



# Article A Geochemical and Agronomic Evaluation of Technosols Made from Construction and Demolition Fines Mixed with Green Waste Compost

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Abstract: Construction and demolition fines (C&D-fines) and green waste compost (GWC) are two commonly generated urban waste materials that represent repositories of geochemical value. Here technosols were produced from volumetric mixtures of these materials ranging from 0-100% C&Dfines, with the remaining proportion comprised of GWC. Agronomic assessment was carried out by way of pot and rhizobox plant growth experiments with ryegrass, barley and pea to determine germination, plant mass and rooting behaviours. Geochemical and mineralogical evaluation was achieved by soil pore water solution measurements combined with X-ray powder diffraction analyses respectively, to characterise the technosols and their distinct deviations from a reference agricultural geogenic soil (soil). The results demonstrated that germination, growth and root mass/surface area of vegetation were up to 80-fold greater after 30-days in the technosol composed of equal volumes of the two materials (50% C&D-fines: 50% GWC) compared to the soil. High concentrations of Ca and Mg in pore waters (550–800 mg  $\cdot$ L<sup>-1</sup>) were dominant features of the technosols, in contrast to the soil (<50 mg·L<sup>-1</sup>), resulting from gypsum and calcite enrichment of the C&D-fines. In contrast, the GWC represented a source of soluble K ( $450-1000 \cdot \text{mg} \cdot \text{L}^{-1}$ ). Highly elevated Ca concentrations in extended leaching tests of the C&D-fines reflected ongoing gypsum dissolution, whereas soluble Mg and K were rapidly depleted from the GWC. In summary, short-term performance of the technosols as plant growth substrates was strong despite their geochemical and mineralogical distinction from soil. Gleaning additional geochemical value from combining urban wastes in this way is potentially suited to myriad scenarios where geogenic soils are contaminated, sealed or otherwise absent. Further assessment will now be needed to determine the geochemical longevity of the technosols before wider scale applications can be recommended.

Keywords: technosol; urban soil; pore water; gypsum; green waste compost; construction waste

# 1. Introduction

In recent years, increasing efforts have been made to repurpose urban wastes to produce fertile soil-like plant growth substrates that can be used for a variety of applications where access to soil is limited, such as where impermeable/sealed urban areas pervade or where topsoil is polluted or denuded [1–4]. These types of artificial substrates, whose characteristics and pedogenesis are dominated by their technical origin, are sometimes called technical soils or technosols [5]. Depending on their end-use, they may be engineered to comprise a balance of free-draining mineral and organic materials which provide a balance of nutrients and do not leach excess pollutants [6]. Several studies have successfully constructed technosols with favourable soil-like properties that are able to perform a wide range of functions from plant growth and decorative greening to active sequestration of  $CO_2$  from the atmosphere [7–9]. Indeed, one of the most recent analyses on the topic of constructed technosols stated that such substrates produced from a wide variety of waste materials have a high potential to provide multiple soil functions in urban areas [10], with



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**Copyright:** © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). applications not limited to greening, but also including the growth of food crops [11]. An additional advantage of urban applications arises when technosol components can be sourced locally to their end usage, avoiding long-distance transportation of wastes for disposal by other means [12], or similar transportation related costs incurred securing adequate supplies of soil ex-situ.

Both mineral and organic derived urban waste materials are now vastly abundant and widely recycled. An example of such material are construction and demolition material (C&D), of which 3.5 m tonnes are produced annually in Scotland alone (2007 data [13]). One of the first steps of processing C&D for recycling involves the removal of coarse materials from the mixture to leave a material known as C&D-fines, with a particle size distribution similar to soils (<15 mm). These fines are also composed of soil that is inevitably incorporated into C&D, but their bulk is primarily concrete, cement, plaster, wood, metals, and plastics [13]. Whilst the majority of C&D can be recycled or reused, C&D-fines can comprise a substantial portion of all C&D by mass and are most likely destined for landfill. Such C&D-fines are characterised by highly variable concentrations of inorganic elements and organic compounds as a result of their heterogeneous nature [14]. Separately to C&Dfines, increasing volumes of composted organic wastes have also arisen in the last 20 years as a result of ever more strict targets to reduce biodegradable municipal wastes disposed of to landfill [15]. This has resulted in the application of composted organic wastes for large scale soil manufacturing, replacement and improvement projects [7,16]. In Scotland 225,000 tonnes of compost were produced in 2017 with nearly half of that derived from green waste sources [17]. In common with mineral-derived wastes, organic wastes also exhibit wide ranging chemical properties depending on their source materials, along with their biological, chemical and physical maturity [18]. Therefore, a clear abundance of C&D-fines and organic waste base materials exist that could be utilised to create technosols. Such substrates have been variously produced and tested previously, but generally these have consisted of waste materials blended with extant soil [10,19,20], with few studies testing technosols produced without the input of geogenic soils [11]. Therefore, there is a paucity of detailed study of technosols produced solely from wastes in terms of mineralogy, geochemistry and plant growth performance, and it was thus deemed pertinent to conduct the following study.

