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Research article

Can recovered road sweeping wastes provide a soil or soil amendment alternative? An investigation of temporal variability of physico-chemical parameters

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ABSTRACT

By 2050, 90% of the Earth's topsoil is considered 'at risk' (according to the UN). Within the UK, more than 6 million hectares are at risk of compaction or erosion and soils remain one of the largest components of landfills (e.g. 28 million tonnes in 2016–55% of tonnage received). Hence, sustainable uses and solutions to maintain and restore soils are required. Street sweeping – a routine maintenance operation – handling diverse materials (e.g. grit, litter, leaves, glass, bitumen etc.), and thus containing potentially harmful elements, requiring landfill disposal (or incineration). However, with appropriate physico-chemical treatment, reclamation of gravel, sand, and fine residues (clay and silt) can be ensured. The latter making up approximately 30% of total solids collected, that could provide a 'circular economy' solution as soil or soil amendment, i.e. providing soil functions and essential ecosystem services (e.g. source of raw material, hosting biodiversity, carbon pool), thus, reducing the need for 'virgin material'.

Consistent physical (e.g. moisture content, organic matter) parameters suggest 'good' soil properties, able to support plant growth. Chemical properties revealed 'urban' signature of contaminants, i.e. metal(loid) concentrations, whereas high levels of total petroleum hydrocarbons (TPHs), which in part, were attributed to treatment process chemicals. These were found to biodegrade by >70% during storage (using different remediation techniques). Although the material was outside of ranges to be certified as a top- or subsoil (BS 3882 or BS 8601), the suitability within 'public open space' (and 'commercial') surroundings was evident.

This study provides the first long-term (over a 12-months period) physico-chemical characterisation of fine residues of recovered road sweeping material (or waste-derived material), following British Standards Institution (BSI) guidelines. Based on the determined characteristics, it aims to; **(i)** consider physico-chemical characteristics in an "urban soil" context (including temporal variability), to **(ii)** contextualise the material within soil British Standard specifications, e.g. for topsoil and subsoil, and **(iii)** evaluate their suitability for use as a soil/soil amendment in relation to human health screening values, e.g. 'soil guideline values' (SGVs), 'safety for use limits' (S4UL) and 'category 4 screening levels' (C4SL).

1. Introduction

Street sweeping is a routine maintenance operation, removing material from the roadway prior to their introduction into waterways (Lloyd et al., 2018). Residues collected from street cleansing consist of diverse materials, including litter, grit, leaves, glass, paper, bitumen and plastics (among others), and thus may contain potentially harmful elements (PHEs) such as heavy metals and other organic compounds, e.g. total petroleum hydrocarbons (TPHs; EA, 2012). Because of rapid urbanization and high demand for environmental cleanliness (i.e. reducing road dust re-suspension, improving air quality and disease prevention; Das and Wiseman, 2024; Fact. MR, 2019; Ragazzi et al.,

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2023), municipal regions across the globe spend significant amounts (i.e. US $65 million in San Francisco, United States) on street cleaning and waste management (Fact. MR, 2019). Moreover, the street sweeping market is projected to be valued at more than US $3 billion by the end of 2027 (Fact. MR, 2019), as it has been shown to reduce resuspension of dust and reducing respiratory health concern metals, e.g. Cu and Zn, from the (urban) environment (Das and Wiseman, 2024; Ragazzi et al., 2023). In Italy, street sweepings contribute 3% of total municipal solid waste (MSW), with 88% of this waste stream being recycled and 12% being landfilled (Ragazzi et al., 2023). Comparably, road sweeping waste in the UK has to be disposed of at a suitable facility, i.e. licensed landfill or incineration (EA, 2012; Lloyd et al., 2018). No data about the amount of street cleansing residues (SCRs) collected from UK local authorities is available, however, in 2021/2022 "household waste" that include street sweepings, totalled to 26.1 million tonnes, of which 2.1 million tonnes (8.1%) were landfilled (DEFRA, 2023a). The Waste Data Flow (WDF) network reported SCR recovery of less than 70,500 tonnes (in 2013; WasteDataFlow, 2013). Within the northwest of England, 333 thousand tonnes (9.1%) of wastes are recycled, whereas 45.4% (1666 thousand tonnes) are recycled, and 42.5% (1562 thousand tonnes) are incinerated (3.1% - 112 thousand tonnes "Other"; DEFRA, 2023a). However, these numbers do not incorporate SCR separately and it is not well documented how much is recently landfilled, recycled and/or re-used. Additionally, landfill sites are a 'depleting resource' with a remaining total capacity of 345,742,301 m^3 (end 2021; EA, 2024) for hazardous waste, and the re-use of recovered material would aid the UK Government's waste minimising strategy (DEFRA, 2023b). Moreover, according to the United Nations Sustainable Development Goals (UN SDGs), 7 goals directly or indirectly impact soils or cannot be achieved without soil, e.g. 'zero hunger' (Goal 2) or 'life on land' (Goal 15; SSA, 2024). An estimated 90% of the Earth's topsoil is currently considered 'at risk' by 2050 (UN FAO, 2022). In the UK > 6 million hectares of soil are at risk of compaction or erosion and soils remain one of the largest components of landfills (e.g. 28 million tonnes in 2016–55% of tonnage received; DEFRA, 2019), requiring sustainable uses and solutions to maintain and restore the UK's soils (EA, 2023). Treatment of SCRs can ensure reclamation of gravel and sands, whereas finer material (i.e. clay and silts) are currently sent to landfill. Fine-sized particles play an important role in the fate of contaminants, i.e. ability to adsorb a variety of inorganic and organic contaminants (Biswas et al., 2020; Schoonheydt and Johnston, 2013) thus, suggesting potential contamination of clay and silt fractions. These fractions of road sweeping residues account for around 30% of the total solids collected, which could provide an alternative material as soils and soil amendments for the use as tree soil, structural soil and/or other growing media (PAS115:2021). Due to the decline in soil resources, recovered material (i.e. from road sweepings) could provide essential qualities in ecosystem services, e.g. carbon pool, source of raw material and hosting biodiversity (Adhikari and Hartemink, 2016), e.g. supporting plant life, by also reducing the need for "virgin material" (i.e. dug-up and transported to site) and being used close to its source (PAS115:2021). Further, the process by which road sweeping wastes are recovered involves the separation of soil fractions, facilitating the blending of closely specified soil mixes.

This study provides the first temporal (over a 12-months period) physico-chemical characterisation of fine residues of recovered road sweeping wastes or waste-derived material (WDM). Based on the determined characteristics, it aims to: **(i)** consider physico-chemical characteristics in an "urban soil" context (including temporal variability), to **(ii)** contextualise the material within soil British Standard specifications (for topsoil and subsoil), and **(iii)** evaluate their suitability for use as a soil/soil amendment in relation to human health (using relevant regulatory screening values).

2. Materials and methods

2.1. Sample collection

All samples were obtained from processed material at UBU Environmental Ltd, based in Walkden, Manchester (UK). SCRs were collected from various locations (e.g. residential, roadways, commercial and industrial) within a 50-mile radius of Greater Manchester by a fleet of approximately 120 sweepers. Once material was transported to site, the road sweepings underwent a treatment process (Fig. S1) that included (a) density separation and attrition, to remove plastics and leaves and (b) washing and separation of constituents into different sizes, e.g. aggregates (40-5 mm), sand (2–0.06 mm) and silt/clay (0.06–0.002 mm and <0.002 mm). Reclaimed aggregates and sand can already be re-used in construction and landscaping (UBU, 2023). As such, the focus of this investigation was on the fine silt and clay-like material, hereafter defined as waste-derived material (WDM).

Sampling of the WDM was undertaken in accordance with British Standard Institute (BSI) guidelines, i.e. BS EN 12579:2013 and BS ISO 18400-102:2017 on a biweekly basis over a 12-months period. In brief, to obtain a representative sample of the processed material, 12 incremental samples (approximately 0.5 L each) were taken from the freshly produced bulk material from different locations of the pile (Fig. S2). Subsequently, incremental samples were combined, thoroughly mixed, and reduced in size by coning and quartering to obtain a final sample for physico-chemical, inorganic and organic analyses. Samples were stored in containers in accordance with BS ISO 18400-105:2017, e.g. amber glass vials for organic compounds, in a cool and dark (at 4 °C ± 2 °C) environment (fridge) until analysis.

2.2. Analytical methods – physico-chemical characterisation

All analysis was performed in line with relevant International Organization for Standardization (ISO) and British Standard Institution (BSI) methods. Due to the large number of different tests performed, detailed methods are not provided here. Instead, each method has been referenced in Table 1, and analytical details and QA/QC procedures are detailed in the Supplementary information (Tables S 1 to Tab. S5).

Table 1
Overview of British Standard Institute guidelines applied for physico-chemical characterisation of PAS115 material, including analytical technique.

Parameter	BSI document/ guideline	Analytical technique
pH	BS EN 13037:2011	pH probe/meter
Electrical Conductivity	BS EN 13038:2011	Conductivity probe/meter
Dry residue/moisture content	BS EN 15934:2012, BS EN 13040:2007	Not applicable (oven drying)
Bulk density	BS EN ISO 17892-2:2014	Not applicable (oven drying)
Organic matter content	BS EN ISO 15935:2021	Loss on Ignition (LOI)
Particle size & distribution	BS EN ISO 17892-4:2016	Sieving; Particle Size Analyser (Malvern 3000)
C wt% and N wt%	ISO 10694:1995 (Carbon), ISO 13878:1998 (Nitrogen)	Carbon/Nitrogen (CN) analyser
Water-soluble elements and nutrients (as ions)	BS EN 13652:2001	Ion Chromatography (IC)
Inorganic compounds, e.g. metals/ metalloids	Extraction: BS ISO 16729:2013 Analysis: BS EN ISO 22036:2024, BS EN 16171:2016	Inductively coupled plasma – optical emission spectroscopy (ICP-OES) and inductively coupled plasma – mass spectrometry (ICP-MS)
Organic compounds, e.g. total petroleum hydrocarbons (TPHs)	BS EN ISO 16703:2011	Gas chromatography – flame-ionisation detection (GC-FID)

General physico-chemical characterisation of the WDM, including pH, electrical conductivity (Ec), bulk density, particle size and distribution, organic matter and carbon and nitrogen contents, are presented in section 3.1. Water-soluble elements and nutrients are presented in section 3.2, whereas metal(loid) and total petroleum hydrocarbons are presented in section 3.3**.** and **3.4**, respectively.

2.3. Statistical analysis and data visualisation

Graphical visualisation was conducted using R (v. 4.4.0; R Core Team, 2021) and RStudio (v. 2023.12.0–369; RStudio Team, 2021) with the visualisation package "ggplot2" (Wickham, 2016). Statistical analysis was undertaken using 'jamovi' (The jamovi project, 2020). Datasets were tested for normal distribution using a Shapiro-Wilk test, due to its higher statistical power compared to other statistical tests, irrespective of sample size (Razali and Wah, 2011). Outcomes for normality informed the use of parametric or non-parametric test for dataset comparison. For instance, group comparison was undertaken using '*t*-test' (parametric) or 'Kruskal-Wallis/Wilcoxon' (non-parametric; non-parametric pairwise comparison) test statistics, whereas 'Pearson's r (parametric)' or 'Spearman's ρ (non-parametric)' was used for comparison of (linear) relationships.

3. Results and discussion

3.1. Physico-chemical properties of recovered WDM

Physico-chemical characteristics of the WDM are displayed in Table 2. According to the UK soil texture classification (Natural England, 2008), the WDM can be classified as "sandy silty loam" or "silty loam", with consistent moisture contents, ranging between 34 and 46%, and a dry bulk density between 0.75 and 1.1 g cm^{-3} (wet: 1.34–1.71 g cm^{-3}).

Soils in urban environments are affected by compaction, i.e. high bulk density, and thus, affecting or restricting root growth (Banaitis et al., 2007; Edmondson et al., 2011; C.Y. Jim, 1998a,b,c; C.Y. Jim, 1998a,b,c; Lehmann and Stahr, 2007; Lorenz and Lal, 2009; Pickett and Cadenasso, 2009; Pitt et al., 2008; Smetak et al., 2007). For instance, bulk densities >1.60 g cm^{-3} have been found to affect root growth, whereas >1.75 g cm^{-3} restrict root growth (USDA, 2019). Soil bulk densities in urban areas in China have been found in ranges of 1.14–1.70 g cm^{-3} (Nanjing) and 1.14–2.63 g cm^{-3} (Hongkong) (C.Y. Jim, 1998a,b, c; Yang et al., 2005; Yang and Zhang, 2015). Comparably, Dobson et al. (2021) reported allotment soil bulk densities in ranges of 0.22–1.52 g cm^{-3} in UK cities (e.g. Birmingham, Nottingham, Liverpool etc.), whereas for Manchester, minimal data is available for topsoil bulk densities; ranging between 0.6 and >1.2 g cm^{-3} (BGS, 2024). Nonetheless, bulk densities of the recovered material show an ideal (<1.40 g cm^{-3}) value for plant growth (USDA, 2019).

