



Use of composts in the remediation of heavy metal contaminated soil

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ABSTRACT

High levels of heavy metals in soil can ultimately lead to pollution of drinking water and contamination of food. Consequently, sustainable remediation strategies for treating soil are required. The potential ameliorative effect of several composts derived from source-separated and mixed municipal wastes were evaluated in a highly acidic heavily contaminated soil (As, Cu, Pb, Zn) in the presence and absence of lime. Overall, PTE (potentially toxic element) amelioration was enhanced by compost whilst lime had little effect and even exacerbated PTE mobilization (e.g. As). All composts reduced soil solution PTE levels and raised soil pH and nutrient levels and are well suited to revegetation of contaminated sites. However, care must be taken to ensure correct pH management (pH 5–6) to optimize plant growth whilst minimizing PTE solubilization, particularly at high pH. In addition, ‘metal excluder’ species should be sown to minimize PTE entry into the food chain.

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1. Introduction

Effective treatment of municipal solid waste (MSW) represents an important environmental, social and economic issue in most industrialised countries, and is associated with major long-term problems when not adequately processed. The Landfill Directive [1] states that no waste may be deposited in landfill without it first being treated to reduce its environmental footprint. Mechanical Biological Treatment (MBT) can be used to treat residual mixed wastes (after recyclables have been removed) to produce a stabilized, compost-like substance, and it is clear that volumes of these ‘wastes’ will increase – requiring a sustainable route for their final disposal [2]. As soil organic matter levels have declined greatly in recent years [3], it is advantageous to recycle as much of this ‘waste’ organic matter as possible, without unduly increasing the loading of contaminants onto uncontaminated soils. Due to the negative perception associated with the addition of waste products to agricultural land, one proposed use for mixed waste composts is in the restoration of post-industrial sites and in the remediation of land contaminated with heavy metals and organic pollutants [4].

Removal strategies for heavy metals are generally carried out “ex situ”, however, this causes a significant deterioration of soil structure and often comes at a high economic cost, limiting its use on large contamination areas. In contrast, biostabilization techniques are typically carried out “in situ” and are less expensive. Soils

can naturally reduce mobility and bioavailability of heavy metals as they are retained in soil by sorption, precipitation and complexation reactions [4,5]. This natural attenuation process (natural remediation) can be accelerated by the addition of organic amendments [6,7]. Kiiikkilä et al. [5] found that an application of an organic mulch to a heavy metal contaminated forest soil decreased the toxicity of soil solution to bacteria. Liming is the most common method of treatment, and can lead to the precipitation of heavy metals as metal-carbonates, and significantly reduces the exchangeable fraction of heavy metals within soils [8]. An investigation by Krebs et al. [9], into the effect of organic and inorganic fertilisers +/- lime, found that lime reduced the uptake of Cd, Cu and Zn compared to fertilized but un-limed soils.

We propose that due to their similar properties to sewage sludge and mulch, composts can be used for the successful biostabilisation of heavy metal contaminated soil. The aim of this study was to evaluate the success of contrasting compost types to raise the pH and nutrient status of the soil, promote plant growth, decrease the environmentally-available metal pool in soil and reduce plant metal uptake.

2. Materials and methods

2.1. Substrate characteristics

Chemical characteristics of the soil and composts used in the experiment are listed in Table 1. A heavy metal contaminated soil (ca. 200 kg) was collected one day before the onset of experimentation from Parys Mountain, Anglesey, North Wales (53°23'22"N,

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Table 1
Chemical properties of the substrates used in the plant growth trials. All values in mg kg⁻¹ dry matter unless otherwise stated.

	Soil	Composts				
	C	G	GF	GFP	MSW	PB
Moisture content (%)	13.4 ± 0.1	41.2 ± 2.5	52.7 ± 3.8	55.9 ± 1.1	56.7 ± 1.7	59.7 ± 0.2
Organic matter (%)	2.5 ± 0.2	25.2 ± 2.9	44.2 ± 1.9	39.8 ± 2.2	42.2 ± 3.7	93.7 ± 0.2
pH	2.27 ± 0.03	8.11 ± 0.18	7.80 ± 0.16	8.12 ± 0.09	7.28 ± 0.03	5.51 ± 0.04
EC ^a (mS cm ⁻¹)	2.9 ± 0.1	0.7 ± 0.2	1.5 ± 0.4	1.4 ± 0.4	3.6 ± 0.8	0.7 ± 0.1
Total C (%)	0.7 ± 0.3	13.2 ± 0.9	22.7 ± 3.8	21.9 ± 0.3	24.6 ± 4.3	39.9 ± 0.1
Total N (%)	BD ^b	0.62 ± 0.06	1.20 ± 0.21	1.37 ± 0.88	0.97 ± 0.17	1.05 ± 0.01
Total P (mg g ⁻¹)	ND ^c	2.8 ± 0.6	5.0 ± 1.3	5.9 ± 0.7	0.9 ± 0.2	0.5 ± 0.1
Total K (mg g ⁻¹)	15.4 ± 1.3	7.4 ± 1.1	9.9 ± 2.3	10.8 ± 0.6	10.1 ± 0.6	5.0 ± 0.1
Total Ca (mg g ⁻¹)	6.5 ± 0.6	2.2 ± 0.4	4.1 ± 1.2	7.8 ± 0.6	51.8 ± 5.3	11.1 ± 1.1
Total Na (mg g ⁻¹)	1.5 ± 0.1	1.1 ± 0.2	2.0 ± 0.7	2.5 ± 0.1	8.3 ± 1.1	0.9 ± 0.1
KCl-extractable NO ₃ ⁻	1.7 ± 0.1	1.2 ± 0.5	176 ± 72	170 ± 16	21.9 ± 11.8	587 ± 24
KCl-extractable NH ₄ ⁺	13 ± 1	33 ± 2	71 ± 8	51 ± 12	29 ± 6	663 ± 29
Olsen P	3 ± 1	119 ± 5	248 ± 27	267 ± 43	132 ± 32	ND
NH ₄ OAc-extractable K	9 ± 1	1113 ± 230	1283 ± 211	1070 ± 226	2925 ± 382	2743 ± 23
Total As	259 ± 59	BD	BD	BD	17 ± 7	BD
Total Co	3.1 ± 1.8	25.2 ± 6.7	14.4 ± 1.6	13.8 ± 2.2	14.5 ± 13.3	4.3 ± 0.8
Total Cr	0.6 ± 0.1	37.4 ± 2.8	18.9 ± 2.2	20.1 ± 1.8	48.1 ± 13.3	4.5 ± 0.3
Total Cu	4735 ± 1023	66.4 ± 39.5	36.5 ± 10.3	37.4 ± 3.4	329 ± 83	14.9 ± 0.8
Total Mo	BD	BD	BD	BD	9.4 ± 0.6	12.1 ± 0.6
Total Ni	BD	31.3 ± 2.3	32.5 ± 12.0	18.2 ± 2.2	87.2 ± 19.2	8.6 ± 4.4
Total Pb	16883 ± 1753	40.0 ± 2.2	59.6 ± 4.5	45.7 ± 6.7	906 ± 324	14.5 ± 1.3
Total Zn	846 ± 68	56.5 ± 3.3	57.0 ± 11.7	54.8 ± 9.9	505 ± 216	5.4 ± 1.5

