



## Research article

## Potential of Fe sludge addition to increase the water holding capacity of sandy soil substrates

Lydia Pohl<sup>a,\*</sup>, Pauline Winkler<sup>b,c,1</sup>, Robert Mikutta<sup>b,d</sup>, Jan Rücknagel<sup>e</sup>, Werner Gerwin<sup>f</sup><sup>a</sup> Soil-Plant Systems, Brandenburg University of Technology Cottbus-Senftenberg, Cottbus, Germany<sup>b</sup> Soil Science and Soil Protection, Martin Luther University Halle-Wittenberg, Halle/Saale, Germany<sup>c</sup> Research Institute for Postmining Landscapes, Finsterwalde, Germany<sup>d</sup> Just Transition Center, Martin Luther University Halle-Wittenberg, Halle/Saale, Germany<sup>e</sup> Department of Agronomy and Organic Farming, Martin Luther University Halle-Wittenberg, Halle/Saale, Germany<sup>f</sup> Research Center Landscape Development and Mining Landscapes, Brandenburg University of Technology Cottbus-Senftenberg, Cottbus, Germany

## ARTICLE INFO

## Keywords:

Iron hydroxide sludge

Ochre

AMD sludge

Soil amendment

Soil additives

Water storage

## ABSTRACT

Iron (Fe) hydroxide sludge is a by-product of open-pit lignite mining that accumulates in large quantities during acid mine drainage (AMD) treatment, where  $\text{Fe}^{2+}$  is precipitated to mitigate its environmental impact on aquatic ecosystems. Large quantities accrue, and the majority of Fe sludge is currently landfilled, although it may hold potential for beneficial reuse, for example, as a soil amendment. Hence, this study investigated the potential of Fe sludge to improve the water-holding capacity of sandy soils. A pure quartz sand and three sandy soil substrates were mixed with three different amounts of Fe oxide sludge (15, 30, and 60 t ha<sup>-1</sup>) in pelletized and powdered form. Plant-available water-holding capacity (AWHC) was measured for all treatments, and results were compared to controls without Fe oxide sludge addition. The quartz sand's AWHC increased at all application rates of Fe sludge. In natural sandy soil substrates, Fe sludge increased AWHC at the highest application rate only in the soil material with an initial AWHC of <10 vol%. The application of powdered Fe sludge was found to be more effective than pelletized sludge. We conclude that Fe oxide sludge applied as powder has the potential to enhance the AWHC of soils with an initial AWHC <10 vol%, thus improving the quality of sandy substrates in post-mining areas. Yet, application of Fe sludge to improve soil physical properties should always consider their simultaneous impact on soil chemical properties, such as pH buffering, carbon accumulation, and effects on potentially harmful trace elements.

## 1. Introduction

Globally, open-pit lignite mining is devastating whole landscapes by damaging soil and contaminating water resources by acid mine drainage (AMD). Pyrite ( $\text{Fe}^{(II)}\text{S}_2$ ) is a common mineral found in the overburden material of lignite mines. During mining, the groundwater table is lowered, and the overburden is excavated, exposing pyrite to oxygen. When water seeps through the dumped overburden, it becomes enriched in products of pyrite oxidation, typically including sulphuric acid and ferrous iron ( $\text{Fe}^{2+}$ ). The acidic  $\text{Fe}^{2+}$ -enriched groundwater partly discharges into rivers with  $\text{Fe}^{2+}$  undergoing oxidation and precipitation as short-range-ordered Fe oxides and hydroxides (hereafter referred to as Fe oxides), damaging entire aquatic ecosystems (Akcil and Koldas, 2006; Evangelou and Zhang, 1995).

For example, in Lusatia - a still active lignite mining region in eastern Germany - groundwater was lowered for mining in an area of up to 2100 km<sup>2</sup> (Grünwald and Schoenheinz, 2014). In that region, the River Spree is most affected by AMD and is thus treated with lime and flocculants to raise the pH and facilitate precipitation of Fe hydroxides (Friedland et al., 2021). Before treatment, the average Fe load of the River Spree was 3.9 t per day in 2023, with individual peak loads reaching up to 68.1 t d<sup>-1</sup> (Uhlmann et al., 2024). Consequently, approx. 60,000 tons of Fe sludge accumulate annually in Lusatia (LMBV, 2023). With AMD being a global problem (Otunola and Mhangara, 2024), thousands of tons of Fe sludge are produced worldwide by similar water purification plants (Chen et al., 2015; Sapsford et al., 2015; Zinck and Griffith, 2013). The vast majority of Fe sludge is currently landfilled and only used economically to a limited extent (summarized in Yu et al., 2022),

\* Corresponding author.

E-mail address: [lydia.pohl@b-tu.de](mailto:lydia.pohl@b-tu.de) (L. Pohl).<sup>1</sup> Authors contributed equally to this work.

resulting in disposal costs in the millions (Zinck and Griffith, 2013). For cost, capacity, and environmental reasons, alternative ways to dispose of or even use the Fe oxide sludge are urgently needed.

Fe oxides are natural soil constituents accumulating in the course of soil development. Due to their small particle size, they belong to the silt and clay fraction (Cornell and Schwertmann, 2003), with such fine soil particles known to have a positive impact on a soil's water-holding capacity (WHC). At pH values below their point of zero charge ( $\text{pH}_{\text{pzc}}$ : 8–9), Fe oxides have mainly positive surface charges and thus interact with the negatively charged functional groups of organic matter as well as with the negative charged sites of silicate surfaces (Chen et al., 2014; Cornell and Schwertmann, 2003; Gu et al., 1994). These interactions contribute to aggregate formation (Duiker et al., 2003), potentially having an effect on soil hydraulic properties. Furthermore, the binding of organic matter to Fe oxide surfaces, to some extent, protects the respective organic matter from microbial decomposition (Eusterhues et al., 2005; Kaiser and Guggenberger, 2000; Lützow et al., 2008). In the long term, the amount of soil organic matter may thus increase in Fe oxide-amended sandy soils, potentially contributing to the soil's WHC (Hudson, 1994; Williams et al., 2016; Yost and Hartemink, 2019). The use of Fe oxide sludge as an additive to sandy soils, which are characterized by low WHC, thus bears the potential to be a cost-effective solution for improving soil WHC as well as enhancing the economic potential of the sludge.

Various soil amendments, e.g., bentonite (Suzuki et al., 2007), biochar (Basso et al., 2013; Verheijen et al., 2019; Yu et al., 2013), termite mound material (Suzuki et al., 2007), compost (Ozores-Hampton et al., 2011; Tester, 1990), and also artificial polymers (Rodionov et al., 2012) have been successfully tested globally to increase the water-holding capacity of sandy soils. However, these materials are specifically retrieved (bentonite) or produced (biochar, polymers) with high energy input, or their retrieval destroys biodiversity hotspots (termite mounds). Furthermore, organic amendments may exhibit an intense but short-lived effect (Eden et al., 2017) and have to be applied repeatedly for a long-term effect. Fe oxide sludge, in contrast, is a byproduct of lignite mining, and so its provision as a soil amendment does not cause any extra energy input. Due to the stability of Fe oxides in most soils (oxic and  $\text{pH} > 3$ ), a one-time application may thus be sufficient for generating positive long-term effects.

While Fe-rich by-products have been studied as soil amendments, most research has focused on chemical interactions, such as the remediation of contaminated soils (Doi et al., 2005; Olimah et al., 2015; Simiele et al., 2022), phosphorus retention (Fenton et al., 2012), or their application as phosphorus fertilizers (Dobbie et al., 2005) — whereas studies on their impact on physical soil properties remain limited. Existing studies predominantly examined sludges from drinking water treatment plants, mostly aluminum-based (Bugbee and Frink, 1985; Kerr et al., 2022; Moodley and Hughes, 2006; Rengasamy et al., 1980), or of sewage sludge (Epstein et al., 1976; Lindsay and Logan, 1998; Logan and Harrison, 1995). For example, results showed that sludge addition can increase the available water holding capacity of soils by 23–85 % (Epstein et al., 1976; Logan and Harrison, 1995; Rengasamy et al., 1980) while Lindsay and Logan (1998) reported no significant effect. The majority of studies used loams for sludge application tests (Epstein et al., 1976; Kerr et al., 2022; Lindsay and Logan, 1998; Logan and Harrison, 1995; Moodley and Hughes, 2006). Studies with sands, naturally exhibiting the lowest water holding capacities and therefore likely profiting most from soil amendments, are rare (Rengasamy et al., 1980). Furthermore, field tests frequently did not mention the incorporation depth of sludges (Lindsay and Logan, 1998) or the time when samples were taken after sludge application (Epstein et al., 1976).

Fe sludges may be applied to soils in two different modes, either as pressed pellets or as powder. Pellets represent the most convenient option for the application of Fe sludge due to reduced dust formation, easier storage, and better compatibility with agricultural application equipment. Similar advantages have been demonstrated for other

pelletized mineral fertilizers, such as those based on sewage sludge ash (Cwalina et al., 2025), industrial biosludge (Sandberg et al., 2024), or biochar-compost mixtures (Sung-inthara et al., 2024). The pelletized material, however, could contain a higher share of small pores (e.g., fine pores  $< 0.2 \mu\text{m}$ ) and potentially cause lower plant-available water-holding capacity (AWHC) compared to sludge powder, which might additionally be distributed in soil more homogeneously. Although some studies have examined the potential of Fe sludge as soil amendments, the influence regarding the water-holding capacity of sandy soils, particularly plant-available water, has not yet been systematically investigated. This study, therefore, aimed at determining whether Fe oxide sludge can directly increase the water-holding capacity of sandy soils. We hypothesized that (i) the larger the application rate of Fe oxide-rich amendment, the larger the increase in WHC as well as AWHC, and (ii) sludge powder is more effective in elevating AWHC of sandy soils than pelleted Fe sludge. To test our hypotheses, we applied different levels of powdered and pelleted Fe oxide sludges to pure quartz sand as well as three sandy soil substrates, containing 73–97 % sand and  $< 0.1$ – $1.2$  % organic carbon, and measured WHC as well as AWHC for these mixtures and respective control treatments without Fe sludge addition.