Table 2
Physico-chemical characteristic of the WDM throughout a 12-months biweekly sampling regime (N = 24).

Parameter	Minimum	Maximum	Mean ± 1× Std. Dev.	95th percentile
pH [unitless]	7.58	8.87	8.32 ± 0.379	8.81
Ec [μS cm^{-1}]	199	913	495 ± 186	834
TDS [ppm][a]	127	584	317 ± 119	534
Moisture [%]	34.2	46.9	43.1 ± 2.68	45.6
OM (LOI) [%]	6.71	15.8	10.3 ± 1.91	14.0
Bulk density [g cm^3 (wet)]	1.34	1.71	1.51 ± 0.09	1.68
Bulk density [g cm^3 (dry)]	0.746	1.11	0.856 ± 0.09	1.03
Carbon [wt%]	6.85	9.34	8.01 ± 0.597	9.18
Nitrogen [wt%]	0.190	0.310	0.243 ± 0.032	0.300
Clay [%]	0.910	5.18	2.80 ± 1.09	4.69
Silt [%]	54.7	83.9	75.2 ± 7.84	82.5
Sand [%]	12.4	44.4	22.0 ± 8.63	39.7

QA/QC for pH, Ec and carbon and nitrogen contents displayed in Table S1.
[a] TDS calculated from Ec using 640 scale.

The pH and electrical conductivity (Ec) in the recovered material show alkaline conditions with low anion and cation concentrations. Soil pH is the primary factor for the availability of trace metals in soils, with higher mobility of anions, and conversely lower mobility for cationic species in soils with higher pHs (Antoniadis et al., 2017b). Hence, alkaline pH of the material may hinder the transport of (plant) nutrients, e.g. phosphorus and manganese and potentially harmful elements (PHEs), e.g. Zinc (Zn) in the material. However, alkaline conditions have been reported in urban soils in Hungary (pH: 7.6–9.1; Puskás and Farsang, 2009) and China (pH: 8.5–9.5; Jim, 1998b), attributed to calcareous filling material (e.g. cement and concrete) (Yang and Zhang, 2015). No statistically significant ($P > 0.05$) differences between analysed seasons were recorded for pH, OM% and moisture content, whereas electrical conductivity (Ec) showed statistically significant differences ($p = 0.04$) between spring (583 ± 106 μS cm^{-1}) and summer (306 ± 111 μS cm^{-1}), with the highest Ec recorded in winter (640 ± 227 μS cm^{-1}). Ec is affected by a variety of soil properties, e.g. porosity, soil texture (particularly clay content), soil moisture and temperature (USDA, 2011). Elevated Ec in winter is likely linked to the application of de-icing salts that can have detrimental impacts on the health and growth of urban trees though osmotic stress and ion toxicity (Bryson and Barker, 2002; Czerniawska-Kusza et al., 2004; Equiza et al., 2017; Shannon et al., 2020). Albeit an increase in Ec in the recovered material during colder months, values were consistently below 'problematic' salinity (>4000 μS cm^{-1}) values, regardless of season, that would affect growth and microbial activity, i.e. by mobilizing potentially toxic elements (e.g. lead, cadmium and mercury; Shannon et al., 2020).

Soil organic carbon (SOC) plays an important role in the natural carbon cycle and has an extensive influence on soil properties and functions (BSSS, 2022). Carbon contents (C wt%) in the WDM ranged from 6.9% (69 g kg^{-1}) to 9.3% (93 g kg^{-1}), which is comparable to concentrations for clay/silt soil in the UK (BGS, 2024). Comparably, soil organic matter (SOM) in the material was recorded at 10 ± 1.91%OM, which in soils has the capability to increase the overall retention capacity, contributes to improved plant growth conditions (i.e. increased water-holding capacity and improved soil structure) and creates ligands with elements, decreasing element availability (Antoniadis et al., 2017a). Urban soils are often carbon-depleted compared to natural soils, with reported OM% of 3.5 ± 0.4% for different land-use types, that can be increased (about doubled to 7.1 ± 0.4%) using soil amendments (e.g. compost and biochar; Wu and Yu, 2023). Manchester road dust samples showed OM% (by LOI) between 4.02 and 19.84%, which are comparable to this study's results, suggesting natural (e.g. plant fragments) and anthropogenic sources (e.g. vehicle exhaust and tyre wear; Robertson et al., 2003; Rogge et al., 1993) as primary contributors. Moreover, elevated OM% suggest a fertile soil providing an enhanced rooting environment and moisture (Hatten and Liles, 2019; Oldfield et al., 2018). Further, TIC of approximately 1% suggest a buffering capacity towards (anthropogenic) acidification and maintaining a consistent pH (Antoniadis et al., 2017b).

Soil Carbon-Nitrogen ratios (C/N ratio) are an indicator of SOM quality, playing a crucial role in soil microbial activity and influencing mineralisation and nitrification processes (Amorim et al., 2022; He et al., 2023; Lehtonen et al., 2016; Tao et al., 2020; Vanguelova et al., 2024). For instance, a C/N ratio <15 indicates rapid mineralisation and release of N that is available for plant growth but also may result in leaching of nutrients, e.g. NO_3^- (at C/N ratio <25), whereas C/N > 35 indicates microbial immobilisation, i.e. converting inorganic-N [NH_4^+-N and NO_3^--N] into organic forms that are not (readily) plant available (Brust, 2019; Cao et al., 2021; Emmett, 2007; Gundersen et al., 2006; Vanguelova et al., 2024). C/N ratios in the WDM ranged between 27 and 41 suggesting a 'equilibrium' state between mineralisation and immobilisation (Brust, 2019), hence, suggesting plant available nitrogen with a tendency to immobilize nitrogen. Nonetheless, due to the higher the C/N ratio in the WDM, a greater stability of the soil organic carbon (SOC) is suggested, that subsequently may be important for terrestrial carbon sequestration (He et al., 2023).

Overall, the physico-chemical characteristics of the WDM is comparable to 'urban' soils, with higher pH, higher bulk density and enrichment in carbonates (Gerasimova et al., 2003; Savich et al., 2007; Vodyanitskii, 2015). However, results also suggest a fertile, moisture retaining, light and alkaline waste-derived "soil" (RHS, 2024) that may provide an alternative for urban greening programmes, comparable to silty soils.

3.2. Water-soluble elements and nutrients in the WDM

Temporal variability for water-soluble elements and nutrients was recorded in the WDM (Table S6). Elevated levels for chloride (Cl^-) were recorded in spring and winter, whereas concentrations of sulfate (SO_4^{2-}) were consistent throughout the seasons. Cations, sodium (Na^+) and calcium (Ca^{2+}) and magnesium (Mg^{2+}) were elevated in winter. Elevated levels of Na^+ and Cl^- (and Ca^{2+} and Mg^{2+}) during colder weather is likely linked to the use of de-icing salt, containing salt (NaCl) and salt additives ($CaCl_2$ and $MgCl_2$; Charola et al., 2017). Although an important plant micro-nutrient, excessive chloride (Cl^-; anion of chlorine), from natural (e.g. sea spray) or anthropogenic sources (e.g. coal burning, combustion or fertilization), can have detrimental impacts on soils and plants (Geilfus, 2019). Due to its high mobility in soils, i.e. weak adsorption to positively charged soil particles and no assimilation by microorganisms (Geilfus, 2019; Miller et al., 2011b; Wang et al., 1987), Cl^- can easily leach through water-filled soil pores (Geilfus, 2019; Miller et al., 2011a). Limit values for landfilling of wastes range from 800 (inert) to 25,000 mg kg^{-1} (hazardous; Waste Acceptance Criteria, WAC), whereas a threshold of 188 mg L^{-1} for general quality of groundwater bodies, has been specified (ALS, 2017; UK Government, 2015). The U.S. Environmental Protection Agency (U.S. EPA) has set a threshold of 230 mg L^{-1} for Cl^- for chronic exposure to aquatic life (860 mg L^{-1} acute exposure; EPA, 1988). Cl^- concentrations of the WDM of 100 mg L^{-1} ($\pm$90.42 g L^{-1}) are below WAC thresholds, but could exceed the groundwater bodies threshold, thus, suggesting the potential of leaching into water bodies. However, WDM-Cl^- concentrations are consistently below the UK groundwater bodies limit value (188 mg L^{-1}). Further, Cl^- can also be taken up by plants via the xylem, accumulating in the shoots (Geilfus, 2019). Cl^- can replace hydroxides in aluminium and iron-hydroxides, which is pH dependent, with lower pH favouring the replacement (Geilfus, 2019; Wang and Yu, 1998). Alkaline pHs in the WDM suggest little hydroxide replacement. Therefore, water-soluble Cl^- concentrations are considered to either be retained within WDM, i.e. be utilised for plant growth, when used as a growing medium, or is going to be removed via water.

Inorganic nitrogen, e.g. nitrite (NO_2^-), nitrate (NO_3^-) and ammonium (NH_4^+) were generally found at low concentrations (Table S6). Anthropogenic activities (and land-use) alter the nutrient cycle in urban soils, due to (in-)direct addition or removal of nutrients and modifications of factors affecting the cycle (O'Riordan et al., 2021). However, low concentrations in the WDM indicate that threats by inorganic nitrogen leaching can be considered negligible, with NO_3^- and NH_4^+ potentially being (readily) utilised by soil organisms (i.e. bacteria) and plants. In general, NO_3^- concentrations were recorded below detection limits (DL), however, it is likely that nitrifying microorganism (e.g. *nitrosomonas* and *nitrosospira*; Hayatsu et al., 2021) in the WDM utilised NH_4^+. Further investigation of microbial communities is warranted to identify potential uses of inorganic nitrogen in the WDM.

Sulfate (SO_4^{2-}) and Phosphate (PO_4^{3-}) are not discussed here, because concentrations were below DL (Table S6) and therefore, considered negligible to evaluate potential environmental impacts (i.e. on water system). However, total sulfur and phosphorus (HNO_3 extractable) were recorded in ranges of 1933–3631 mg kg^{-1} and 639–947 mg kg^{-1}, respectively. Organic matter contains around 95% of sulfur in soils, which during breakdown and/or decomposition releases plant available SO_4^{2-} (Churka Blum et al., 2013; Narayan et al., 2023). Comparably, phosphorus plays a fundamental role in the regulation of physiological responses and stress tolerance in plants (e.g. heat, salinity, drought, waterlogging and metal toxicity; Hawkesford et al., 2023; Khan et al., 2023; Lambers, 2022). Hence, with decreasing pH of the WDM over time, i.e. through biogeochemical processes (Neina, 2019), an increase of P-release may be expected. Comparably, water-soluble concentrations for potassium (K), magnesium (Mg) and calcium (Ca) were 4.073 $\pm$ 3.139 mg L^{-1}, 9.142 $\pm$ 8.334 mg L^{-1} and 88.84 $\pm$ 79.74 mg L^{-1}, respectively, whereas total concentrations (HNO_3 extractable; mg kg^{-1}) in the WDM were recorded at 5349 $\pm$ 877 mg kg^{-1} (K), 8755 $\pm$ 1288 mg kg^{-1} (Mg) and 95,449 $\pm$ 7956 mg kg^{-1} (Ca). Elevated K, Mg and Ca in the WDM suggest (additional) anthropogenic sources such as construction and demolition (K, Mg; NAEI, 2024a; 2024b) and industrial processes (Ca; NAEI, 2024c), most likely from sweeping locations within industrial areas and/or new-build housing estates.

The data suggests that plant-growth relevant elements are 'stored' in non-soluble forms, likely due to the presence of the treatment chemical (i.e. polymer) used to aid separation of fine materials. However, it is possible that during biodegradation of the polymer and thus, likely pH changes, elements may become more mobile that can be (readily) taken up by plants (Neina, 2019). Additionally, the WDM pH (Table 1) suggest the availability of K, Mg and Ca, and the presence of high OM% (and sulfur) will aid to decrease the pH and thus, make required elements more available over time (i.e. soil ageing; Neina, 2019), which could be an important nutrient source when used in a confined environment (e.g. urban tree pit). Low concentrations of water-soluble elements, e.g. chloride and inorganic nitrogen within the WDM are most likely linked to the wash process, i.e. remaining within the treatment water (of which 90% of is re-used). These are below relevant environmental standards (e.g. WAC, groundwater), suggesting no environmental hazards from the material when used as a growing medium. Total concentrations of plant-relevant elements suggest a 'store' that may become available through soil ageing processes (including microbial activities). However, long-term environmental behaviour studies of the WDM are required to evaluate potential releases and subsequent plant availability and/or potential contamination of waterways.