The aims of this study were to: (1) manufacture a range of soil-like substrates (technosols) using solely C&D-fines and green waste compost; (2) assess key mineralogical and geochemical characteristics of these technosols distinguishing them from a reference agricultural geogenic soil; (3) test selected plant performance parameters (germination, growth and root mass); (4) and evaluate the results in relation to the use of waste materials to produce soil-like substrates for a variety of applications.

#### 2. Materials and Methods

## 2.1. Materials Selection and Characterisation

Two base components were selected for use in this study according to ease of local availability in bulk quantity. Construction and demolition waste fines (C&D-fines) and Green Waste Compost (GWC) accredited to BSI PAS100 standard were supplied by Binn Group Ltd. (Perth, UK) which is the largest independent waste management company in Scotland. Both materials were supplied at particle sizes of <15 mm. A geogenic reference agricultural topsoil (<30 cm depth to surface) was included as a control, hereafter referenced to as "soil", to which the technosols could be compared. This soil was classified as a freely drained humus iron podzol ("Entic Podzol" [4]) of sandy-loam texture developed on old red sandstone [21] and was collected from an upland farm near Laurencekirk (Aberdeenshire, UK; 56.53° N 2.32° W). Following their collection all materials were airdried in a greenhouse at 18 °C with occasional turning for three weeks, then sieved to a particle size of <6 mm to remove larger debris, resulting in a size fraction suitable for pot testing. Sub-samples were further sieved to <2 mm for mineralogical and chemical analysis. Total carbon and nitrogen concentrations (C%, N%) were determined for soil, C&D-fines

and GWC, using a Flash EA 1112 Series Elemental Analyser (Thermo Scientific, Waltham, MA, USA).

Detailed mineralogical analyses were performed on the soil and C&D-fines. The air dried and sieved materials described above were prepared for X-ray powder diffraction (XRPD) by McCrone milling 3 g of sample for 12 min in ethanol and spray drying the resulting slurry to obtain random powder specimens as described previously by Hillier [22]. Diffraction data were recorded by scanning from 4–70 °C on a D8 instrument (Bruker, Billerica, MA, USA) using Ni-filtered Cu-K $\alpha$  radiation, a motorized anti-scatter screen, and a Lynxeye XE detector. Identification and quantification of the minerals within the soil and C&D-fines from the XRPD data was carried out using the full pattern summation approach implemented in the powdR package for R [23]. Briefly, observed diffraction data were modelled as the sum of contributions from pure crystalline (e.g., quartz), disordered (e.g., clay minerals) and amorphous components (e.g., glass), from which accurate quantification was achieved using Reference Intensity Ratios [24]. Final quantitative estimates for the mineral composition of each base material are expressed in terms of weight percent of crystalline and disordered soil mineral components.

In order to characterise and quantify the aqueous removal (leaching) of elements from the soil, C&D-fines and GWC, a leaching column test was performed. The procedure used here followed that of Beesley et al. [25] with minor modifications. Duplicate glass columns (XK50, Pharmacia Biotech, Amersham, UK), 20 cm long with a 5 cm internal diameter were packed with 50 g of air-dried material, as described above. Columns were leached upwards from their base with de-ionised water (pH 5.5) until saturation, whereby a constant flow rate was maintained (1 mL·min<sup>-1</sup>) by a peristaltic pump. Leaching from the base was favoured to gravitational extraction to reduce preferential flow paths and ensure as full leaching of the matrix as possible. Leachates were collected every 15 min until 120 min, resulting in 8 samples (fractions, denoted "F") in total. After filtration (0.45  $\mu$ m) samples were analysed for dissolved organic carbon (DOC) and total dissolved nitrogen (TDN), measured using a TOC-VE instrument (Shimadzu, Tokyo, Japan). Further elemental analysis of the leachates (As, Ca, Cr, Cu, K, Mg, Na, total dissolved phosphorous (TDP), Pb & Zn) was carried out by ICP-MS (XSERIES 2 instrument; Thermo Scientific, Waltham, MA, USA). A rhodium standard was added to each sample to monitor and compensate for changes in instrument sensitivity during analysis. Concentrations were converted to mass using the volume of leachate obtained and mass of soil/material in each column, then converted into  $mg \cdot kg^{-1}$  leached during the total duration of the test following the method in Mitchell et al. [26].