## 2. Materials and methods

### 2.1. Preparation and characterization of soil additives based on Fe oxide sludge

The Fe oxide material was collected from a Fe sludge basin in the post-mining area of Lusatia in Eastern Germany. The basin was created in the 1970s to deposit Fe oxide sludge precipitating from mining-affected water through oxidation and alkalization (Uhlmann et al., 2019). Due to the long deposition time, the material has been heavily rooted, e.g., by reeds. The material was sieved ( $> 40 \text{ mm}$ ), dried at  $60^\circ\text{C}$ , ground ( $< 2 \text{ mm}$ ) with a cutting mill (SM 200, Retsch, Haan, Germany) to shred the remaining plant residues, and mixed with 5 % clay (w:w). The natural clay material originated from a mining area near Plessa (Southeast Germany) and was mainly composed of illite and kaolinite according to X-ray diffraction (XRD) analysis (data not shown). The Fe-clay mixture was moistened and press agglomerated using an extruder (type PZVM8E, Händle, Mühlacker, Germany). Even though the Fe sludge pellets contain small amounts of clay and plant residues, they are further referred to as 'Fe sludge pellets'; control pellets composed of pure clay material were produced in the same way (Fig. 1). In order to use the identical material for both treatments, half of the Fe pellets were ground again by hand to produce a powder. The properties of the respective material are summarized in Table 1. The total carbon ( $\text{C}_t$ ) and total nitrogen ( $\text{N}_t$ ) content were determined by dry combustion with a CN analyzer (varioMicro cube, Elementar, Langenselbold, Germany). To determine the organic carbon (OC) content, samples were treated in a muffle furnace at  $550^\circ\text{C}$  (DIN, 2021) and subsequently measured by dry combustion to determine the remaining inorganic carbon (IC) content. The OC content was calculated as the difference between  $\text{C}_t$  and IC. The specific surface area of samples was obtained using the BET method based on the physisorption of  $\text{N}_2$  gas at  $77 \text{ K}$  (Brunauer et al., 1938). Nitrogen adsorption was measured at 11 points in the partial pressure range of 0.05–0.3 with an Autosorb-1 analyzer (Quantachrome, Boynton Beach, USA). The total Fe ( $\text{Fe}_t$ ) content was determined via pressure digestion of the ground sample in *aqua regia* ( $\text{HNO}_3 + \text{HCl}$ ) at a solid-to-solution ratio of  $1:20 \text{ (g mL}^{-1}\text{)}$ , with subsequent measurement of Fe in the solute by inductively coupled plasma optical emission spectrometry (ICP-OES; iCAP 6000 Series, Thermo Scientific, USA). In addition, pedogenic Fe, including crystalline and short-range-ordered (SRO) Fe oxides, was determined by dithionite-citrate-bicarbonate extraction ( $\text{Fe}_{\text{DCB}}$ ) (Mehra and Jackson, 1958), and the SRO Fe oxide fraction was extracted with acid ammonium oxalate ( $\text{Fe}_{\text{AAO}}$ ) (Schwertmann, 1964), combined with subsequent measurement



Fig. 1. Manufactured Fe-sludge pellets (left) and clay mineral pellets (right).

Table 1

Properties of the Fe sludge material used for this study. Mean values and respective mean ranges were calculated based on duplicates. Where appropriate, values are expressed on a dry-weight basis.

|                                                         | Fe sludge material | Clay material |
|---------------------------------------------------------|--------------------|---------------|
| pH <sub>CaCl2</sub>                                     | 7.4                | 3.3           |
| Specific surface area [m <sup>2</sup> g <sup>-1</sup> ] | 146.6 ± 3.8        | 27.6 ± 0.6    |
| C <sub>t</sub> [mg g <sup>-1</sup> ]                    | 55.7 ± 2.4         | 1.4 ± 0.0     |
| OC [mg g <sup>-1</sup> ]                                | 50.1 ± 2.5         | 1.0 ± 0.0     |
| N <sub>t</sub> [mg g <sup>-1</sup> ]                    | 2.5 ± 0.3          | 1.3 ± 0.4     |
| C:N ratio                                               | 22                 | 1             |
| Fe <sub>t</sub> [mg g <sup>-1</sup> ]                   | 250.5 ± 4.7        | 15.2 ± 0.1    |
| Fe <sub>DCB</sub> [mg g <sup>-1</sup> ]                 | 265.8 ± 0.3        | n.d.          |
| Fe <sub>AAO</sub> [mg g <sup>-1</sup> ]                 | 265.7 ± 6.2        | n.d.          |

**Notes:** C<sub>t</sub> = total carbon; OC = organic carbon; N<sub>t</sub> = total nitrogen; Fe<sub>t</sub> = total iron; Fe<sub>DCB</sub> = dithionite-citrate-bicarbonate-extractable iron; Fe<sub>AAO</sub> = acid ammonium-oxalate-extractable iron.

of Fe in the extracts by ICP-OES (Ultima 2, Horiba Jobin-Yvon S.A.S., Longjumeau, France). The Fe<sub>t</sub>, Fe<sub>AAO</sub>, and Fe<sub>DCB</sub> values are nearly identical (Table 1), indicating that the Fe minerals in the sludge are mainly SRO Fe oxides, such as ferrihydrite.

## 2.2. Quartz sand and sandy soil substrates

Carbon-free, pure quartz sand was washed with ultrapure water until an electrical conductivity of <3 μS cm<sup>-1</sup> and dried at 40 °C. Sandy soil substrates were taken from three different sites in Lusatia, Brandenburg (Germany): (I) soil substrate of a reclamation site in the lignite mining area Welzow South (0–30 cm; Schillem et al., 2019), (II) a naturally grown arable soil of a marginal agricultural field near Heinersbrueck (0–25 cm), and (III) soil substrate at the long-term post-mining research site “Chicken Creek” located within the lignite opencast mine Welzow South (15–25 cm; Gerwin et al., 2009). The sampling depth at each site was selected to ensure that the collected soil material was both representative of the respective substrate and sufficiently homogeneous for experimental comparison. This is particularly relevant in post-mining landscapes, where technically redeposited soil substrates often exhibit considerable heterogeneity due to layered deposition of different materials (Gerwin et al., 2009). The soil substrates were dried at room temperature and sieved to <2 mm. For texture analysis, samples were treated with 25 % HCl and 30 % H<sub>2</sub>O<sub>2</sub> to remove carbonate and organic matter and subsequently measured using laser diffractometry (Beckman Coulter LS 13320 PIDS, Indianapolis, USA). According to respective results (Table 2), the substrates are classified as fine sandy medium sand (I), medium sandy fine sand (II), and loamy sand (III) (AG Boden, 2024).

Table 2

Properties of the quartz sand and soil substrates used for the study. Mean values and standard deviation were calculated based on triplicates for C<sub>t</sub>, N<sub>t</sub>, and textural data, while mean ranges were calculated based on duplicates for the remaining parameters. Where appropriate, values are expressed on a dry-weight basis.

|                                         | Pure quartz sand         | Welzow South           | Heinersbrueck          | Chicken Creek |
|-----------------------------------------|--------------------------|------------------------|------------------------|---------------|
| pH <sub>CaCl2</sub>                     | 7.0                      | 7.5                    | 4.3                    | 7.4           |
| C <sub>t</sub> [mg g <sup>-1</sup> ]    | 0.4 ± 0.0                | 0.9 ± 0.0              | 12.1 ± 0.4             | 3.8 ± 0.1     |
| OC [mg g <sup>-1</sup> ]                | 0.4 ± 0.0                | 0.9 ± 0.0              | 12.1 ± 0.4             | 3.7 ± 0.1     |
| N <sub>t</sub> [mg g <sup>-1</sup> ]    | <0.1                     | 0.1 ± 0.0              | 1.1 ± 0.1              | 0.2 ± 0.0     |
| C:N ratio                               | –                        | 9                      | 11                     | 19            |
| Fe <sub>t</sub> [mg g <sup>-1</sup> ]   | 3.7 ± 0.1                | 2.7 ± 0.2              | 4.3 ± 0.1              | 8.0 ± 0.0     |
| Fe <sub>DCB</sub> [mg g <sup>-1</sup> ] | 0.8 ± 0.1                | 0.6 ± 0.1              | 2.3 ± 0.1              | 2.6 ± 0.2     |
| Fe <sub>AAO</sub> [mg g <sup>-1</sup> ] | 0.1 ± 0.0                | 0.1 ± 0.0              | 2.0 ± 0.0              | 0.5 ± 0.0     |
| Coarse sand [%] (<2000 μm - > 630 μm)   | 32.1 ± 6.0               | 12.6 ± 1.0             | 4.4 ± 2.5              | 11.7 ± 0.8    |
| Medium sand [%] (<630 μm - > 200 μm)    | 62.5 ± 4.8               | 59.2 ± 1.3             | 32.2 ± 0.6             | 39.7 ± 0.8    |
| Fine sand [%] (<200 μm - > 63 μm)       | 4.4 ± 0.9                | 24.6 ± 0.5             | 52.7 ± 2.2             | 21.6 ± 0.5    |
| Silt [%] (>2 μm - < 63 μm)              | 0.5 ± 0.2                | 2.7 ± 0.1              | 8.5 ± 0.3              | 21.7 ± 0.7    |
| Clay [%] (<2 μm)                        | 0.4 ± 0.1                | 0.8 ± 0.0              | 2.2 ± 0.1              | 5.3 ± 0.3     |
| textural class                          | coarse sandy medium sand | fine sandy medium sand | medium sandy fine sand | loamy sand    |

**Notes:** C<sub>t</sub> = total carbon; OC = organic carbon; N<sub>t</sub> = total nitrogen; Fe<sub>t</sub> = total iron; Fe<sub>DCB</sub> = dithionite-citrate-bicarbonate-extractable iron; Fe<sub>AAO</sub> = acid ammonium-oxalate-extractable iron.

The OC, C<sub>t</sub>, N<sub>t</sub>, and Fe contents were determined as described for the Fe sludge material above. The physicochemical properties of the quartz sand and soil substrates are given in Table 2.