^a Electrical conductivity.

^b BD = below limit of detection (<3.75 mg kg⁻¹ for PTEs, <0.01% for N).

^c ND = Not determined

4°20'54''W). Parys Mountain was extensively mined for copper ore from the 18th century until the 20th century. The site covers an area of 200 ha and is covered with heavy metal contaminated mine spoil, dominated by sulphide minerals including pyrite, chalcopyrite, sphalerite and galena, with lesser amounts of other minerals [10].

Green waste-derived compost (G), green waste and catering waste-derived compost (GF), green waste, catering waste and paper waste-derived compost (GFP), and municipal solid waste-derived compost (MSW) were produced using a commercially available CT-5[®] and EcoPOD[®] in-vessel composting system (ORM Ltd., Canterbury, Kent, UK and Ag-Bag International Ltd., Warrenton, OR, USA) located at the Ffridd Rasmus Waste Treatment Facility, Harlech, North Wales (52°52'59''N, 4°06'43''W). The green waste compost (G) was made from 4 t of source-separated shredded municipal green waste obtained from the Penhesgyn Gors Landfill Site, Anglesey, North Wales (53°14'45''N, 4°11'45''W). The GF compost was made from a mixture of 1.2 t of source-separated catering waste collected from commercial hotels and restaurants and 2.8 t source-separated shredded green waste. The GFP compost was made from 2 t source-separated shredded green waste, 1.6 t source-separated catering waste, and 0.4 t source-separated shredded waste paper. The MSW compost was made from 8 t mixed municipal waste which had been pre-processed through a commercial DANO Drum pulverisation plant (Keppel-Seghers UK Ltd., Wolverhampton, UK) and the fine, largely biodegradable fraction collected by passage through a trommel screen with 38 mm mesh size. Only the fine fraction (<5 cm) was used, and this contained 64 ± 3% organic matter ($n = 18$).

2.2. Plant growth trials

A fully factorial, randomised complete block design experiment was set up with 21 plastic plant pots in a heated greenhouse with a day/night rhythm of 20/18 °C photoperiod of 16 h and augmented with 400 W Sun SON-T horticultural lamps. Six substrates were used in the trials including: contaminated soil (control; C), the four composts described above (G, GF, GFP and MSW) and a commercially available peat-based compost (PB; Humax[®], L & P Peat Ltd.,

Carlisle, UK). Each of the composts were mixed 60:40 (v/v) with the contaminated soil, giving a maximum mass of soil of 2.29 kg fresh weight in the control treatment. All treatments were carried out with and without lime addition to the growing media (Gem[®] Garden Lime, 53% CaO, Gem Gardening, Accrington, UK), applied at rates determined by the SMP lime requirement method ($n = 6$) [11], giving a dose of 109 g lime per pot. The soil and compost were mechanically homogenised before lime addition. *Agrostis capillaris* L. (Common bent grass) was sown in all pots at a density of 4 g seed m⁻², and the plants grown for 64 d before being harvested.

2.3. Sampling and analysis

Moisture content was determined by drying samples at 80 °C for 24 h and organic matter content was determined as loss-on-ignition at 450 °C overnight. pH (Hanna Instruments pH 209 pH meter) and electrical conductivity (EC) (Jenway 4010 EC meter) were determined in a 1:2 (v/v) slurry, after mixing for 1 h. Total C and N were determined using a CHN2000 analyser (LECO Corp., St Joseph, MI). Prior to elemental analysis, substrates were air dried (25 °C, 14 d) and plant samples dried at 80 °C before being ground in a T1-100 vibrating sample mill (Heiko Co. Ltd., Fukushima, Japan) equipped with tungsten grinding vessels. Subsamples of the ground material were then digested using HNO₃ [12] for pseudo-total concentrations of PTEs (potentially toxic elements). Nitrate and ammonium were extracted with 1 M KCl at a 1:5 (w/v) fresh sample:extractant ratio for 1 h on a reciprocating shaker at 250 rev min⁻¹ [13]. Nitrate and ammonium were determined using a San⁺⁺ segmented flow analyser (Skalar Inc., Norcross, GA). Plant-available nutrients were extracted with 1 M NH₄OAc (pH 7.0) using a 1:5 (w/v) fresh sample:extractant ratio for 1 h on a reciprocating shaker at 250 rev min⁻¹. K, Na and Ca were analysed using a Sherwood 410 flame photometer (Sherwood Scientific, Cambridge, UK). Extractable PTEs and P were extracted using 0.5 M acetic acid using 1:5 (w/v) fresh sample:extractant ratio [14]. PTEs were determined by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) using a Fissions PlasmaQUAD II Turbo ICP-MS (limit of detection: 0.025 mg kg⁻¹). Phosphate was determined colorimetrically using the method of Murphy and Riley [15].

