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RESEARCH ARTICLE

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From waste to soil: Can we create functioning manufactured soils by recycling rock processing waste?

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Abstract

Rock mining industries do not only exploit and transform extensive areas of land, but also produce vast amounts of rock waste material that lacks an adequate utilization. Some of these rock wastes have the potential to provide nutrients to plants and can therefore have positive impacts on soil properties. Consequently, we tested their potential for valorization as components of manufactured soils for use in urban areas. We conducted a 10-week incubation experiment of soil mesocosms with sunflowers (*Helianthus annuus* L.) to evaluate the performance of manufactured soils with respect to plant growth and soil properties. We used three common rock materials (augite-porphyry, greywacke-hornfels, basalt), ground to powder and mixed into natural soils of either clayey or sandy texture. In order to test the performance under challenging environmental conditions, we applied a drought treatment in addition to a regular watering treatment. All manufactured soils were able to maintain plant growth, although the yield of aboveground biomass was significantly lower compared to the original soils. However, the effects of the water regime and the original soils on the overall plant growth were stronger than the effect of the rock powders, indicating that the manufactured soils were not hampering plant development more than challenging environmental conditions. The preparation of the manufactured soils altered the grain size distribution of the originally sandy and clayey soils. Since the rock powders contributed mainly to the silt-sized particles, their addition to soils may improve the physical properties of the soil, especially the plant's available water content. We used wet-sieving to isolate aggregate size fractions and thus analyse the formation of soil aggregates. The manufactured soils had a higher mass contribution of microaggregate-sized particles, although this was mostly attributed to the presence of silt-sized rock powder particles instead of aggregate formation. The total organic carbon (OC) content of the original soils was diluted in the manufactured soils, as the rock powders did not contain OC. However, the manufactured soils may have the potential for future OC storage due to the abundance of OC-free mineral surfaces, which can retain organic matter as well as capture CO_2 through enhanced weathering of primary minerals. Based on this work, the tested rock materials have the potential to be utilized as components in manufactured soils in the urban context that provide soil-like functions, particularly in terms of sustaining plant growth. For improved results, additional measures to initiate a rapid development of soil structure are highly recommended, for example, by adding an easily decomposable source of organic matter.

KEYWORDS

artificial soil, circular economy, constructed soil, land reclamation, mineral waste, nature-based solutions, organic carbon, soil rehabilitation, Technosol, urban green infrastructure

1 | INTRODUCTION

A functioning soil stores organic carbon (OC) and provides water and nutrients for plant growth and living organisms, while being resistant to erosive forces. A soil is a living ecosystem that needs to be considered and restored as a whole, encompassing its biological, chemical, and physical parameters, requirements, and functions (DeJong et al., 2011; Lehmann et al., 2020).

However, soil degradation, resulting in the loss of fertile and functioning soil, is a major challenge for humanity. In particular, human settlements and urban expansion lead to land degradation through soil sealing and land take for urban growth. In this context, the United Nations estimated that by 2050, 68% of the world's population will live in urban areas (United Nations, 2019). Human settlements require not only vast areas of land, but also large volumes of building materials from mine sites for construction purposes. For example, Germany needed 600 M tons of rock products from mine sites in 2020 alone, which in turn generated 200 M tons of mineral waste (German Environment Agency, 2022). The operations of the rock mining industry not only provide products for the construction sector but also generate a large amount of rock waste material for which finding an adequate utilization has great economic and environmental potential. These rock wastes are usually of a similar mineral and chemical composition to the mined products, but are not saleable as a product for its intended purpose, e.g., due to imperfections in the mineral structure or pre-weathered conditions that affect the hardness of the material (Strzałkowski, 2021).

Since functional soil is a scarce resource, particularly in urban areas, there is a need for solutions to increase its volume and availability (Teixeira da Silva et al., 2018). It would save resources, and costs and avoid greenhouse gas emissions to reuse both excavated soil and rock waste to minimize the amount of waste and create functional soils for these areas. Such a strategy would fit in with the European Union's initiative to promote a circular economy (European Commission, 2020; Rodríguez-Espinosa et al., 2021).

A current attempt is to use residues from the mining industry as a component in so-called manufactured soils (Deeb et al., 2020). Some of the rock wastes have the potential to deliver nutrients to plants and may therefore be mixed with natural soils and valorized as manufactured soils for the rehabilitation of degraded landscapes (Haraldsen & Pedersen, 2003). Unlike other mineral wastes, such as demolition products or overburden material, waste rock is generally considered to be free of anthropogenic contaminants (although geogenic contamination, such as heavy metals, can be a problem) (Hitch et al., 2010).

The produced manufactured soils are mixtures of mineral and organic components, which may serve as replacements for natural soils (Haynes et al., 2022). Previous attempts have been made, e.g., by using non-toxic foundry sands (Dayton et al., 2010) or municipal green waste and coal fly ash (Belyaeva & Haynes, 2009) as a component of manufactured soils. Their use is promising for landscaping purposes and rehabilitation of wasteland, brownfield sites, and mined areas (Haynes et al., 2022; Sparke et al., 2011), as well as for green infrastructure in urban areas (Deeb et al., 2020). They have also been successfully used for the restoration of sites affected by acid mine drainage (Taylor et al., 2014).

Manufactured soils thus represent an excellent opportunity to recycle and valorize waste products, remediate disturbed and degraded landscapes, and might expand the limited resource "functional soil" in urban areas (Deeb et al., 2020). Because the manufactured soils can vary widely in their constituents and intended functionality, it is necessary to investigate their composition and performance, e.g., with respect to plant growth and other desired soil properties. The raw materials have to be tested beforehand to rule out potential hazards or toxicity. The soils should be functional in terms of chemical and physical stability and in providing essential ecosystem services. Since the materials are physically mixed, they should have the potential to mature rapidly with respect to physical and chemical stability, OC storage, and plant growth support. One indicator of successful soil development is soil aggregation, which is a general process of soil formation (Jenny, 1941) and reflects soil resistance to erosion (Barthès & Roose, 2002), as well as its potential for OC protection (Tisdall & Oades, 1982).

Here, we evaluated the performance of manufactured soils intended for use in an urban context based on three common rock materials (augite-porphyry, greywacke-hornfels, basalt) ground to powder and mixed with topsoil material of (i) clayey and (ii) sandy texture. We used an experimental set-up with mesocosms to test the development and performance of the soils in a controlled environment. For this, we conducted a 10-week greenhouse experiment with the manufactured soils along natural control soils planted with sunflowers (*Helianthus annuus* L.). Sunflowers are good indicators of soil functionality in an urban context because they require a relatively high pH and germination temperature and are sensitive to soil compaction, which is a known problem in young manufactured soils (Séré et al., 2010). We aimed to test soil functional attributes of the newly mixed soils in terms of sustained plant growth, promoted OC storage and aggregate size distribution within the framework of potential future use in the urban context.

In addition, we evaluated the resistance of the constructed soils to drought, because urban soils are susceptible to such challenging environmental conditions, which are exacerbated in the urban heat island (Rötzer et al., 2021; Ward et al., 2016) and are likely to be even more pronounced in a changing climate (IPCC, 2023). We aimed to investigate, whether the use of the rock materials to produce manufactured soils could increase the available volume of functional soil for applications in the urban context, such as leisure areas or green infrastructure for water management.

2 | MATERIALS AND METHODS

2.1 | Components and preparation of the manufactured soils

The manufactured soil mixtures were produced using two natural soils of contrasting textures and three different rock materials finely ground to loam and silt loam textures mixed with the soils in a 3:1 (w:w) soil:rock powder ratio.