## 2.3. Experimental design

There is currently no standardized method for testing the influence of soil amendments such as Fe sludge on AWHC under controlled laboratory conditions. Our experimental setup, however, follows the approach used in comparable studies (Kerr et al., 2022; Logan and Harrison, 1995; Moodley and Hughes, 2006). In detail, three amounts (6.1, 12.2, and

24.4 g) of dried Fe sludge pellets or powder were mixed with 350 g of pure quartz sand or three different sandy soil substrates. The mixtures were filled into steel cylinders ( $V = 248 \text{ cm}^3$ ,  $d = 7.2 \text{ cm}$ ,  $h = 6.1 \text{ cm}$ ) and covered with a mesh at the bottom to keep the samples in the cylinder. In relation to the surface area of the cylinders, this results in Fe sludge application rates of 15, 30, and  $60 \text{ t ha}^{-1}$ , which is equivalent to 1.7, 3.4 and 6.5 wt%. These rates fall within the range of application levels used in previous studies: 5–50 wt% (Doi et al., 2005), 5 wt% (Hodson et al., 2023), or 0.015–3 wt% (Fenton et al., 2012). Since no systematic studies have yet investigated the impact of Fe sludge on the AWHC of sandy soils, the selected application levels reflect amounts manageable in practice, consistency with previously tested amendment levels, and the need to establish an empirical basis for potential field application. In addition, identical amounts of clay minerals were mixed with 350 g of pure quartz sand to compare the effect of clay material and Fe sludge on AWHC. Pure quartz sand and sandy soil substrates without any additions were used as controls, and each treatment was replicated 5 times.

The packed cylinders were water-saturated overnight by capillary rise and subsequently dried at  $40^\circ\text{C}$  for 48–72 h. This procedure was repeated three times to simulate natural soil structure formation by wet-dry cycles and the concomitant swelling and shrinking of the material. The mixtures in the packed cylinders varied in volume due to the varying amounts of added Fe sludge and clay minerals and the slightly different textures of the soil substrates used. Consequently, the filling height differed among treatments and was thus measured at 3 points and averaged to calculate the exact sample volume for subsequent bulk density determination.

The AWHC of each mixture and unamended control was calculated as the difference between the volumetric water content at field capacity and at the permanent wilting point (PWP). Field capacity is defined as the volumetric water content after gravitational drainage has ceased, whereas PWP defines the water content, at which soil water is retained in fine pores and thus not available for plants. Matric potentials reported for field capacity are highly variable, with the most commonly cited value being  $-60 \text{ hPa}$  (commonly used in Germany), while the permanent wilting point (PWP) is typically associated with a matric potential of  $-15,000 \text{ hPa}$  (Hartge and Horn, 2016). To determine the respective water contents, cylinders were water-saturated by capillary rise and then drained on a sand bed at  $-60 \text{ hPa}$  until equilibrium. Afterwards, cylinders were weighed to determine gravimetric water content. They were then further dewatered at  $-316 \text{ hPa}$ , a pressure step relevant for distinguishing different pore sizes, weighed again, and subsequently oven-dried at  $105^\circ\text{C}$  for 24 h to determine dry mass. The five repetitions of each treatment were mixed to take three subsamples that were filled into smaller steel rings ( $d = 4.9 \text{ cm}$ ,  $h = 1 \text{ cm}$ ). Samples in these rings were again water-saturated and then exposed to  $-15,000 \text{ hPa}$  in high-pressure chambers for dewatering down to the PWP. Gravimetric water content was again determined after equilibrium. The gravimetric values (wt%) were converted to volumetric water content (vol%) using cylinder-specific bulk densities. The AWHC was finally calculated as the difference between the mean water content at field capacity ( $-60 \text{ hPa}$ ) and the mean water content at PWP ( $-15,000 \text{ hPa}$ ). By exposing all samples to standardized matric potentials, resulting water contents and AWHC values can be directly compared across treatments to assess the effects of Fe sludge amendments.

In addition to AWHC, pore size distribution was determined according to Amelung et al. (2018) by calculating the vol% of wide macropores ( $>50 \mu\text{m}$ ), narrow macropores ( $10\text{--}50 \mu\text{m}$ ), medium-sized pores ( $0.2\text{--}10 \mu\text{m}$ ) and fine pores ( $<0.2 \mu\text{m}$ ). Water contents of samples after exposure to  $-60 \text{ hPa}$ ,  $-316 \text{ hPa}$  and  $-15,000 \text{ hPa}$  were determined by weighing and associated pore volumes were calculated as follows: wide macropores were estimated as the difference between total pore volume and the water content at  $-60 \text{ hPa}$ ; narrow macropores as the water retained between  $-60 \text{ hPa}$  and  $-316 \text{ hPa}$ ; medium pores as the water retained between  $-316 \text{ hPa}$  and  $-15,000 \text{ hPa}$ ; and fine pores as the

residual water content at  $-15,000 \text{ hPa}$ . The total pore volume is equivalent to the difference between sample volume and volume of the solid substance, which was determined by assuming a particle density of  $2.65 \text{ g cm}^{-3}$  for the soil substrate material and  $2.73 \text{ g cm}^{-3}$  as the mean value for the illite ( $2.8 \text{ g cm}^{-3}$ ) and kaolinite ( $2.65 \text{ g cm}^{-3}$ ) dominated clay material (Flint and Flint, 2002). The particle density of the Fe-sludge/clay mixture was determined with a helium pycnometer (Ultrapyc 5000, ANTON PAAR, Ostfildern-Scharnhausen, Germany), resulting in a density of  $2.69 \text{ g cm}^{-3}$ .

## 2.4. Statistical analysis

Data was tested for normal distribution using the Shapiro-Wilk test, followed by Levene's test for homoscedasticity. Due to partially non-normal distributed data, the non-parametric Kruskal-Wallis test ( $p < 0.05$ ) with Dunn test post-hoc comparisons (Bonferroni correction method) was used to test for significant differences between water contents of different treatments at  $-60 \text{ hPa}$  and  $-15,000 \text{ hPa}$ . Due to the experimental design (5 replicates at  $-60 \text{ hPa}$  and 3 replicates at  $-15,000 \text{ hPa}$ ), testing for significant differences in AWHC (difference of water content at  $-60 \text{ hPa}$  and  $-15,000 \text{ hPa}$ ) was not possible. Statistical analyses were performed using R 4.2.2 (RStudio Team, 2016).

## 3. Results

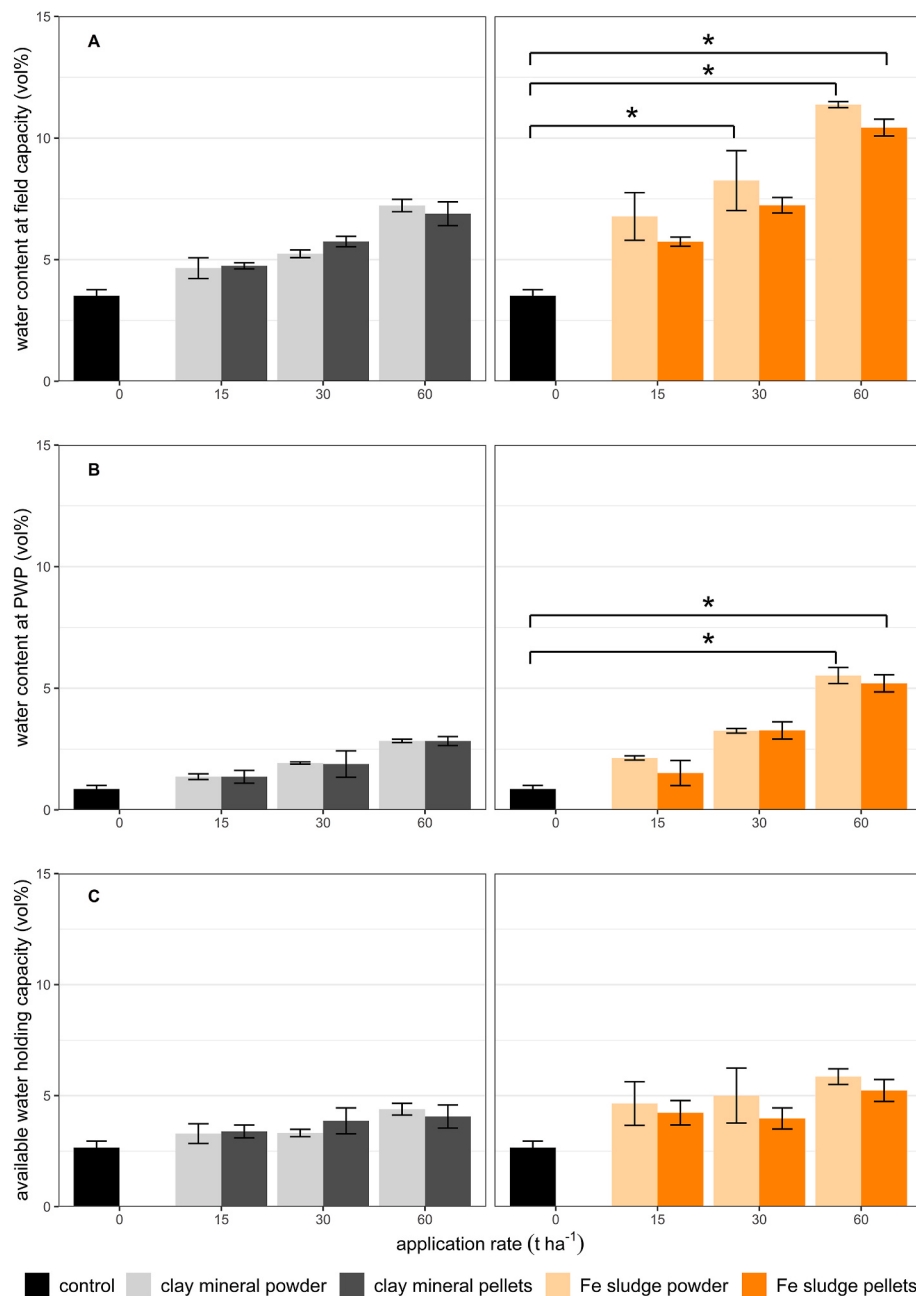
### 3.1. Fe sludge increases the water-holding capacity and plant-available water content of quartz sand

As expected for pure quartz sand, the WHC was generally low ( $3.5 \pm 0.2 \text{ vol}\%$ ; Fig. 2A). However, the experiment with pure quartz sand demonstrated that its WHC increased with the amount of applied clay minerals and Fe sludge material (Fig. 2A). Differences in WHC between the quartz sand control and the quartz sand mixed with clay minerals were smaller and not statistically significant ( $p > 0.1$ ) compared to differences between the quartz sand control and the quartz sand mixed with Fe sludge material. Here, the differences were significant ( $p < 0.05$ ) at an application rate of  $\geq 30 \text{ t Fe sludge ha}^{-1}$ . Hence, Fe sludge seems to be more effective in terms of increasing the WHC. For example, the application of  $60 \text{ t ha}^{-1}$  of Fe sludge powder significantly increased WHC from  $3.5 \pm 0.2$  to  $11.4 \pm 0.1 \text{ vol}\%$ , compared to the clay mineral powder, which only caused an increase to  $7.2 \pm 0.3 \text{ vol}\%$ . For the Fe sludge material, application as powder tends to be more effective in increasing the quartz sand's WHC compared to Fe sludge pellets (Fig. 2A), though differences between powder and pellets were not statistically significant at any application rate.

