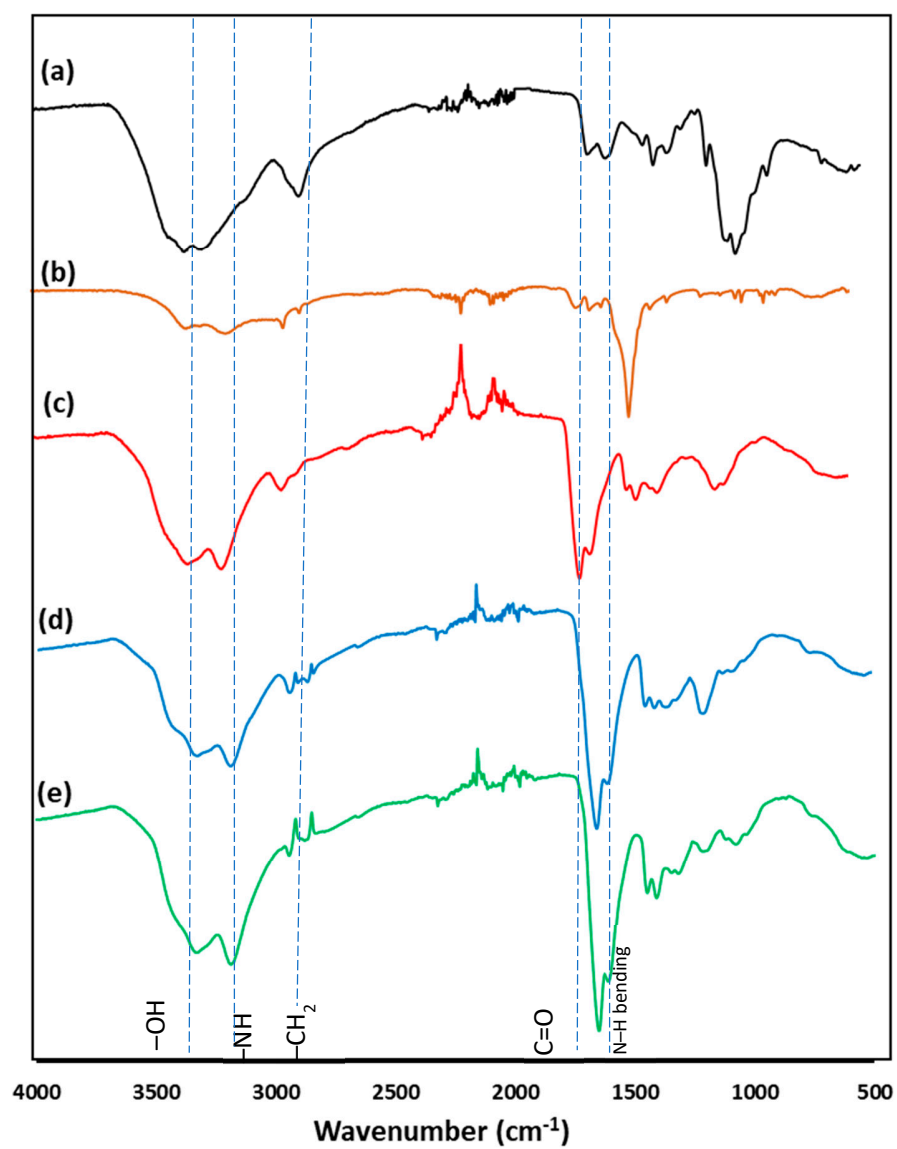


Figure S3. ATR-FTIR spectra of (a) chitosan of 85% DD; (b) PAM; (c) C-PAM of 1:3 ratio; (d) C-PAM of 1:5 ratio and (e) C-PAM of 1:7 ratio.

