Supplementary material for A Two-step Leaching Process using Thiourea for the Recovery of Precious Metals from Waste Printed Circuit Boards

Serap Ubiç[*], Rasoul Khayyam Nekouei, Veena Sahajwalla

Centre for Sustainable Materials Research and Technology (SMaRT), School of Materials Science and Engineering, UNSW Sydney, 2052, Australia.

Corresponding author's email: s.ubic@unsw.edu.au

Table S-I. The replicates of recovery rate of chemical applications alongside their respective standard deviations, conducted as preliminary steps prior to the selection of nitric acid leaching with metals presented.

	0.5M HNO_3		0.5M H_2SO_4	
	Min (%)	Standard Deviation	Min (%)	Standard Deviation
Cu	94.95	2.86	1.93	0.24
Fe	88.07	2.47	70.16	3.63
Ni	80.43	5.65	16.64	6.32
Pb	94.69	1.64	3.98	0.04
Zn	67.00	6.91	59.17	7.27
Sn	35.00	8.55	82.20	7.40
Au	1.25	0.14	0.00	0.00
Pd	33.31	1.11	1.44	0.52

Note: (%) indicates that recovery rate of metals shown and Min: stands for minimum

Table S-II. The replicate tests of recovery rates of varying nitric acid concentrations(M) in **Figure 2**, alongside their associated standard deviations of shown metals in the first stage of leaching.

	1M		2M		3M	
	Min (%)	Standard Deviation	Min (%)	Standard Deviation	Min (%)	Standard Deviation
Cu	84.03	10.58	61.43	9.23	94.95	3.57
Fe	83.33	7.22	62.39	7.35	91.57	5.96
Ni	83.00	9.66	61.85	6.82	80.43	4.49
Pb	83.44	6.59	62.61	6.15	94.69	2.83
Sn	26.59	5.23	28.10	0.97	67.00	0.76
Zn	63.78	7.46	54.01	1.41	57.09	4.57
Au	0.38	0.38	0.32	0.61	1.18	0.05
Pd	21.00	9.52	12.10	9.96	33.31	2.03

Table S-III. The replicate tests of recovery rates of different temperature level of **Figure 3**, alongside their associated standard deviations of shown metals in the first stage of leaching.

	40 °C		60 °C	
	Min (%)	Standard Deviation	Min (%)	Standard Deviation
Cu	98.72	0.09	94.40	3.84
Fe	85.16	4.46	79.00	9.37
Ni	81.50	2.89	78.42	2.38
Pb	94.72	0.07	86.50	6.10
Sn	57.51	5.50	48.59	12.25
Zn	60.16	0.15	60.42	0.04
Au	0.58	0.29	0.98	0.19
Pd	34.66	0.61	34.27	1.83

Table S- IV. The duplicate tests of varied concentrations of Thiourea (M) in **Figure 4** with their corresponding standard deviations after the second stage of leaching.

	0.5M		1M	
	Min (%)	Standard Deviation	Min (%)	Standard Deviation
Cu	0.18	0.05	0.16	0.08
Ni	2.36	0.75	2.11	2.76
Pb	0.38	0.15	0.22	0.40
Sn	0.01	0.08	0.06	0.23
Zn	12.91	4.25	13.00	9.68
Au	27.20	4.15	49.00	2.83
Pd	66.02	8.55	77.00	15.56

Table S-V. The duplicate trials with recovery rates for the different concentration of ferric ion (g/L) in **Figure 5** with their corresponding standard deviations following the second stage of leaching.

	0 g/l		6 g/l		9 g/l	
	Min (%)	Standard Deviation	Min (%)	Standard Deviation	Min (%)	Standard Deviation
Cu	0.09	0.04	0.16	0.07	0.16	0.04
Ni	1.99	0.55	1.80	0.22	2.11	1.03
Pb	0.10	0.29	0.18	0.03	0.22	0.31
Sn	0.00	0.02	0.06	0.01	0.06	0.08
Zn	9.04	1.67	10.30	1.96	13.00	4.43
Au	39.80	3.51	42.27	4.78	45.1	2.79
Pd	66.20	15.67	73.48	2.52	76.2	0.57

Table S- VI. The replicate tests of recovery rate of the varied concentration of sulfuric acid (M) in **Figure 6** with their corresponding standard deviations following the second stage of leaching.