The water content at the permanent wilting point (PWP) likewise increased with the application of clay minerals and Fe sludge material, with a larger increase for Fe sludge (Fig. 2B). Application of  $60 \text{ t ha}^{-1}$  clay mineral powder increased the water content at PWP three-fold from  $0.9 \pm 0.2 \text{ vol}\%$  to  $2.8 \pm 0.1 \text{ vol}\%$ , whereas the Fe sludge powder resulted in a significant maximum increase to  $5.5 \pm 0.3 \text{ vol}\%$ . For the Fe sludge material amended as pellets, the water content at PWP of the sludge-quartz mixtures was not statistically different from that applied as powder, irrespective of the Fe sludge application rate (Fig. 2B). Despite the concomitant increase of WHC and water content at PWP, the plant-available water holding capacity (AWHC) was still larger in quartz sand amended with Fe oxide sludge powder compared to the quartz sand control (Fig. 2C). At the highest application rate of  $60 \text{ t ha}^{-1}$ , the AWHC more than doubled upon application of Fe oxide sludge powder from  $2.7 \pm 0.3 \text{ vol}\%$  to  $5.9 \pm 0.4 \text{ vol}\%$ .

### 3.2. Fe-sludge has minimal impact on the plant-available water content in soil substrates

Field capacity is distinctly larger in sandy soil substrates ( $\geq 13 \text{ vol}\%$ ) compared to the pure quartz sand and is largest ( $>20 \text{ vol}\%$ ) in the

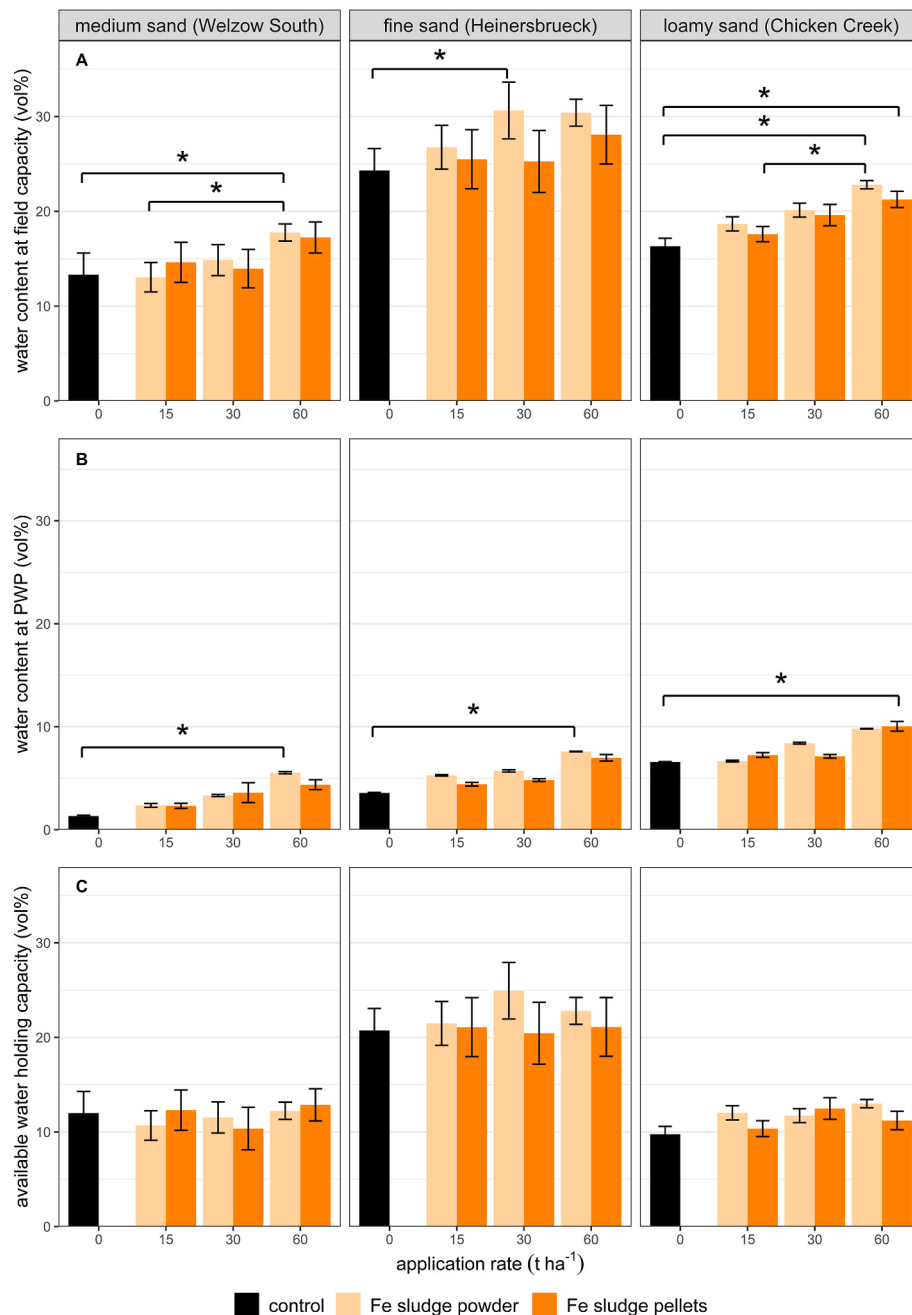


**Fig. 2.** Water content at field capacity (A) and at the permanent wilting point (PWP) (B) for the quartz sand depending on the application rate of clay material and Fe sludge. Error bars were calculated for five replicates for the water content at field capacity ( $-60$  hPa) (A) and three replicates for the water content at PWP ( $-15,000$  hPa) (B). Asterisks (\*) indicate statistically significant differences ( $p < 0.05$ ). Statistical comparisons were conducted both within treatments (i.e., across different application rates) and between treatments (i.e., between clay and Fe sludge amendments), but no significant differences were observed in the data presented. For clarity, non-significant results are not shown. Available water holding capacity (AWHC) (C) was calculated as the difference between the mean water content at field capacity and the mean water content at the permanent wilting point. The standard deviation ( $\pm$ ) was calculated as the square root of the sum of the squared differences of the mean values. Due to the experimental design, testing for significant differences in AWHC was not possible.

organic matter-rich fine sand (Fig. 3A). Addition of Fe oxide sludge significantly increased WHC at the largest application rate ( $60 \text{ t ha}^{-1}$ ) in the medium sand (Welzow South) and the loamy sand (Chicken Creek), with effects being generally larger for the Fe sludge powder than compared to the respective amounts of pellets (Fig. 3A). For the medium sand, WHC increased from  $13.3 \pm 2.3$  to a maximum of  $17.8 \pm 0.9 \text{ vol}\%$ , and for the loamy sand, from  $16.3 \pm 0.8$  to  $22.8 \pm 0.4 \text{ vol}\%$ . In the organic matter-rich fine sand (Heinersbrueck), Fe sludge powder addition also significantly increased WHC ( $24.3 \pm 2.3$  to  $30.6 \pm 3.0 \text{ vol}\%$ ), however, only at the medium application rate of  $30 \text{ t ha}^{-1}$ . Statistical differences in WHC between Fe sludge powder and pellets were not

significant for all tested soil substrates and application rates.

The concomitant increase in water content at PWP (Fig. 3B) diminishes the effect of Fe sludge addition on AWHC (Fig. 3C). There is a slight increase in AWHC in natural sandy soil substrates with the addition of Fe sludge powder. However, standard deviations are relatively high for soil substrates. The largest effect of Fe sludge powder was found for the loamy sand with an increase of AWHC from  $9.8 \pm 0.8$  to  $13.0 \pm 0.4 \text{ vol}\%$  at the largest application rate of  $60 \text{ t ha}^{-1}$  (Fig. 3C). On average, the application of Fe sludge powder resulted in slightly higher AWHC values and lower standard deviations compared to pellet application (Fig. 3C).



**Fig. 3.** Water content at field capacity (A) and at PWP (B) for the sandy soil substrates depending on the application rate of Fe sludge. Error bars were calculated for five replicates for the water content at field capacity ( $-60$  hPa) (A) and three replicates for the water content at PWP ( $-15,000$  hPa) (B). Asterisks (\*) indicate statistically significant differences ( $p < 0.05$ ). Statistical comparisons were conducted both within treatments (i.e., across different application rates) and between treatments (i.e., between different sandy soil substrates), but no significant differences were observed in the data presented. For clarity, non-significant results are not shown. Available water holding capacity (AWHC) (C) was calculated as the difference between the mean water content at field capacity and the mean water content at the permanent wilting point. The standard deviation ( $\pm$ ) was calculated as the square root of the sum of the squared differences of the mean values. Due to the experimental design, testing for significant differences in AWHC was not possible.