3.3. Metal(loid) concentrations in the WDM

Metal(loid) concentrations, e.g. macro- and micronutrients (i.e. Ca, K, iron [Fe], boron [B]) (Tables S7 and S8), as well as PHEs that may have negative impacts on environmental and human health, such as arsenic (As), Cadmium (Cd), Chromium (Cr), Nickel (Ni) and Lead (Pb), were recorded at consistent concentrations in the WDM. For instance, Cr, Ni and Co and Pb showed comparable (non-significant) concentrations throughout the year (Fig. 1), whereas seasonal variability was recorded for certain elements. Highest As concentrations were recorded in spring (13.4 $\pm$ 2.82 mg kg^{-1}), whereas lowest was recorded in winter (9.27 $\pm$ 0.0572 mg kg^{-1}; Fig. 1A). Similarly, Hg showed statistically significant (Wilcoxon test, $P < 0.05$) differences for spring/summer and winter (Fig. 1G), whereas Zn showed seasonal differences for spring and summer. In contrast, autumn was the season with highest Cd (1.06 $\pm$ 0.103 mg kg^{-1}) compared to summer (0.814 $\pm$ 0.119 mg kg^{-1}; Fig. 1B). Zn concentrations were consistent between seasons (Fig. 1H) with statistically significant ($P < 0.05$) differences between spring (359 $\pm$ 29.2 mg kg^{-1}) and summer (435 $\pm$ 58.3 mg kg^{-1}), suggesting additional Zn re-suspended soil and/or atmospheric deposition. Cr (Fig. 1C), Ni (Fig. 1D), Co (Fig. 1E) and Pb (Fig. 1F) did not show significant seasonal variation.

Arsenic in soils is soil-type dependant and primarily from natural sources, i.e. minerals, whereas anthropogenic inputs are linked to fossil fuel/biomass combustion, industrial effluents, As-containing pesticides, alloys and electronics and pigments and paints (Baker et al., 2018; Patel

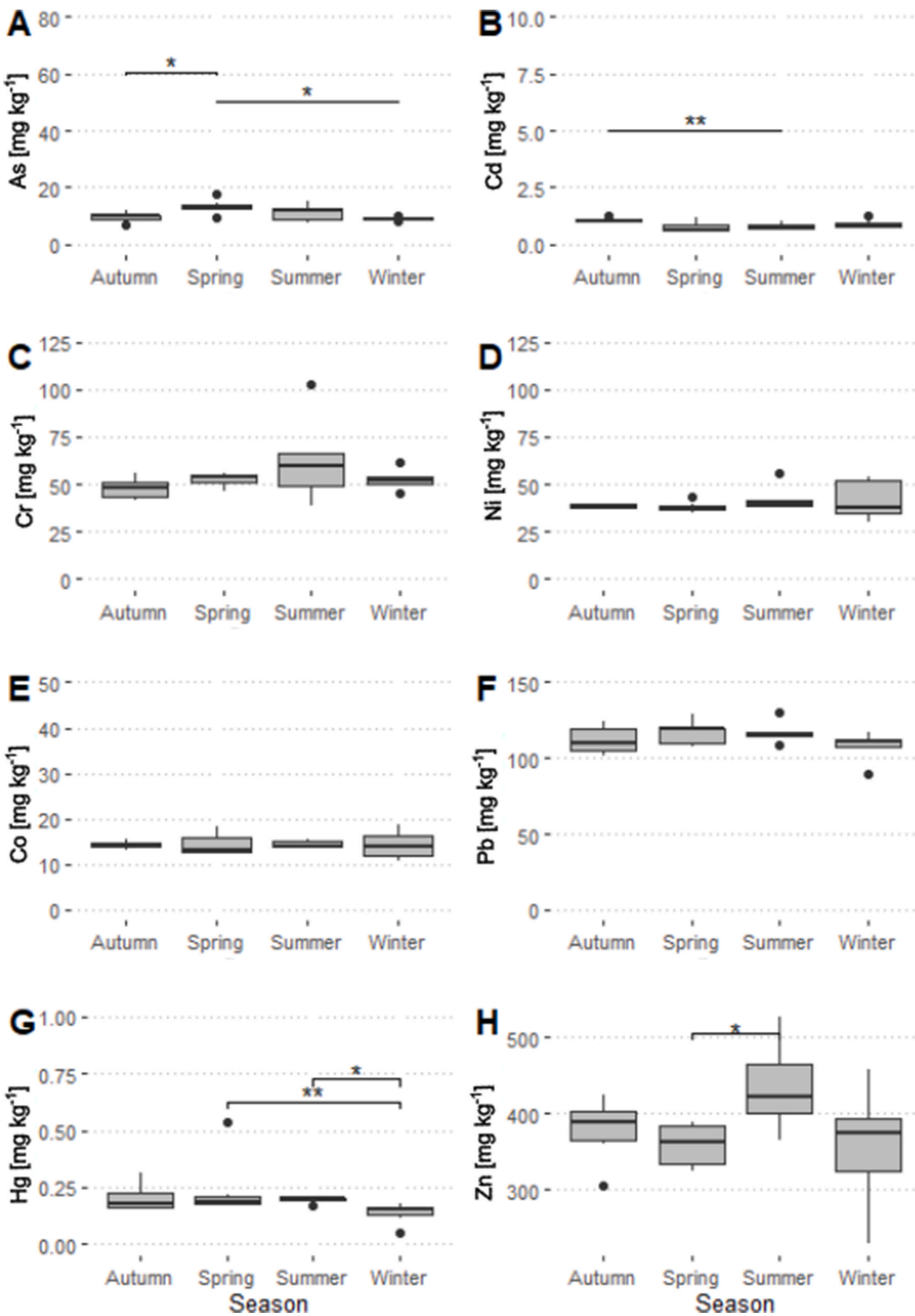

Fig. 1. Seasonal variability of PHEs [A: Arsenic; B: Cadmium; C: Chromium; D: Nickel; E: Cobalt; F: Lead; G: Mercury; H: Zinc] in WDM; displayed with significant differences between seasons (Wilcoxon test, $^{*}P < 0.05$; $^{**}P < 0.01$).
note: different scaling of y-axis.

et al., 2023; Shankar et al., 2014). As and Cd concentrations for Greater Manchester (NSI - GBase Topsoil) have been found at >9.4 mg kg^{-1} and >0.37 mg kg^{-1}, respectively (BGS, 2024). WDM-As concentrations are within comparable regions to Greater Manchester 'Topsoil' concentrations, likely representing natural sources. Elevated As levels during spring suggest a potential impact from seasonal conditions (i.e. being drier, less wet – compared to autumn/winter) and input variability (i.e. sweeping locations – industrial), which, however, are still below 'general' As concentrations reported for the UK (32 mg kg^{-1}; Ander et al., 2013).

Cadmium is a very mobile and toxic element with anthropogenic sources in soil from combustion, sewage sludge, traffic, metal industries, pigments and alloys (ATSDR, 2007; Bigalke et al., 2017; Kubier et al., 2019; Merkel and Sperling, 1998; Mirlean and Roisenberg, 2006; Sprynskyy et al., 2011). Comparable to As, Cd concentrations in the WDM are within ranges of the 'background' soil concentrations, thus, representing the 'urban signature', i.e. from sweeper waste, that slightly vary with season (i.e. wet vs. dry). For instance, in Europe, Cd concentrations in municipal solid wastes in range of 0.3–12 mg kg^{-1} have been reported (EU, 2007; Kubier et al., 2019). Interestingly, As and Cd were significantly ($P < 0.05$) negatively correlated (Pearson's $r = -0.63$; Fig. S4) with each other, which is likely linked to the alkaline pH of the material, i.e. stabilising Cd and increase the As solubility (Tica et al., 2011; Yao et al., 2019).

Hg, Cu, Zn and Pb are considered 'typical urban' contaminants (Yang and Zhang, 2015) that are associated with mining operations, chemical industries, manufacturing industries (e.g. textiles) and petroleum refining (Nagajyoti et al., 2010). Hg-concentrations in UK Topsoils was found in ranges <0.097 to >0.163 mg kg^{-1} with generally higher concentrations 0.980 mg kg^{-1} (95% percentile; Tipping et al., 2011) within urban areas. Ander et al. (2013) reported 'normal background concentrations (NBCs)' for mercury in urban areas of 1.9 mg kg^{-1} in the UK. WDM-Hg was recorded in ranges from 0.048 to 0.534 mg kg^{-1} (0.310 mg kg^{-1}; 95% percentile), lower than reported for UK urban areas, thus, suggesting no additional Hg input into urban soils, when used as such.

Topsoil Pb and Zn concentrations in NW England are recorded >133 mg kg^{-1} and >137 mg kg^{-1} (BGS, 2024), respectively, indicating "background" contamination from the 'urban' sweeping location. Moreover, elevated concentrations and temporal variability of PHEs has been reported in road-dust samples across Manchester (UK), with Pb and Zn concentrations ranging between 71 and 660 mg kg^{-1} and 50–589 mg kg^{-1}, respectively (Robertson and Taylor, 2007). These values are comparable to concentrations for the recovered material (Pb: 119 ± 22 mg kg^{-1}; Zn: 384 ± 64 mg kg^{-1}), suggesting a contribution from anthropogenic sources; Pb – pigment additives and additive for aviation fuel, electronic waste, solar cells (containing lead salts) and batteries (Collin et al., 2022; Hollingsworth and Rudik, 2021; Obeng-Gyasi, 2019; Yuan et al., 2012; Zou et al., 2018), Zn – vehicle emissions (e.g. tyre and brake wear) and road furniture (e.g. galvanized steel) and dissolved zinc (e.g. urban runoff; Councell et al., 2004; Desaulty et al., 2020; Legret and Pagotto, 1999; Zarcinas and Rogers, 2002). Hence, Zn and Pb concentrations represent 'general' urban (and Manchester-based) concentrations. While Zn concentrations are above the 'phytotoxic' threshold limits for 'Topsoil' (BS3882 - Section 4) with Zn is less mobile/'available' at these high pHs, warranting additional investigation of its potential effects on plant growth.

Nickel (Ni; Fig. 1D) was positively correlated with Mn, Fe that are all naturally occurring in soils; however, correlation of metals could be linked to anthropogenic sources from tyre and brake wear, potentially also resulting from sweeping activities. Additionally, Zn and Cu were positively correlated with each other (Pearson's $r = 0.83$; Fig. S4) further suggesting vehicular emissions as primary sources. For instance, previous studies have reported emissions of Mn, Fe, Cu, Ni and Zn (among others) from exhaust pipes, whereas Zn and Cu have been associated with engine lubricant oil and brake wear (Zn and Cu) (Grieshop et al., 2006; Harrison et al., 2012; HEI, 2006; Ondráček et al., 2011; Sternbeck et al., 2002; Wang et al., 2021). Hence, the WDM metal concentrations are primarily influenced by anthropogenic emissions that represent 'urban' soil conditions.

Seasonal variability was detected for certain elements (As, Cd, Hg and Zn), however the concentrations within the WDM are temporally consistent and within comparable ranges of elemental background (i.e. topsoil) concentrations, thus, suggesting "urban" signatures (e.g. vehicular sources) of metal(loid)s in the WDM. Significant seasonal variability (Fig. 1) is likely resulting from different meteorological conditions (e.g. temperature, precipitation etc.) and/or atmospheric deposition (Men et al., 2018; Ngai et al., 2022; Wang et al., 2024), as well as potential variability in input material (i.e. sweeping locations). For instance, Niepsch et al. (2024) showed spatial variability of airborne metals (using a lichen biomonitoring approach) across Manchester, suggesting a potential addition of metals from atmospheric deposition. Additionally, de-icing salt (NaCl) may change the behaviour of accumulated contaminants in collected residues, resulting in elevated mobilisation of contaminants (Norrström and Jacks, 1998) during colder months, subsequently impacting WDM chemical composition that warrants additional investigations.