The natural soils were sourced from the topsoil (0–20 cm) of two Cambisols (IUSS Working Group WRB, 2015) with contrasting texture in southern Germany (mean annual temperature of ca. 9°C and a mean annual precipitation of ca. 645 mm). The sandy soil with a texture of 69% sand, 17% silt, and 14% clay (classified as “sandy loam”, IUSS Working Group WRB, 2015) was formed on fluvial gravels of the Danube river (Neuburg a.d. Donau, Germany), with an OC content of 8 $mg\,g^{-1}$, 0.6 $mg\,g^{-1}$ inorganic carbon content, and a OC:N ratio of 9. The clayey soil, with a texture of 10% sand, 38% silt, and 52% clay (classified as “clay”, IUSS Working Group WRB, 2015), was formed on calcite and dolomite (Bamberg, Germany), with an OC content of 8 $mg\,g^{-1}$, an inorganic carbon content of 7.7 $mg\,g^{-1}$, and a OC:N ratio of 10. The original soils' texture and chemical properties are shown in Table 1. The soils were air-dried and sieved to <5 mm before mixing with the rock powders.

The three rock materials augite-porphyry, greywacke-hornfels, and basalt (provided by Basalt-Actien-Gesellschaft, Linz am Rhein, Germany) were chosen as they represent typical rock waste from stone mines used to provide materials for road construction, civil engineering, and building construction in Central Europe. The rocks were provided as powder, with silt as dominating grain size, and a negligible OC (<1.1 $mg\,g^{-1}$) and inorganic carbon content (<4.9 $mg\,g^{-1}$). The particle size, textural class, and chemical properties of the rock powders are shown in Table 1, and their mineral composition (as determined by XRD analysis) can be found in Table S1. The total elemental concentration in the rock powder eluate (as determined by batch analysis according to DIN 19529) is shown in Table S2.

The manufactured soils were prepared by manually mixing each natural soil with one of the three rock powders in a dry state. Four soils were prepared based on the sandy soil (with 5 replicates each): (i) the pure sandy soil (“sandy control”), (ii) sandy soil mixed with augite-porphyry (“sandy + porphyry”), (iii) sandy soil mixed with basalt (“sandy + basalt”), (iv) sandy soil mixed with greywacke-hornfels (“sandy + hornfels”).

Accordingly, four soils were prepared based on the clayey soil (with 5 replicates each): (i) the pure clayey soil (“clayey control”), (ii) clayey soil mixed with augite-porphyry (“clayey + porphyry”), (iii) clayey soil mixed with basalt (“clayey + basalt”), (iv) clayey soil mixed with greywacke-hornfels (“clayey + hornfels”). An overview of the experimental design is presented in Figure 1.

2.2 | Experimental setup of the mesocosm experiment

The mesocosm experiment was conducted in the greenhouse with an average air temperature of 23.2°C and an average air humidity of 58.5% throughout the experiment.

Each mesocosm (4000 cm^3) was filled with 4 kg of manufactured soil mixture (5 replicates of each mixture, leading to 80 mesocosms in total). All mesocosms were randomly distributed in the greenhouse according to stratified randomization principles. For assessment of the plant growth, one sunflower seedling (*H. annuus* L.)

TABLE 1 Particle size, textural class, and chemical properties of the control soils, rock powders and manufactured soils.

	Control soil		Rock powder			Manufactured soils					
						Clayey soil			Sandy soil		
	Clayey soil	Sandy soil	Porphyry	Hornfels	Basalt	+ Porphyry	+ Hornfels	+ Basalt	+ Porphyry	+ Hornfels	+ Basalt
Sand (0.063–2 mm) [%]	10	69	33	20	14	20	15	12	64	53	57
Silt (0.002–0.063 mm) [%]	38	17	43	56	70	37	43	50	21	28	29
Clay (<0.002 mm) [%]	52	14	24	24	16	43	42	38	15	19	14
Texture (FAO/WRB)	Clay	Sandy loam	Loam	Silt loam	Silt loam	Clay	Silty clay	Silty clay loam	Sandy loam	Sandy loam	Sandy loam
pH ($CaCl_2$)	7.2	6.4	8.0	5.9	8.2	7.4	6.9	7.5	6.8	6.3	6.9
Organic carbon (OC) [$mg\,g^{-1}$]	22.5	7.5	1.1	0.8	0.7	17.2	17.1	17.1	5.9	5.8	5.8
Inorganic carbon [$mg\,g^{-1}$]	7.7	0.6	4.9	0.1	1.8	7.0	5.8	6.2	1.7	0.5	0.9
Nitrogen (N) [$mg\,g^{-1}$]	2.5	0.9	—	—	—	1.9	1.9	1.9	0.7	0.7	0.7
OC:N ratio	10	9	—	—	—	—	—	—	—	—	—

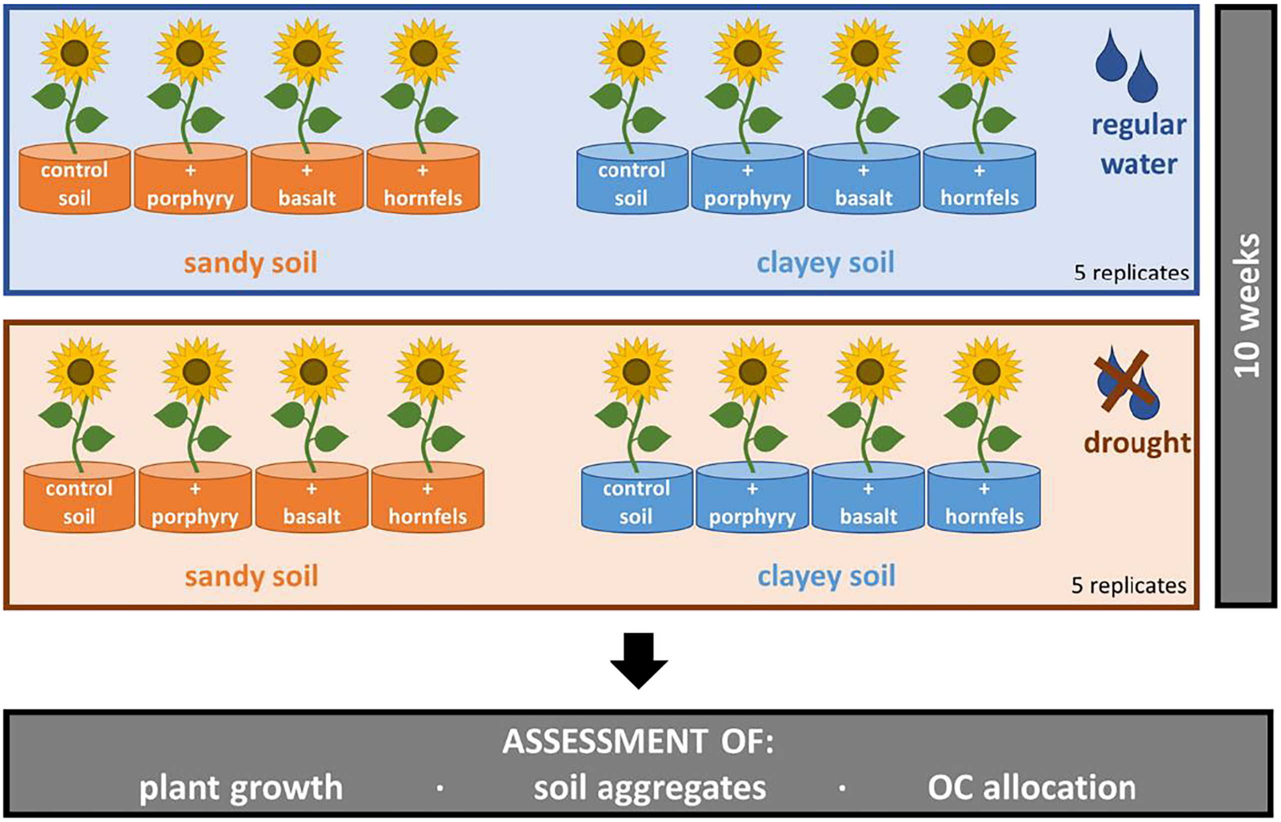

FIGURE 1 Overview of the manufactured soils and experimental design.

was planted per mesocosm. The seedlings ("Suntastic", Kiepenkerl, Bruno Nebelung, Everswinkel, Germany) were germinated on a nutritious fleece and further pre-grown for 3 weeks in potting soil under well-watered conditions. We used sunflowers as bioindicators of adequate soil functionality in an urban context because they require a relatively high pH and germination temperature, adequate water supply during flowering, and are sensitive to soil compaction. They also meet the aesthetic demands of an urban green space.