### 3.3. Effects of Fe sludge on bulk density, pore volume, and pore-size distribution

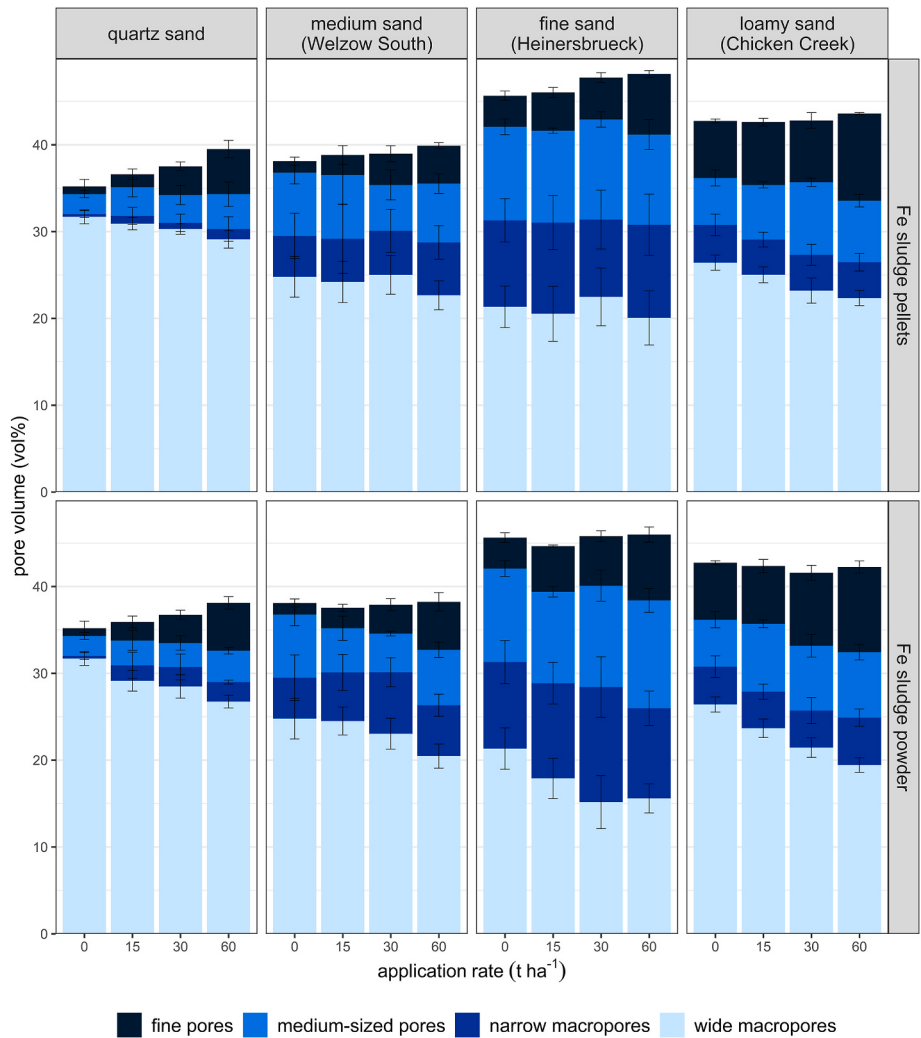
Addition of Fe sludge to quartz sand significantly decreased bulk density, with a more pronounced effect observed for pellets compared to powder (Table 3). The decrease in bulk density due to the addition of Fe sludge pellets is also observed in sandy soil substrates, especially in the medium and fine sand. In contrast, the addition of Fe sludge powder results in an increase in bulk density at the lowest application rate ( $15 \text{ t ha}^{-1}$ ) in sandy soil substrates, compared to their respective control, but

returns to control levels at the highest application rate ( $60 \text{ t ha}^{-1}$ ) for medium and fine sand. Conversely, in loamy sand, bulk density increases with higher application rates of Fe sludge powder.

The quartz sand's decrease in bulk density upon Fe sludge pellet or powder addition is accompanied by an increase in total pore volume (Table 3). That rise in pore volume stems from an increase in the proportion of fine and medium-sized pores as well as narrow macropores, that more than compensates for the concomitant decrease in wide macropores (Fig. 4). Overall, the shift in the proportion of macropores from wide to narrow is more pronounced in the quartz sand when Fe

**Table 3**  
Bulk density and total pore volume for the mixtures depending on the application rate of Fe sludge and clay mineral material.

|                      | appl. rate | quartz sand           |                    | medium sand           |                    | fine sand             |                    | loamy sand            |                    |
|----------------------|------------|-----------------------|--------------------|-----------------------|--------------------|-----------------------|--------------------|-----------------------|--------------------|
|                      |            | bulk density          | pore volume        | bulk density          | pore volume        | bulk density          | pore volume        | bulk density          | pore volume        |
|                      |            | [g cm <sup>-3</sup> ] | [cm <sup>3</sup> ] | [g cm <sup>-3</sup> ] | [cm <sup>3</sup> ] | [g cm <sup>-3</sup> ] | [cm <sup>3</sup> ] | [g cm <sup>-3</sup> ] | [cm <sup>3</sup> ] |
| control              | 0          | 1.72 ± 0.02           | 71.7 ± 2.4         | 1.64 ± 0.01           | 81.1 ± 1.6         | 1.46 ± 0.02           | 108.4 ± 2.5        | 1.53 ± 0.01           | 97.0 ± 0.9         |
| clay mineral pellets | 15         | 1.72 ± 0.02           | 72.7 ± 2.3         |                       |                    |                       |                    |                       |                    |
|                      | 30         | 1.73 ± 0.02           | 72.5 ± 2.3         |                       |                    |                       |                    |                       |                    |
|                      | 60         | 1.69 ± 0.01           | 80.1 ± 1.4         |                       |                    |                       |                    |                       |                    |
| clay mineral powder  | 15         | 1.71 ± 0.03           | 74.7 ± 1.9         |                       |                    |                       |                    |                       |                    |
|                      | 30         | 1.74 ± 0.01           | 71.0 ± 0.6         |                       |                    |                       |                    |                       |                    |
|                      | 60         | 1.73 ± 0.02           | 75.3 ± 1.2         |                       |                    |                       |                    |                       |                    |
| Fe sludge pellets    | 15         | 1.68 ± 0.02           | 77.5 ± 2.1         | 1.63 ± 0.03           | 84.7 ± 3.8         | 1.45 ± 0.01           | 111.6 ± 2.3        | 1.53 ± 0.01           | 98.1 ± 1.7         |
|                      | 30         | 1.66 ± 0.01           | 81.4 ± 1.9         | 1.62 ± 0.02           | 86.7 ± 3.4         | 1.41 ± 0.02           | 109.2 ± 2.5        | 1.53 ± 0.02           | 100.3 ± 3.6        |
|                      | 60         | 1.61 ± 0.02           | 91.5 ± 3.5         | 1.60 ± 0.01           | 92.9 ± 1.3         | 1.40 ± 0.01           | 114.3 ± 1.8        | 1.51 ± 0.00           | 106.6 ± 0.5        |
| Fe sludge powder     | 15         | 1.70 ± 0.02           | 75.0 ± 2.3         | 1.66 ± 0.01           | 80.3 ± 1.4         | 1.48 ± 0.00           | 105.9 ± 0.5        | 1.54 ± 0.02           | 97.2 ± 3.0         |
|                      | 30         | 1.68 ± 0.02           | 78.9 ± 1.9         | 1.65 ± 0.02           | 82.7 ± 2.4         | 1.46 ± 0.02           | 101.2 ± 2.5        | 1.56 ± 0.02           | 95.5 ± 3.3         |
|                      | 60         | 1.65 ± 0.02           | 86.1 ± 1.6         | 1.64 ± 0.03           | 86.6 ± 3.9         | 1.46 ± 0.02           | 104.9 ± 3.7        | 1.55 ± 0.02           | 101.0 ± 3.0        |



**Fig. 4.** Pore size distributions and pore volumes of quartz sand and three sandy soil substrates amended with Fe sludge pellets and Fe sludge powder, respectively. Pores were defined as fine pores (<0.2 μm), medium-sized pores (0.2–10 μm), narrow macropores (10–50 μm), and wide macropores (>50 μm).

sludge was added as powder (Fig. 4).  
In the sandy soil substrates, the addition of Fe sludge powder or pellets only slightly affected the total pore volume. Irrespectively, we observed an increasing proportion of fine pores at the expense of wide

macropores in the sandy soil substrates with increasing Fe sludge addition, with a clearer trend for the applied powder. Solely, the loamy sand, characterized by the lowest proportion of medium-sized pores, exhibits a slight increase in these medium-sized pores relevant for the

water supply of plants (Fig. 4). Hence, the increase in AWHC of the loamy sand upon Fe sludge powder addition can be explained by the increased contribution of medium-sized pores. The observed differences in AWHC and pore structure changes among the substrates likely reflect their textural characteristics. Substrates with lower fine sand fractions (e.g., quartz sand:  $4.4 \pm 0.9\%$ ; Chicken Creek:  $21.6 \pm 0.5\%$ ) exhibited more pronounced increases in medium and fine pores upon Fe sludge addition than those with higher fine sand content (e.g., Heinersbrueck:  $52.7 \pm 2.2\%$ ). In summary, the application of Fe sludge as powder or pellet has been demonstrated to increase, particularly the proportion of fine pores in all investigated sandy substrates at the expense of large macropores, whereas the increase of medium-sized pores was only recognizable for the pure quartz sand and loamy sand from the Chicken Creek site.

## 4. Discussion

### 4.1. Impact of Fe sludge on plant-available water-holding capacity in sandy soils

To the best of our knowledge, data on WHC and AWHC in sandy soils with Fe oxide sludge amendment do not yet exist, while data on the effect of other soil amendments are rare and mainly concentrate on the effect of biochar (e.g., Basso et al., 2013; Herawati et al., 2021; Ibrahim and Alghamdi, 2022; Yu et al., 2013). For example, Yu et al. (2013) studied the effect of 3 w% biochar (equivalent to about  $65 \text{ t ha}^{-1}$ ) applied to loamy sand and measured an increase in WHC from 16 to 19 vol%. This is in the range of our sandy soils amended with  $60 \text{ t ha}^{-1}$  Fe oxide sludge. However, Yu et al. (2013) did not take water held at the PWP into account, and the actual increase in available water is most likely smaller. Basso et al. (2013) measured the AWHC of sandy loam (68 % sand, 25 % silt) mixed with 3 and 6 w% biochar and incubated for 91 days in freely draining columns with weekly watering. After 15 days, no significant difference in AWHC between the control and the biochar-amended sandy loam was found. However, after 91 days, the AWHC of both biochar-amended soils was significantly larger (19 vol%) than the AWHC of the control (14 vol%). This temporal dynamic indicates that improvements in AWHC following soil amendments may develop progressively as biological activity and soil structure evolve.