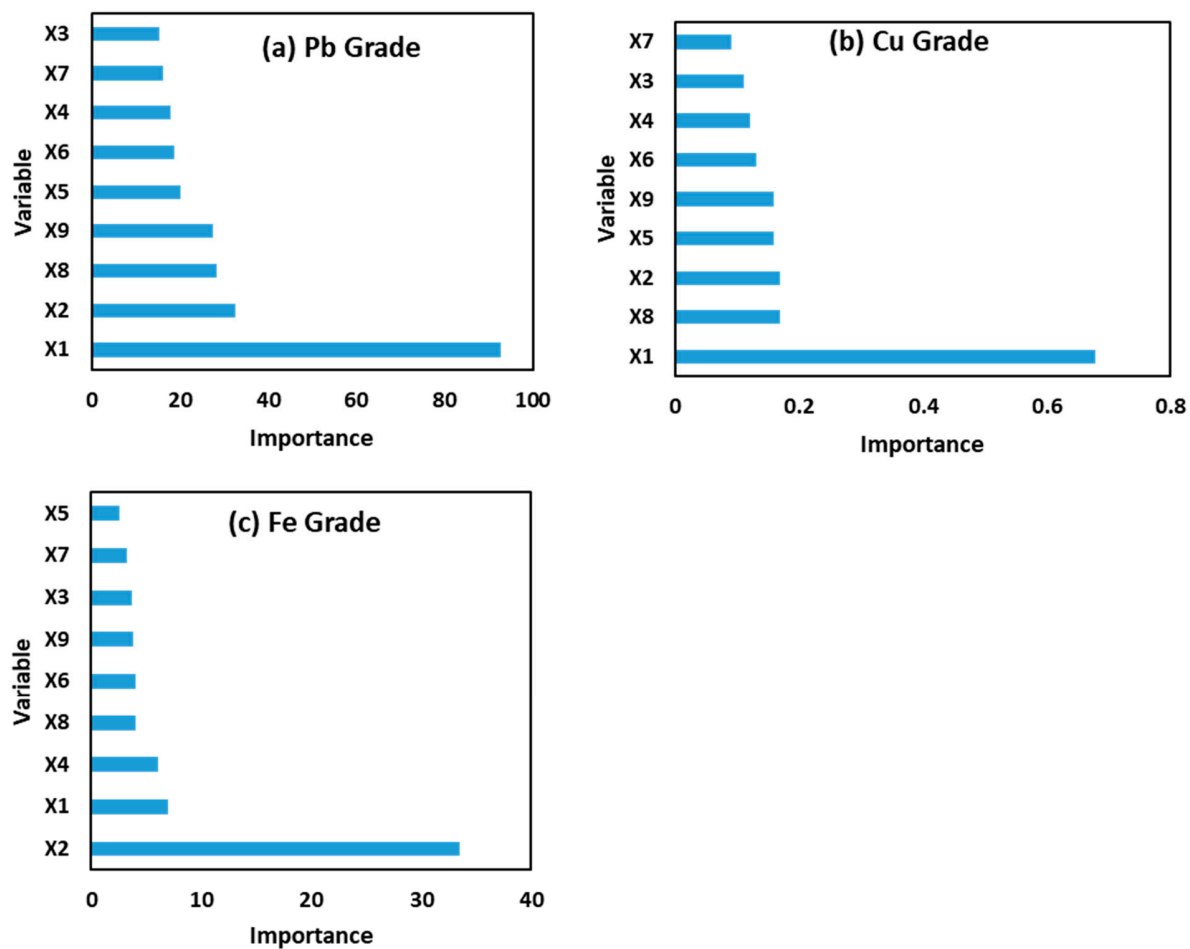


Figure S4. Variables importance of the random forest model inputs for the grades of (a) lead; (b) copper and (c) iron.