Plant-available PTEs were determined in soil solution. Soil solution was collected from each pot overnight at each sampling interval using 10 cm Rhizon-MOM® in situ soil solution samplers (Rhizosphere Research Products, Wageningen, The Netherlands), and was analysed using the same methods as detailed for the extracts from the substrate samples. Humic substance-C in soil solution was estimated by measuring the absorbance at 400 nm on a VERSAmax tunable microplate reader (Molecular Devices Corp., Sunnyvale, CA) and calibration with a commercial humic acid standard solution of known dissolved organic C content (H16752 Humic acid Na salt; Sigma Chem. Co., St Louis, MO).

2.4. Statistical analysis

All data were inputted into SPSS v14.0 (SPSS Inc., Chicago, IL), and a 2-way fully factorial ANOVA was performed, using lime as the primary factor, and compost treatment as the secondary factor. Tukey's Honestly Significant Difference (HSD) post hoc test was used to differentiate between the compost treatments. Pearson's correlations were also carried out to assess the effect of each variable on plant biomass. With the exception of soil solution data, all nutrient and PTE content values are expressed on a dry weight basis.

3. Results

3.1. Substrates and plant growth

The initial chemical analysis of the substrates illustrated that the contaminated soil was extremely acidic, nutrient poor and contained extremely high levels of PTEs, especially Cu, Pb and Zn (Table 1). In comparison to the source-separated and commercial composts, the MSW-derived compost was very similar in most of its chemical and physical properties, with the exception of its higher EC and PTE content. Whilst these PTE values were significantly greater than the other composts, and may cause concern if repeatedly applied to agricultural land, the concentrations of Cu and Zn remained very low in comparison to those already present in the contaminated soil.

Without any soil amendment, the seeds failed to germinate in the contaminated soil, and even after lime amendment, both the above- and below-ground biomass remained very low (Fig. 1). Overall, lime application had no significant effect on the above-ground biomass in any of the compost treatments ($P > 0.05$, $n = 72$), and actually resulted in a negative growth response in the green waste-derived compost treatment ($P < 0.05$, $n = 6$). Apart from this,

lime had no significant effect ($P > 0.05$, $n = 30$) on below-ground biomass from any of the other compost treatments. Of all the chemical variables, only pH was significantly affected by lime application across the whole dataset ($P < 0.001$, $n = 72$), although surprisingly there was no significant increase in soil solution Ca in any of the compost treated soils after the addition of lime ($P > 0.05$, $n = 72$).

With the exception of the green waste-derived compost, all the composts enhanced both above- and below-ground biomass production in the contaminated soil in the absence of lime (Fig. 1). The peat-based compost produced the highest above-ground biomass ($P < 0.05$, $n = 72$), although there was no significant difference between the GFP, MSW and PB composts in below-ground biomass measurements ($P > 0.05$, $n = 36$). Surprisingly, neither compost nor lime addition induced a significant change in soil solution nitrate, ammonium or phosphate concentration (Table 2).

3.2. PTE uptake and availability

Fig. 2 illustrates the PTE content of above-ground biomass of *A. capillaris* L. grown in the 12 different treatments (five composts and control, all with or without lime addition). With the exception of the green waste-derived compost, all the lime-amended composts produced plants with reduced foliar PTE content in comparison to the limed control treatment without compost. As there was no plant growth in the non-lime amended control treatment, no similar comparisons could be drawn. Generally, however, foliar PTE accumulation was lower in compost treated soils when lime was not added in comparison to soil that had received both lime and compost. From EU and UK regulations [16,17], it can be seen that foliar Zn concentrations remained well below the European guidelines for safe animal feedstuffs (limit 150 mg kg^{-1}) for all treatments, whilst only the PB compost complied with Cu threshold limit of 10 mg kg^{-1} . Similarly, the foliar threshold limit for Pb of 40 mg kg^{-1} was exceeded by all treatments, whereas without lime addition, As was reduced to below detection limits (foodstuff limit 4 mg kg^{-1}) for the GF, GFP, MSW and PB treatments. Foliar Cd concentrations were below the limit of detection for all treatments (data not presented). Although no Ni could be detected in the contaminated soil, significant amounts were accumulated in the above-ground biomass from all compost treatments (range $15\text{--}109 \text{ mg kg}^{-1}$; data not presented) relative to published standards [18].