The mesocosms were subject to two irrigation treatments, which consisted of one regular watering and one drought treatment (Figure 1). For the regular watering treatment, the mesocosms were watered to reach 30%–40% of the soil field capacity. The field capacity was determined according to the German guidelines for soil classification (KA5) based on the data on soil texture, bulk density and OC content, assuming that the manufactured soils have initially no considerable soil structure. For the drought treatment, the mesocosms were watered to reach 15%–25% of the soil field capacity. The watering was done automatically with drip points (4 for the well-watered and 2 for the drought treatment, a total watering time of 34 s per day) inserted into each mesocosm. The soil moisture was monitored weekly with a moisture meter inserted into the bulk soil (Delta-T Devices, Cambridge, England).

The mesocosms were harvested after 10 weeks, when all sunflowers had reached the maturity stage and flowered at least once. After harvesting, the roots were shaken to remove adhering soil aggregates and gently washed under a water flow to remove the remaining soil. The amount of soil removed during the root washing was negligible and not considered in the present experiment. The shoot length of the sunflowers was measured and leaves, blossoms, shoots and roots were collected, dried at 60°C for 1 week and weighed to obtain their biomass. The soil was air-dried for 1 month and sieved to <2 mm for further analyses.

2.3 | Soil analyses

2.3.1 | Soil texture and pH

Soil texture analyses were carried out as described in Mayer et al. (2018) for the original soils, rock powders, and manufactured soil mixtures. Briefly, 30 g of sample were treated with 20 mL of 0.025 M $Na_4P_2O_7$ for dispersion and 30%-H_2O_2 for organic matter removal. Prior to the wet-sieving to obtain the sand fractions, samples were treated with 200 mL of 0.025 M $Na_4P_2O_7$ and ultrasonicated at 450 J mL^{-1} for dispersion (Sonopuls UW 2200, Bandelin, Berlin, Germany). The silt and clay content of the <63 mm fraction was determined by X-ray sedimentation (Sedigraph III Plus Particle Size Analyser, Micromeritics, Aachen, Germany).

The pH of the manufactured soils as well as the control soils was determined in a soil and water solution of 1:2.5 (w:w) with a pH meter (SevenEasy, Mettler Toledo, Columbus, OH, USA).

2.3.2 | Aggregate size distribution

The aggregate size distribution of the original and manufactured soils was determined after the incubation under well-watered and drought conditions based on the wet-sieving approach adapted from Elliott (1986), leading to four aggregate size classes: large macroaggregates (>2000 μm), small macroaggregates (250–2000 μm), large microaggregates (63–250 μm), and small microaggregates (<63 μm), expressed in g aggregate per 100 g soil. Briefly, 100 g of air-dried soil were placed subsequently onto a 2000, 250 and 63 μm sieve, submerged in distilled water for 5 min and further moved vertically up and down in water (30 cycles). All aggregate size classes collected from the respective sieves together with the <63 μm class were oven-dried at 60°C and weighed. Stones, roots and organic matter particles were removed with tweezers in the macroaggregate size classes.

2.3.3 | Carbon and nitrogen content

The total carbon (TC) and nitrogen (N) contents were measured in all bulk soil samples and aggregate size fractions by dry combustion in elemental analysers (for bulk soil: vario MAX cube, Elementar, Langenselbold, Germany; for aggregates: HEKAtech, Wegberg, Germany). For the bulk soil, the inorganic carbon (IC) content was determined by calcimetry (NEN-ISO 10693) based on calcium carbonate ($CaCO_3$) detection according to the Scheibler method (Scheibler's Calcimeter, Eijkelkamp, Giesbeek, the Netherlands) as described in Pihlap et al. (2019). The OC content in the bulk soil was then calculated as the difference between TC and IC contents. For the aggregate size classes, the IC was removed prior to the OC measurement using HCl. Briefly, a silver capsule was filled with 5 mg of milled sample material and 20 μL of 2 M HCl and placed in the oven at 60°C for 15 h as described in Vidal et al. (2019).

2.4 | Statistical analyses

The effect of the factors rock powder, original soil and irrigation level on OC concentration in bulk soils, plant biomass and aggregate size distribution was tested for statistical significance by ANOVA (significance level alpha = .05) (Table S3). Homoscedasticity and normality of residuals were checked using the Shapiro–Wilk test and graphical inspection of residuals. All statistical analyses were performed in R (R version 4.3.1, "Beagle Scouts", R Core Team, 2023) using the packages "car" (Fox & Weisberg, 2019), "dplyr" (Wickham, François, et al., 2023), "readxl" (Wickham & Bryan, 2023), and "tidyr" (Wickham, Vaughan, & Girlich, 2024). Orthogonal contrasts were computed for the comparison of specific treatment groups (R package "lsmeans", Lenth, 2016) (Table S4).

3 | RESULTS

3.1 | Texture of the manufactured soils

The preparation of the manufactured soils altered the grain size distribution of the originally sandy and clayey soils (Figure 2), as the rock powders were mostly made of silt-sized particles (Table 1).

The manufactured soils made from the sandy soil showed a shift in the grain size distribution towards finer particle sizes, as the silt fraction increased in the manufactured soils from 17% up to 26% silt content (mean value of all manufactured sandy soils) (Table 1, Figure 2). The highest silt addition was caused by the basalt powder, which increased the silt content to 29%. The increase in the silt fraction resulted in a relative decrease in the sand fraction from 69% in the original soil to 58% in the manufactured soils (mean value of all manufactured sandy soils).

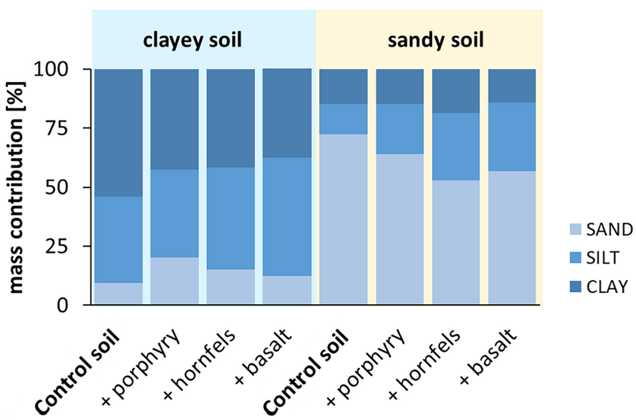

FIGURE 2 Texture [mass-% of the fractions sand, silt and clay] of the manufactured soils and respective control soils of clayey (blue background) and sandy (yellow background) texture. Texture thresholds are 0.063–2 mm for sand, 0.002–0.063 mm for silt, and < 0.002 mm for clay.

The manufactured soils based on the clayey soil showed a shift in the soil texture from finer towards coarser texture, as the high silt content of the rock powders diluted the clay-sized fraction of the original soils (Figure 2, Table 1). The clay content decreased from 52% in the originally clayey soil to 41% in the manufactured soils, whereas the silt content increased from 38% to 43% in the manufactured soils (mean value of all manufactured clayey soils). The basalt powder had the strongest effect, leading to a shift of the texture class from clay (initial soil) to silty clay loam in the manufactured soil (IUSS Working Group WRB, 2015).

3.2 | Elemental composition of the eluate and soil pH

All rock powder eluates contain elements that may function as macro- and micronutrients, providing mainly potassium (K), magnesium (Mg), sulfur (S) and calcium (Ca). The highest values were observed for the greywacke-hornfels, adding 85 $mg\,L^{-1}$ K, 141 $mg\,L^{-1}$ Mg and 80 $mg\,L^{-1}$ Ca to the eluate (Table S2). Phosphorus (P) was not detected in a significant amount in any rock powder eluate. No rock powder eluate contained a significant amount of the measured potentially toxic elements, i.e. aluminium (Al), chromium (Cr), nickel (Ni), and titanium (Ti) (Table S2).