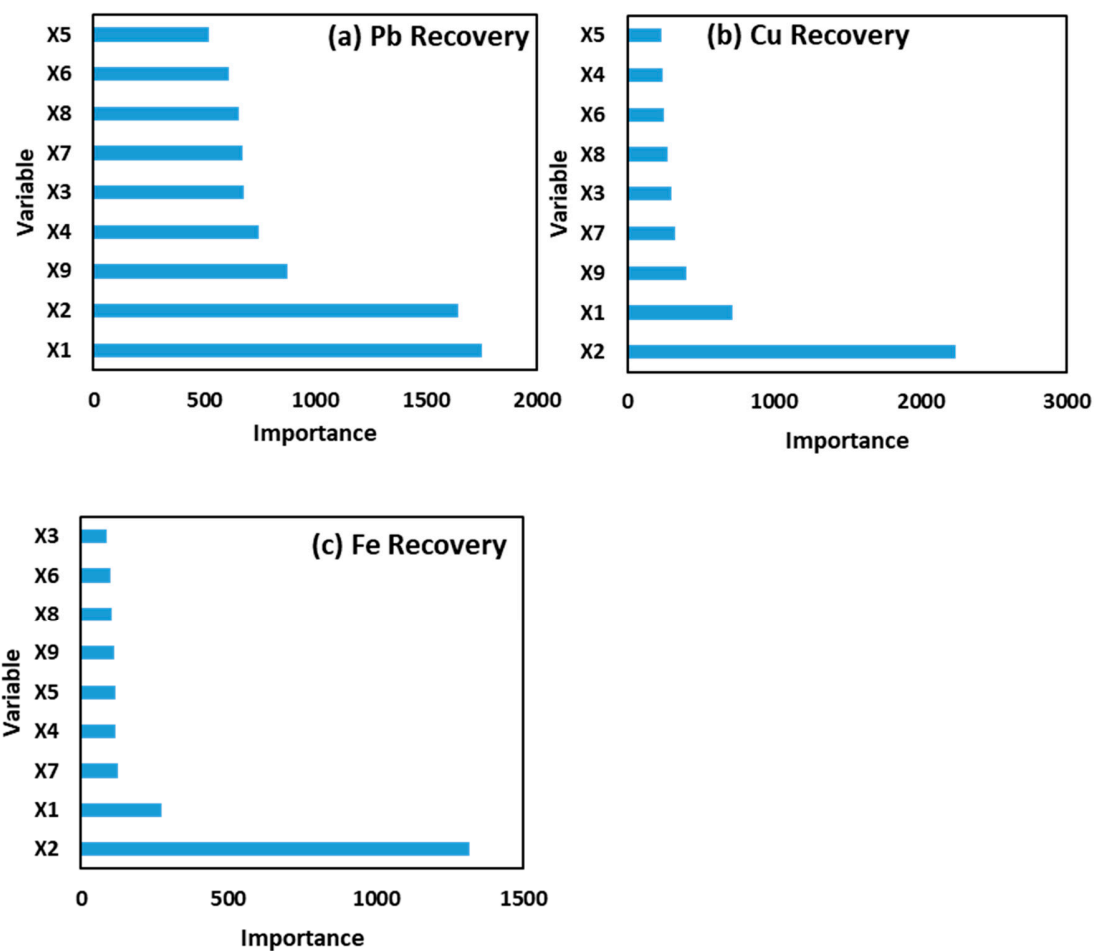


Figure S5. Variables importance of the random forest model inputs for the recoveries of (a) lead; (b) copper and (c) iron.

Table S1. ML models inputs and outputs for experiments 1-35.

No	Inputs									Outputs (%)							
	X1	X2	X3	X4	X5	X6	X7	X8	X9	Pb grade	Pb rec.	Fe grade	Fe rec	Cu grade	Cu rec.	Zn grade	Zn rec.
1	85	5	75	8.5	500	600	75	1500	6	18.21	65.51	5.64	22.81	1.84	46.65	6.42	22.00
2	85	3	100	10	400	600	75	1250	3	15.03	56.09	5.06	21.25	1.52	40.21	5.94	21.14
3	85	5	125	10	400	700	75	1250	6	17.49	60.32	5.30	20.56	1.70	41.38	5.39	17.72
4	95	5	100	7	400	600	75	1500	6	11.32	31.72	10.07	31.74	2.05	40.53	0.70	1.87
5	85	5	100	10	500	600	100	1250	6	16.53	41.68	5.13	14.55	1.66	29.53	4.79	11.50
6	85	3	100	10	400	600	75	1250	8	18.22	59.38	5.89	21.57	1.89	43.46	5.65	17.54
7	85	7	100	8.5	400	600	50	1000	6	14.98	85.97	5.99	38.63	1.75	71.13	2.08	11.38