3.4. Total petroleum hydrocarbon (TPH) concentrations in the WDM

WDM- TPH concentrations ranged between 344 mg kg^{-1} (dwt) and 17,057 mg kg^{-1} (dwt; Fig. 2B) with a discernible seasonal variability, and statistically significant difference ($P < 0.05$) between seasons (Fig. 2B). Interestingly, autumn showed the highest TPH values in the WDM, most likely due to biogenic organic compounds (BOCs) from leaf litter (e.g. humic and fulvic acids), collected during routine sweeping. Vane et al. (2021) reported TPH concentrations between 72-4673 mg kg^{-1} for urban soils in London (UK), also highlighting the importance of background hydrocarbon compounds in soils, though, indicating anthropogenic influences (e.g. fuels spills, road dust bitumen) for TPH concentrations >500 mg kg^{-1}. Applying this threshold to this study shows that 92% ($N = 24$ of 26) of samples are "anthropogenically" influenced. Moreover, TPH concentrations of 7281 ± 1201 mg kg^{-1} within soils sampled 1 m from a highway in Moscow (Russia) were reported, and a primary impact from vehicular sources and subsequent "uptake" during sweeping operations is suggested (Nikolaeva et al., 2017). However, during the treatment process, petroleum-based chemicals are used and a potential increase of TPH levels from those chemicals was considered.

To assess a potential influence from (petroleum-based) treatment chemicals, antifoaming agent and polymer was extracted and analysed (according to BS EN ISO 16703:2011), resulting in a TPH concentrations of 21,845 mg kg^{-1} (polymer wet weight), 230,846 mg kg^{-1} (anti-foam wet weight; Fig. 2A), respectively. Hence, a contribution from the treatment chemicals, containing C_{12}-C_{15} and C_{20}-C_{50} hydrocarbons to the WDM-TPH profile was evidenced (Fig. S5). Differences in chemical dosing, depending on the input material (i.e. moisture, fines contents etc.), may also artificially increase the WDM-TPH profile throughout the year. Here, we calculated a minimum addition of 675 mg kg^{-1} to 891 mg kg^{-1} TPHs to the WDM profile, based on the chemical dosing, concentration, and production volume (Tables 9 and Tab. S10). Hence, adjusted TPH levels of the WDM are likely to be lower, when removing the "influence" from treatment chemicals. Petroleum-based chemicals, i.e. antifoaming agents and flocculation aids, are commonly used in wastewater treatment plants (WWTPs) to aid minimisation of general foaming-related issues and liquid-solid separation (Collivignarelli et al., 2020; Dlangamandla et al., 2021). Comparably, WDM treatment chemicals are used to aid separation and flocculation of the fine residues, which according to the manufacturer reduce by 70% (flocculation aid – hydrocarbons, C_{12}-C_{15} – readily biodegradable: 67.6%/28 days [OECD 301F]; 68.8%/28 days [OECD 306]; 61.2%/61 days [OECD 304A]; isotridecanol, ethoxylated – readily biodegradable: >60%/28 days [OECD 301B] SNF, 2020) and 30% (antifoam agent – petroleum

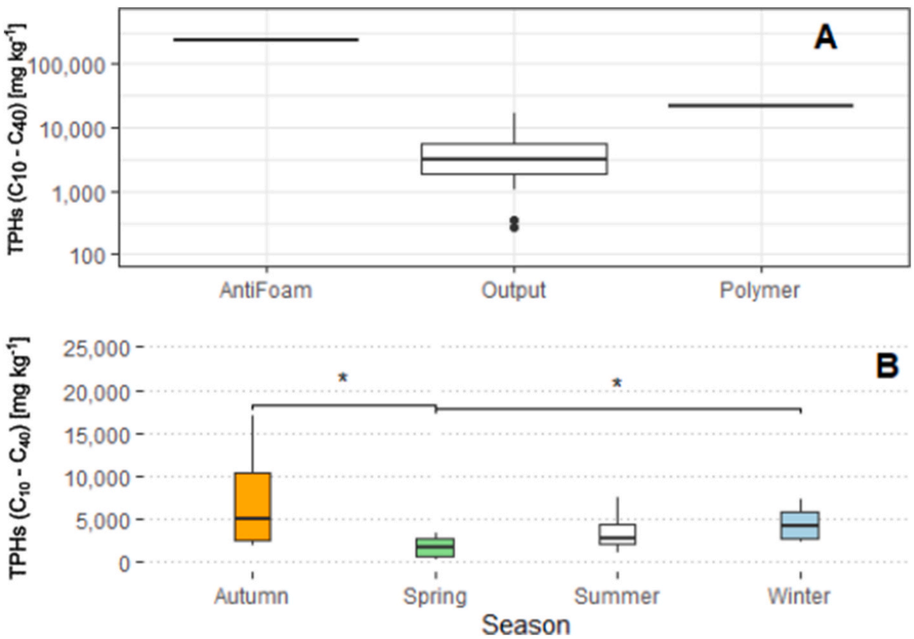

Fig. 2. (A) TPH concentrations in treatment chemicals (anti-foam [$N = 1$] and polymer [$N = 1$]) and WDM ('Output') [N = 25] [log_{10}-scale; C_{10}-C_{40} mg kg^{-1} wet weight], and (B) seasonal variation of TPH concentrations [mg kg^{-1}; dry weight] in WDM; significant differences at $P < 0.05$ (*) between seasons displayed as brackets above and colour-coded bars.(For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

distillates, solvent dewaxed heavy paraffinic - inherently biodegradable: 31.13%/28-days [OECD 301F]; SNF, 2021) within 4-weeks. This was tested using different storage/remediation techniques (i.e. 'as is', 'aeration', 'washing and aeration' and 'biopile') over a 6-week period from freshly recovered material (Fig. 3; detailed information about treatment/remediation options in Table S11).

Environmental "ageing" trials (Fig. 3) suggest a breakdown of the polymer with increasing storage time. A general decrease in TPH concentrations by >70% were recorded independent of remediation techniques, with storage 'as is' and 'washing and aeration' showed a reduction by −162% and −99%, respectively (Table S11). However, after 6-weeks WDM-TPH concentrations were found <1000 mg kg^{-1} in remediated material, suggesting minimal risk for non-residential uses. Degradation and adsorption (and volatilisation) of TPHs in soils are indirectly influenced by environmental factors, i.e. suitable temperature ranges and nutrients enhance the microbial degradation (Alavi et al., 2014; Arnold et al., 1999; Coulon et al., 2022; Karhu et al., 2014; Muskus et al., 2020; Wang et al., 2010; Wu et al., 2016, 2022), whereas the adsorption of (polar) TPHs (e.g. aromatic hydrocarbons) is promoted by higher clay contents and organic matter (Baccot et al., 2020; Kuei--Jyum Yeh and Young, 2003; Pérez et al., 2011; Sang et al., 2020; Wu et al., 2022). Additionally, studies reported that plants (e.g. grasses, legumes, ornamental plants and trees) and associated microorganisms can aid phytoremediation of TPHs (Aftab et al., 2021; Hussain et al.,

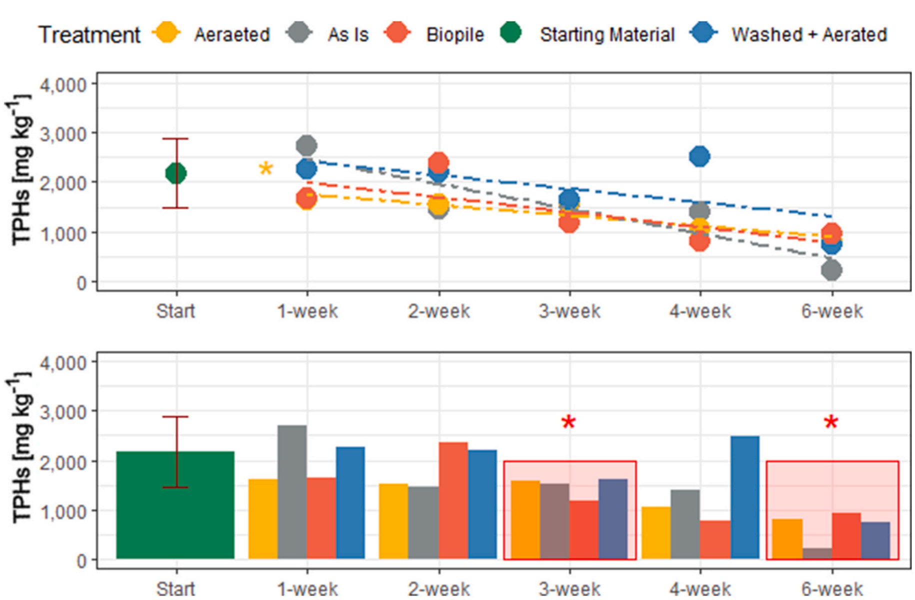

Fig. 3. TPH concentrations in the WDM over 6-week period (with trendline; above) and displayed as bar plot (below) depending on different treatment/remediation techniques (see Tab. SI for further details) during storage; error bar displayed on starting material (fresh WDM) as 32.45%CV derived from repeated ($N = 21$) measurements of 3 g L^{-1} QC solution. Statistically significant differences (one-sample t-test; $P < 0.05$) marked by * - recorded for 'aerated' material compared to starting TPH value (above), and after 3-week and 6-week of storage (compared to starting TPH concentration).

2022; Khan et al., 2019, 2021; Liu et al., 2012). Further, moisture is an important factor for bacterial activity, with an optimum at 60% (Haghollahi et al., 2016; Ossai et al., 2024; Ren et al., 2022), whereas the WDM was within 43.1% (±2.63%), lower than the optimum but suggesting appropriate conditions due to its elevated organic matter content (~11 OM%; Table 2). Therefore, when blending the WDM with compost and/or biochar will aid removal of TPHs (Hussain et al., 2022; Nguyen et al., 2023).

Total petroleum hydrocarbons (TPHs) were found as 'problematic', (i.e. for waste-disposal and potential human health impacts), which could be attributed to treatment chemicals and background organics (e.g. leaf material) during autumn, with values > 10,000 mg kg^{-1} (Fig. 2). Nonetheless, an influence from treatment chemicals was evidenced, which biodegrade with increasing storage time. Additionally, to further remove TPHs from the WDM, the use of water-based flocculation aids and/or considerations to use 'enzymatic' bioremediation additives, will likely reduce the TPH levels. Hence, incorporating minor process changes to remove TPH sources from the WDM and aid biological remediation, i.e. promoting microbial communities inherent in the WDM, will aid transitioning into a more environmentally friendly and sustainable business practice and maintain a consistent "quality" of the WDM when used as a soil or soil amendment.

4. Potential uses as soil and soil amendment in relation to human health and soil screening values

The British Standards Institution (BSI) provides specifications for soils used in landscaping projects, e.g. Topsoil (BS 3882) and Subsoil (BS 8601), that need to be met for a commercially available soil to be certified to the relevant standard. Due to the alkaline characteristics of the WDM, parameters were compared against values for "multipurpose" and "calcareous" specifications only (Table 3).

Results in Table 3 show that the WDM varies in clay contents below the BS 3882 minimum value (5%), whereas other characteristics (i.e. pH and EC) were within specification limits. However, plant nutrients were consistently below the specified values, whereas potentially phytotoxic elements (e.g. Ni and Cu), except for zinc (Zn), are within specifications. Hence, the WDM could not be certified as a BS 3882 or BS 8601 soil, however, could warrant revision or incorporation of recovered material into available and/or new soil standards (e.g. BS 8640). Nonetheless, total concentrations, e.g. for Mg and K, are much higher compared to the water-soluble fraction, suggesting that these may become (plant) available over time. It is worth mentioning that input material may potentially be amended, i.e. adding a stock of clay, to maintain a consistent (and in BS 3882 ranges) clay content.

To identify potential uses for the WDM as soil or soil amendment, concentrations of priority contaminants were compared to screening values, e.g. UK Environment Agency "soil guideline values" (EA SGVs), "category 4 screening levels" (C4SL) and "suitable 4 use levels" (S4UL). In this study, the primary focus is on "commercial" and "greening" applications, however, EA SGVs, C4SL and S4UL values presented in Table 4 include 'residential' land-uses (with and without homegrown produce) to evaluate wider material suitability.