The rock powders derived from augite-porphyry and basalt had a pH of about 8 (Table 1), which led to an increased pH in the manufactured soils as compared to the original soils (no statistical validation, Table S5). The pH of the originally sandy soil increased from 6.4 to 7.5 in the respective manufactured soils, while the pH of the originally clayey soil increased only slightly from 7.2 to 7.5.

The water regime caused a slightly lower pH under drought in the manufactured soils based on sandy soil (Table S5).

3.3 | Organic carbon content

The OC content of the original soils ($22.5 \pm 0.5\,mg\,OC\,g^{-1}$ soil for the clayey soil and $7.5 \pm 0.1\,mg\,OC\,g^{-1}$ soil for the sandy soil) was reduced by the rock powder addition in the manufactured soils, as the rock powders did not contain a significant OC amount (Table 1) and therefore "diluted" the original soils' OC content (ANOVA, $F(3,73) = 138.232$, $p < .001$***, Table S3) (Figure 3). This means that the overall OC content in the manufactured soils was mostly defined by the OC content of the original soils (ANOVA, $F(1,75) = 3585.485$, $p < .001$***).

The OC content after the incubation was slightly lower than the starting OC content (Figure 3), with a significant effect of the watering treatment, leading to lower OC contents under drought (ANOVA, $F(1,75) = 6.571$, $p = .013$*). The OC reduction due to the drought treatment was stronger in the manufactured soils prepared from the clayey soil (t-ratio = 2.199, $p = .06$, Table S4), especially with augite-porphyry addition (Figure 3).

3.4 | Plant growth

All manufactured soils maintained plant growth, although the aboveground biomass yield was significantly reduced compared to the original soils ($F(3,71) = 7.020$, $p < .001$***, Table S3), with the lowest yield observed in the manufactured soils based on the clayey soil (t-ratio = 3.107, $p = .06$, Table S4) (Figure 4).

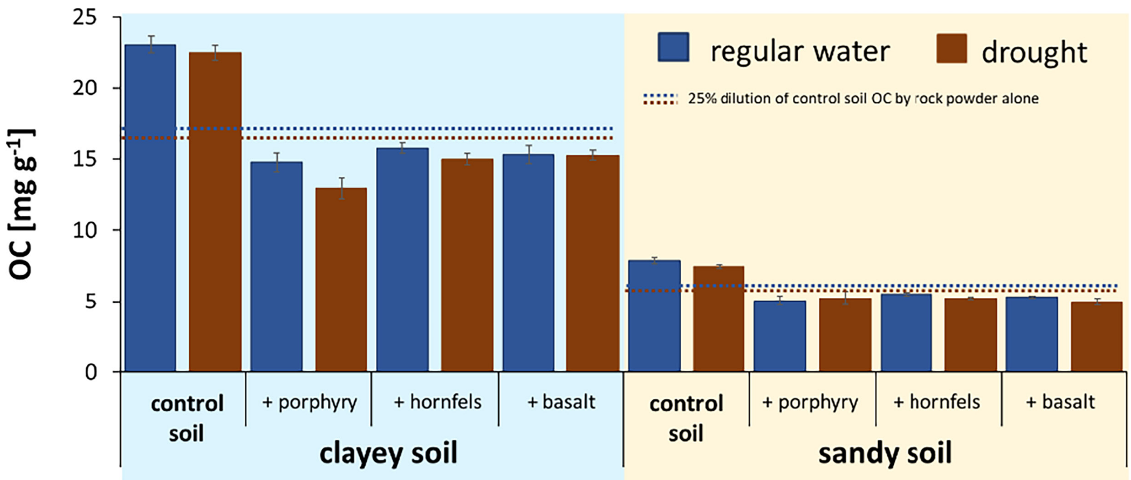

FIGURE 3 OC content [$mg\,OC\,g^{-1}$ soil] of the manufactured soils and respective control soils of sandy and clayey texture affected by either regular water (blue bars) or drought treatment (red bars).

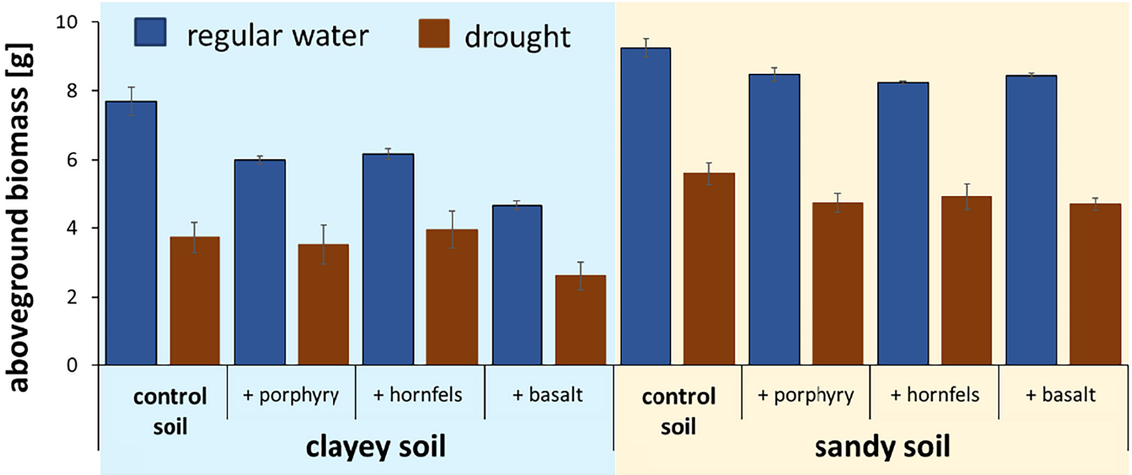

FIGURE 4 Plant growth, assessed as aboveground biomass [g dry mass] in the manufactured soils and respective control soils of sandy and clayey texture affected by either regular water or drought treatment.

However, the effect of the water-regime and the original soil properties on the overall plant growth was stronger than the effect of the rock powder addition. The water-regime affected the plant growth the most, with an overall biomass reduction of 43% under drought ($F(1,73)=247.893$, $p<.001$***). The effect of the water-regime was significant for both soil textures (clayey soil: t-ratio$=15.529$, $p<.001$, sandy soil: t-ratio$=13.019$, $p<.01$). The initial soil was the second strongest factor influencing plant growth, with higher biomass yields in the sandy soils ($F(1,73)=79.866$, $p<.001$***). The overall biomass reduction due to the rock powder addition was only significant for the clayey soils (t-ratio$=3.107$, $p=.005$), but not for the sandy soils (t-ratio$=1.688$, $p=.09$).

3.5 | Soil aggregates

The aggregate size fractionation showed that the manufactured soils had an increased amount of microaggregate-sized particles (Figure 5). The effect of the rock powder addition was stronger than the effect of the original soil in terms of aggregate size distribution (rock powder, $F(3,73)=770.637$, $p<.001$***, original soil $F(1,75)=202.039$, $p<.001$***, Table S3). The water level had a smaller but significant effect on the aggregate size distribution ($F(1,75)=65.299$, $p<.001$***), by causing an increased abundance of small macroaggregates under drought.

The OC content of the macroaggregate fractions remained unchanged with the rock powder addition, whereas the OC content of the microaggregate fraction was reduced, irrespective of the water-regime (Figure S1).

4 | DISCUSSION

4.1 | Rock powder to improve soil textural features

The addition of the rock powder, regardless of the specific type, added mainly silt-sized particles to the soils (Table 1, Figure 2). This results in a coarser texture of the clay-rich topsoil substrate, whereas the texture of the sand-rich soil substrates became finer. In our experiment, the original soil textures were clay and sandy loam (FAO, WRB, 2014), whereas after the rock powder addition, the texture of the originally clayey soil was classified as silty clay (Table 1).