## 2.2. Technosol Production and Testing

Following the characterisation of the materials as described above, the technsols were created by mixing different volume ratios of C&D-fines and GWC (Table 1) in a cement mixer until, as far as possible, a homogenous mixture was achieved. Thereafter bulk mixtures were retained for the experimental procedures described as follows.

**Table 1.** Composition of the technosols and their application in experimental work, as indicated by 'x'. Term C&D denotes construction and demolition fines and GWC denotes green waste compost.

		Components	Experiment		
	C&D % vol.	GWC % vol.	soil % vol.	pot experiment	rhizoboxes
50/50	50	50	0	х	х
75/25	75	25	0	х	x
90/10	90	10	0	х	
100/0	100	0	0	x	
Soil	0	0	100	x	x

#### 2.2.1. Pot Experiments with Ryegrass

Equal volumes of the four different technosols and of the soil were placed into separate 1 L pots, with 5 replicates per mixture. Filter papers (Whatman no.2) were placed at the bottom of each pot prior to filling and moistened to prevent the unconsolidated substrates being washed through the pots. The experiment was set up in a growth chamber to ensure controlled conditions. The positions of the pots in the growth chamber were randomised and all pots were irrigated with de-ionised water until the substrate was saturated, and left to drain naturally for 48 h, after which their weight was maintained by watering every two days, if required. One rhizon pore water sampler (Eijkelkamp Agrisearch Equipment, The Netherlands) was inserted at an angle of approximately 45° in each pot, before 100 seeds (approx. 0.3 g) of perennial ryegrass (*Lolium perenne*) were evenly distributed on the surface of each pot. Experiments lasted for 30 days (16-h-day/8-h-night cycle, 17 °C and 70% relative humidity) and were used to determine ryegrass germination and growth.

Pore water samples were collected from the rhizon samplers in each pot using removable needles and vacuum tubes twice, at 26 and 30 days after germination of the ryegrass; a 4-day period between sample extraction was found sufficient to ensure that a great enough volume of pore water was collected for subsequent laboratory analysis, resulting in 10 pore water samples per technosol/soil. After pore water sampling had finished, the number of [live] germinated seeds were counted before ryegrass harvest was performed on the same day (day 30). Shoot dry mass per pot was measured after plant tissues had been air-dried for three days at 30 °C. All pore water samples were analysed for the same parameters as described above (Section 2.1) for column leachates. These samples did not require filtration because the rhizon sampler performs 0.45  $\mu$ m filtration in-situ as pore waters are extracted.

#### 2.2.2. Rhizobox Experiment with Pea and Barley

The best performing technosols from the ryegrass pot experiment (50/50 and 75/25) were further tested for root proliferation in a rhizobox experiment. Rhizoboxes manufactured from PVC ( $40 \times 5 \times 2$  cm) were used to channel root growth into a narrow aperture, which could be viewed or scanned via a removable shutter, to determine root architecture/measure root surface area. Replicate rhizoboxes (three per substrate and plant species) were filled from their base with 180 g of dried industrial sand as an inert material, topped up to the edge with either the 50/50 or 75/25 technosols, then irrigated with de-ionised water until the substrate was saturated and left to drain for 48 h at ambient temperature.