3.3. Soil solution PTE concentration change over time

From Fig. 3, it can be seen that with the exception of As, the general trend was for all PTEs to be reduced in concentration in the

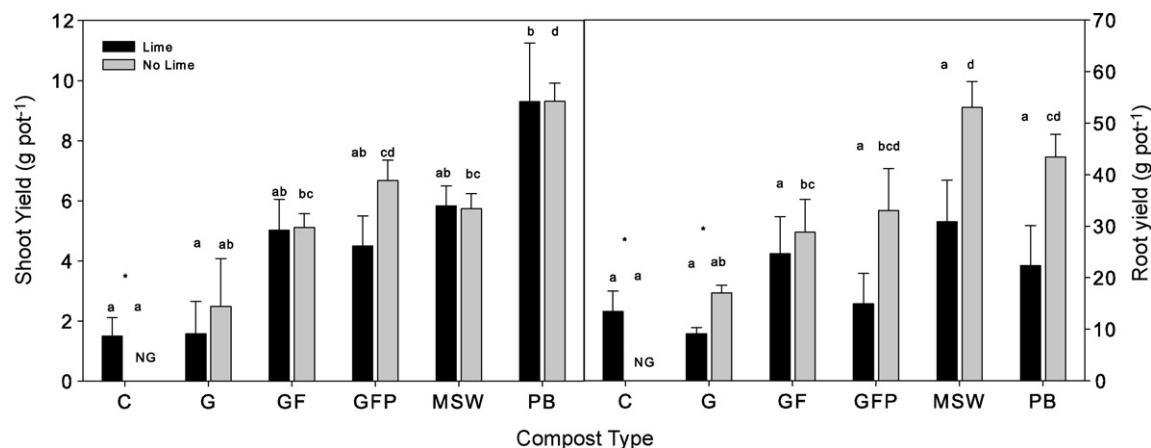


Fig. 1. Influence of compost type and lime application on root and shoot biomass after being grown in a PTE contaminated soil for 2 months. (*) denotes significant difference ($P < 0.05$) between lime treatments for each compost treatment, while different letters for each lime treatment denote significant differences ($P < 0.05$) between compost treatments. NG = no growth.

Table 2
Chemical properties of the soils and soil solutions from each treatment after 64 days of growth. Soil solution values in mg l^{-1} , all other values in mg kg^{-1} , apart from where stated separately. BD = below LOD ($<3.75 \text{ mg kg}^{-1}$ for pseudo-total PTEs, and $<0.05 \text{ mg kg}^{-1}$ for extractable PTEs).

	Soil (Control)		Treatment G		Treatment GF		Treatment GFP		Treatment MSW		Treatment PB	
	Lime	No lime	Lime	No lime	Lime	No lime	Lime	No lime	Lime	No lime	Lime	No lime
Moisture content (%)	10.1 ± 1.7	13.3 ± 1.7	20.5 ± 1.4	22.4 ± 1.6	20.4 ± 1.6	21.0 ± 1.4	21.1 ± 2.9	23.3 ± 1.7	20.6 ± 1.5	24.4 ± 2.5	29.6 ± 2.8	26.7 ± 4.8
Organic matter (%)	5.4 ± 3.2	2.6 ± 0.2	6.7 ± 0.8	7.8 ± 1.7	6.3 ± 1.6	9.9 ± 1.5	8.0 ± 1.8	8.7 ± 0.3	7.2 ± 1.2	9.8 ± 2.8	12.4 ± 1.4	9.0 ± 2.1
Soil solution pH	7.08 ± 0.07	2.91 ± 0.04	7.24 ± 0.03	6.83 ± 0.19	7.19 ± 0.06	6.92 ± 0.07	7.34 ± 0.04	6.94 ± 0.06	7.27 ± 0.03	7.29 ± 0.02	7.27 ± 0.04	4.28 ± 0.09
Soil solution EC (mS cm^{-1})	1.5 ± 0.3	1.0 ± 0.1	1.0 ± 0.1	0.8 ± 0.1	2.1 ± 0.3	1.7 ± 0.3	2.1 ± 0.4	2.5 ± 0.6	1.6 ± 0.3	2.4 ± 0.2	1.6 ± 0.4	1.0 ± 0.1
Soil solution NO_3^-	0.50 ± 0.20	2.69 ± 0.54	0.76 ± 0.07	1.02 ± 0.18	0.92 ± 0.18	1.35 ± 0.14	2.33 ± 1.12	1.40 ± 0.10	1.16 ± 0.20	1.26 ± 0.09	1.38 ± 0.19	1.61 ± 0.13
Soil solution NH_4^+	0.12 ± 0.07	5.10 ± 0.61	0.03 ± 0.01	0.04 ± 0.02	0.05 ± 0.02	0.07 ± 0.01	0.06 ± 0.02	0.15 ± 0.07	0.02 ± 0.01	0.07 ± 0.01	0.11 ± 0.08	0.03 ± 0.01
Soil solution P	0.25 ± 0.02	0.20 ± 0.00	0.32 ± 0.03	0.31 ± 0.02	0.27 ± 0.02	0.61 ± 0.30	0.27 ± 0.02	0.29 ± 0.02	0.26 ± 0.02	0.23 ± 0.01	0.24 ± 0.01	0.19 ± 0.01
Soil solution K	1.68 ± 0.94	6.56 ± 1.21	89.3 ± 16.8	79.9 ± 22.5	122 ± 44	164 ± 28	109 ± 22	85.6 ± 33.8	11.5 ± 4.9	13.6 ± 3.0	BD	0.71 ± 0.11