Concentrations of metal(loids) in the recovered material were consistently below the screening values (Table 4), therefore suggesting no adverse human health impacts, and its suitability to be used as a soil in a "public open space – POS" surrounding, i.e. urban tree soil. Solely, WDM concentrations for Chromium (IV) and TPHs were above screening values for residential uses (with and without homegrown produce), suggesting that the material is not suitable for residential areas, however, it is still suitable for uses in commercial surroundings (Table 4). Comparably, albeit temporal variability with a maximum value of 17,057 mg kg^{-1} TPHs (C_{10} to C_{40}; mg kg^{-1} dwt) was recorded within the WDM, TPH concentrations were also below POS screening values. However, speciation into individual TPHs was not undertaken, but a primary influence of diesel-range TPHs (C_{10}-C_{28}) and from the treatment chemical (C_{12}-C_{15}; C_{20}-C_{30}) was recorded. The latter, biodegrading (with or without additional additives), reducing the overall WDM-TPH profile. Additional investigations for persistent organic pollutants (POPs), e.g. polychlorinated biphenyls (PCBs), e.g. from road marking paint (Megson et al., 2019, 2024), per and polyfluoroalkyl substances (PFAS; Ehsan et al., 2024) and 6PPD-Quinone (from tyre rubber; Bohara et al., 2024; Chen et al., 2023) could be beneficial using targeted or non-targeted approaches as these pollutants may be present in road sweepings.

The results indicate the material is safe for use as substrate for urban planting programmes in commercial and/or public open spaces (i.e. parks, roadside vegetation). Moreover, it could provide an alternative

Table 3
British Standards Institute (BSI) soil certifications for Topsoil (BS 3882) and Subsoil (BS 8601) in comparison to the WDM; colouring indicates values within (green) or outside (yellow) of values specified in the respective standard document for different soil types.

	Parameter	BS 3882 multipurpose	BS 3882 calcareous	BS 8601 multipurpose	BS 8601 calcareous	Waste-derived (WDM)
Soil texture	Sand (%)		20-85			12 to 44
	Silt (%)		0-65			54 to 84
	Clay (%)		5-30			0.9 to 5.2
Soil pH	pH (in H_2O)	5.5-8.5	7.5-9.0	5.5-8.5	7.5-8.5	8.32 ± 0.37
Electrical Conductivity	µS cm^{-1}	3300	N/A	N/A	N/A	405 ± 138
LOI (%)	Loss-On-Ignition	3-20	3-20	max. 2	max. 2	**Tab. 2**
C:N ratio	C wt%/ N wt%	<20:1	<20:1	N/A	N/A	27:1 to 41:1
Carbonate	TIC (wt%)	N/A	>1	N/A	N/A	0.72 ± 0.35
Plant nutrients	Nitrogen	>0.15	>0.15	N/A	N/A	**Tab. 2**
	Phosphate (mg L^{-1})	16-140	16-140	N/A	N/A	<0.43 to 3.0
	Potassium (mg L^{-1})	121-1500	121-1500	N/A	N/A	<0.062 to 8.0
	Magnesium (mg L^{-1})	51-600	51-600	N/A	N/A	3.06 to 44.6
Phytotoxic elements†	Zinc (Zn)		<300			229 to 527 (384 ± 64^{X})
	Copper (Cu)		<200			72 to 172 (127 ± 23^{X})
	Nickel (Ni)		<110			30 to 56 (41 ± 6^{X})

† for pH >7.0; ^{X} displayed as mean ± 1x standard deviation; values for LOI (%) and nitrogen (N wt%) are displayed in Table 2

Table 4
Soil screening values (EA SVG, C4SL, S4UL) [mg kg^{-1}] for "commercial" (comm) and "public open space" (POS, park) and residential (RES) with and without (w/and wo/) homegrown produce land-use types, based on 6% soil organic matter (SOM); n.d. – not defined, EC – equivalent carbon, for organic compounds the first value represents aliphatics, the second aromatics; antimony (Sb) was removed due to no defined values (n.d.) for screening values; potentially harmful elements (PHEs) for human health are highlighted in light red.

Element	EA SVG (comm)	C4SL (comm)	S4UL (comm)	C4SL (POS)	S4UL (POS)	S4UL (RES – w/homegrown)	S4UL (RES – wo/homegrown)	WDM (for POS)
		Inorganic						
Arsenic (As)	640	640	640	170	170	37	n. d.	10.8 ± 2.60
Beryllium (Be) †	n. d.	n. d.	12	n. d.	63	1.7	1.7	<2
Boron (B)	n. d.	n. d.	240000	n. d.	46000	290	11000	20 ± 4
Cadmium (Cd)	230	410	190	880	560	11	85	0.892 ± 0.200
Chromium (III)	n. d.	n. d.	8600	n. d.	33000	910	910	53.5 ± 11.9
Chromium (VI)	n. d.	49	33	250	220	6	6	(assuming all Cr as Cr VI)
Copper (Cu)	n. d.	n. d.	68000	n. d.	44000	2400	7100	127 ± 23
Lead (Pb)	n. d.	2300	n. d.	1300	n. d.	n. d.	n. d.	119 ± 22.4
Nickel (Ni)	n. d.	n. d.	980	n. d.	800	130	180	41 ± 6
Mercury (elemental)	26	n. d.	58	n. d.	30	1.2	1.2	0.192 ± 0.092
Molybdenum (Mo)	n. d.	n. d.	n. d.	n. d.	n. d.	n. d.	n. d.	2.50 ± 0.93
Selenium (Se)†	13000	n. d.	12000	n. d.	1800	250	430	<2.0
Vanadium (V)	n. d.	n. d.	9000	n. d.	5000	410	1200	38.9 ± 11.4
Zinc (Zn)	n. d.	n. d.	730000	n. d.	170000	3700	40000	384 ± 64
		Organic						
EC >10-12	n.d.	n.d.	47000 / 34000	n.d.	24000 / 10000	760 / 380	770 / 1200	4298 ± 3892 (dry wt)‡

growing medium for tree nurseries, in green walls and green roofs, due to its good moisture retention, potentially requiring less watering; thus reducing water-use (and costs). Additional growth trials, using different trees (and plants) can aid to identify potential impacts of low or high elemental concentrations in the material on plant growth and assess the environmental risks. Further, human health risk assessments (HHRA) using modelling tools, e.g. contaminated land exposure assessment (CLEA) showed no adverse human health impacts (from metal(loids) to the most vulnerable receptor (female child, 0–6 years), when used in a 'public open space' surrounding with no buildings, however, bioaccessibility assessments according to internationally recognised procedures (BS ISO 17924:2018; BS ISO 22190:2020; Denys et al., 2012) could provide additional insights into potential impact on human health using different exposure routes (e.g. digestion, inhalation and dermal).

5. Conclusion

This study investigated physico-chemical properties in fine residues of waste-derived material (WDM), including inorganic (i.e. metal(loids) and nutrients) and organic (i.e. TPHs) contaminants over a 12-months period. This, first of its kind, extensive characterisation has shown comparable (and for certain properties enhanced) physico-chemical properties to 'urban soils'. Consistent chemical profiles suggest 'good' soil properties (i.e. moisture, organic content, CN ratio etc.) that may support plant growth, e.g. urban trees, although the WDM could not be "certified" as a standardised Topsoil/Subsoil. Total petroleum hydrocarbons (TPHs) showied elevated concentrations (up to 17,000 mg kg^{-1}) and seasonal variability, i.e. linked to treatment chemicals and biogenic compounds from leaf material. Nonetheless, TPHs values in the material were below guideline values for use in 'public open space', and in combination with inherent biodegradability (of treatment chemicals) and/or moving to non-hydrocarbon-based chemicals, combined with enzymatic breakdown will likely further reduce TPHs levels. Further, WDM chemical concentrations were below relevant human health risk associated soil guideline vales (e.g. EA SGVs, S4UL and C4SL for public open space) suggesting that the material could provide a suitable sustainable soil alternative to 'virgin' material.

Soils in the UK (and world-wide) are under threat by contamination, erosion and compaction, sustainable management practices are required, and therefore, the use of recovered material can provide a viable solution for finite soil resources. This is of particular relevance when providing a "circular economy solution" within a regional context where "local resources" (e.g. road sweepings) can be re-used, whilst minimising transportation and/or storage requirements. Moreover, the WDM can be blended with other (recovered) material (e.g. aggregates and sand from same treatment process) and/or soil amendments (i.e. biochar) to improve physical characteristics (e.g. porosity) and be prepared to fit site-specific requirements. This illustrates the variety of potential uses of the material. Considering the UN SGDs of sustainable soil and threats (i.e. compaction and erosion), the use of recovered material as growing medium could aid to restore degraded soil, promoting sustainable uses (i.e. instead of virgin materials) support of ecosystem services (i.e. biodiversity) and carbon sequestration (i.e. climate change mitigation).

CRediT authorship contribution statement

Daniel Niepsch: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Edward Randviir:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Rebecca Murphy-Peers:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Emma Coulthard:** Writing – review & editing, Supervision, Resources, Project administration. **David Hackett:** Writing – review & editing. **David McKendry:**

Validation, Software, Methodology, Formal analysis. **David Megson:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.124928.

Data availability

Data are available within the article or its supplementary materials.

References

Adhikari, K., Hartemink, A.E., 2016. Linking soils to ecosystem services — a global review. Geoderma 262, 101–111. https://doi.org/10.1016/j.geoderma.2015.08.009.

Aftab, N., Saleem, K., Khan, A.H.A., Butt, T.A., Mirza, C.R., Hussain, J., Farooq, G., Tahir, A., Yousaf, S., Zafar, M.I., Nawaz, I., Iqbal, M., 2021. Cosmos sulphureus Cav. is more tolerant to lead than copper and chromium in hydroponics system. Int. J. Environ. Sci. Technol. 18, 2325–2334. https://doi.org/10.1007/s13762-020-02981-w.

Alavi, N., Mesdaghinia, A.-R., Naddafi, K., Mohebali, G., Daraei, H., Maleki, A., Alaei, L., 2014. Biodegradation of petroleum hydrocarbons in a soil polluted sample by oil-based drilling cuttings. Soil Sediment Contam.: Int. J. 23, 586–597. https://doi.org/10.1080/15320383.2014.847900.

ALS, 2017. Waste acceptance Criteria (WAC): thresholds. ALS Environmental. Availabla at: https://www.alsglobal.se/website/var/assets/media-uk/pdf/datasheets/waste-management/als_wm_wac_limits_v1_2014.pdf. (Accessed 11 July 2023).

Amorim, H.C.S., Hurtarte, L.C.C., Souza, I.F., Zinn, Y.L., 2022. C:N ratios of bulk soils and particle-size fractions: global trends and major drivers. Geoderma 425, 116026. https://doi.org/10.1016/j.geoderma.2022.116026.

Ander, E.L., Johnson, C.C., Cave, M.R., Palumbo-Roe, B., Nathanail, C.P., Lark, R.M., 2013. Methodology for the determination of normal background concentrations of contaminants in English soil. Sci. Total Environ. 454–455, 604–618. https://doi.org/10.1016/j.scitotenv.2013.03.005.

Antoniadis, V., Golia, E.E., Shaheen, S.M., Rinklebe, J., 2017a. Bioavailability and health risk assessment of potentially toxic elements in Thriasio Plain, near Athens, Greece. Environ. Geochem. Health 39, 319–330. https://doi.org/10.1007/s10653-016-9882-5.

Antoniadis, V., Levizou, E., Shaheen, S.M., Ok, Y.S., Sebastian, A., Baum, C., Prasad, M.N.V., Wenzel, W.W., Rinklebe, J., 2017b. Trace elements in the soil-plant interface: phytoavailability, translocation, and phytoremediation–A review. Earth Sci. Rev. 171, 621–645. https://doi.org/10.1016/j.earscirev.2017.06.005.

Arnold, S.S., Fernandez, I.J., Rustad, L.E., Zibilske, L.M., 1999. Microbial response of an acid forest soil to experimental soil warming. Biol. Fertil. Soils 30, 239–244. https://doi.org/10.1007/s003740050614.

ATSDR, 2007. Arsenic - ToxFAQs TM. U.S. Agency for Toxic Substances and Disease Registry, Atlanta, GA.

Baccot, C., Pallier, V., Thom, M.T., Thuret-Benoist, H., Feuillade-Cathalifaud, G., 2020. Valorization of extracted organic matter from municipal solid waste leachate: application to soils from France and Togo. Waste Manag. 102, 161–169. https://doi.org/10.1016/j.wasman.2019.10.040.

Baker, B.A., Cassano, V.A., Murray, C., 2018. Arsenic exposure, assessment, toxicity, diagnosis, and management: guidance for occupational and environmental physicians. J. Occup. Environ. Med. 60, e634–e639. https://doi.org/10.1097/JOM.0000000000001485.

Banaitis, M., Langley-Turnbaugh, S., Aboueissa, A., 2007. Variations of soil organic carbon in three urban parks: a Maine case study. Int. J. Appl. Environ. Sci. 2 (2), 119–128.

BGS, 2024. UK soil observatory (UKSO) - map viewer [WWW Document]. URL. https://mapapps2.bgs.ac.uk/ukso/home.html, 5.21.24.