8	85	5	125	8.5	400	600	50	1250	3	12.99	71.79	8.71	54.10	1.88	73.34	1.47	7.72
9	85	5	125	10	400	500	75	1250	6	16.02	64.95	10.18	46.39	2.09	59.90	1.32	5.09
10	85	3	100	10	400	600	75	1250	8	19.00	50.46	5.78	17.26	1.93	36.12	6.01	15.22
11	95	5	100	7	400	600	75	1000	6	7.80	28.02	8.37	33.82	1.60	40.66	0.71	2.44
12	85	5	125	8.5	500	600	75	1500	6	17.32	75.38	10.67	52.25	2.25	69.30	1.29	5.33
13	95	5	100	8.5	400	700	50	1250	6	9.47	29.47	9.79	34.26	1.65	36.35	0.59	1.75
14	85	5	75	10	400	700	75	1250	6	11.18	57.77	6.68	38.82	1.39	50.79	0.82	4.06
15	75	5	100	8.5	400	500	50	1250	6	20.20	93.86	8.91	46.58	2.27	74.69	1.85	8.18
16	85	5	75	8.5	400	600	100	1250	3	15.38	58.25	9.06	38.60	1.93	51.68	1.17	4.22
17	85	3	100	7	400	600	75	1250	8	15.28	50.68	4.93	18.40	1.63	38.27	5.60	17.71
18	85	5	100	7	500	600	50	1250	6	11.88	48.02	9.23	41.96	1.84	52.48	1.26	4.87
19	85	5	125	7	400	700	75	1250	6	14.28	41.30	10.47	34.06	2.45	49.97	1.37	3.79
20	85	5	75	8.5	300	600	75	1500	6	15.99	43.63	10.49	32.19	2.33	44.87	0.93	2.41
21	85	5	125	8.5	400	600	100	1250	3	12.66	49.46	8.88	39.04	1.88	51.84	1.05	3.92
22	85	3	100	8.5	300	700	75	1250	6	13.21	52.06	4.82	21.38	1.46	40.54	6.08	22.82
23	85	5	125	7	400	500	75	1250	6	11.98	47.17	8.83	39.10	1.89	52.59	1.56	5.84
24	85	5	100	8.5	400	600	75	1250	6	14.62	45.94	10.16	35.92	2.21	49.05	1.14	3.42
25	75	3	75	8.5	400	600	75	1250	6	16.33	54.68	5.54	20.87	1.67	39.43	4.36	13.91
26	85	5	125	8.5	300	600	75	1000	6	12.46	49.00	8.06	35.62	1.80	49.99	1.14	4.25
27	95	5	100	8.5	400	700	100	1250	6	9.85	30.17	9.63	33.20	1.66	36.01	0.62	1.81
28	85	7	100	8.5	300	700	75	1250	6	17.96	60.61	7.80	29.62	2.41	57.42	1.70	5.47
29	75	5	100	7	400	600	75	1000	6	23.23	84.92	9.11	37.48	2.77	71.63	2.23	7.77
30	85	5	100	8.5	400	500	75	1500	3	12.93	56.08	8.43	41.13	1.60	49.10	1.22	5.03
31	85	5	75	7	400	500	75	1250	6	14.52	46.81	9.00	32.63	2.05	46.69	1.80	5.53
32	85	5	125	8.5	300	600	75	1000	6	12.46	43.28	7.33	28.61	1.71	41.93	1.18	3.89
33	85	5	100	8.5	400	600	75	1250	6	15.15	56.38	9.26	38.74	1.92	50.44	1.45	5.13
34	95	3	125	8.5	400	600	75	1250	6	17.05	48.95	5.20	16.80	1.80	36.43	6.32	17.30
35	85	3	100	8.5	400	600	100	1500	6	17.18	49.69	5.68	18.48	1.83	37.32	6.39	17.61

Table S 2. ML models inputs and outputs for experiments 36-70.

No	Inputs									Outputs (%)							
	X1	X2	X3	X4	X5	X6	X7	X8	X9	Pb grade	Pb rec.	Fe grade	Fe rec	Cu grade	Cu rec.	Zn grade	Zn rec.
36	85	5	125	8.5	300	600	75	1500	6	15.01	48.25	8.74	31.58	1.94	44.05	0.99	3.04
37	95	5	100	8.5	300	600	75	1250	8	8.53	26.23	9.65	33.38	1.55	33.60	0.59	1.74
38	85	7	100	8.5	400	600	100	1500	6	21.48	74.52	8.10	31.59	2.58	63.23	1.91	6.31
39	75	7	125	8.5	400	600	75	1250	6	18.02	88.48	9.09	50.21	2.46	85.27	2.20	10.29
40	85	5	125	8.5	500	600	75	1500	6	13.89	47.70	9.60	37.07	1.94	47.08	1.18	3.87
41	85	3	100	8.5	400	600	50	1500	6	16.06	51.37	5.22	18.77	1.67	37.66	6.10	18.60