Soil solution Na	25.8 ± 4.8	30.8 ± 5.3	63.4 ± 14.7	40.6 ± 5.6	156 ± 33	145 ± 22	182 ± 42	188 ± 41	136 ± 27	205 ± 30	86.9 ± 24.5	53.8 ± 7.9
Soil solution Ca	158 ± 22	16.7 ± 4.8	88.2 ± 11.5	66.1 ± 11.0	160 ± 13	124 ± 19	156 ± 27	179 ± 32	162 ± 22	195 ± 15	151 ± 39	78.0 ± 10.1
Soil solution humic C	1.86 ± 1.05	0.64 ± 0.46	4.96 ± 0.43	4.35 ± 0.79	5.51 ± 1.38	7.99 ± 0.80	5.67 ± 0.69	5.50 ± 0.97	2.96 ± 0.37	3.44 ± 0.34	5.19 ± 0.44	0.56 ± 0.04
Total As	352 ± 38	259 ± 60	472 ± 67	335 ± 42	421 ± 103	412 ± 68	454 ± 43	423 ± 23	445 ± 26	525 ± 101	332 ± 83	406 ± 32
Total Co	9.14 ± 0.70	BD	6.35 ± 0.49	BD	5.61 ± 1.09	BD	8.29 ± 6.20	BD	BD	BD	4.32 ± 1.67	BD
Total Cr	BD	BD	BD	6.22 ± 1.66	BD	BD	BD	BD	21.0 ± 14.4	6.81 ± 0.25	BD	BD
Total Cu	5420 ± 430	4736 ± 1023	2610 ± 285	4296 ± 967	3635 ± 160	3279 ± 568	3676 ± 616	3367 ± 100	3112 ± 62	3597 ± 267	4386 ± 586	3564 ± 171
Total Mo	23.3 ± 1.6	BD	26.9 ± 2.4	BD	10.1 ± 8.8	BD	BD	4.64 ± 0.51	BD	5.62 ± 0.46	BD	BD
Total Ni	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD
Total Pb (mg g^{-1})	28.7 ± 2.5	16.9 ± 1.8	32.6 ± 17.7	20.0 ± 0.3	21.0 ± 4.1	14.3 ± 0.9	18.1 ± 1.6	19.4 ± 2.1	15.7 ± 2.6	15.6 ± 1.0	18.6 ± 0.4	21.1 ± 4.5
Total Zn	1139 ± 160	846 ± 68	742 ± 142	894 ± 87	934 ± 87	781 ± 172	1525 ± 810	1130 ± 203	690 ± 41	966 ± 159	751 ± 79	789 ± 82
HOAc extractable As	BD	BD	BD	BD	BD	BD	BD	0.37 ± 0.19	BD	BD	BD	BD
HOAc extractable Co	0.16 ± 0.09	BD	0.40 ± 0.02	0.11 ± 0.01	0.28 ± 0.07	BD	0.39 ± 0.06	BD	0.55 ± 0.06	0.15 ± 0.02	0.25 ± 0.06	BD
HOAc extractable Cr	0.26 ± 0.03	0.15 ± 0.03	0.37 ± 0.04	0.26 ± 0.01	0.30 ± 0.02	0.26 ± 0.01	0.33 ± 0.00	0.26 ± 0.01	0.35 ± 0.01	0.33 ± 0.02	0.32 ± 0.01	0.23 ± 0.05
HOAc extractable Cu	1.23 ± 0.08	1.68 ± 1.04	0.70 ± 0.26	BD	0.47 ± 0.30	BD	0.41 ± 0.15	BD	3.12 ± 0.38	6.01 ± 0.69	0.12 ± 0.06	BD
HOAc extractable Mo	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD
HOAc extractable Ni	1.23 ± 0.86	BD	3.15 ± 0.16	BD	2.42 ± 0.70	BD	3.41 ± 0.62	BD	5.30 ± 0.86	1.17 ± 0.23	1.93 ± 0.97	BD
HOAc extractable Pb	917 ± 351	138 ± 37	559 ± 82	136 ± 46	430 ± 113	75.9 ± 18.5	345 ± 132	104 ± 32	219 ± 44	201 ± 26	246 ± 66	137 ± 42
HOAc extractable Zn	BD	BD	0.65 ± 0.04	1.62 ± 0.47	0.30 ± 0.15	1.73 ± 0.12	0.59 ± 0.14	2.08 ± 0.25	11.2 ± 1.9	14.7 ± 1.7	BD	BD