A higher silt content can improve a soil's physical condition with respect to water-holding capacity, as silty textured natural soils have a higher number of medium-sized pores (10–0.2 μm diameter) that ensure water availability for plants (Dexter, 1988). The originally clayey soil texture is associated with many fine pores (<0.2 μm), whose water cannot be used by plant roots (Childs & Collis-George, 1950; Christensen, 1944; Dexter, 1988). On the other hand, the coarse pores of the originally sandy soil supposedly cannot hold a sufficient amount of water, which could lead to rapid drainage and water-limited conditions, especially during dryer seasons (Ladányi et al., 2021). However, it is important to note that due to the less developed soil structure, newly constructed soils often have a higher permeability and lower water retention than natural soils of similar texture in their early stages of development (Ugolini et al., 2020; Yilmaz et al., 2019). Still, pedogenetic processes in well-managed manufactured soils with plant cover, soil organisms and an adequate OC content can rapidly lead to a development of soil structure so that their hydraulic properties may approach

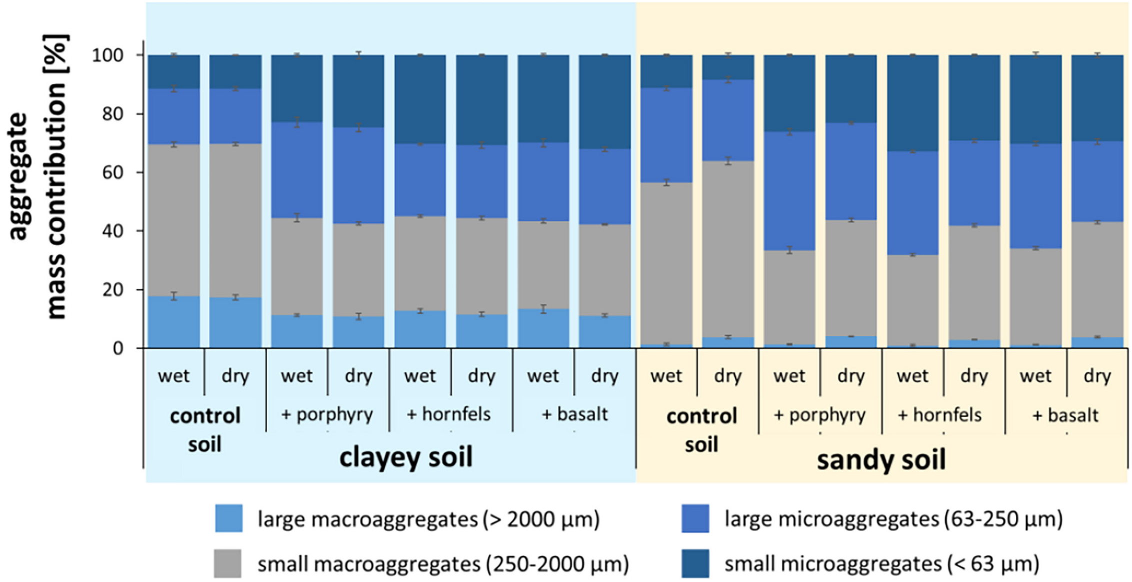

FIGURE 5 Aggregate size distribution, assessed as mass contribution of the four size fractions (large and small macroaggregates, large and small microaggregates; mass-%) in the manufactured soils and respective control soils of sandy and clayey texture affected by either regular water (wet) or drought (dry) treatment. Data table can be found in Table S6.

those of natural soils within a few years (Deeb et al., 2016; Scalenghe & Ferraris, 2009; Séré et al., 2010).

The development of a stable soil structure is also crucial in preventing erosion. Especially soils with a silty texture are vulnerable to erosion when lacking structural stability. In those soils, stable soil aggregates are necessary to prevent soil loss by water and wind erosion (Barthès & Roose, 2002; Zobeck & Van Pelt, 2015).

It can be concluded, that the use of rock powders of adequate grain size, i.e. mostly silt size, could improve soil physical properties, although it may be more expensive to grind the rocks to this fine grain size. However, there is a risk of adverse effects on soil structural stability if no additional measures are taken to induce aggregation. It may be advantageous to base the manufactured soils on natural soils with sandy texture. Here, the added silt could have a greater potential to improve the physical properties in terms of the texture-related increased storage of plant available water.

4.2 | Plant growth as a proxy for soil functionality in urban environments

Although the overall biomass yield was lower in the manufactured soils than in the natural topsoil material, all manufactured soils were able to support plant growth even under drought conditions with flowering sunflowers (Figure 4). This is a promising result, as the use of manufactured soils in urban environments requires plant growth for aesthetic and functional reasons (Wang et al., 2019), whereas the overall biomass yield is less important. An urban green area or even greened infiltration swale does not need to support high yields but needs to meet aesthetic demands. Since sunflowers are sensitive to soil compaction, their growth and flowering indicate an adequate structure of the tested manufactured soils during the first months of maturation (Séré et al., 2010). The maintenance of plant growth even under drought stress is important in the urban context, as these ecosystems are often facing increased heat and evaporation, due to the so-called urban heat island phenomenon (Chen et al., 2023; Oke, 1982; Ward et al., 2016).

The plant growth in the manufactured soils based on the sandy soil was maintained at almost the same level as in the original soil. This suggests that using a sandy soil substrate may be preferable when designing manufactured soils, especially if a higher plant biomass is desired. The three different rock powders did not differ much in their performance with respect to plant yield, except of the basalt powder, which led to a lower plant yield in the clayey soil mixture. This could possibly be attributed to a limited nutrient supply, given the lowest concentrations of potentially nutritive elements were found in the eluate from the basalt (although only elements were measured, not actual nutrients, Table S2). Nevertheless, no potentially phytotoxic element was detected in the eluate of any rock powder (Table S2).

A well-established vegetative cover can help to accelerate soil development in manufactured soils, due to the plant root action and influence on soil organisms (Deeb et al., 2016; Gunathunga et al., 2023). It has been shown, that a diverse plant community can be especially useful for this purpose (Gunathunga et al., 2023). The tested sunflowers performed well under the experimental conditions, but since not all plant species are suitable for the specific conditions of an urban environment (relatively high soil pH, nutrient load and soil temperature), further research is needed to identify suitable plant species and communities for the individual characteristics and intended functions of the manufactured soils.

Overall, the maintenance of plant growth even under drought conditions promises sufficient functional attributes of the manufactured soils with respect to a future use in urban environments. In order to maximize the plant yield, the combination of a sandy soil with greywacke-hornfels was the most promising. Moreover, selecting rock powders that release nutrients into the soil solution after weathering can reduce the need for additional fertilizer.

4.3 | Soil aggregate development needs to be fostered by additional measures

Due to the manual mixing of the materials, manufactured soils initially lack a stable aggregated structure. Soil aggregate fractionation can be used as proxy to assess the manufactured soils' structure development. The aggregate size distribution indicated that the majority of particle accumulation occurred within the microaggregate fraction (<250 and <63 μm) (Figure 5). As the added rock powders contained mostly particles of silt- and clay-size (<63 μm) (Table 1), the increased microaggregate fraction can rather be attributed to the pure mineral particles in this size fraction than to the formation of new aggregates. This is further supported by the OC content in the aggregate fractions, which was lower in the microaggregate fraction with rock powder addition, whereas the OC content of the macroaggregate fraction remained unchanged (compared to the respective original soils) (Figure S1). This suggests an unchanged aggregate size distribution of the original soil even after the addition of the rock powder. The powder particles did not appear to be integrated into the aggregates during the short-term incubation experiment.

This was in contrast to our expectations, as previous experiments with artificial soils suggested that mineral particles can be assembled to stable soil aggregates after a maturation time of a few weeks by biochemical degradation of organic matter alone, without requiring the action of roots and physical forces such as wet-dry cycles (Bucka, Felde, et al., 2021; Rabbi et al., 2020). However, these studies were conducted with mineral mixtures without any pre-existing aggregation, incubated in presence of an easily degradable organic matter source. In the present experiment, the initial OC was already associated with mineral surfaces and bound in the existing soil aggregates of different size, and was therefore less available. As there was no input of soil organic matter beyond the plant roots (c.f. Section 4.4), this indicates that the fresh OC from root exudates or microbial products, together with the action of the plant roots themselves (Guhra et al., 2022; Ruiz et al., 2023), were not sufficient to act as binding agent and facilitate aggregation of the rock powder particles within the time frame of our experiment. This suggests that the additional provision of a fresh and easily degradable OC source could be beneficial to initiate soil aggregate formation in the manufactured soils during the first vegetation period. These organic amendments can also be provided by the urban waste stream and thus further contribute to resource recycling. A previous experiment with manufactured soils already suggested the need of an easily degradable OM source for fostering soil aggregate development (Bucka, Pihlap, et al., 2021). Organic amendments are considered as very important for remediating drylands and to accelerate the restoration processes therein (Hueso-González et al., 2018), which can be transferred to soils within an urban context.