42	85	5	100	8.5	400	600	75	1250	6	12.48	49.61	7.99	35.72	1.64	46.05	1.02	3.87
43	85	5	100	8.5	400	600	75	1250	6	11.32	48.38	7.73	37.17	1.62	48.90	1.18	4.79
44	85	5	100	8.5	400	700	75	1500	3	13.19	43.92	8.52	31.92	1.87	43.96	1.06	3.35
45	75	5	100	8.5	400	700	50	1250	6	22.50	90.87	9.52	43.26	2.54	72.38	1.80	6.94
46	85	5	125	8.5	500	600	75	1000	6	11.04	48.26	6.10	29.97	1.40	43.17	1.05	4.37
47	85	5	75	7	400	700	75	1250	6	10.66	50.20	7.37	39.03	1.52	50.50	1.27	5.72
48	85	5	75	8.5	500	600	75	1000	6	11.02	49.50	7.71	38.95	1.57	49.92	1.44	6.16
49	95	5	100	8.5	500	600	75	1250	8	7.50	29.42	9.65	42.56	1.45	40.31	0.57	2.13
50	85	7	100	7	400	600	75	1250	8	12.07	86.11	5.01	40.20	1.52	76.72	2.44	16.59
51	95	7	75	8.5	400	600	75	1250	6	19.22	92.13	8.69	46.87	2.21	74.92	1.64	7.47
52	85	7	100	8.5	500	500	75	1250	6	12.41	74.85	6.00	40.72	1.64	70.06	1.90	10.93
53	85	5	100	8.5	400	500	75	1500	8	12.87	43.06	8.18	30.78	1.71	40.42	1.20	3.82
54	85	5	100	7	500	600	100	1250	6	12.97	53.78	8.39	39.10	1.84	53.98	1.60	6.31
55	85	5	100	8.5	400	600	75	1250	6	12.60	45.24	8.55	34.52	1.83	46.36	1.32	4.51
56	75	5	100	8.5	400	700	50	1250	6	20.84	90.70	8.84	43.25	2.32	71.36	1.61	6.66
57	85	5	100	7	300	600	100	1250	6	15.28	45.03	9.08	30.10	2.25	46.77	1.73	4.86
58	85	5	75	8.5	300	600	75	1000	6	13.05	43.93	8.37	31.70	1.90	45.27	1.41	4.53
59	85	7	100	10	400	600	75	1250	8	12.55	85.81	5.85	45.00	1.58	76.19	1.47	9.58
60	75	5	100	10	400	600	75	1500	6	24.39	89.98	9.22	38.27	2.05	53.57	1.65	5.79
61	85	3	100	8.5	400	600	50	1000	6	18.32	43.83	5.44	14.62	1.80	30.38	6.79	15.47
62	95	5	100	8.5	400	500	100	1250	6	8.40	27.80	10.12	37.65	1.49	34.89	0.58	1.83
63	95	5	100	8.5	400	500	50	1250	6	8.85	24.63	10.00	31.30	1.53	30.09	0.55	1.45
64	75	5	100	8.5	400	500	100	1250	6	22.31	75.18	10.35	39.21	2.81	66.93	2.08	6.70
65	95	5	100	8.5	400	700	50	1250	6	14.04	93.09	6.90	51.46	1.76	82.37	1.84	11.60
66	75	3	125	8.5	400	600	75	1250	6	18.81	49.19	5.85	17.21	1.93	35.65	5.08	12.67
67	85	7	100	7	400	600	75	1250	3	17.07	86.31	8.13	46.25	2.09	74.60	1.93	9.32
68	85	7	100	8.5	400	600	50	1500	6	15.76	76.04	7.94	43.07	1.98	67.46	1.56	7.18
69	95	3	75	8.5	400	600	75	1250	6	20.68	44.21	7.59	18.25	2.07	31.34	5.95	12.11
70	85	5	100	8.5	400	600	75	1250	6	13.07	45.91	8.90	35.14	1.87	46.43	1.38	4.60

Table S3. ML models inputs and outputs for experiments 71-105.