For this test barley and pea were used because each produces a different root architecture, barley yielding more prolific fine root hairs, whilst pea produces numerous thick primary and secondary roots. Seeds of barley (*Hordeum vulgare* L. cv. Optic) and pea (*Pisum sativum* L. cv. Corus) were surface sterilized by washing in 70% ethanol for 1 min, followed by a 5% H<sub>2</sub>O<sub>2</sub> wash for 5 min, and finally five serial washes with sterilised distilled water. After sterilisation, the seeds were pre-germinated in Petri dishes with wet filter papers in an incubator at 25 °C for three days. Plantlets that had similar root development were transplanted to rhizoboxes, sowing one barley or pea plantlet 1 cm below the surface in each rhizobox. In order to promote nodulation, pea plantlets were inoculated with 2 mL ( $1 \times 107$  UFC mL<sup>-1</sup>) culture of Rhizobium leguminosarum bv. viciae grown on liquid tryptone yeast (TY) medium at 28 °C for two days (Legume Technology, East Bridgford, Nottingham, UK).

Plants were cultivated in a growth chamber under controlled conditions (16-h-day/ 8-h-night cycle, 17 °C and 70% relative humidity) for a duration of 30 days. Rhizoboxes were placed at an angle of  $45^{\circ}$  to favour a uniform root development and were watered every two days. After 30 days roots were revealed by removing a sliding shutter, washed out over a 2 mm sieve in order to remove soil/substrates and kept in 30% (*v*/*v*) ethanol until their analysis. Clean roots were scanned with an Expression 10000XL (Epson, Tokyo, Japan) scanner at 600 dpi resolution, and root parameters analysed to determine surface area using winRHIZO Pro (Regent Instruments Inc., Quebec, QC, Canada) software.

#### 2.3. Statistical and Data Analysis

Where appropriate statistical analysis was carried out in SPSS v.14 (IBM, Chicago, IL, USA). Briefly, data were tested for normality and, if required, transformed logarithmically for further statistical analysis by one-way ANOVA to assess differences amongst technosols. Accordingly, differences amongst means were further assessed using Tukey's post-hoc testing. Significance was assigned to p < 0.05.

## 3. Results

#### 3.1. Geochemistry and Mineralogy

The components of the substrates displayed distinctly different C and N concentrations, largely reflecting their origin: soil, C&D-fines and GWC had C% of 2.2, 12 and 31 respectively and N% of 0.1, 0.7 and 2% respectively. To some extent the mineralogy of the soil and C&D-fines were very similar, reflecting the inevitable incorporation of soil and local parent material into the waste material during demolition and transportation. More specifically, the mineral composition of the soil was dominated by common soil minerals including quartz (46%), feldspars (11% plagioclase and 11% K-feldspar), mixed layer dioctahedral clay minerals (16%), muscovite (8%) and kaolinite (4%), whilst the composition of C&D-fines also contained quartz (41%), feldspars (17% plagioclase, 7% K-feldspar) and muscovite (5%). Where the C&D-fines substantially diverged from the soil was in the presence of gypsum (13%) and calcite (7%). Further to these mineral components of C&D-fines, a diffuse background in the diffraction data associated with X-ray amorphous components was also noted, which could be attributed to organic matter, glass, and plastic, all of which were observed by eye in the base material (not shown).

The column leaching test was designed to promote exhaustion of the soluble pool of measured elements and indicate potential longevity of the geochemical impact of the base substrate materials on leachate chemistry. The soil leached considerably lower concentrations of K, Ca and Mg compared to both C&D-fines and GWC during the total extent of the test (Table 2). Such low concentrations for the soil could be expected since it is derived from a geogenic parent material (old red sandstone) and has been subject to weathering processes over thousands of years, unlike the C&D-fines and GWC. These geochemical differences were exemplified in the leaching curves showing high concentrations of Ca and Mg from the C&D-fines, leached most rapidly in the earliest fractions of the column test, compared to GWC and control soil (Figure 1a,c). On a per unit mass basis, the most highly leachable element measured by the column procedure was Ca, with ~4% of initial mass lost as dissolved Ca from the C&D-fines during the 120-min duration of the test (Figure 1a.), resulting in a removal of 32000 mg Ca per  $kg^{-1}$  of C&D-fines (Table 2). Notably the total amount of Ca leached from the C&D-fines was approximately 100 and 470 times than that of the soil and GWC respectively (Table 2). The highest concentrations of K were observed in the leachates from the GWC, reflected in the steep decline of the leaching curve from its F1 concentration of 1000 mg $\cdot$ L<sup>-1</sup> (Figure 1b).

Table 2 also shows that DOC and TDN removal from the C&D-fines was greater than the GWC and soil., whereas TDP removal was greatest from GWC, in common with K. Heavy metal concentrations in the leachates (e.g., As, Cr, Cu, Pb and Zn) were either low or below detection limits resulting in removals of <3 mg·kg<sup>-1</sup> (data not shown).