It has also been suggested that soil organisms, e.g., earthworms, can have a substantial impact on the formation and stability of soil aggregates in newly constructed soils (Deeb et al., 2017). Since our experimental design did not include larger soil organisms such as earthworms, future studies may benefit from taking the role of soil organisms into account if accelerated soil aggregate development is desired.

The drought treatment increased the content of macroaggregates in the manufactured soils (Figure 5). Drying of previously moist soils causes water menisci to shrink, bringing mineral particles into contact with each other (Kemper & Rosenau, 1984; Paradiś et al., 2017). This suggests, that even a one-time drought event can foster the occlusion of the newly added rock powder particles into an aggregated soil structure, as it has been previously shown for repeated wet-dry cycles (Denef et al., 2002; Dexter, 1988). As such fluctuations in the water content are common in natural soils, they are expected to promote the formation of soil structure in the manufactured soils under field conditions. Jangorzo et al. (2018) even ranked the effect of wet-dry cycles higher than the influence of plants in terms of soil aggregate formation in manufactured soils.

To conclude, the development of a stable aggregated soil structure (as measured by aggregate size distribution) could not be observed in the manufactured soils within one vegetation period. Therefore, measures to initiate a rapid development of aggregates are highly recommended, e.g. by addition of an easily decomposable organic matter source or hydraulic consolidation by repeated wet-dry cycles.

4.4 | Soil organic carbon storage potential

The initial soil OC content was reduced by 25% with the addition of the OC-free rock powders, resulting in an OC content of 17 mg OC g^{-1} for mixtures prepared from the clayey soil and 6 mg OC g^{-1} for the mixtures prepared from the sandy soil (Figure 3). OC is a crucial component of natural soils, as it adds to the cation-exchange capacity (Syers et al., 1970), provides water retention potential (Lal, 2020; Scott et al., 1986) and ensures stable soil structure (Dexter, 1988; Golchin et al., 1994; Tisdall & Oades, 1982). In natural soils, OC is mostly introduced by litter from aboveground and belowground biomass (Kögel-Knabner, 2002). To avoid an OC limitation in newly created manufactured soils, there is usually a certain OC source like plant litter or compost added to the mixture to make sure that enough OC is available to initiate soil development (Haynes et al., 2022). By using natural topsoil material to prepare our manufactured soil mixtures, we assumed that the remaining OC content (upon dilution by the OC-free rock powders) would be sufficient to deliver essential soil functionality, without addition of OC.

All manufactured soils supported plant growth and therefore, we expected a transfer of OC into the soils, mostly through rhizodeposits. However, within the frame of our experiment, the OC content became even slightly more depleted than the pure dilution effect due to the OC-free rock powder (Figure 3). This suggests, that plant growth does not always lead to immediate OC increase in the newly prepared manufactured soils and may even deplete the existing OC during initial stages of the soil development, which has been suggested by Dijkstra et al. (2021). A study by Deeb et al. (2017) also suggested that plant roots may have a short-term negative effect on the OC content in young Technosols, as they tend to increase the porosity, leading to increased accessibility of OC to microbial degradation. However, we assume that the short timeframe of our experiment was simply not enough to capture any OC addition by rhizodeposition. The sunflowers in our experiment were harvested after reaching maturity stage and therefore the possible OC input could have happened only by the roots through root litter and rhizodeposits, without any aboveground litter, which is also considered a major source of soil OC (Cotrufo et al., 2015; Kögel-Knabner, 2002). Furthermore, the soil adhering to the plant roots was washed away in order to collect the roots, which may have led to an underestimation of the OC introduced by root exudates (Kuzyakov & Domanski, 2000). However, due to the maintained plant growth, a future addition of OC can be expected in the manufactured soils, which has also been observed in long-term studies with constructed soils (Rees et al., 2019).

The OC-free mineral surfaces of the clay- and silt-sized particles added with the rock powder provide a high potential of future OC storage through organo-mineral interactions in the manufactured soils (Ruiz et al., 2023). In addition, the fine mineral particles are susceptible to weathering, facilitating potential OC storage on the surface of newly formed pedogenic minerals (Kaiser & Guggenberger, 2003).

Furthermore, the use of silicate-rich rock powders may contribute to the capture of atmospheric carbon dioxide (CO_2) via the so-called terrestrial enhanced weathering (Beerling et al., 2018; Moosdorf et al., 2014; Schuiling & Krijgsman, 2006). The chemical weathering of the silicate-rich rock powders, may lead to the release of cations that can react with CO_2-forming (bi-)carbonate minerals. Especially the used greywacke-hornfels might be promising in this context, delivering the highest concentrations of magnesium and calcium to the soil solution (Table S2), whereas basalt powder is commonly used for CO_2 capture via enhanced weathering (Beerling et al., 2018).

Overall, although not visible within one vegetation cycle, we expect a future OC storage in the manufactured soils, due to the presence of much OC-free mineral surface area that may interact with organic matter in addition to enhanced weathering processes that may capture CO_2.

5 | CONCLUSIONS

We tested the performance of manufactured soils made from three different powdered rock materials (augite-porphyry, greywacke-hornfels, basalt) mixed with natural soils of either clayey or sandy texture.

The maintenance of plant growth of the tested sunflowers, even under drought, demonstrates the functionality of all tested manufactured soils in the context of urban use.

Introducing silt-sized rock powders to natural topsoil soils with original sandy texture is a promising management approach given that the silt-sized particles can enhance the water retention of the manufactured soils.

The formation of new aggregates could not be observed in the manufactured soils within one vegetation period and we recommend the addition of an easily decomposable source of organic matter to initiate rapid aggregate development.

Despite not being visible within a single vegetation cycle, we expect a future OC storage in the manufactured soils, due to the abundance of OC-free mineral surfaces that can interact with organic matter and by potential capture of CO_2 through enhanced weathering processes.

In conclusion, the tested manufactured soils offer a promising solution to upcycle fine ground rock waste material into functional soils within the frame of a future use in urban development. The most promising results were observed by basing the manufactured soils on a sandy topsoil substrate, while the various rock powders differed only slightly in their performance.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

Barthès, B., & Roose, E. (2002). Aggregate stability as an indicator of soil susceptibility to runoff and erosion; validation at several levels. *Catena*, *47*, 133–149. https://doi.org/10.1016/S0341-8162(01)00180-1

Beerling, D. J., Leake, J. R., Long, S. P., Scholes, J. D., Ton, J., Nelson, P. N., Bird, M., Kantzas, E., Taylor, L. L., Sarkar, B., Kelland, M., DeLucia, E., Kantola, I., Müller, C., Rau, G., & Hansen, J. (2018). Farming with crops and rocks to address global climate, food and soil security /631/449 /706/1143 /704/47 /704/106 perspective. *Nature Plants*, *4*, 138–147. https://doi.org/10.1038/s41477-018-0108-y

Belyaeva, O. N., & Haynes, R. J. (2009). Chemical, microbial and physical properties of manufactured soils produced by co-composting municipal green waste with coal fly ash. *Bioresource Technology*, *100*, 5203–5209. https://doi.org/10.1016/j.biortech.2009.05.032

Bucka, F. B., Felde, V. J. M. N. L., Peth, S., & Kögel-Knabner, I. (2021). Disentangling the effects of OM quality and soil texture on microbially mediated structure formation in artificial model soils. *Geoderma*, *403*, 115213. https://doi.org/10.1016/j.geoderma.2021.115213

Bucka, F. B., Pihlap, E., Kaiser, J., Baumgartl, T., & Kögel-Knabner, I. (2021). A small-scale test for rapid assessment of the soil development potential in post-mining soils. *Soil and Tillage Research*, *211*, 105016. https://doi.org/10.1016/j.still.2021.105016

Chen, H., Jeanne Huang, J., Li, H., Wei, Y., & Zhu, X. (2023). Revealing the response of urban heat Island effect to water body evaporation from main urban and suburb areas. *Journal of Hydrology*, *623*, 129687. https://doi.org/10.1016/j.jhydrol.2023.129687

Childs, E. C., & Collis-George, N. (1950). The control of soil water. *Advances in Agronomy*, *2*, 233–272.