While such studies provide useful references, the mechanisms underlying the effects of biochar and Fe sludge differ substantially. Biochar increases soil water retention primarily through its high internal porosity and surface area (Liu et al., 2017). In contrast, Fe sludges, which contain large amounts of SRO Fe oxides, may enhance soil water retention not only through their own porosity but also likely by promoting soil aggregation (Duiker et al., 2003). In our experiment, the slight to moderate increase in AWHC in pure quartz sand and the loamy sand due to the addition of Fe-sludge can be explained by clay-sized sludge particles occupying wide macropores (Bodman and Constantin, 1965) as confirmed by the observed decrease in these pores. The distinct increase in fine pores in all sands upon Fe sludge addition might further be due to (micro)aggregates containing fine pores (Totsche et al., 2018; Yudina et al., 2022) that seem to occur in Fe sludge pellets or form during wetting and drying of Fe sludge powders. The overall decrease in bulk density upon Fe sludge addition as pellets is an effect of larger particles being added to a packing of smaller particles, disproportionately increasing overall porosity (Wickland et al., 2006).

Distinct effects of Fe sludge addition on AWHC were only found for substrates and soils with the lowest initial AWHC (pure quartz sand with  $2.7 \pm 0.3 \text{ vol}\%$  and loamy sand with  $9.8 \pm 0.8 \text{ vol}\%$ ) and at the highest Fe sludge application rate ( $60 \text{ t ha}^{-1}$ ). This also implies that the effect of Fe sludge addition to sandy soils with respect to AWHC can be variable, and not every sand substrate benefits from the incorporation of Fe oxide sludge, as was the case for the medium sand from Welzow South and the fine sand from Heinersbrueck.

According to the German Manual of Soil Mapping (AG Boden, 2024),

an AWHC of  $<11 \text{ vol}\%$  is considered as very low, and of 11 to  $<15 \text{ vol}\%$  is considered as low. Thus, the increase for the loamy sand from Chicken Creek from  $9.8 \pm 0.8 \text{ vol}\%$  to  $13.0 \pm 0.4 \text{ vol}\%$  resulted in an upgrade. This rise of  $+3.2 \text{ vol}\%$  refers to an incorporation depth of the added Fe oxide sludge of about 6 cm (filling height of cylinders) and is thus equivalent to nearly 2 L of plant-available water that can be additionally stored per  $\text{m}^2$  of soil. These 2 L may enable plants to overcome short dry periods, providing sufficient previous precipitation to fill the additional water-storing pores. For a respective increase in plant-available water to depths  $>6 \text{ cm}$ , Fe sludge addition has to increase accordingly (e.g., to about  $100 \text{ t ha}^{-1}$  for 10 cm incorporation depth with an additional 3.3 L plant-available water). Consequently, the effect of Fe oxide sludge application on the AWHC of sandy soils is similar to that of biochar, with the difference that Fe oxide sludge is a readily available byproduct in mining regions, while biochar has to be specifically produced. If the water storage effects pay off, higher application rates have to be tested in field trials. Possibly, effects per ton of Fe sludge might be larger under natural soil conditions, including plant growth and microbial activity. The fine-pored sludge material may facilitate, for example, the formation of moist microenvironments. It has been demonstrated that the moisture level of fine-pored plant residue can exceed that of the surrounding bulk soil via the so-called 'sponge effect' (Kravchenko et al., 2017), being more pronounced in coarse-textured than in fine-textured soil material (Kutlu et al., 2018).

### 4.2. Soil chemical implications of Fe sludge amendment

Besides enhancing AWHC, other positive effects of Fe sludge application may occur, e.g., carbon sequestration and hence humus accumulation, which may justify the expense of its application. With an OC content of 5 % (Table 1), the added Fe sludge provides a considerable amount of carbon to the soil substrates. For example, when applied at the highest rate ( $60 \text{ t ha}^{-1}$ ) this corresponds to an OC input of  $3 \text{ t ha}^{-1}$ . While biochar organic carbon is relatively stable due to its complex structure, organic carbon in Fe sludges is stabilized through its interaction with the Fe oxide surfaces. Fe oxides have been shown to strongly bind organic carbon, thereby protecting it from microbial degradation and contributing to its long-term accumulation in soils (Bramble et al., 2025; Kaiser and Guggenberger, 2000). For example, Silva et al. (2015) observed an increase in soil carbon following the application of Fe-rich biosolids in the topsoil (0–20 cm), with the highest carbon accumulation observed after 3–6 years.

Although Fe sludge predominantly consists of Fe oxides, it may also contain a range of adsorbed and co-precipitated trace elements, including potentially toxic metals such as Cu, Cd, Cr, Ni, Zn (Fenton et al., 2009; Yu et al., 2022) or metalloids like As (Valente et al., 2011). In soils, Fe oxides are known for their high sorption capacity, influencing the mobility and bioavailability of both nutrients and contaminants (Eick et al., 1999; Fischer et al., 2007; Goldberg et al., 1993, 1996; Stumm et al., 1980). Consequently, applying Fe oxide sludge to soil may introduce hazardous metal(oid)s that have accumulated at Fe oxide surfaces (McKenzie, 1980), and promote the specific adsorption of essential nutrients such as P, Mo, B, and Zn. Both processes may impair plant nutrition, reduce fertilizer use efficiency, and potentially offset beneficial effects such as improved plant-available water-holding capacity. For example, Hodson et al. (2023) reported reduced plant growth of winter wheat in sandy clay loam amended with Fe sludge, likely due to reduced P availability. However, plant roots excrete organic acids and form mutualistic interactions with arbuscular mycorrhizal fungi to overcome P fixation (Gerke et al., 1994; Smith et al., 2011). In addition, the high affinity of Fe oxides for metal(oid)s is also actively exploited in remediation efforts: Fe sludge is applied to contaminated soils to immobilize toxic elements such as As, Pb, and Cd, thereby reducing their environmental and biological availability (Doi et al., 2005; Olimah et al., 2015; Simiele et al., 2022). Thus, Fe oxide sludge applied to soil may not only be considered as a source but also as a sink for hazardous

metal(oid)s, which is most valuable in sandy soils with low sorption capacity, as further metal(oid)s might be added with fertilizers and compost (Blume and Brümmer, 1991).

Further, Fe oxide sludge can influence soil pH. As the material is actively precipitated from AMD through the addition of lime and flocculants, it typically exhibits a neutral to slightly alkaline character. The Fe sludge used in our study, for example, had a pH of 7.4, even though it was deposited <50 years ago. Although we did not assess soil pH after sludge application, the material's chemical properties suggest a potential to buffer soil acidity, particularly in sandy soils with low buffering capacity. For example, Olimah et al. (2015) observed a significant pH increase in an As-contaminated soil following the addition of 5 wt% Fe sludge, while Simiele et al. (2022) reported that Fe sludge, especially when combined with organic amendments, mitigated soil acidification more effectively than biochar alone. A higher soil pH not only improves general soil conditions but also reduces the solubility and mobility of toxic metal(oid)s such as Pb and As. This further supports the use of Fe sludge in acidic, sandy soils where low pH and poor sorption capacity often coincide with elevated environmental risks.

#### 4.3. Experimental limitations and transferability to field conditions

The methodology applied in this study, relying on mixing sandy substrates with Fe sludge and packing the remoulded mixtures into steel cylinders, deviates from standard field-based approaches, which typically use undisturbed field samples to preserve the natural soil structure. However, in many post-mining areas, soils are technically redeposited and lack a naturally developed structure. In such cases, homogenized laboratory mixtures can reasonably reflect the initial conditions of substrates amended with Fe sludge. Moreover, even under practical conditions, the incorporation of Fe sludge into the upper soil layer would disturb the existing substrate structure, resulting in conditions similar to those simulated in this study. Particularly in light of the limited practical experience and regulatory uncertainties currently restricting the field application of Fe sludges, laboratory experiments remain a crucial first step for assessing their effects under controlled conditions. However, given that only one specific Fe sludge was examined, further studies are needed to assess how the observed effects may vary across different sludge types. Fe sludges exhibit substantial variability in physicochemical and mineralogical properties due to differences in their origin and treatment conditions (Singh et al., 1999; Valente and Gomes, 2009). Differences in Fe contents, mineral phases (e.g., ferrihydrite vs. goethite), pH, sulfate concentration, and residual neutralization agents (e.g., lime) influence not only the chemical behavior but potentially also soil hydraulic responses following sludge amendment. Therefore, future research should assess a broader spectrum of Fe sludges under field conditions, with particular attention to their mineralogical composition and particle characteristics, which are known to affect aggregation, porosity, and water retention in amended soils.

## 5. Conclusions

Our study, for the first time, showed that Fe sludge addition has the potential to increase AWHC in sandy substrates but only in those that comprise a very low initial AWHC of <10 vol%. Increases in AWHC were observed only in one out of three sandy soil substrates, thus questioning the general suitability of Fe oxide sludge for improving plant-available water capacity in all sandy soils. Our results thus call for studies that test Fe oxide sludges for a larger number of natural sandy soils. Apart from this, we found that WHC increased with increasing application doses of Fe oxide sludge, thus at least partly supporting our hypothesis that larger application rates increase the WHC. Under the experimental conditions, the Fe-sludge powder was more effective in augmenting WHC than the pelletized material, but there was no distinct difference regarding AWHC. Although the pellets are potentially easier to handle in agricultural practice, it must be considered whether the higher

production costs and the lower efficiency in terms of WHC justify their application. Given that Fe sludge application increased AWHC already at the lowest application rate of 15 t ha<sup>-1</sup>, we estimate for an incorporation depth of 30 cm that an application level of >75 t ha<sup>-1</sup> would be required for increasing AWHC of sandy soils, provided no other soil properties are harmed. Soils with very low initial AWHC and, in particular, those characterized by low organic matter content, acidic pH, and/or increased concentrations of potentially toxic elements, could benefit not only from improved WHC, but also from pH buffering, carbon stabilization, and immobilization of metal(oid)s. Although these additional properties were not assessed in this study, the combined agronomic and environmental potential of Fe sludge warrants further investigation, especially in regions where conventional amendments are economically or logistically less feasible. This is of particular concern for regions experiencing increasing temperatures or declining precipitation under climate change conditions, as well as an increasing abundance of dry spell periods.

#### CRedit authorship contribution statement

**Lydia Pohl:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Pauline Winkler:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Robert Mikutta:** Writing – review & editing. **Jan Rücknagel:** Writing – review & editing. **Werner Gerwin:** Writing – review & editing, Conceptualization.

#### Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Lydia Pohl reports financial support was provided by Federal Ministry of Education and Research (BMBF). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Acknowledgements

We would like to thank Steffi Schillem for providing the soil material from Welzow South and Heinersbrueck. Manuela Abendroth, Silvio Kahl, Steffen Both, Alexandra Boritzki, and Philipp Röhnisch are gratefully acknowledged for laboratory analyses and assistance. The study was funded by the Federal Ministry of Education and Research (BMBF) within the funding alliance LIL - Landinnovation Lausitz and the research project StabilOrg: Development of innovative stabilized organo-mineral complexes for sustainable soil amelioration ("Entwicklung neuartiger, stabiler organo-mineralischer Komplexe zur nachhaltigen Bodenverbesserung"). In particular, we would like to thank P.U.S. Produktions-und Umweltservice GmbH (Lauta, Germany) and Keraton Kies-und Tongruben GmbH (Plessa, Germany) for providing the Fe sludge and clay material. Five anonymous reviewers are gratefully acknowledged for their helpful comments and suggestions.

#### Data availability

Data will be made available on request.

#### References

- AG Boden, 2024. KA 6: Bodenkundliche Kartieranleitung. 6. Auflage. Hannover.
- Akcil, A., Koldas, S., 2006. Acid Mine Drainage (AMD): causes, treatment and case studies. *J. Clean. Prod.* 14 (12–13), 1139–1145.

- Amelung, W., Blume, H.-P., Fleige, H., Horn, R., Kandeler, E., Kögel-Knabner, I., Kretzschmar, R., Stahr, K., Wilke, B.-M., 2018. Scheffer/Schachtschabel Lehrbuch Der Bodenkunde. Springer, Berlin, Heidelberg.
- Basso, A.S., Miguez, F.E., Laird, D.A., Horton, R., Westgate, M., 2013. Assessing potential of biochar for increasing water-holding capacity of sandy soils. *GCB Bioenergy* 5 (2), 132–143.
- Blume, H.P., Brümmer, G., 1991. Prediction of heavy metal behavior in soil by means of simple field tests. *Ecotoxicol. Environ. Saf.* 22 (2), 164–174.
- Bodman, G.B., Constantin, G.K., 1965. Influence of particle size distribution in soil compaction. *Hilgardia* 36, 567–591.
- Bramble, D.S.E., Schöning, I., Brandt, L., Poll, C., Kandeler, E., Ulrich, S., Mikutta, R., Mikutta, C., Silver, W.L., Totsche, K.U., Kaiser, K., Schrumph, M., 2025. Land use and mineral type determine stability of newly formed mineral-associated organic matter. *Commun. Earth Environ.* 6 (1).
- Brunauer, S., Emmett, P.H., Teller, E., 1938. Adsorption of gases in multimolecular layers. *J. Am. Chem. Soc.* 60 (2), 309–319.
- Bugbee, G.J., Frink, C.R., 1985. Alum sludge as a soil amendment: effects on soil properties and plant growth 827. The Connecticut Agricultural Experiment Station. New Haven, USA, p. 8.
- Chen, C., Dynes, J.J., Wang, J., Sparks, D.L., 2014. Properties of Fe-organic matter associations via coprecipitation versus adsorption. *Environ. Sci. Technol.* 48 (23), 13751–13759.
- Chen, Z., Wang, X., Ge, Q., Guo, G., 2015. Iron oxide red wastewater treatment and recycling of iron-containing sludge. *J. Clean. Prod.* 87, 558–566.
- Cornell, R.M., Schwertmann, U., 2003. The Iron Oxides: Structure, Properties, Reactions, Occurrences and Uses, second ed. WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. Second, Completely Revised and Extended Edition.
- Cwalina, P., Obidziński, S., Sienkiewicz, A., Kowczyk-Sadowy, M., Piekut, J., Bagińska, E., Mazur, J., 2025. Production and quality assessment of fertilizer pellets from compost with Sewage Sludge Ash (SSA) addition. *Materials* 18 (5).
- DIN, 2021. Boden, Abfall, Behandelte Bioabfall Und Schlamm – Bestimmung Des Glühverlusts: Deutsche Fassung EN 15935:2021. Beuth Verlag GmbH, Berlin, p. 15.
- Dobbie, K.E., Heal, K.V., Smith, K.A., 2005. Assessing the performance of phosphorus-saturated ochre as a fertilizer and its environmental acceptability. *Soil Use Manag.* 21 (2), 231–239.
- Doi, M., Warren, G., Hodson, M.E., 2005. A preliminary investigation into the use of ochre as a remedial amendment in arsenic-contaminated soils. *Appl. Geochem.* 20 (12), 2207–2216.
- Duiker, S.W., Rhoton, F.E., Torrent, J., Smeck, N.E., Lal, R., 2003. Iron (Hydr)Oxide crystallinity effects on soil aggregation. *Soil Science Soc. of Amer. J.* 67 (2), 606–611.
- Eden, M., Gerke, H.H., Houot, S., 2017. Organic waste recycling in agriculture and related effects on soil water retention and plant available water: a review. *Agron. Sustain. Dev.* 37 (2), 1.
- Eick, M.J., Brady, W.D., Lynch, C.K., 1999. Charge properties and nitrate adsorption of some acid Southeastern soils. *J. Environ. Qual.* 28 (1), 138–144.
- Epstein, E., Taylor, J.M., Chaney, R.L., 1976. Effects of sewage sludge and sludge compost applied to soil on some soil physical and chemical properties. *J. Environ. Qual.* 5 (4), 422–426.
- Eusterhues, K., Rumpel, C., Kögel-Knabner, I., 2005. Organo-mineral associations in sandy acid forest soils: importance of specific surface area, iron oxides and micropores. *Eur. J. Soil Sci.* 56 (6), 753–763.
- Evangelou, V.P., Zhang, Y.L., 1995. A review: pyrite oxidation mechanisms and acid mine drainage prevention. *Crit. Rev. Environ. Sci. Technol.* 25 (2), 141–199.
- Fenton, O., Healy, M.G., Rodgers, M., 2009. Use of ochre from an abandoned metal mine in the south east of Ireland for phosphorus sequestration from dairy dirty water. *J. Environ. Qual.* 38 (3), 1120–1125.
- Fenton, O., Kirwan, L., Ó hUallacháin, D., Healy, M.G., 2012. The effectiveness and feasibility of using ochre as a soil amendment to sequester dissolved reactive phosphorus in runoff. *Water Air Soil Pollut.* 223, 1249–1261.
- Fischer, L., Brümmer, G.W., Barrow, N.J., 2007. Observations and modelling of the reactions of 10 metals with goethite: adsorption and diffusion processes. *European J. Soil Sci.* 58 (6), 1304–1315.
- Flint, A.L., Flint, L.E., 2002. 2.2 particle density. In: Dane, J.H., Clarke Topp, G. (Eds.), *Methods of Soil Analysis: Part 4 Physical Methods*. SSSA Book Series. Soil Science Society of America, Madison, WI, USA, pp. 229–240.
- Friedland, G., Grüneberg, B., Hupfer, M., 2021. Geochemical signatures of lignite mining products in sediments downstream a fluvial-lacustrine system. *Sci. Total Environ.* 760, 143942.
- Gerke, J., Römer, W., Jungk, A., 1994. The excretion of citric and malic acid by proteoid roots of *Lupinus albus* L.; effects on soil solution concentrations of phosphate, iron, and aluminum in the proteoid rhizosphere in samples of an oxisol and a luvisol. *J. Plant Nutrition & Soil* 157 (4), 289–294.
- Gerwin, W., Schaaf, W., Biemelt, D., Fischer, A., Winter, S., Hüttl, R.F., 2009. The artificial catchment “Chicken Creek” (Lusatia, Germany)—A landscape laboratory for interdisciplinary studies of initial ecosystem development. *Ecol. Eng.* 35 (12), 1786–1796.
- Goldberg, S., Forster, H.S., Godfrey, C.L., 1996. Molybdenum adsorption on oxides, clay minerals, and soils. *Soil Science Soc. of Amer. J.* 60 (2), 425–432.
- Goldberg, S., Forster, H.S., Heick, E.L., 1993. Boron adsorption mechanisms on oxides, clay minerals, and soils inferred from ionic strength effects. *Soil Science Soc. of Amer. J.* 57 (3), 704–708.
- Grünwald, U., Schoenheinz, D., 2014. Bergbaubedingte Gewässerversauerung in der Niederlausitz - Ursachen, Ausmaß und Minderungskonzepte. *Hydrol. Wasserbewirtsch.* 58 (5), 274–285.
- Gu, B., Schmitt, J., Chen, Z., Liang, L., McCarthy, J.F., 1994. Adsorption and desorption of natural organic matter on iron oxide: mechanisms and models. *Environ. Sci. Technol.* 28 (1), 38–46.
- Hartge, K.H., Horn, R. (Eds.), 2016. *Essential Soil Physics: an Introduction to Soil Processes, Functions, Structure and Mechanics*. Schweizerbart Science Publishers, Stuttgart, p. 391.
- Herawati, A., Mujiyo, Syamsiyah, J., Baldan, S.K., Arifin, I., 2021. Application of soil amendments as a strategy for water holding capacity in sandy soils. *IOP Conf. Ser. Earth Environ. Sci.* 724 (1), 12014.
- Hodson, M.E., Islam, M., Metcalf, M., Wright, A.C.M., 2023. Amendments of waste ochre from former coal mines can potentially be used to increase soil carbon persistence. *Appl. Geochem.* 151, 105618.
- Hudson, B.D., 1994. Soil organic matter and available water capacity. *J. Soil Water Conserv.* (49), 189–194.
- Ibrahimi, K., Alghamdi, A.G., 2022. Available water capacity of sandy soils as affected by biochar application: a meta-analysis. *Catena* 214 (1), 106281.
- Kaiser, K., Guggenberger, G., 2000. The role of DOM sorption to mineral surfaces in the preservation of organic matter in soils. *Org. Geochem.* 31 (7–8), 711–725.
- Kerr, H.C., Johnson, K.L., Toll, D.G., 2022. Reusing Fe water treatment residual as a soil amendment to improve physical function and flood resilience. *Soil* 8 (1), 283–295.
- Kravchenko, A.N., Toosi, E.R., Guber, A.K., Ostrom, N.E., Yu, J., Azeem, K., Rivers, M.L., Robertson, G.P., 2017. Hotspots of soil N<sub>2</sub>O emission enhanced through water absorption by plant residue. *Nat. Geosci.* 10 (7), 496–500.
- Kutlu, T., Guber, A.K., Rivers, M.L., Kravchenko, A.N., 2018. Moisture absorption by plant residue in soil. *Geoderma* 316, 47–55.
- Lindsay, B.J., Logan, T.J., 1998. Field response of soil physical properties to sewage sludge. *J. Environ. Qual.* 27 (3), 534–542.
- Liu, Z., Dugan, B., Masiello, C.A., Gonnermann, H.M., 2017. Biochar particle size, shape, and porosity act together to influence soil water properties. *PLoS One* 12 (6), e0179079.
- LMBV, 2023. Sanierungsbericht 2023.: Daten, Fakten Und Informationen Zur Bergbausanierung Und Verwahrung in Der Lausitz Und Mitteldeutschland Im Jahr 2023, p. 84.
- Logan, T.J., Harrison, B.J., 1995. Physical characteristics of alkaline stabilized sewage sludge (N-Viro soil) and their effects on soil physical properties. *J. Environ. Qual.* 24 (1), 153–164.
- Lützw, M. von, Kögel-Knabner, I., Ludwig, B., Matzner, E., Flessa, H., Ekschmitt, K., Guggenberger, G., Marschner, B., Kalbitz, K., 2008. Stabilization mechanisms of organic matter in four temperate soils: development and application of a conceptual model. *Z. Pflanzenernähr. Dueng. Bodenkd.* 171 (1), 111–124.
- McKenzie, R.M., 1980. The adsorption of lead and other heavy metals on oxides of manganese and iron. *Soil Res.* 18 (1), 61.
- Mehra, O.P., Jackson, M.L., 1958. Iron Oxide Removal from Soils and Clays by a Dithionite-Citrate System Buffered with Sodium Bicarbonate. *Clay Clay Miner* 7, 317–327.
- Moodley, M., Hughes, J.C., 2006. The effects of a polyacrylamide-derived water treatment residue on the hydraulic conductivity, water retention and evaporation of four contrasting South African soils and implications for land disposal. *Water Sci. Technol.* 54 (5), 227–234.
- Olimah, J.A., Shaw, L.J., Hodson, M.E., 2015. Does ochre have the potential to be a remedial treatment for As-contaminated soils? *Environ. Pollut.* 206, 150–158.
- Otunola, B.O., Mhangara, P., 2024. Global advancements in the management and treatment of acid mine drainage. *Appl. Water Sci.* 14 (9), 100839.
- Ozores-Hampton, M., Stansly, P.A., Salame, T.P., 2011. Soil chemical, physical, and biological properties of a sandy soil subjected to long-term organic amendments. *J. Sustain. Agric.* 35 (3), 243–259.
- Rengasamy, P., Oades, J.M., Hancock, T.W., 1980. Improvement of soil structure and plant growth by addition of alum sludge. *Commun. Soil Sci. Plant Anal.* 11 (6), 533–545.
- Rodionov, A., Nii-Annang, S., Bens, O., Trimborn, M., Schillem, S., Schneider, B.U., Raab, T., Hüttl, R.F., 2012. Impacts of soil additives on crop yield and C-Sequestration in post mine substrates of Lusatia, Germany. *Pedosphere* 22 (3), 343–350.
- RStudio Team, 2016. *RStudio, Inc., Boston, MA*.
- Sandberg, M., Frodeson, S., Brunzell, L., Tumuluru, J.S., 2024. Forest industrial waste materials upgraded to fertilizer pellets for forest soil. *Sustainability* 16 (7).
- Sapsford, D., Santonastaso, M., Thorn, P., Kershaw, S., 2015. Conversion of coal mine drainage ochre to water treatment reagent: production, characterisation and application for P and Zn removal. *J. Environ. Manag.* 160, 7–15.
- Schillem, S., Schneider, B.U., Zeihser, U., Hüttl, R.F., 2019. Effect of N-modified lignite granulates and composted biochar on plant growth, nitrogen and water use efficiency of spring wheat. *Arch. Agron Soil Sci.* 65 (13), 1913–1925.
- Schwertmann, U., 1964. Differenzierung der Eisenoxide des Bodens durch Extraktion mit Ammoniumoxalat-Lösung. *Z. Pflanzenernähr. Dueng. Bodenkd.* 105 (3), 194–202.
- Silva, L.C.R., Doane, T.A., Corrêa, R.S., Valverde, V., Pereira, E.I.P., Horwath, W.R., 2015. Iron-mediated stabilization of soil carbon amplifies the benefits of ecological restoration in degraded lands. *Ecol. Appl.* 25 (5), 1226–1234.
- Simiele, M., Lebrun, M., Bourgerie, S., Trupiano, D., Scippa, G.S., Morabito, D., 2022. Biochar, ochre, and manure maturation in an acidic technosol helps stabilize as and Pb in soil and allows its vegetation by *Salix triandra*. *Environments* 9 (7).
- Singh, B., Wilson, M.J., McHardy, W.J., Fraser, A.R., Merrington, G., 1999. Mineralogy and chemistry of ochre sediments from an acid mine drainage near a disused mine in Cornwall, UK. *Clay Miner.* 34 (2), 301–317.
- Smith, S.E., Jakobsen, I., Grønlund, M., Smith, F.A., 2011. Roles of arbuscular mycorrhizas in plant phosphorus nutrition: interactions between pathways of phosphorus uptake in arbuscular mycorrhizal roots have important implications for