# 3.2. Growth Parameters of Ryegrass, Barley and Pea

Ryegrass germination and mass in the pot experiments differed greatly according to substrate composition. The technosol 50/50 produced significantly greater shoot dry mass compared to all other technosols and the soil, whilst the only technosol that did not contain GWC (100/0) resulted in significantly lower ryegrass yields than the soil (Figure 2a). In fact, GWC presence appeared the greatest determinant in ryegrass mass yield, as exemplified by the photographs of the pots before harvest (below Figure 2).

data, see Figure 1.

1 _1		Component		-
mg∙kg <sup>⊥</sup>	C&D	GWC	Soil	
DOC	6325	3402	432	
TDN	745	521	42	
TDP	17	794	0.8	
К	617	6396	47	
Ca	38416	392	82	
Mg	530	109	8.3	

**Table 2.** Total accumulated removal of dissolved organic carbon (DOC), total dissolved nitrogen (TDN), total dissolved phosphorus (TDP) and other selected elements as determined by the column leaching test ( $mg \cdot kg^{-1}$ ). Values are mean of duplicate columns; for selected leachate concentration



**Figure 1.** Column leaching experiment showing concentrations of (**a**) Ca, (**b**) K and (**c**) Mg in leachates (mg L<sup>-1</sup>) from the individual components of the technosols and soil. Each fraction "F" indicates an increment in time (see method). Values are mean of duplicate columns (error bars +/ – S.E.M). For total accumulate removal data, see Table 2.

The pH of the sampled pore water in the pot test was lowest for the control soil (pH 5.5) and similar for all substrates (pH 7; Figure 2b). Mean concentrations of Ca, K and Mg were much higher in the porewaters of all technosols (~550–800 mg·L<sup>-1</sup>, ~450–1000 mg·L<sup>-1</sup> and ~300–400 mg·L<sup>-1</sup> respectively) compared to soil (<50 mg·L<sup>-1</sup>; Figure 2b.). Heavy metals, such as As, Cr, Cu, Pb and Zn were at or below detection limits in all pore water samples (data not shown).

Following the pot test, the two most successful substrates in terms of germination and plant mass were selected for a more detailed growth and root mass test. Barley and pea shoot dry mass, as determined in the rhizobox experiment, was significantly greater in both substrates tested when compared to the soil. Further, the 50/50 technosol resulted in significantly greater shoot and root mass than the 75/25 mixture (Table 3). The 50/50 substrate yielded largest mean root surface area (RSA) measured, for barley at ~200 cm<sup>2</sup>, nearly 100 times that of the soil ( $2.5 \text{ cm}^2$ ; Table 3). Similar results were measured for pea RSA, though in the case of both barley and pea RSA, there was no significant increase for 75/25 as compared to the soil. The root scan imagery (Figure 3) shows the proliferation of many fine root hairs in the barley rhizosphere for 50/50, as compared to the soil, whilst the root architecture of pea plants was different, and consisted of a greater extent of thick secondary roots with fewer root hairs. From the root imagery it is also possible to see how the inoculation of R. leguminosarum resulted in nodulation on pea roots in the case of the 50/50 substrate, but not in the soil (Figure 3).



**Figure 2.** Pot experiment showing (**a**) Ryegrass germination (%) and shoot dry mass (g/pot) after 30 days; (**b**) Concentrations of Ca, K, Mg (mg L<sup>-1</sup>), and pH in pore water samples collected at 30 days. Pictures below x-axis show typical ryegrass mass before harvesting. All values are mean (+/–SEM), n = 10. Shoot mass bars with different letter above them indicate significant statistical differences.

Barley			Pea			
	Shoot mass (mg)	Root mass (mg)	Root Surface area (cm <sup>2</sup> )	Shoot mass (mg)	Root mass (mg)	Root Surface area (cm <sup>2</sup> )
50/50	488 (27) c	173 (28) b	191 (31) b	1430 (78) c	85 (3.1) b	130 (17) b
75/25	134 (27) b	10 (4.3) a	13 (6.4) a	519 (57) b	44 (10) a	44 (5.1) a
Soil	12 (2) a	9.4 (1.1) a	2.5 (0.5) a	37 (1.9) a	43 (2) a	37 (2.6) a

**Table 3.** Barley and pea growth parameters as measured in the rhizobox experiment. Values are means of triplicate rhizoboxes (+/- S.E.M). Values with different letter beside them indicate significant statistical differences within columns.