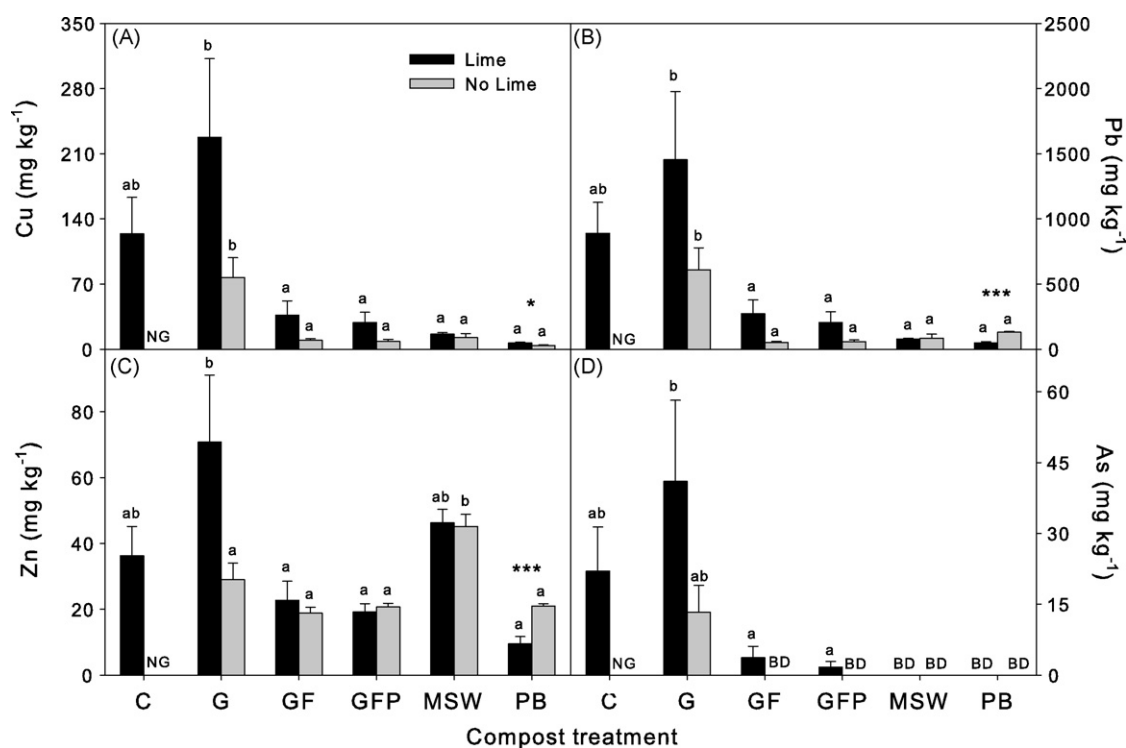


Fig. 2. Influence of compost type and lime on the foliar PTE content of plants grown in a PTE contaminated soil for 2 months. (*) and (***) denote significant difference ($P < 0.05$ and $P < 0.001$) between lime treatments for each compost treatment, while different letters denote significant differences between compost treatments for each lime treatment ($P < 0.05$). NG = no growth, BD = below limit of detection ($< 3.75 \text{ mg kg}^{-1}$).

soil solution over the 64 day experimental period. Lime amendment had a highly significant effect on PTE concentrations in the contaminated soil control treatment, inducing a 20-fold reduction in soil solution Cu and Pb concentrations, and a 2-fold reduction in Zn. In contrast, lime addition resulted in a significant rise in soil solution As concentration ($P < 0.01$, $n = 12$). This finding for As is mirrored for all other compost treatments, with the exception of the MSW treatment, where no significant difference was recorded ($P > 0.05$, $n = 12$). With the exception of the control treatment, lime also caused a significant increase in the amount of Zn in soil solution by day 64. However, no consistent response pattern was observed for Cu and Pb across all the compost amendment treatments.

The relationship of PTE concentrations with soil solution pH is shown in Fig. 4. Overall, across all time-points and treatments, pH was significantly negatively correlated with soil solution Cu, Pb and Zn ($P < 0.01$, $n = 334$) with the threshold for significant PTE solubilization occurring at around pH 3.5. In contrast, As mobilization was significantly positively correlated with soil solution pH ($P < 0.01$, $n = 334$) with the threshold value for mobilization being around pH 6.0.

4. Discussion

4.1. Use of composts in land restoration

This study clearly demonstrated that a range of waste-derived composts of varying quality can all be used to alleviate PTE toxicity in a heavily contaminated soil. Further, the success of plant establishment was not correlated with legislative compost standards used to conventionally assess compost quality [18]. Typically, these standards are formulated specifically for the use of composts destined for agriculture, horticulture and amenity sites (e.g. public parks and gardens). While this approach is justified where public or environmental health may be compromised, we feel that these rigid standards will provide legislative and social barriers for use

of composts in post-industrial, contaminated sites. Considering the large amounts of low grade composts that are now being produced in efforts to divert waste from landfill (e.g. MBT- and MSW-derived composts), there is an urgent need to find good uses for these products. Alongside others, our research suggests that remediation and stabilization of PTE contaminated sites may provide a viable option but that appropriate standards need to be developed to promote industry adoption of this approach. Similarly, research also suggests that these composts can also accelerate the removal and stabilization of organic pollutants present in soil [19].

4.2. Metal dynamics in soil

With the exception of As, PTE concentrations in the soil solution progressively declined over the 64 days of the trial. This response pattern can be attributed to several factors which were most likely to have occurred simultaneously. Firstly, some leaching of PTEs from the soil matrix may have occurred in response to the regular watering regime. However, based on the vast reserves of PTEs in the soil and the fact that the contaminated soil has been exposed to decades of leaching (annual rainfall 840 mm) we do not think this can explain all of our findings. This hypothesis is supported to some extent by the reduction in soil solution electrical conductivity in all treatments and particularly for Zn in the unamended control soil where no plant growth occurred. Secondly, a small reduction in soil solution PTE concentration could have occurred in response to plant foliar uptake. In this case, however, it would be expected that the soil solution would be rapidly replenished due to desorption of PTEs from the solid phase. PTEs may also have become sorbed onto root surfaces. Although not quantified here due to the impossibility of separating soil particles from roots, a study by Ginn et al. [20] suggests that this could induce significant changes in PTE mobility in plant-soil systems. Thirdly, PTE reduction could have occurred due to progressive binding of PTEs to the added compost which is known to be rich in metal binding sites [5,21]. Concurrent with