Bigalke, M., Ulrich, A., Rehmus, A., Keller, A., 2017. Accumulation of cadmium and uranium in arable soils in Switzerland. Environ. Pollut. 221, 85–93. https://doi.org/10.1016/j.envpol.2016.11.035.

Biswas, B., Labille, J., Prelot, B., 2020. Clays and modified clays in remediating environmental pollutants. Environ. Sci. Pollut. Res. 27, 38381–38383. https://doi.org/10.1007/s11356-020-09828-4.

Bohara, K., Timilsina, A., Adhikari, K., Kafle, A., Basyal, S., Joshi, P., Yadav, A.K., 2024. A mini review on 6PPD quinone: a new threat to aquaculture and fisheries. Environ. Pollut. 340, 122828. https://doi.org/10.1016/j.envpol.2023.122828.

Brust, G.E., 2019. Management strategies for organic vegetable fertility. In: Safety and Practice for Organic Food. Elsevier, pp. 193–212. https://doi.org/10.1016/B978-0-12-812060-6.00009-X.

Bryson, G.M., Barker, A.V., 2002. Sodium accumulation in soils and plants along Massachusetts roadsides. Commun. Soil Sci. Plant Anal. 33, 67–78. https://doi.org/10.1081/CSS-120002378.

BS EN 13037, 2011. Soil improvers and growing media. Determination of pH.

BS EN 15934, 2012. Sludge, treated biowaste, soil and waste. Calculation of dry matter fraction after determination of dry residue or water content.

BS EN 13040, 2007. Soil improvers and growing media. Sample preparation for chemical and physical tests, determination of dry matter content, moisture content and laboratory compacted bulk density.

BS EN ISO 17892-2, 2014. Geotechnical investigation and testing. Laboratory testing of soil. Determination of bulk density.

BS EN ISO 15935, 2021. Soil, waste, treated biowaste and sludge. Determination of loss on ignition.

BS EN 13652, 2001. Soil improvers and growing media. Extraction of water soluble nutrients and elements.

BS ISO 16729, 2013. Soil quality. Digestion of nitric acid soluble fractions of elements.

BS EN ISO 22036, 2024. Environmental solid matrices. Determination of elements using inductively coupled plasma optical emission spectrometry (ICP-OES).

BS EN 16171, 2016. Sludge, treated biowaste and soil. Determination of elements using inductively coupled plasma mass spectrometry (ICP-MS).

BS EN ISO 16703, 2011. Soil quality. Determination of content of hydrocarbon in the range C_{10} to C_{40} by gas chromatography.

BS EN 13038, 2011. Soil improvers and growing media. Determination of electrical conductivity.

BS EN 12579, 2013. BS EN 12579:2013. Soil improvers and growing media. Sampling.

BS EN ISO 17892-4, 2016. BS EN ISO 17892-4:2016. Geotechnical investigation and testing. Laboratory Testing of Soil. Determination of Particle Size Distribution.

BS ISO 17924, 2018. BS ISO 17924:2018. Soil quality - assessment of human exposure from ingestion of soil and soil material. Procedure for the Estimation of the Human Bioaccessibility/bioavailability of Metals in Soil.

BS ISO 18400-102, 2017. BS ISO 18400-102:2017. Soil quality. Sampling. Selection and application of sampling techniques.

BS ISO 18400-105, 2017. BS ISO 18400-105:2017. Soil Quality. Sampling - Packaging, Transport, Storage and Preservation of Samples.

BSSS, 2022. Science note: Soil Carbon. British Society of Soil Science. Available at: https://soils.org.uk/wp-content/uploads/2022/05/BSSS_Science-Note_Soil-Carbon_Final_May22_75YRS_DIGITAL.pdf (accessed: 09/08/2024).

BS ISO 22190:, 2020. Soil Quality - Use of extracts for the assessment of bioavailability of trace elements in soils.

Cao, Y., He, Z., Zhu, T., Zhao, F., 2021. Organic-C quality as a key driver of microbial nitrogen immobilization in soil: a meta-analysis. Geoderma 383, 114784. https://doi.org/10.1016/j.geoderma.2020.114784.

Charola, A.E., Rousset, B., Blaeuer, C., 2017. Deicing salts: an Overview. In: SWBSS 2017. Presented at the 4th International Conference on Salt Weathering of Buildings and Stone SculpturesAt: Potsdam, SWBSS 2017. Potsdam.

Chen, X., He, T., Yang, X., Gan, Y., Qing, X., Wang, J., Huang, Y., 2023. Analysis, environmental occurrence, fate and potential toxicity of tire wear compounds 6PPD and 6PPD-quinone. J. Hazard Mater. 452, 131245. https://doi.org/10.1016/j.jhazmat.2023.131245.

Churka Blum, S., Lehmann, J., Solomon, D., Caires, E.F., Alleoni, L.R.F., 2013. Sulfur forms in organic substrates affecting S mineralization in soil. Geoderma 200–201, 156–164. https://doi.org/10.1016/j.geoderma.2013.02.003.

Collin, S., Baskar, A., Geevarghese, D.M., Ali, M.N.V.S., Bahubali, P., Choudhary, R., Lvov, V., Tovar, G.I., Senatov, F., Koppala, S., Swamiappan, S., 2022. Bioaccumulation of lead (Pb) and its effects in plants: a review. Journal of Hazardous Materials Letters 3, 100064. https://doi.org/10.1016/j.hazl.2022.100064.

Collivignarelli, M.C., Baldi, M., Abbà, A., Caccamo, F.M., Carnevale Miino, M., Rada, E.C., Torretta, V., 2020. Foams in wastewater treatment plants: from causes to control methods. Appl. Sci. 10, 2716. https://doi.org/10.3390/app10082716.

Coulon, F., Campo, P., Walton, C., Alamar, M.C., Cowley, T., Marsay, N., Tezyapar, I., 2022. Qualitative and Quantitative Comparison of Field-Based Analytical Technologies for Petroleum Hydrocarbons Determination in Soils.

Councell, T.B., Duckenfield, K.U., Landa, E.R., Callender, E., 2004. Tire-wear particles as a source of zinc to the environment. Environ. Sci. Technol. 38, 4206–4214. https://doi.org/10.1021/es034631f.

Czerniawska-Kusza, I., Kusza, G., Dużyński, M., 2004. Effect of deicing salts on urban soils and health status of roadside trees in the Opole region. Environ. Toxicol. 19, 296–301. https://doi.org/10.1002/tox.20037.

Das, S., Wiseman, C.L.S., 2024. Examining the effectiveness of municipal street sweeping in removing road-deposited particles and metal(loid)s of respiratory health concern. Environ. Int. 187, 108697. https://doi.org/10.1016/j.envint.2024.108697.

DEFRA, 2023a. Local Authority Collected Waste Management - Annual Results 2021/2, 9.6.24.

DEFRA, 2023b. Policy paper: the waste prevention programme for England: maximising Resources, Minimising Waste. https://www.gov.uk/government/publications/waste-prevention-programme-for-england-maximising-resources-minimising-waste/the-waste-prevention-programme-for-england-maximising-resources-minimising-waste#introduction, 9.6.24.

DEFRA, 2019. UK Statistics on Waste.

Denys, S., Caboche, J., Tack, K., Rychen, G., Wragg, J., Cave, M., Jondreville, C., Feidt, C., 2012. In vivo validation of the unified BARGE method to assess the bioaccessibility of arsenic, antimony, cadmium, and lead in soils. Environ. Sci. Technol. 46, 6252–6260. https://doi.org/10.1021/es3006942.

Desaulty, A.-M., Perret, S., Maubec, N., Négrel, P., 2020. Tracking anthropogenic sources in a small catchment using Zn-isotope signatures. Appl. Geochem. 123, 104788. https://doi.org/10.1016/j.apgeochem.2020.104788.

Dlangamandla, C., Basitere, M., Okeleye, B.I., Chidi, B.S., Karabo Obed Ntwampe, S., 2021. Biofoam formation and defoamation in global wastewater treatment systems. Water Pract. Technol. 16, 1–18. https://doi.org/10.2166/wpt.2020.113.

Dobson, M.C., Crispo, M., Blevins, R.S., Warren, P.H., Edmondson, J.L., 2021. An assessment of urban horticultural soil quality in the United Kingdom and its contribution to carbon storage. Sci. Total Environ. 777, 146199. https://doi.org/10.1016/j.scitotenv.2021.146199.

EA, 2024. Remaining landfill capacity. https://www.data.gov.uk/dataset/237825cb-dc10-4c53-8446-1bcd35614c12/remaining-landfill-capacity, 9.6.24.

EA, 2023. Summary of the state of the environment: soil. https://www.gov.uk/government/publications/state-of-the-environment/summary-state-of-the-environment-soil, 9.9.24.

EA, 2012. Recovery of Street Sweepings and Gully Emptyings. Environment Agency. Available art: https://www.wastedataflow.org/documents/guidancenotes/Specific/LATS_street_sweepings_guidance.pdf. (Accessed: 17/04/2023).

Edmondson, J.L., Davies, Z.G., McCormack, S.A., Gaston, K.J., Leake, J.R., 2011. Are soils in urban ecosystems compacted? A citywide analysis. Biol. Lett. 7, 771–774. https://doi.org/10.1098/rsbl.2011.0260.

Ehsan, M.N., Riza, M., Pervez, M.N., Li, C.-W., Zorpas, A.A., Naddeo, V., 2024. PFAS contamination in soil and sediment: contribution of sources and environmental impacts on soil biota. Case Studies in Chemical and Environmental Engineering 9, 100643. https://doi.org/10.1016/j.cscee.2024.100643.

Emmett, B.A., 2007. Nitrogen saturation of terrestrial ecosystems: some recent findings and their implications for our conceptual framework. In: Brimblecombe, P., Hara, H., Houle, D., Novak, M. (Eds.), Acid Rain - Deposition to Recovery. Springer, Netherlands, Dordrecht, pp. 99–109. https://doi.org/10.1007/978-1-4020-5885-1_12.

EPA, 1988. Ambient Water Quality Criteria for Chloride. U.S. Environmental Protection Agency, Washington D.C.

Equiza, M.A., Calvo-Polanco, M., Cirelli, D., Señorans, J., Wartenbe, M., Saunders, C., Zwiazek, J.J., 2017. Long-term impact of road salt (NaCl) on soil and urban trees in Edmonton, Canada. Urban For. Urban Green. 21, 16–28. https://doi.org/10.1016/j.ufug.2016.11.003.

EU, 2007. Risk Assessment Report—Cadmium Oxide and Cadmium Metal: Part I. European Union.

Fact, M.R., 2019. Street Sweeper Market Outlook (2019-2027).

Geilfus, C.-M., 2019. Chloride in soil: from nutrient to soil pollutant. Environ. Exp. Bot. 157, 299–309. https://doi.org/10.1016/j.envexpbot.2018.10.035.

Gerasimova, M.I., Stroganova, M.N., Mozharova, N.V., Prokof'eva, T.V., 2003. Antropogennye Pochvy: Genezis, Geografiya, Rekultivatsiya (In Russian) (Anthropogenic Soils: Genesis, Geography, and Remediation), Smolensk, 2003).

Grieshop, A.P., Lipsky, E.M., Pekney, N.J., Takahama, S., Robinson, A.L., 2006. Fine particle emission factors from vehicles in a highway tunnel: effects of fleet composition and season. Atmos. Environ. 40, 287–298. https://doi.org/10.1016/j.atmosenv.2006.03.064.

Gundersen, P., Schmidt, I.K., Raulund-Rasmussen, K., 2006. Leaching of nitrate from temperate forests effects of air pollution and forest management. Environ. Rev. 14, 1–57. https://doi.org/10.1139/a05-015.

Haghollahi, A., Fazaelipoor, M.H., Schaffie, M., 2016. The effect of soil type on the bioremediation of petroleum contaminated soils. J. Environ. Manag. 180, 197–201. https://doi.org/10.1016/j.jenvman.2016.05.038.

Harrison, R.M., Jones, A.M., Gietl, J., Yin, J., Green, D.C., 2012. Estimation of the contributions of brake dust, tire wear, and resuspension to nonexhaust traffic particles derived from atmospheric measurements. Environ. Sci. Technol. 46, 6523–6529. https://doi.org/10.1021/es300894r.

Hatten, J., Liles, G., 2019. A 'healthy' balance – the role of physical and chemical properties in maintaining forest soil function in a changing world. In: Developments in Soil Science. Elsevier, pp. 373–396. https://doi.org/10.1016/B978-0-444-63998-1.00015-X.