**Figure 3.** Rhizobox experiment showing; (**a**) pea and barley growth before removal and scanning; (**b**) pea shoot growth with root imagery below; (**c**) barley shoot growth with root imagery below.

#### 4. Discussion

# 4.1. Geochemical and Plant-Growth Performance of Technosols

Short-term plant growth performance of our technosols in terms of biomass and rooting suggests that applications for these convenient and easy-to-produce substrates would include greening, horticulture and urban agriculture. Given that our reference soil was a humus-iron podzol, with acidic tendencies and derived from sandstone, it is at the less base rich and fertile end of the Scottish soil spectrum. The 50/50 technosol produced strong ryegrass biomass, barley and pea root proliferation in comparison to the soil and other technosols tested. Geochemically the technosols are dissimilar to Scottish soils in that they exhibit high concentrations of Ca in leachates and porewaters (Figures 1 and 2), which may go some way to explaining the relatively high performance in plant growth in the technosols during the 30-day pot experiments and would compare favourably to many other Scottish soils in this regard. Mineralogically this distinction comes from the enrichment of gypsum (CaSO<sub>4</sub> 2H<sub>2</sub>O) and calcite (CaCO<sub>3</sub>) in the C&D-fines, with the latter also accounting for the circumneutral pH of porewaters sampled from the technosols (Figure 2b). Gypsum is too soluble to persist in Scottish soils, and the presence of 13% gypsum within the C&D-fines is sourced from the widespread use of plasterboard as a

building material. Together the gypsum (13%) and calcite (7%) in the C&D-fines help to account for the leaching of Ca from this material being ~470 times higher than that of the soil per unit mass (Table 2). Given the relatively high solubility of gypsum compared to all other identified minerals within the C&D-fines, ongoing leaching beyond the duration of the tests performed here would eventually result in the depletion of gypsum from the technosols composed of this material, resulting in substrates with very different geochemistry after prolonged weathering in the field; this should be borne in mind with regards to prospective applications of such composed technosols. Calcite in the C&D-fines could account for the leaching of Mg from this material being 64 times greater than the soil per unit mass (Table 2) since Mg is a common substitute for Ca in geogenic calcite. The same trends have been seen in tests of 33 different samples of mixed C&D wastes from Denmark, where releases of 200–1600 mg·kg<sup>-1</sup> Ca were measured in one stage batch leaching tests [14]. The elevated leaching of Ca in C&D-fines wastes is not surprising as concrete (containing calcite) and plasterboard (containing gypsum) comprise ~60% of total demolition arisings [13], with a fraction of the smaller particles from this bulk ending up in the C&D-fines following removal of larger concrete blocks for aggregates and the recycling of plasterboard. Thus, it follows that relatively soluble mineral sources of Ca will be a geochemical trait of technosols composed of C&D-fines, as also noted Prado et al [11]. The persistence of a soluble source of Ca may result in a substrate subject to 'exhaustion' of reserves of other nutrients and trace elements over time at different rates, resulting in unusual stochiometry in comparison to, for example, agricultural soils, especially those which are improved in a controlled manner to maintain balanced fertility, such as urban allotment soils. This could impact on their use in the long-term without 'topping-up' of some kind, for example with fertilisers or other sources of minerals (for example, wood ashes).

In other studies, reserves of available nutrients in technosols have also been attributed to their organic component, such as compost [27]. Our results also show green waste compost to be the primary source of K (Table 2; Figures 1b and 2b) and TDP (Table 2) in leachates. Such effects have also been measured in soil pore waters over 2 years in field experiments conducted on technosols made from other base materials mixed with composts [16] and is to be expected as a result of the mineralisation of compost over time. During the mineralogical analysis detailed above, additional amorphous phases that could not be accurately identified were detected, so that it was evident that C&D-fines also contained some organic matter as well as potentially glass and amorphous supplementary cementitious materials [28]. This is also evident by the high removal rate of dissolved organic carbon (DOC) from the C&D-fines, even in comparison to the GWC (Table 2). Demolition wastes in UK have been shown to comprise as much as 7% wood derived waste [13], which probably contributed to this. Previous studies have shown that water-extractable organic carbon can be leached in higher concentration from raw woody biomass compared to composted material, which is more stable [29].