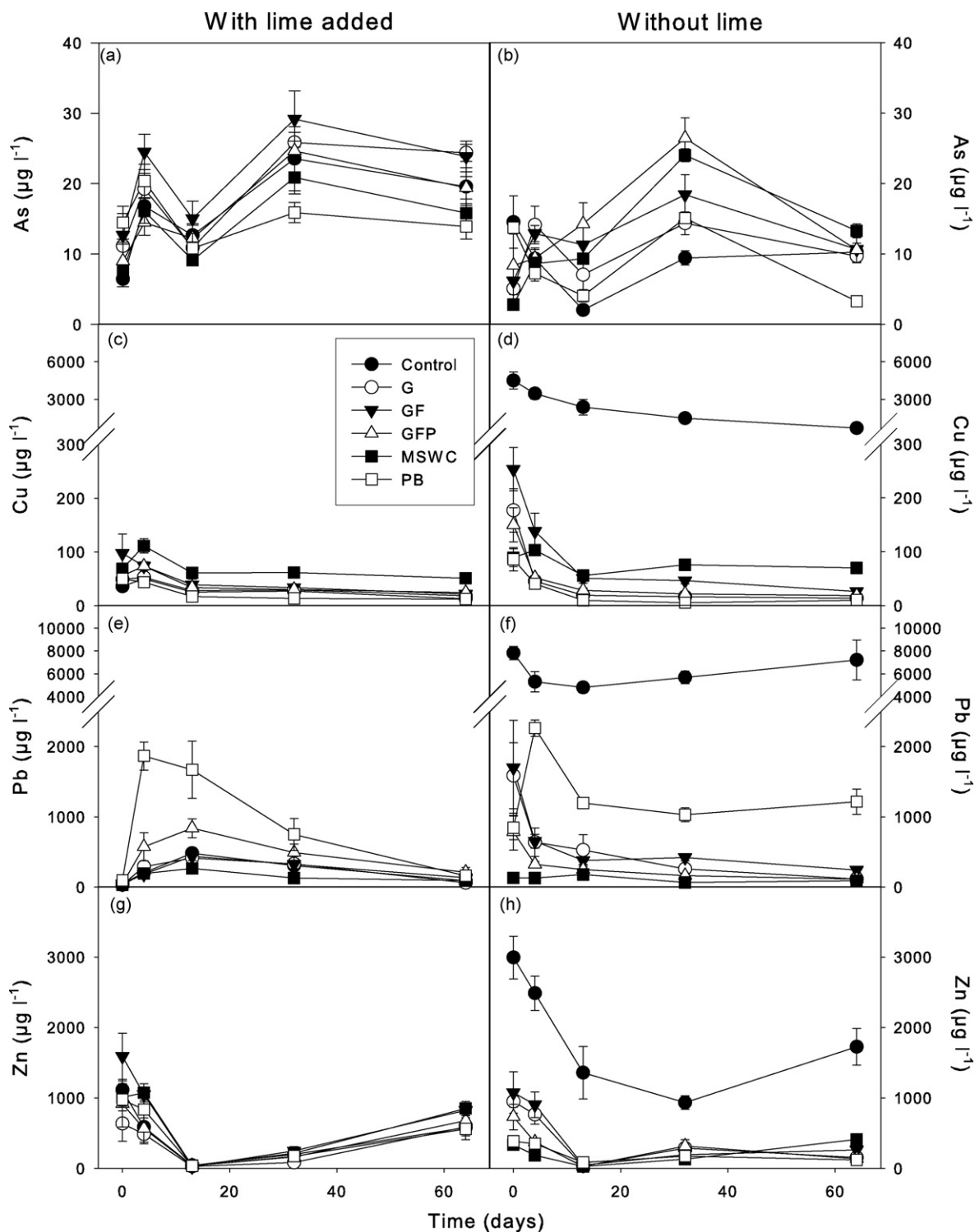


Fig. 3. Influence of compost type and lime on the temporal dynamics of PTEs in soil solution over a 2 months growth period. (a) Arsenic with lime, (b) arsenic without lime, (c) copper with lime, (d) copper without lime, (e) lead with lime, (f) lead without lime, (g) zinc with lime, (h) zinc without lime.

this PTE binding, the composts induced a gradual alkalisation of the soil which would induce precipitation of metal hydroxides and carbonates making them less bioavailable [22]. Although CaCO_3 addition may also have induced metal precipitation in the soil [7], the observation that a significant reduction in PTE concentration occurred in the non-limed treatments indicates that compost may have a greater liming potential due to its stronger ability to buffer soil pH.

In the case of Pb, the temporal pattern in soil solution appeared to be highly compost specific with the response largely related to the differential compost-induced shifts in pH [5]. In some cases, compost addition appeared to transiently stimulate Pb mobilization. Schwab et al. [23] also reported an increase of 20 mg Pb l^{-1} in leachate collected from a contaminated soil amended with aged cattle manure. They attributed this increase to high levels of dissolved organic C (DOC) in the manure which would theoret-