Hawkesford, M.J., Cakmak, I., Coskun, D., De Kok, L.J., Lambers, H., Schjoerring, J.K., White, P.J., 2023. Functions of macronutrients. In: Marschner's Mineral Nutrition of Plants. Elsevier, pp. 201–281. https://doi.org/10.1016/B978-0-12-819773-8.00019-8.

Hayatsu, M., Katsuyama, C., Tago, K., 2021. Overview of recent researches on nitrifying microorganisms in soil. Soil Sci. Plant Nutr. 67, 619–632. https://doi.org/10.1080/00380768.2021.1981119.

He, J., Chen, B., Xu, W., Xiang, C., Kuang, W., Zhao, X., 2023. Driving factors for soil C:N ratio in woody plant communities across northeastern Qinghai-Tibetan Plateau. Catena 233, 107504. https://doi.org/10.1016/j.catena.2023.107504.

HEI, 2006. Characterization of Metals Emitted from Motor Vehicles. Helath Effects Institute, Boston (MA).

Hollingsworth, A., Rudik, I., 2021. The effect of leaded gasoline on elderly mortality: evidence from regulatory exemptions. Am. Econ. J. Econ. Pol. 13, 345–373. https://doi.org/10.1257/pol.20190654.

Hussain, F., Khan, A.H.A., Hussain, I., Farooqi, A., Muhammad, Y.S., Iqbal, M., Arslan, M., Yousaf, S., 2022. Soil conditioners improve rhizodegradation of aged petroleum hydrocarbons and enhance the growth of Lolium multiflorum. Environ. Sci. Pollut. Res. 29, 9097–9109. https://doi.org/10.1007/s11356-021-16149-7.

ISO 10694, 1995. Soil quality — Determination of organic and total carbon after dry combustion (elementary analysis).

ISO 13878, 1998. Soil quality — Determination of total nitrogen content by dry combustion ("elemental analysis").

Jim, C.Y., 1998a. Urban soil characteristics and limitations for landscape planting in Hong Kong. Landsc. Urban Plann. 40, 235–249. https://doi.org/10.1016/S0169-2046(97)00117-5.

Jim, C.Y., 1998b. Physical and chemical properties of a Hong Kong roadside soil in relation to urban tree growth. Urban Ecosyst. 2, 171–181. https://doi.org/10.1023/A:1009585700191.

Jim, C.Y., 1998c. Soil compaction at tree-planting sites in urban Hong Kong. In: Neely, G., Watson, G.W. (Eds.), The Landscape below Ground II: Proceedings from the Second International Workshop on Tree Root Development in Urban Soils, Held in March 1998. International Society of Arboriculture, Cahmpaign, IL, pp. 166–178.

Karhu, K., Auffret, M.D., Dungait, J.A.J., Hopkins, D.W., Prosser, J.I., Singh, B.K., Subke, J.-A., Wookey, P.A., Ågren, G.I., Sebastià, M.-T., Gouriveau, F., Bergkvist, G., Meir, P., Nottingham, A.T., Salinas, N., Hartley, I.P., 2014. Temperature sensitivity of soil respiration rates enhanced by microbial community response. Nature 513, 81–84. https://doi.org/10.1038/nature13604.

Khan, A.H.A., Ayaz, M., Arshad, M., Yousaf, S., Khan, M.A., Anees, M., Sultan, A., Nawaz, I., Iqbal, M., 2019. Biogeochemical cycle, occurrence and biological treatments of polycyclic aromatic hydrocarbons (PAHs). Iran J Sci Technol Trans Sci 43, 1393–1410. https://doi.org/10.1007/s40995-017-0393-8.

Khan, A.H.A., Kiyani, A., Cheema, A.S., Tareen, U., Nawaz, I., Iqbal, M., Yousaf, S., 2021. Integrative application of soil conditioners and bio-augmentation for enhanced heavy metal stabilization from wastewater and improved growth of nicotiana alata L. And petunia hydrida L. J. Plant Growth Regul. 40, 240–253. https://doi.org/10.1007/s00344-020-10094-4.

Khan, F., Siddique, A.B., Shabala, S., Zhou, M., Zhao, C., 2023. Phosphorus plays key roles in regulating plants' physiological responses to abiotic stresses. Plants 12, 2861. https://doi.org/10.3390/plants12152861.

Kubier, A., Wilkin, R.T., Pichler, T., 2019. Cadmium in soils and groundwater: a review. Appl. Geochem. 108, 104388. https://doi.org/10.1016/j.apgeochem.2019.104388.

Kuei-Jyum Yeh, C., Young, C.-C., 2003. Effects of soil fines and surfactant sorption on contaminant reduction of coarse fractions during soil washing. Journal of Environmental Science and Health, Part A 38, 2697–2709. https://doi.org/10.1081/ESE-120024457.

Lambers, H., 2022. Phosphorus acquisition and utilization in plants. Annu. Rev. Plant Biol. 73, 17–42. https://doi.org/10.1146/annurev-arplant-102720-125738.

Legret, M., Pagotto, C., 1999. Evaluation of pollutant loadings in the runoff waters from a major rural highway. Sci. Total Environ. 235, 143–150. https://doi.org/10.1016/S0048-9697(99)00207-7.

Lehmann, A., Stahr, K., 2007. Nature and significance of anthropogenic urban soils. J. Soils Sediments 7, 247–260. https://doi.org/10.1065/jss2007.06.235.

Lehtonen, A., Palviainen, M., Ojanen, P., Kalliokoski, T., Nöjd, P., Kukkola, M., Penttilä, T., Mäkipää, R., Leppälammi-Kujansuu, J., Helmisaari, H.-S., 2016. Modelling fine root biomass of boreal tree stands using site and stand variables. For. Ecol. Manag. 359, 361–369. https://doi.org/10.1016/j.foreco.2015.06.023.

Liu, R., Jadeja, R.N., Zhou, Q., Liu, Z., 2012. Treatment and remediation of petroleum-contaminated soils using selective ornamental plants. Environ. Eng. Sci. 29, 494–501. https://doi.org/10.1089/ees.2010.0490.

Lloyd, L.N., Fitch, G.M., Singh, T.S., Smith, J.A., 2018. Characterization of Residuals Collected from Street Sweeping Operations.

Lorenz, K., Lal, R., 2009. Biogeochemical C and N cycles in urban soils. Environ. Int. 35, 1–8. https://doi.org/10.1016/j.envint.2008.05.006.

Megson, D., Benoit, N.B., Sandau, C.D., Chaudhuri, S.R., Long, T., Coulthard, E., Johnson, G.W., 2019. Evaluation of the effectiveness of different indicator PCBs to estimating total PCB concentrations in environmental investigations. Chemosphere 237, 124429. https://doi.org/10.1016/j.chemosphere.2019.124429.

Megson, D., Idowu, I.G., Sandau, C.D., 2024. Is current generation of polychlorinated biphenyls exceeding peak production of the 1970s? Sci. Total Environ. 924, 171436. https://doi.org/10.1016/j.scitotenv.2024.171436.

Men, C., Liu, R., Wang, Q., Guo, L., Shen, Z., 2018. The impact of seasonal varied human activity on characteristics and sources of heavy metals in metropolitan road dusts. Sci. Total Environ. 637–638, 844–854. https://doi.org/10.1016/j.scitotenv.2018.05.059.

Merkel, B., Sperling, B., 1998. Hydrogeochemische Stoffsysteme Teil II.