No	Inputs									Outputs (%)							
	X1	X2	X3	X4	X5	X6	X7	X8	X9	Pb grade	Pb rec.	Fe grade	Fe rec	Cu grade	Cu rec.	Zn grade	Zn rec.
71	85	5	125	8.5	400	600	100	1250	8	12.12	48.44	9.08	40.83	1.68	47.34	1.14	4.36
72	85	5	125	8.5	400	600	50	1250	8	11.55	35.96	7.63	26.72	1.56	34.40	1.25	3.72
73	85	5	75	8.5	300	600	75	1500	6	15.09	51.85	9.72	37.58	1.89	45.78	1.29	4.21
74	75	5	100	8.5	500	600	75	1250	3	24.37	83.51	6.67	25.69	2.47	59.70	1.91	6.23
75	85	5	75	8.5	500	600	75	1000	6	10.89	52.95	7.42	40.54	1.63	55.93	1.41	6.53

76	75	7	75	8.5	400	600	75	1250	6	24.23	91.51	8.95	38.00	2.60	69.34	1.81	6.51
77	95	5	100	10	400	600	75	1500	6	15.81	92.66	8.64	56.92	1.86	77.22	1.73	9.64
78	85	5	100	8.5	400	700	75	1000	3	12.53	51.95	8.21	38.28	1.71	50.20	1.29	5.09
79	75	5	100	8.5	400	700	100	1250	6	19.16	97.47	11.36	64.97	2.26	81.37	1.64	7.95
80	75	5	100	8.5	400	500	100	1250	6	20.73	89.11	8.21	39.69	2.23	67.68	1.65	6.76
81	85	5	75	8.5	500	600	75	1500	6	11.09	45.43	11.36	52.32	1.65	47.86	1.12	4.39
82	85	5	75	8.5	300	600	75	1000	6	9.18	21.50	8.54	22.48	1.94	32.05	0.62	1.38
83	75	5	100	10	400	600	75	1000	6	18.41	94.86	8.54	49.49	2.33	84.68	2.08	10.19
84	75	5	100	8.5	400	700	100	1250	6	23.46	92.62	0.65	2.89	2.48	69.13	1.47	5.52
85	95	5	100	8.5	400	500	100	1250	6	16.35	96.09	7.39	48.82	2.07	85.75	2.05	11.49
86	85	3	100	7	400	600	75	1250	8	18.12	50.71	5.83	18.36	1.93	38.19	6.20	16.55
87	85	7	100	10	400	600	75	1250	8	15.03	74.74	6.70	37.46	1.86	65.43	1.66	7.88
88	85	3	100	8.5	500	700	75	1250	6	19.44	49.85	5.93	17.11	2.02	36.56	5.27	12.87
89	85	5	100	8.5	400	600	75	1250	6	8.92	27.28	9.56	32.91	1.59	34.37	0.60	1.75
90	75	5	100	8.5	500	600	75	1250	8	13.41	75.24	9.41	59.33	1.79	71.12	1.37	7.33
91	85	5	100	8.5	400	500	75	1000	3	7.29	24.81	8.59	32.90	1.46	35.03	0.62	2.03
92	95	5	100	10	400	600	75	1000	6	16.50	92.57	6.20	39.14	1.86	73.86	2.03	10.88
93	85	5	125	8.5	500	600	75	1000	6	8.67	19.87	8.76	22.59	1.47	23.74	0.50	1.09
94	85	5	100	10	300	600	100	1250	6	16.75	95.04	5.92	37.80	1.84	73.73	2.29	12.37
95	85	7	100	10	400	600	75	1250	3	13.86	78.96	6.38	40.90	1.77	71.12	1.72	9.37
96	75	5	100	8.5	400	500	50	1250	6	17.26	71.87	10.41	48.72	2.21	64.93	1.75	6.96
97	95	5	100	8.5	400	700	100	1250	6	20.69	99.73	7.81	42.34	2.43	82.57	2.13	9.78
98	85	3	100	8.5	500	500	75	1250	6	18.53	50.42	5.97	18.26	2.01	38.72	6.12	15.86
99	85	5	75	8.5	400	600	100	1250	8	21.27	96.67	6.93	35.42	2.23	71.55	2.35	10.17
100	75	5	100	8.5	300	600	75	1250	3	17.77	71.39	11.12	50.22	2.33	66.21	1.64	6.27
101	95	5	100	8.5	300	600	75	1250	3	19.98	84.35	6.95	32.97	2.32	69.15	2.10	8.45
102	85	5	100	8.5	400	500	75	1000	8	19.21	93.24	6.74	36.81	2.15	73.57	2.62	12.12
103	85	5	100	10	300	600	50	1250	6	20.30	95.72	6.83	36.25	2.04	67.86	2.11	9.50
104	85	7	100	8.5	500	700	75	1250	6	14.69	79.97	6.04	36.99	1.81	69.58	1.72	8.91
105	85	5	100	8.5	400	700	75	1000	8	18.18	96.92	7.28	43.65	2.18	82.09	2.17	11.00