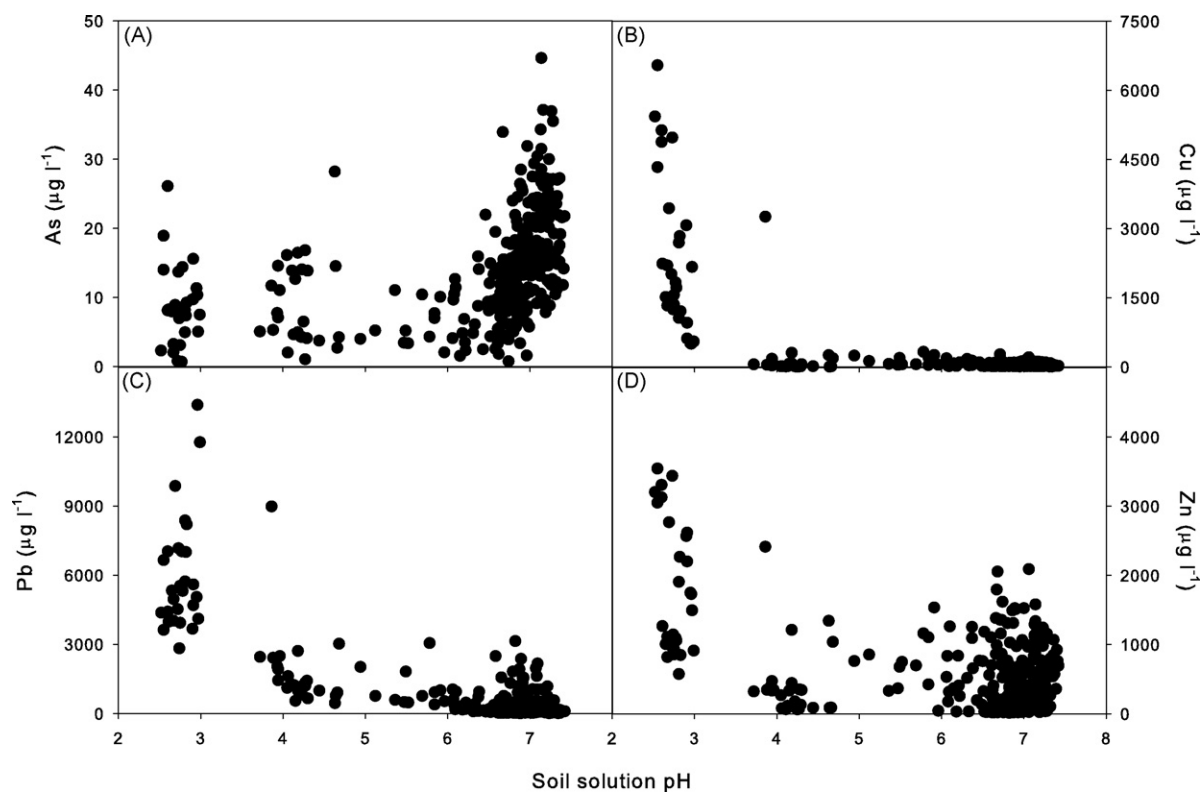


Fig. 4. Relationship between soil solution pH and PTE concentration ($n=334$): (a) As concentration, $r^2=0.393$, $P<0.01$; (b) Cu concentration, $r^2=-0.667$, $P<0.01$; (c) Pb concentration, $r^2=-0.791$, $P<0.01$; (d) Zn concentration, $r^2=-0.491$, $P<0.01$.

ically lead to increased PTE complexation, reduced sorption and greater rates of vertical mass transfer in soil. Our results, however, show a significant negative correlation between dissolved humic substances and Pb in soil solution ($r^2=-0.315$, $P<0.01$). This relationship can partially be explained by the fact that the treatments with the highest humic substance content also had the highest pH ($r^2=0.456$, $P<0.01$).

Although As binds strongly to both Fe and Al hydroxides, and to a lesser extent organic matter, this binding is inversely correlated with pH as occurred in this study [24]. From a risk assessment perspective it is unfortunate that both lime and compost stimulated As release into the soil solution. This finding suggests that there is a fine balance between immobilizing some PTEs whilst preventing the release of others. From Fig. 4 it can be seen that the safest range to bring about soil remediation without risking PTE release lies in the range pH 5–6. From this perspective, our results suggest that co-addition of lime and compost should be moderated by a thorough optimization of rate, and that takes into account the liming potential of the compost itself. Fortunately, this pH is likely to be suitable for most plant species used in land restoration. As the pH and PTE buffering capacity varies significantly between different compost types, the rate of compost application required to achieve the optimal pH for PTE immobilization requires careful consideration. Currently, compost application rates for restoration are normally chosen based on either their availability, economic cost, PTE loading or nutrient content but not on their de-acidifying potential. It would therefore be useful to undertake further scientific trials to try and characterize different compost types in terms of 'lime equivalents'. In particular, a correlation of these buffer potential results with other measures which can be simply implemented by industry would be desirable (e.g. near infrared reflectance spectroscopy [25]).

4.3. Plant growth and PTE accumulation

The compost-induced increase in both above- and below-ground biomass in the PTE contaminated soil contrasts with findings from some previous studies [26] while remaining in line with others [27]. This suggests that the impact of compost is highly context specific. In addition, our results show that it is also highly compost specific. This compost-induced alleviation of phytotoxicity has been ascribed to an enhanced nutrient availability and physical structure of the substrate. However, it is also possible that the composts introduced keystone species that were previously absent in the highly acidic and contaminated substrate. These new organisms may have provided additional functionality to the soil ecosystem (e.g. mesofauna such as collembola to stimulate organic matter turnover, nitrifying bacteria to facilitate enhanced N cycling, mycorrhizal symbionts to enable better stress tolerance, etc). Although compost application can induce changes in soil microbial diversity [28], in many studies composts have not resulted in a significant shift in microbial community structure [29,30]. This suggests again that compost response is highly context specific and probably relates to the wide diversity in microbial community structure between different compost types as well as that of the substrate it is introduced into [31]. Further work is therefore required to determine how changes in diversity may impact upon their subsequent environmental response.

Although routinely used for remediating PTE contaminated sites, plants in the lime-treated soil responded poorly in comparison to the composts presumably due to the high rate of application in this experiment, and its lack of balanced nutrients and an increase in some PTEs. As discussed previously, the addition of lime therefore requires careful optimization where organic matter is also added.

Despite much higher levels of As, Cu, Pb and Zn present in the MSW compost, we found that this had little effect on plant uptake, with the exception of Zn. This suggests that total PTE concentrations in composts may not provide a reliable indicator of PTE phytoavailability. Further work is therefore required to determine the chemical form and long-term stability of PTEs in composts added to soil.

5. Conclusions

We conclude that the use of composts for biostabilisation of an acidic, PTE contaminated soil was successful in terms of increasing the chemical status of the soil, and therefore the biomass of *A. capillaris* L. These effects were not greatly augmented by the addition of lime, and in some cases lime application actually decreased yield and increased PTE uptake. We conclude that with compost application to PTE contaminated sites, careful consideration of soil pH is required to ensure optimal PTE immobilization and that further work be carried out to develop new tools for predicting the neutralizing potential of different compost types. Whilst yield was greatly increased, the PTE content of the above-ground biomass is of concern, with potentially toxic levels of Cu and Pb present in leaves from most treatments. We therefore suggest that care be taken when selecting species to grow on sites stabilised with composts to ensure that 'metal excluding' species or varieties (e.g. *Festuca rubra* cv. Merlin) are chosen to reduce the risk of animal toxicity due to grazing and ingestion of high levels of PTEs. With regard to MSW-derived composts, further work is required to ensure that their higher PTEs remain in an unavailable form in the long term.

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