	0.05M		0.1M		0.2M	
	Min (%)	Standard Deviation	Min (%)	Standard Deviation	Min (%)	Standard Deviation

Cu	0.09	0.59	0.25	0.01	0.10	0.13
Ni	2.78	0.39	1.81	0.32	2.77	0.06
Pb	0.20	0.21	0.19	0.03	0.23	0.20
Sn	0.00	0.02	0.07	0.03	0.02	0.20
Zn	11.32	2.02	10.35	3.33	11.4	4.67
Au	40.00	1.76	42.20	5.64	40.00	7.28
Pd	66.00	9.29	73.50	1.46	76.2	0.76

Table S- VII. The replicate tests with minimum recovery rates and their respective standard deviations following the second stage of leaching, where temperature levels were varied in **Figure 7**.

	25 °C		50 °C	
	Min (%)	Standard Deviation	Min (%)	Standard Deviation
Cu	0.20	0.25	0.16	0.08
Ni	8.24	4.12	2.11	2.77
Pb	0.65	0.14	0.22	0.39
Sn	0.13	0.29	0.06	0.22
Zn	50.00	3.14	13.07	9.62
Au	38.5	2.63	49.04	2.72
Pd	90.00	6.10	77.05	16.23

Table S-VIII-a. The tests for the kinetics of leaching were conducted within a 6-hour timeline in the first stage of leaching in manuscript in **Table 3**.

Elements / Time(min)	Cu (ppm)	Fe (ppm)	Ni (ppm)	Pb (ppm)	Sn (ppm)	Zn (ppm)	Au (ppb)	Pd (ppb)
2m	259	1008	63.1	148.7	251.6	12.9	0.65	29.5
5m	309	1008	67.8	149.0	265.0	13.9	0.99	36.8
10m	343	1013	70.6	149.7	269.2	14.4	1.12	42.5
15m	351	1011	70.0	147.4	266.8	14.4	1.18	42.7
20m	362	1002	72.2	149.9	276.8	14.8	1.61	42.4
30m	366	1017	69.6	152.7	265.6	14.4	1.79	41.1
40m	678	1032	75.0	157.2	273.8	17.6	1.98	62.7
50m	774	1035	76.2	154.0	278.4	18.6	2.41	69.3
60m	842	1034	75.4	158.2	274.2	18.8	2.67	80.3
75m	952	1040	76.1	158.8	277.8	19.4	2.92	79.9
90m	1040	1038	77.1	157.0	281.2	20.0	3.30	85.9
120m	1222	1046	79.1	157.4	287.6	21.3	3.75	96.6
180m	1440	1053	79.6	156.2	290.4	22.8	4.63	115
240m	1660	1052	82.0	161.3	298.2	24.6	5.61	128
300m	1716	1102	83.2	170.7	304.2	25.3	6.53	133
360m	1769	1104	83.6	165.6	304.8	25.6	6.57	135

Table S-VIII-b. The Standard deviations of duplicate tests for the kinetics of leaching were conducted within a 6-hour timeline in the first stage of leaching in **Table 3**.