#### 4.2. Optimising the Technosol Recipe

It has recently been suggested that efficacious selection of technosol components be based on a pedological assessment of their end-usage. Gonzalez-Mendez & Chavez-Garcia [20] point to the importance of matching function with form by selecting materials with suitable soil-substituting qualities, for example water holding in arid regions, or pollutant filtering in urban settings. This approach implies that some materials with suboptimal chemical, biological or physical characteristics may be discarded in preference to more optimal soil forming materials, which may be scarcer locally, when formulating technosol "recipes". Our selection was based on local availability; in Scotland 3.5 m tonnes of C&D waste is produced annually (2007 data [13]), of which a considerable proportion is the C&D-fines fraction currently destined for landfill. Based on this excess we were able to obtain the material for our experiments locally, taking those materials without other immediate markets. On this basis we formulated our technsols to include just two components. Other recent studies have created and tested technosols also on the basis of locally available materials to address local need. For example, Amaral-Filho et al. [19] created base mixtures of coal waste and geogenic soil, supplemented with additional organic amendments, to create substrates for mine land reclamation. The general addition of organic amendments for improving degraded soils and promoting vegetation cover on poorly fertile land is well established [30] and represents good practice for soil creation. Deeb et al. [31,32] conducted detailed evaluations of soil moisture retention in technosols consisting of volumes of GWC up to 50% mixed with carbonate rich excavation material (subsoil), finding that increased compost volumes favourably impacted macro-pore range, with attendant consequences to moisture retention. However, their work also discovered that such large volumes of compost had few advantageous impacts on aggregate stability of technosols without the additional impacts of earthworm working, or root biomass. Other researchers have also pointed towards scenarios where the addition of large volumes of composts to create technosols may be counter-productive to other soil functions, such as C storage, due to reduced soil bulk density following mass input of organic matter [16].

## 4.3. Potential Disadvantages of Using Wastes

Any mixture of waste materials will always have some less-than favourable qualities. Previous studies monitoring, for example, leachates derived from technosols composed from waste materials have identified high concentrations of nitrates [33] and sulphates [34] close to or exceeding legislative limits. Wastes which are not highly sorted to remove plastics and other debris, for example, may result in a visually displeasing substrate and one which is unsuitable for certain uses. Urban agricultural or allotment applications, where soils are regularly worked by hand and interaction with soils is frequent, may not be suitable outlets for technosols containing plastic and glass fragments. Recent evidence also shows that the presence of micro-plastics in soils can impact plant-growth performance [35]. In our work we did not consider the physical properties of technosols, and how this may impact plant growth, but the stability of aggregates has been suggested to represent an important factor controlling the availability of nutrients in technosols [27].

Waste materials are often highly heterogeneous and may have elevated concentrations of pollutants, depending on their origins. A study testing technosols composted of C&D materials and GWC from Mexico City determined that the concentrations of readily available heavy metals were not a limiting factor for tomato plant growth, soil pH and electrical conductivity being more important driving factors [11]. However, their study did suggest that caution be exercised when mixing mineral and organic wastes due to the potential for co-mobilisation of metals by soluble organic matter. Indeed, that is an important point in the present study because our technosols contain up to 50% of their volume in the form of organic waste. From the high cumulative removal rates of DOC from both the C&D and GWC used in our work, as compared that that of the geogenic soil, it is clear that complexation and transport of metals, and indeed organic contaminants, may be facilitated by the characteristics of the wastes used. Thence, this will be an important additional facet to study as this work progresses further, especially if urban agricultural applications of technosols are considered, whereby vegetation grown is destined for human consumption.

# 5. Conclusions

Combining two commonly available urban waste materials in simple volumetric mixtures has created technical substrates (technosols) which are geochemically distinct from geogenic soil, yet well capable of supporting ryegrass, barley and pea growth, producing vigorous above and belowground biomass. The irregular geochemistry of the technosols, compared to geogenic soil, may somewhat limit their usage if it transpires that reserves of trace elements and nutrients contained within their individual components are easily exhausted. Along with this, it remains to be seen whether measured or perceived contamination associated with some technosol [wastes] components may steer their application away from urban food growing, and towards greening substrates only. Nonetheless, geochemically and agronomically, technosols from wastes can provide a vital outlet for surplus materials which may otherwise be disposed of before their value is exhausted.

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