Miller, J.J., Beasley, B.W., Drury, C.F., Zebarth, B.J., 2011a. Transport of residual nutrients through intact soil cores amended with fresh or composted beef cattle manure for nine years. Compost Sci. Util. 19, 267–278. https://doi.org/10.1080/1065657X.2011.10737009.
Miller, J.J., Beasley, B.W., Drury, C.F., Zebarth, B.J., 2011b. Accumulation and redistribution of residual chloride, nitrate, and soil test phosphorus in soil profiles amended with fresh and composted cattle manure containing straw or wood-chip bedding. Can. J. Soil Sci. 91, 969–984. https://doi.org/10.4141/cjss2011-048.
Mirlean, N., Roisenberg, A., 2006. The effect of emissions of fertilizer production on the environment contamination by cadmium and arsenic in southern Brazil. Environ. Pollut. 143, 335–340. https://doi.org/10.1016/j.envpol.2005.11.022.
Muskus, A.M., Krauss, M., Miltner, A., Hamer, U., Nowak, K.M., 2020. Degradation of glyphosate in a Colombian soil is influenced by temperature, total organic carbon content and pH. Environ. Pollut. 259, 113767. https://doi.org/10.1016/j.envpol.2019.113767.
NAEI, 2024a. Pollutant information: potassium. https://naei.energysecurity.gov.uk/node/65, 9.9.24.
NAEI, 2024b. Pollutant information: magnesium [WWW Document]. URL. https://naei.energysecurity.gov.uk/node/61, 9.9.24.
NAEI, 2024c. Pollutant information: calcium [WWW Document]. URL. https://naei.energysecurity.gov.uk/node/57, 9.9.24.
Nagajyoti, P.C., Lee, K.D., Sreekanth, T.V.M., 2010. Heavy metals, occurrence and toxicity for plants: a review. Environ. Chem. Lett. 8, 199–216. https://doi.org/10.1007/s10311-010-0297-8.
Narayan, O.P., Kumar, P., Yadav, B., Dua, M., Johri, A.K., 2023. Sulfur nutrition and its role in plant growth and development. Plant Signal. Behav. 18, 2030082. https://doi.org/10.1080/15592324.2022.2030082.
Natural England, 2008. Technical Information Note TIN037 - Soil Texture.
Neina, D., 2019. The role of soil pH in plant nutrition and soil remediation. Applied and Environmental Soil Science 1–9. https://doi.org/10.1155/2019/5794869, 2019.
Ngai, K.W., Mak, M.W., Ko, H.S., Pun, K.L., 2022. Seasonal variation of heavy metal contents in road dust from residential, industrial and rural areas of Hong Kong. Trans. Hong Kong Inst. Eng. 29, 191–199. https://doi.org/10.33430/V29N3THIE-2020-0049.
Nguyen, T.-B., Sherpa, K., Bui, X.-T., Nguyen, V.-T., Vo, T.-D.-H., Ho, H.-T.-T., Chen, C.-W., Dong, C.-D., 2023. Biochar for soil remediation: a comprehensive review of current research on pollutant removal. Environ. Pollut. 337, 122571. https://doi.org/10.1016/j.envpol.2023.122571.
Niepsch, D., Clarke, L.J., Jones, R.G., Tzoulas, K., Cavan, G., 2024. Lichen biomonitoring to assess spatial variability, potential sources and human health risks of polycyclic aromatic hydrocarbons (PAHs) and airborne metal concentrations in Manchester (UK). Environ. Monit. Assess. 196, 379. https://doi.org/10.1007/s10661-024-12522-4.
Nikolaeva, O., Rozanova, M., Karpukhin, M., 2017. Distribution of traffic-related contaminants in urban topsoils across a highway in Moscow. J. Soils Sediments 17, 1045–1053. https://doi.org/10.1007/s11368-016-1587-y.
Norrström, A.C., Jacks, G., 1998. Concentration and fractionation of heavy metals in roadside soils receiving de-icing salts. Sci. Total Environ. 218, 161–174. https://doi.org/10.1016/S0048-9697(98)00203-4.
Obeng-Gyasi, E., 2019. Sources of lead exposure in various countries. Rev. Environ. Health 34, 25–34. https://doi.org/10.1515/reveh-2018-0037.
Oldfield, E.E., Bradford, M.A., Wood, S.A., 2018. Global meta-analysis of the relationship between soil organic matter and crop yields. https://doi.org/10.5194/soil-2018-21.
Ondráček, J., Schwarz, J., Ždímal, V., Andělová, L., Vodička, P., Bízek, V., Tsai, C.-J., Chen, S.-C., Smolík, J., 2011. Contribution of the road traffic to air pollution in the Prague city (busy speedway and suburban crossroads). Atmos. Environ. 45, 5090–5100. https://doi.org/10.1016/j.atmosenv.2011.06.036.
O'Riordan, R., Davies, J., Stevens, C., Quinton, J.N., Boyko, C., 2021. The ecosystem services of urban soils: a review. Geoderma 395, 115076. https://doi.org/10.1016/j.geoderma.2021.115076.
Ossai, I.C., Hamid, F.S., Aboudi-Mana, S.C., Hassan, A., 2024. Synergistic actions of biostimulation and bioaugmentation in microbial biodegradation of total petroleum hydrocarbons (TPH) using keratinaceous materials. Water Air Soil Pollut. 235, 541. https://doi.org/10.1007/s11270-024-07341-9.
PAS115, 2021. Road sweeping and gully waste (non-hazardous). Materials derived for future use in soils or soil amendments. Specification. https://doi.org/10.3403/30413854.
Patel, K.S., Pandey, P.K., Martín-Ramos, P., Corns, W.T., Varol, S., Bhattacharya, P., Zhu, Y., 2023. A review on arsenic in the environment: contamination, mobility, sources, and exposure. RSC Adv. 13, 8803–8821. https://doi.org/10.1039/D3RA00789H.
Pérez, M.A.P., Moreira-Turcq, P., Gallard, H., Allard, T., Benedetti, M.F., 2011. Dissolved organic matter dynamic in the Amazon basin: sorption by mineral surfaces. Chem. Geol. 286, 158–168. https://doi.org/10.1016/j.chemgeo.2011.05.004.
Pickett, S.T.A., Cadenasso, M.L., 2009. Altered resources, disturbance, and heterogeneity: a framework for comparing urban and non-urban soils. Urban Ecosyst. 12, 23–44. https://doi.org/10.1007/s11252-008-0047-x.
Pitt, R., Chen, S.-E., Clark, S.E., Swenson, J., Ong, C.K., 2008. Compaction's impacts on urban storm-water infiltration. J. Irrigat. Drain. Eng. 134, 652–658. https://doi.org/10.1061/(ASCE)0733-9437(2008)134:5(652.
Puskás, I., Farsang, A., 2009. Diagnostic indicators for characterizing urban soils of Szeged, Hungary. Geoderma 148, 267–281. https://doi.org/10.1016/j.geoderma.2008.10.014.
R Core Team, 2021. R: A Language and Environment for Statistical Computing.
Ragazzi, M., Zuccato, C., Schiavon, M., Rada, E.C., 2023. Overview and possible approach to street sweeping criticalities. Energy Rep. 9, 117–124. https://doi.org/10.1016/j.egyr.2023.05.245.
Razali, N.M., Wah, Y.B., 2011. Power comparisons of shapiro-wilk , Kolmogorov-smirnov, lilliefors and anderson-darling tests. Journal of Statistical Modeling and Analytics 2, 21–33. https://doi.org/10.1515/bile-2015-0008.
Ren, K., Teng, F., Liu, S., Liu, X., 2022. Analysis of the effect of soil remediation processes contaminated by heavy metals in different soils. Water 14, 4004. https://doi.org/10.3390/w14244004.
RHS, 2024. Soil types [WWW Document]. URL. https://www.rhs.org.uk/soil-composts-mulches/soil-types, 7.10.24.
Robertson, D.J., Taylor, K.G., 2007. Temporal variability of metal contamination in urban road-deposited sediment in Manchester, UK: implications for urban pollution monitoring. Water Air Soil Pollut. 186, 209–220. https://doi.org/10.1007/s11270-007-9478-x.
Robertson, D.J., Taylor, K.G., Hoon, S.R., 2003. Geochemical and mineral magnetic characterisation of urban sediment particulates, Manchester, UK. Appl. Geochem. 18, 269–282. https://doi.org/10.1016/S0883-2927(02)00125-7.
Rogge, W.F., Hildemann, L.M., Mazurek, M.A., Cass, G.R., Simoneit, B.R.T., 1993. Sources of fine organic aerosol. 3. Road dust, tire debris, and organometallic brake lining dust: roads as sources and sinks. Environ. Sci. Technol. 27, 1892–1904. https://doi.org/10.1021/es00046a019.
RStudio Team, 2021. RStudio. Integrated Development for R.
Sang, X., Miao, Q., Bao, M., Li, H., Yan, D., Sun, P., 2020. The interaction between dispersed crude oil droplets and particulate matter. Environ. Sci.: Process. Impacts 22, 1397–1407. https://doi.org/10.1039/D0EM00114G.
Savich, V.I., Fedorin, Y.V., Khimina, E.G., 2007. Soils of Megapolis, Their Ecological Analysis, Use and Formation (By Example of Moscow).
Schoonheydt, R.A., Johnston, C.T., 2013. Surface and interface chemistry of clay minerals. In: Developments in Clay Science. Elsevier, pp. 139–172. https://doi.org/10.1016/B978-0-08-098258-8.00005-5.
Shankar, S., Shanker, U., Shikha, 2014. Arsenic contamination of groundwater: a review of sources, prevalence, health risks, and strategies for mitigation. Sci. World J. 1–18. https://doi.org/10.1155/2014/304524, 2014.
Shannon, T.P., Ahler, S.J., Mathers, A., Ziter, C.D., Dugan, H.A., 2020. Road salt impact on soil electrical conductivity across an urban landscape. J. Urban Econ. 6, juaa006. https://doi.org/10.1093/jue/juaa006.
Smetak, K.M., Johnson-Maynard, J.L., Lloyd, J.E., 2007. Earthworm population density and diversity in different-aged urban systems. Appl. Soil Ecol. 37, 161–168. https://doi.org/10.1016/j.apsoil.2007.06.004.
SNF, 2021. FLOFOAM™ 139 F - Safety Data Sheet.
SNF, 2020. FLOPAM™ EM 440 LOB - Safety Data Sheet.
Sprynskyy, M., Kowalkowski, T., Tutu, H., Cozmuta, L.M., Cukrowska, E.M., Buszewski, B., 2011. The adsorption properties of agricultural and forest soils towards heavy metal ions (Ni, Cu, Zn, and Cd). Soil Sediment Contam.: Int. J. 20, 12–29. https://doi.org/10.1080/15320383.2011.528467.
SSA, 2024. Soil in the UN SDGs [WWW Document]. URL. https://sustainablesoils.org/about-soils/soils-in-the-sdgs, 11.18.24.
Sternbeck, J., Sjödin, Å., Andréasson, K., 2002. Metal emissions from road traffic and the influence of resuspension—results from two tunnel studies. Atmos. Environ. 36, 4735–4744. https://doi.org/10.1016/S1352-2310(02)00561-7.
Tao, Y., Zhou, X.-B., Zhang, S.-H., Lu, H.-Y., Shao, H., 2020. Soil nutrient stoichiometry on linear sand dunes from a temperate desert in Central Asia. Catena 195, 104847. https://doi.org/10.1016/j.catena.2020.104847.
The jamovi project, 2020. jamovi.
Tica, D., Udovic, M., Lestan, D., 2011. Immobilization of potentially toxic metals using different soil amendments. Chemosphere 85, 577–583. https://doi.org/10.1016/j.chemosphere.2011.06.085.
Tipping, E., Poskitt, J.M., Lawlor, A.J., Wadsworth, R.A., Norris, D.A., Hall, J.R., 2011. Mercury in United Kingdom topsoils; concentrations, pools, and Critical Limit exceedances. Environ. Pollut. 159, 3721–3729. https://doi.org/10.1016/j.envpol.2011.07.011.
UBU, 2023. Aggregate Leaftet.
UK Government, 2015. The Water Framework Directive (Standards and Classification) Directions (England and Wales) 2015.
UN FAO, 2022. FAO Warns 90 Per Cent of Earth's Topsoil at Risk by 2050.
USDA, 2019. Bulk Density/Moisture/Aeration. United States Department of Agriculture.
USDA, 2011. Soil Quality Indicators - Soil Electrical Conductivity.
Vane, C.H., Kim, A.W., Beriro, D., Lowe, S.R., Lopes dos Santos, R.A., Ferreira, A.M.P.J., Collins, C., Nathanail, C.P., Moss-Hayes, V., 2021. Persistent Organic Pollutants in Urban Soils of Central of London, England, UK: Measurement and Spatial Modelling of Black Carbon (BC), Petroleum Hydrocarbons (TPH), Polycyclic Aromatic Hydrocarbons (PAH) and Polychlorinated Biphenyls (PCB). https://doi.org/10.21926/aeer.2102012 aeer 02, 1–1.
Vanguelova, E., Pitman, R., Benham, S., 2024. Responses of forest ecosystems to nitrogen deposition in the United Kingdom. In: Atmospheric Nitrogen Deposition to Global Forests. Elsevier, pp. 183–203. https://doi.org/10.1016/B978-0-323-91140-5.00002-6.
Vodyanitskii, YuN., 2015. Organic matter of urban soils: a review. Eurasian Soil Sci. 48, 802–811. https://doi.org/10.1134/S1064229315080116.
Wang, J.H., Yu, T.R., 1998. Release of hydroxyl ions during specific adsorption of chloride by variable-charge soils. J Plant Nutrition & Soil 161, 109–113. https://doi.org/10.1002/jpln.1998.3581610205.
Wang, J.M., Jeong, C.-H., Hilker, N., Healy, R.M., Sofowote, U., Debosz, J., Su, Y., Munoz, A., Evans, G.J., 2021. Quantifying metal emissions from vehicular traffic

using real world emission factors. Environ. Pollut. 268, 115805. https://doi.org/10.1016/j.envpol.2020.115805.
Wang, P.G., Ji, G.L., Yu, T.R., 1987. Adsorption of chloride and nitrate by variable charge soils in relation to the electric charge of the soil. J Plant Nutrition & Soil 150, 17–23. https://doi.org/10.1002/jpln.19871500105.
Wang, X., Feng, J., Zhao, J., 2010. Effects of crude oil residuals on soil chemical properties in oil sites, Momoge Wetland, China. Environ. Monit. Assess. 161, 271–280. https://doi.org/10.1007/s10661-008-0744-1.
Wang, X., Liu, E., Wang, Z., Xu, J., Liu, L., Nath, B., Zhu, Y., 2024. Variability of metal (loid) contamination in road dust from an urban park and a traffic intersection between two rainfall events and its implications. Soil Sediment Contam.: Int. J. 1–21. https://doi.org/10.1080/15320383.2024.2319859.
WasteDataFlow, 2013. Web Based System for Municipal Waste Data Reporting by UK Local Authorities to Government [online]. Department for Environment, Food and Rural Affairs, London. http://www.wastedataflow.org/home.aspx, 9.9.24.
Wickham, H., 2016. ggplot2: Elegant Graphics for Data Analysis.
Wu, B., Guo, S., Zhang, L., Wang, S., Liu, D., Cheng, Z., Shi, N., 2022. Spatial variation of residual total petroleum hydrocarbons and ecological risk in oilfield soils. Chemosphere 291, 132916. https://doi.org/10.1016/j.chemosphere.2021.132916.
Wu, M., Dick, W.A., Li, W., Wang, X., Yang, Q., Wang, T., Xu, L., Zhang, M., Chen, L., 2016. Bioaugmentation and biostimulation of hydrocarbon degradation and the microbial community in a petroleum-contaminated soil. Int. Biodeterior. Biodegrad. 107, 158–164. https://doi.org/10.1016/j.ibiod.2015.11.019.
Wu, Y., Yu, Y., 2023. Soil carbon, nitrogen and phosphorus fractions and response to microorganisms and mineral elements in zanthoxylum planispinum 'dintanensis' plantations at different altitudes. Agronomy 13, 558. https://doi.org/10.3390/agronomy13020558.
Yang, J., Zhang, G., Zhao, Y., Ruan, X., He, Y., 2005. Application and comparison of soil compaction indexes in the evaluation of urban soils. Trans. Chin. Soc. Agric. Eng. 21, 51–55.
Yang, J.-L., Zhang, G.-L., 2015. Formation, characteristics and eco-environmental implications of urban soils – a review. Soil Sci. Plant Nutr. 61, 30–46. https://doi.org/10.1080/00380768.2015.1035622.
Yao, A., Ju, L., Ling, X., Liu, C., Wei, X., Qiu, H., Tang, Y., Morel, J.L., Qiu, R., Li, C., Wang, S., 2019. Simultaneous attenuation of phytoaccumulation of Cd and as in soil treated with inorganic and organic amendments. Environ. Pollut. 250, 464–474. https://doi.org/10.1016/j.envpol.2019.04.073.
Yuan, W., Li, J., Zhang, Q., Saito, F., 2012. Innovated application of mechanical activation to separate lead from scrap cathode ray tube funnel glass. Environ. Sci. Technol. 46, 4109–4114. https://doi.org/10.1021/es204387a.
Zarcinas, B.A., Rogers, S.L., 2002. [No title found]. Environ. Geochem. Health 24, 191–203. https://doi.org/10.1023/A:1016061407072.
Zou, C., Zhang, L., Hu, X., Wang, Z., Wik, T., Pecht, M., 2018. A review of fractional-order techniques applied to lithium-ion batteries, lead-acid batteries, and supercapacitors. J. Power Sources 390, 286–296. https://doi.org/10.1016/j.jpowsour.2018.04.033.