Elements / Min	Cu(ppm)	Fe(ppm)	Ni(ppm)	Pb(ppm)	Sn(ppm)	Zn(ppm)	Au(ppb)	Pd(ppb)
2m	6.36	12.73	0.78	6.15	8.2	2.05	0.39	6.01
5m	4.95	15.56	4.10	7.78	1.41	1.27	0.56	4.10
10m	30.41	8.49	1.77	5.44	3.68	1.41	0.44	6.43
15m	0.71	0.71	1.98	4.53	9.05	0.64	0.27	6.15
20m	7.78	0.71	0.07	4.17	12.59	0.64	0.36	7.35
30m	3.54	4.95	1.06	9.69	15.98	0.57	0.47	4.17
40m	19.8	7.07	2.83	3.68	28.85	1.56	0.54	6.08
50m	2.83	23.33	2.90	4.95	0.99	1.77	0.79	4.24
60m	5.66	20.51	0.21	5.80	9.33	1.84	0.42	6.58
75m	6.36	13.44	3.61	6.93	16.83	0.07	0.51	4.17
90m	28.28	18.38	9.26	7.78	11.46	2.05	0.64	9.12
120m	8.49	17.68	5.02	4.53	14.57	2.90	0.46	7.50
180m	28.28	13.44	11.03	7.92	10.89	0.99	0.37	3.54
240m	10.61	20.51	8.34	5.87	17.82	1.56	0.93	9.90
300m	18.38	12.02	2.26	6.15	2.26	0.78	1.46	7.78
360m	48.79	7.78	1.13	12.44	2.61	0.71	0.97	8.49

Note: M stands for *minute,* The values were calculated in *parts per million* (ppm) and *parts per billion* ppb.

Table S-IX-a. The tests for the kinetics of leaching were conducted within a 24-hour timeline in the second stage of leaching in manuscript in **Table 3**.

Elements / Time(min)	Cu (ppm)	Ni (ppm)	Pb (ppm)	Sn (ppm)	Zn (ppm)	Au (ppb)	Pd (ppb)
2m	1.45	0.79	0.08	2.06	0.19	2408	322
5m	1.46	0.79	0.09	3.04	0.22	2494	318
10m	1.52	0.80	0.09	4.72	0.22	2511	310
15m	1.59	0.82	0.10	5.72	0.24	2629	323
30m	1.66	0.88	0.11	8.04	0.30	2602	314
60m	1.72	0.89	0.13	12.8	0.40	2620	317
75m	1.74	0.93	0.14	15.0	0.45	2626	317
90m	1.81	0.98	0.15	16.5	0.50	2665	325
120m	1.80	0.98	0.16	20.4	0.55	2687	329
180m	1.88	1.08	0.17	22.8	0.74	2746	334
240m	2.12	1.28	0.21	39.6	1.14	2889	355
360m	2.11	1.27	0.21	39.3	1.12	2823	349
540m	2.59	1.78	0.29	86.2	1.95	3331	411
720m	2.88	2.08	0.33	107.7	2.43	3284	410
1080m	3.04	2.48	0.37	132.7	2.90	3177	400
1440m	3.28	2.96	0.41	154.9	3.57	3283	415

Table S-IX-b. The Standard deviations of duplicate tests for the kinetics of leaching were conducted within a 24-hour timeline in the second stage of leaching in **Table 3**.

Elements Min	Cu(ppm)	Ni(ppm)	Pb(ppm)	Sn(ppm)	Zn(ppm)	Au(ppb)	Pd(ppb)
2m	0.24	0.28	0.05	0.32	0.06	76.36	1.41
5m	0.18	0.26	0.05	0.74	0.06	42.43	2.12
10m	0.14	0.18	0.05	0.86	0.01	46.67	4.24
15m	0.18	0.28	0.01	0.79	0.01	84.85	14.85
30m	0.17	0.24	0.01	1.16	0.07	36.77	9.90
60m	0.21	0.10	0.01	1.21	0.11	39.61	10.61
75m	0.22	0.20	0.01	1.91	0.09	11.31	9.91
90m	0.22	0.22	0.00	2.33	0.12	82.02	9.19
120m	0.24	0.14	0.02	3.61	0.15	38.89	11.31
180m	0.26	0.21	0.01	1.91	0.14	9.90	9.19
240m	0.34	0.42	0.05	3.89	0.31	54.45	9.19
360m	0.33	0.58	0.03	3.54	0.16	9.19	11.31
540m	0.66	0.94	0.10	1.41	0.74	7.07	38.89
720m	0.86	0.69	0.15	0.42	0.80	24.04	6.36
1080m	0.95	0.96	0.11	6.65	1.06	12.73	7.78
1440m	1.11	1.03	0.12	8.98	1.39	20.5	9.19

Note: M stands for *minute,* The values were calculated in *parts per million* (ppm) and *parts per billion* ppb.