Christensen, H. R. (1944). Permeability-capillary potential curves for three prairie soils. *Soil Science*, *57*, 381–390.

Cotrufo, M., Soong, J., Horton, A., Campbell, E., Haddix, M., Wall, D., & Parton, W. (2015). Formation of soil organic matter via biochemical and physical pathways of litter mass loss. *Nature Geoscience*, *8*, 776–779. https://doi.org/10.1038/ngeo2520

Dayton, E. A., Whitacre, S. D., Dungan, R. S., & Basta, N. T. (2010). Characterization of physical and chemical properties of spent foundry sands pertinent to beneficial use in manufactured soils. *Plant and Soil*, *329*, 27–33. https://doi.org/10.1007/s11104-009-0120-0

Deeb, M., Desjardins, T., Podwojewski, P., Pando, A., Blouin, M., & Lerch, T. Z. (2017). Interactive effects of compost, plants and earthworms on the aggregations of constructed Technosols. *Geoderma*, *305*, 305–313.

Deeb, M., Grimaldi, M., Lerch, T. Z., Pando, A., Gigon, A., & Blouin, M. (2016). Interactions between organisms and parent materials of a constructed Technosol shape its hydrostructural properties. *SOIL*, *2*(2), 163–174.

Deeb, M., Groffman, P. M., Blouin, M., Perl Egendorf, S., Vergnes, A., Vasenev, V., Cao, D. L., Walsh, D., Morin, T., & Séré, G. (2020). Using constructed soils for green infrastructure – Challenges and limitations. *SOIL*, *6*, 413–434. https://doi.org/10.5194/soil-6-413-2020

DeJong, J. T., Soga, K., Banwart, S. A., Whalley, W. R., Ginn, T. R., Nelson, D. C., Mortensen, B. M., Martinez, B. C., & Barkouki, T. (2011). Soil engineering in vivo: Harnessing natural biogeochemical systems for sustainable, multi-functional engineering solutions. *Journal of the Royal Society Interface*, *8*, 1–15. https://doi.org/10.1098/rsif.2010.0270

Denef, K., Six, J., Merckx, R., & Paustian, K. (2002). Short-term effects of biological and physical forces on aggregate formation in soils with different clay mineralogy. *Plant and Soil*, *246*, 185–200.

Dexter, A. R. (1988). Advances in characterization of soil structure. *Soil and Tillage Research*, *11*, 199–238.

Dijkstra, F. A., Zhu, B., & Cheng, W. (2021). Root effects on soil organic carbon: A double-edged sword. *New Phytologist*, *230*, 60–65. https://doi.org/10.1111/nph.17082

Elliott, E. T. (1986). Aggregate structure and carbon, nitrogen, and phosphorus in native and cultivated soils. *Soil Science Society of America Journal*, *50*, 627–633. https://doi.org/10.2136/sssaj1986.03615995005000030017x

European Commission. (2020). *Circular economy action plan: For a cleaner and more competitive Europe*. Publications Office of the European Union.

Fox, J., & Weisberg, S. (2019). *An R companion to applied regression*. Sage.

German Environment Agency. (2022). *The use of natural resources*. Resources report for Germany 2022. Dessau-Roßlau.

Golchin, A., Oades, J., Skjemstad, J., & Clarke, P. (1994). Soil structure and carbon cycling. *Soil Research*, *32*, 1043. https://doi.org/10.1071/SR9941043

Guhra, T., Stolze, K., & Totsche, K. U. (2022). Pathways of biogenically excreted organic matter into soil aggregates. *Soil Biology and Biochemistry*, *164*, 108483.

Gunathunga, S. U., Gagen, E. J., Evans, P., Erskine, P. D., & Southam, G. (2023). Anthropedogenesis in coal mine overburden; the need for a comprehensive, fundamental biogeochemical approach. *Science of the Total Environment*, *892*, 164515.

Haraldsen, T. K., & Pedersen, P. A. (2003). Mixtures of crushed rock, forest soils, and sewage sludge used as soils for grassed green areas. *Urban Forestry & Urban Greening*, *2*(1), 41–51.

Haynes, R. J., Zhou, Y.-F., & Weng, X. (2022). Formulation and use of manufactured soils: A major use for organic and inorganic wastes. *Critical Reviews in Environmental Science and Technology*, *52*, 4113–4133. https://doi.org/10.1080/10643389.2021.1989909

Hitch, M., Ballantyne, S. M., & Hindle, S. R. (2010). Revaluing mine waste rock for carbon capture and storage. *International Journal of Mining, Reclamation and Environment*, *24*(1), 64–79. https://doi.org/10.1080/17480930902843102

Hueso-González, P., Muñoz-Rojas, M., & Martínez-Murillo, J. F. (2018). The role of organic amendments in drylands restoration. *Current Opinion in Environmental Science & Health*, *5*, 1–6. https://doi.org/10.1016/j.coesh.2017.12.002

IPCC. (2023). Climate change 2023: Synthesis report. In Core Writing Team, H. Lee, & J. Romero (Eds.), *Contribution of working groups I, II and III to the sixth assessment report of the Intergovernmental Panel on Climate Change* (p. 184). IPCC. https://doi.org/10.59327/IPCC/AR6-9789291691647

IUSS Working Group WRB. (2015). *World reference base for soil resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps*. World soil resources reports no. 106. FAO.

Jangorzo, N. S., Watteau, F., & Schwartz, C. (2018). Ranking of wetting–drying, plant, and fauna factors involved in the structure dynamics of a young constructed Technosol. *Journal of Soils and Sediments*, *18*, 2995–3004.

Jenny, H. (1941). *Factors of soil formation: A system of quantitative pedology*. McGraw-Hill.

Kaiser, K., & Guggenberger, G. (2003). Mineral surfaces and soil organic matter. *European Journal of Soil Science*, *54*, 219–236.

Kemper, W. D., & Rosenau, R. C. (1984). Soil cohesion as affected by time and water content. *Soil Science Society of America Journal*, *48*, 1001–1006.

Kögel-Knabner, I. (2002). The macromolecular organic composition of plant and microbial residues as inputs to soil organic matter. *Soil Biology and Biochemistry*, *34*, 139–162. https://doi.org/10.1016/S0038-0717(01)00158-4

Kuzyakov, Y., & Domanski, G. (2000). Carbon input by plants into the soil. Review. *Journal of Plant Nutrition and Soil Science*, *163*(4), 421–431.

Ladányi, Z., Barta, K., Blanka, V., & Pálffy, B. (2021). Assessing available water content of Sandy soils to support drought monitoring and agricultural water management. *Water Resources Management*, *35*, 869–880. https://doi.org/10.1007/s11269-020-02747-6

Lal, R. (2020). Soil organic matter and water retention. *Agronomy Journal*, *112*, 3265–3277. https://doi.org/10.1002/agj2.20282

Lehmann, J., Bossio, D. A., Kögel-Knabner, I., & Rillig, M. C. (2020). The concept and future prospects of soil health. *Nature Reviews Earth and Environment*, *1*, 544–553. https://doi.org/10.1038/s43017-020-0080-8

Lenth, R. V. (2016). Least-squares means: The R package lsmeans. *Journal of Statistical Software*, *69*, 1–33. https://doi.org/10.18637/jss.v069.i01

Mayer, S., Schwindt, D., Steffens, M., Völkel, J., & Kögel-Knabner, I. (2018). Drivers of organic carbon allocation in a temperate slope-floodplain catena under agricultural use. *Geoderma*, *327*, 63–72. https://doi.org/10.1016/j.geoderma.2018.04.021

Moosdorf, N., Renforth, P., & Hartmann, J. (2014). Carbon dioxide efficiency of terrestrial enhanced weathering. *Environmental Science & Technology*, *48*, 4809–4816. https://doi.org/10.1021/es4052022

Oke, T. R. (1982). The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society*, *108*, 1–24.