- understanding and manipulating plant phosphorus acquisition. *Plant Physiol.* 156 (3), 1050–1057.
- Stumm, W., Kummert, R., Sigg, L., 1980. A ligand exchange model for the adsorption of inorganic and organic ligands at hydrous oxide interfaces. *Croat. Chem. Acta* 53 (2), 291–312.
- Sung-inthara, T., Juntahum, S., Senawong, K., Katekaew, S., Laloon, K., 2024. Pelletization of soil amendment: optimizing the production and quality of soil amendment pellets from compost with water and biochar mixtures and their impact on soil properties. *Environ. Technol. Innov.* 33, 103505.
- Suzuki, S., Noble, A.D., Ruaysoongnern, S., Chinabut, N., 2007. Improvement in water-holding capacity and structural stability of a sandy soil in Northeast Thailand. *Arid Land Res. Manag.* 21 (1), 37–49.
- Tester, C.F., 1990. Organic amendment effects on physical and chemical properties of a sandy soil. *Soil Science Soc. of Amer. J.* 54 (3), 827–831.
- Totsche, K.U., Amelung, W., Gerzabek, M.H., Guggenberger, G., Klumpp, E., Knief, C., Lehndorff, E., Mikutta, R., Peth, S., Prechtel, A., Ray, N., Kögel-Knabner, I., 2018. Microaggregates in soils. *J. Plant Nutr. Soil Sci.* 181 (1), 104–136.
- Uhlmann, W., Hiekel, R., Giering, N., 2024. Weiterführung der Untersuchungen zur Exfiltration von eisenhaltigem, saurem Grundwasser in die Fließgewässer der Lausitz. Monitoring der Eisenbelastung in der Spree und in der Talsperre Spremberg. Jahresbericht, 2023 online available: <https://www.lmbv.de/wp-content/uploads/2024/03/Jahresbericht-2023-zum-Monitoring-der-Eisenbelastung-der-Spree-und-in-der-Talsperre-Spremburg.pdf>.
- Uhlmann, W., Zimmermann, K., Claus, T., Gerstgraser, C., Giebler, S., 2019. Erarbeitung eines strategischen Hintergrundpapiers zu den bergbaubedingten Stoffeinträgen in den Flusseinzugsgebieten Spree und Schwarze Elster: teil 2: zustandsanalyse und Handlungsschwerpunkte. Für das Landesamt für Bergbau, Geologie Und Rohstoffe Brandenburg online available: [https://lbgr.brandenburg.de/sixcms/media.php/9/20210630\\_StratHGP\\_LP2.pdf](https://lbgr.brandenburg.de/sixcms/media.php/9/20210630_StratHGP_LP2.pdf).
- Valente, T.M., Antunes, M.D., Braga, M.A.S., Pamplona, J.M., 2011. Geochemistry and mineralogy of ochre-precipitates formed as waste products of passive mine water treatment. *Geochem. Explor. Environ. Anal.* 11 (2), 103–106.
- Valente, T.M., Gomes, C.L., 2009. Occurrence, properties and pollution potential of environmental minerals in acid mine drainage. *Sci. Total Environ.* 407 (3), 1135–1152.
- Verheijen, F.G., Zhuravel, A., Silva, F.C., Amaro, A., Ben-Hur, M., Keizer, J.J., 2019. The influence of biochar particle size and concentration on bulk density and maximum water holding capacity of sandy vs sandy loam soil in a column experiment. *Geoderma* 347 (1), 194–202.
- Wickland, B.E., Wilson, G.W., Wijewickreme, D., Klein, B., 2006. Design and evaluation of mixtures of mine waste rock and tailings. *Can. Geotech. J.* 43 (9), 928–945.
- Williams, A., Hunter, M.C., Kammerer, M., Kane, D.A., Jordan, N.R., Mortensen, D.A., Smith, R.G., Snapp, S., Davis, A.S., 2016. Soil water holding capacity mitigates downside risk and volatility in US Rainfed maize: time to invest in soil organic matter? *PLoS One* 11 (8), e0160974.
- Yost, J.L., Hartemink, A.E., 2019. Soil organic carbon in sandy soils: a review. *Adv. Agron.* 158, 217–310.
- Yu, C., Dongxu, L., Hongyu, C., Suiyi, Z., Xianze, W., Jiakuan, Y., Xinfeng, X., Eskola, J., Dejun, B., 2022. Review of resource utilization of Fe-rich sludges: purification, upcycling, and application in wastewater treatment. *Environ. Rev.* 30 (3), 460–484.
- Yu, O.-Y., Raichle, B., Sink, S., 2013. Impact of biochar on the water holding capacity of loamy sand soil. *Int. J. Energy Environ. Eng.* 4 (1), 44.
- Yudina, A.V., Klyueva, V.V., Romanenko, K.A., Fomin, D.S., 2022. Micro- within macro: how micro-aggregation shapes the soil pore space and water-stability. *Geoderma* 415, 115771.
- Zinck, J., Griffith, W., 2013. Review of mine drainage treatment and sludge management operations: MEND report 3.43.1. CANMET Mining Min. Sci. Laborat. 101 online available: <https://mend-nedem.org/mend-report/review-of-mine-drainage-treatment-and-sludge-management-operations/>.