Table S4. ML models inputs and outputs for experiments 106-130

No	Inputs									Outputs (%)							
	X1	X2	X3	X4	X5	X6	X7	X8	X9	Pb grade	Pb rec.	Fe grade	Fe rec	Cu grade	Cu rec.	Zn grade	Zn rec.
106	95	7	125	8.5	400	600	75	1250	6	20.32	92.19	8.68	44.30	2.30	73.70	1.58	6.82
107	75	5	100	8.5	300	600	75	1250	8	18.96	69.46	10.57	43.56	2.44	63.18	1.48	5.16
108	75	5	100	7	400	600	75	1500	6	14.92	82.47	9.86	61.32	2.06	80.29	1.56	8.24
109	85	5	100	8.5	400	600	75	1250	6	18.37	96.30	7.42	43.73	2.15	79.75	2.04	10.20

110	85	3	100	7	400	600	75	1250	3	18.49	56.21	0.71	2.43	1.99	42.73	7.22	20.91
111	85	5	125	8.5	300	600	75	1500	6	22.64	96.97	7.96	38.32	2.52	76.13	2.01	8.21
112	85	5	100	7	300	600	50	1250	6	22.19	96.20	7.40	36.06	2.47	75.70	2.13	8.82
113	85	5	75	10	400	500	75	1250	6	18.86	92.64	6.94	38.32	2.03	70.41	2.15	10.05
114	85	7	100	8.5	400	600	100	1000	6	15.52	80.30	6.09	35.43	1.79	65.50	1.88	9.27
115	85	5	100	8.5	400	600	75	1250	6	19.42	92.98	6.97	37.51	2.15	72.89	2.08	9.51
116	85	7	100	8.5	300	500	75	1250	6	11.19	84.45	5.36	45.50	1.48	79.14	1.57	11.32
117	85	3	100	7	400	600	75	1250	3	20.41	45.93	5.63	14.23	2.02	32.06	7.09	15.21
118	85	5	100	10	500	600	50	1250	6	17.36	93.03	6.65	40.08	1.89	71.36	2.02	10.33
119	95	5	100	8.5	500	600	75	1250	3	17.66	94.53	7.10	42.76	2.08	78.61	2.03	10.37
120	85	5	100	8.5	400	700	75	1500	8	20.02	94.65	7.36	39.15	2.04	68.26	1.90	8.58
121	85	7	100	7	400	600	75	1250	8	13.87	85.13	6.16	42.48	1.69	73.19	1.90	11.12
122	85	5	100	8.5	400	600	75	1250	6	18.63	91.49	7.07	39.06	2.18	75.51	2.36	11.07
123	85	5	75	8.5	400	600	50	1250	3	17.90	90.53	6.40	36.40	1.94	69.43	1.92	9.27
124	85	5	75	8.5	400	600	50	1250	8	18.71	99.94	6.68	40.15	1.89	71.40	1.89	9.64
125	85	3	100	8.5	400	600	100	1000	6	14.78	49.84	5.19	19.70	1.72	41.04	6.70	21.53
126	85	7	100	10	400	600	75	1250	3	13.19	44.80	7.06	26.95	1.76	42.31	0.96	3.11
127	95	5	100	8.5	400	500	50	1250	6	19.29	93.85	7.02	38.38	2.16	74.40	2.05	9.50
128	85	3	100	8.5	300	500	75	1250	6	16.88	51.70	5.55	19.12	1.87	40.37	6.29	18.37
129	85	3	100	10	400	600	75	1250	3	18.07	52.12	5.04	16.36	1.60	32.62	5.90	16.21
130	85	7	100	7	400	600	75	1250	3	11.37	63.51	3.06	19.25	1.14	44.99	1.02	5.42