Paradiś, A., Brueck, C., Meisenheimer, D., Wanzek, T., & Dragila, M. I. (2017). Sandy soil microaggregates: Rethinking our understanding of hydraulic function. *Vadose Zone Journal*, *16*, 1–10. https://doi.org/10.2136/vzj2017.05.0090

Pihlap, E., Vuko, M., Lucas, M., Steffens, M., Schloter, M., Vetterlein, D., Endenich, M., & Kögel-Knabner, I. (2019). Initial soil formation in an agriculturally reclaimed open-cast mining area – The role of management and loess parent material. *Soil and Tillage Research*, *191*, 224–237. https://doi.org/10.1016/j.still.2019.03.023

R Core Team. (2023). *A language and environment for statistical computing*. R Foundation for Statistical Computing.

Rabbi, S. M. F., Minasny, B., McBratney, A. B., & Young, I. M. (2020). Microbial processing of organic matter drives stability and pore geometry of soil aggregates. *Geoderma*, *360*, 114033. https://doi.org/10.1016/j.geoderma.2019.114033

Rees, F., Dagois, R., Derrien, D., Fiorelli, J. L., Watteau, F., Morel, J. L., Schwartz, C., Simonnot, M. O., & Séré, G. (2019). Storage of carbon in constructed technosols: In situ monitoring over a decade. *Geoderma*, *337*, 641–648. https://doi.org/10.1016/j.geoderma.2018.10.009

Rodríguez-Espinosa, T., Navarro-Pedreño, J., Gómez-Lucas, I., Jordán-Vidal, M. M., Bech-Borras, J., & Zorpas, A. A. (2021). Urban areas, human health and technosols for the green deal. *Environmental Geochemistry and Health*, *43*, 5065–5086. https://doi.org/10.1007/s10653-021-00953-8

Rötzer, T., Moser-Reischl, A., Rahman, M. A., Hartmann, C., Paeth, H., Pauleit, S., & Pretzsch, H. (2021). Urban tree growth and ecosystem services under extreme drought. *Agricultural and Forest Meteorology*, *308–309*, 108532. https://doi.org/10.1016/j.agrformet.2021.108532

Ruiz, F., Safanelli, J. L., Perlatti, F., Cherubin, M. R., Demattê, J. A. M., Cerri, C. E. P., Otero, X. L., Rumpel, C., & Ferreira, T. O. (2023). Constructing soils for climate-smart mining. *Communications Earth & Environment*, *4*, 219. https://doi.org/10.1038/s43247-023-00862-x

Scalenghe, R., & Ferraris, S. (2009). The first forty years of a Technosol. *Pedosphere*, *19*(1), 40–52.

Schuiling, R. D., & Krijgsman, P. (2006). Enhanced weathering: An effective and cheap tool to sequester CO_2. *Climatic Change*, *74*, 349–354. https://doi.org/10.1007/s10584-005-3485-y

Scott, H. D., Wood, L. S., & Miley, W. M. (1986). *Long-term effects of tillage on the retention and transport of soil water*. Arkansas

Water Resources Center. Fayetteville, AR. PUB125. 45. https://scholarworks.uark.edu/awrctr/83

Séré, G., Schwartz, C., Ouvrard, S., Renat, J. C., Watteau, F., Villemin, G., & Morel, J. L. (2010). Early pedogenic evolution of constructed Technosols. *Journal of Soils and Sediments*, *10*, 1246–1254.

Sparke, S., Putwain, P., & Jones, J. (2011). The development of soil physical properties and vegetation establishment on brownfield sites using manufactured soils. *Ecological Engineering*, *37*, 1700–1708. https://doi.org/10.1016/j.ecoleng.2011.06.041

Strzałkowski, P. (2021). Characteristics of waste generated in dimension stone processing. *Energies*, *14*(21), 7232.

Syers, J. K., Campbell, A. S., & Walker, T. W. (1970). Contribution of organic carbon and clay to cation exchange capacity in a chronosequence of sandy soils. *Plant and Soil*, *33*, 104–112.

Teixeira da Silva, R., Fleskens, L., van Delden, H., & van der Ploeg, M. (2018). Incorporating soil ecosystem services into urban planning: Status, challenges and opportunities. *Landscape Ecology*, *33*, 1087–1102.

Tisdall, J. M., & Oades, J. M. (1982). Organic matter and water-stable aggregates in soils. *Journal of Soil Science*, *33*, 141–163. https://doi.org/10.1111/j.1365-2389.1982.tb01755.x

Taylor, M., Yellishetty, M., & Panther, B. C. (2014). Geotechnical and hydrogeological evaluation of artificial soils to remediate acid mine drainage and improve mine rehabilitation – An Australian case study. In *Mine Planning and Equipment Selection* (pp. 855–865). Springer. https://doi.org/10.1007/978-3-319-02678-7_83

Ugolini, F., Baronti, S., Lanini, G. M., Maienza, A., Ungaro, F., & Calzolari, C. (2020). Assessing the influence of topsoil and technosol characteristics on plant growth for the green regeneration of urban built sites. *Journal of Environmental Management*, *273*(111), 168.

United Nations. (2019). *World urbanization prospects: The 2018 revision (ST/ESA/SER.A/420)*. United Nations.

Vidal, A., Watteau, F., Remusat, L., Mueller, C. W., Nguyen Tu, T. T., Buegger, F., Derenne, S., & Quenea, K. (2019). Earthworm cast formation and development: A shift from plant litter to mineral associated organic matter. *Frontiers in Environmental Science*, *7*, 55. https://doi.org/10.3389/fenvs.2019.00055

Wang, R., Zhao, J., Meitner, M. J., Hu, Y., & Xu, X. (2019). Characteristics of urban green spaces in relation to aesthetic preference and stress recovery. *Urban Forestry & Urban Greening*, *41*, 6–13. https://doi.org/10.1016/j.ufug.2019.03.005

Ward, K., Lauf, S., Kleinschmit, B., & Endlicher, W. (2016). Heat waves and urban heat islands in Europe: A review of relevant drivers. *Science of the Total Environment*, *569–570*, 527–539. https://doi.org/10.1016/j.scitotenv.2016.06.119

Wickham, H., & Bryan, J. (2023). Readxl: Read excel files. 2022. R package version, 1(2). https://CRAN.R-project.org/package=readxl; https://doi.org/10.32614/CRAN.package.readxl

Wickham, H., François, R., Henry, L., Müller, K., & Vaughan, D. (2023). dplyr: A grammar of data manipulation. R package version 1.1.4. https://github.com/tidyverse/dplyr, https://dplyr.tidyverse.org; https://doi.org/10.32614/CRAN.package.dplyr

Wickham, H., Vaughan, D., & Girlich, M. (2024). tidyr: Tidy messy data. R package version 1.3.1. https://github.com/tidyverse/tidyr, https://tidyr.tidyverse.org; https://doi.org/10.32614/CRAN.package.tidyr

Yilmaz, D., Bouarafa, S., Peyneau, P. E., Angulo-Jaramillo, R., & Lassabatere, L. (2019). Assessment of hydraulic properties of technosols using Beerkan and multiple tension disc infiltration methods. *European Journal of Soil Science*, *70*(5), 1049–1062.

Zobeck, T. M., & Van Pelt, R. S. (2015). Wind Erosion. In J. L. Hatfield & T. J. Sauer (Eds.), *Soil management: Building a stable base for agriculture* (pp. 209–227). Wiley. https://doi.org/10.2136/2011.soilmanagement.c14

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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