Received: 4 June 2024 | Accepted: 23 August 2025

DOI: 10.1002/vzj2.70044

Vadose Zone Journal

ORIGINAL ARTICLE

Soil texture governs the influence of different microplastics on soil hydraulic properties

Katharina J. Neubert | **Lutz Weihermüller** | **Harry Vereecken** | **Nicolas Brüggemann**

Forschungszentrum Jülich GmbH, Institute of Bio- and Geosciences, Agrosphere (IBG-3), Wilhelm-Johnen Straße, Jülich, Germany

Correspondence
Katharina J. Neubert, Forschungszentrum Jülich GmbH, Institute of Bio- and Geosciences, Agrosphere (IBG-3), Wilhelm-Johnen Straße, Jülich, Germany.
Email: k.neubert@fz-juelich.de

Assigned to Associate Editor Christina Bogner.

Funding information
German Federal Ministry of Education and Research, Grant/Award Number: 031B0907C

Abstract

Adequate water availability in soil is crucial for optimal plant growth. However, even small amounts of microplastics (MPs) can disrupt the soil pore structure, impacting water retention and hydraulic conductivity, and consequently plant-available water. This study investigated the effects of various MPs on soil water availability and hydraulic properties in three soil types (Luvisol, Albic Luvisol, and Chernozem). Four polymer types—low-density polyethylene, polypropylene (PP), polystyrene (PS) particles, and polyester (PET) microfibers—were tested at a mass concentration of 0.4 weight-%. Results showed that the impact of MPs varied with soil texture and saturated water content. In the Luvisol (silt loam), PET microfibers enhanced porosity, creating more air-filled pore volume, macropores, and increased water retention and saturated hydraulic conductivity. Conversely, PS and PP particles reduced porosity in the Luvisol, enhancing near-saturated hydraulic conductivity, likely due to decreased tortuosity. In the Albic Luvisol (sand), PET microfibers increased porosity and plant-available water, but both microfibers and particles negatively affected saturated and near-saturated hydraulic conductivity, with PS particles and PET microfibers potentially clogging soil pores. In the Chernozem (silt loam), PET microfibers significantly increased air-filled pore volume without changing overall porosity but negatively impacted water retention and plant-available water. The increase in saturated conductivity was likely due to preferential flow paths, while under dry conditions near-saturated hydraulic conductivity decreased, likely due to increased tortuosity.

Plain Language Summary

Water is essential for plant growth, but microplastics (MPs) can alter how soil holds and moves water. This study examined the effects of four plastic types—

Abbreviations: LDPE, low-density polyethylene; MDI, mini-disk infiltrometer; MP, microplastic; PAW, plant-available water; PET, polyester microfibers made of polyethylene terephthalate; PP, polypropylene; PS, polystyrene; WFPS, water-filled pore space.

low-density polyethylene, polypropylene (PP), polystyrene (PS), and polyester (PET) microfibers—on water availability in three soils: Luvisol, Albic Luvisol, and Chernozem. Results showed that MPs impacted soil differently depending on texture. In Luvisol, PET microfibers increased porosity and water retention, while PP and PS reduced it. In Albic Luvisol, PET improved plant-available water, but some MPs clogged pores, reducing water flow. In Chernozem, PET created more air pockets but decreased water retention. These findings highlight how MPs can significantly affect soil structure and water dynamics, influencing plant growth and soil health.

1 | INTRODUCTION

The presence of microplastics (MPs) in soil has emerged as a rising concern (J.-J. Guo et al., 2020; Ya et al., 2021). These small plastic particles and microfibers, which are less than 5 mm in size, have raised questions about their long-term effects on ecosystems and the hydrological and biogeochemical processes within them (Bian et al., 2022; F. Wang et al., 2022). Although our understanding of the full scope of these impacts is still incomplete, it is evident that MPs are steadily accumulating in the environment. In agricultural soils, MPs enter through various pathways, such as plastic mulching (Huang et al., 2020; M. Liu et al., 2018), sewage sludge (Weber et al., 2022), road and tire wear (Rødland et al., 2022), litter, and improper waste disposal, to name just a few. Research has demonstrated that in agricultural fields in Germany, fertilization with sewage sludge and wastewater discharges have particularly served as significant gateways for MP accumulation (Brandes et al., 2021). Shredded synthetic microfibers released from washing machines (Carney Almroth et al., 2018) and MP particles from cleaning and personal care products (Estahbanati & Fahrenfeld, 2016) are the main source in the sewage sludge applied. Even 34 years after the end of sewage sludge application on a German agricultural field, macroplastics at a density of 637.12 items per hectare and up to 56 MP particles per kilogram of dry soil were still present (Weber et al., 2022), and Heinze et al. (2024) found even more than 4 mg MP per kg soil in a Swedish agricultural field.

The composition and prevalence of MPs in agricultural soils have attracted considerable attention in recent studies. A study conducted in northern Germany found that nearly 87% of the MPs identified in agricultural fields were polyethylene (PE), a material commonly used in various plastic products (Harms et al., 2021). This finding is consistent with the substantial production of PE in Germany, which accounts for approximately 30% of the country's total plastics production. PE, in both low-density and high-density forms, is widely used in items such as plastic films due to its ductility, flexibility, and transparency (Fuhr et al., 2019). In addition to PE, polypropylene (PP) is emerging as another type of plastic prevalent in agriculture (M. Liu et al., 2018; Piehl et al., 2018). The high melting point and chemical resistance of PP make it ideal for applications such as bulk bags for seed and fertilizer transportation, as well as soil cover for protection against environmental factors and erosion (Sharma et al., 2022). Polystyrene (PS) and polyester (PET) microfibers have also been identified in agricultural soils (Piehl et al., 2018), with PS accounting for 14% of all particles found, as it is commonly used in packaging and food containers, while PET microfibers, derived from PE terephthalate, are prevalent due to their use as synthetic microfibers (Fuhr et al., 2019). In particular, the presence of PET microfibers in agricultural soils is often associated with sewage sludge fertilization (Büks & Kaupenjohann, 2020). Around 80%–99% of the microfibers contained in wastewater are retained in sewage treatment plants and end up in sewage sludge, resulting in concentrations ranging from 1000 to 56,400 particles kg^{-1} dry sewage sludge (Mahon et al., 2017; Mintenig et al., 2017; Zubris & Richards, 2005). This highlights the complex pathways through which MPs enter agricultural ecosystems.

Research has demonstrated that MP accumulation in agricultural ecosystems is associated with changes in various soil parameters. These changes include alterations in pore structure, which lead to shifts in hydraulic properties (Z. Guo et al., 2022; Z. Wang et al., 2023; G. S. Zhang et al., 2019), bulk density (Ingraffia et al., 2022), as well as aggregate distribution and water-holding capacity (de Souza Machado et al., 2019; Ingraffia et al., 2022). Especially microfibers, due to their linear shape, their ability to entangle soil particles, their hydrophobic nature, and their flexibility, have been shown to promote (Lozano, Aguilar-Trigueros, et al., 2021; Zheng et al., 2016) or reduce soil aggregation (Lozano, Lehnert, et al., 2021). Either way, this rearrangement of soil pores affects the soil-water characteristics, as enlarged pores allow for better drainage and small pores for better water retention. Since soil hydraulic characteristics can be indicators for soil health (Bagnall et al., 2022) and can have a direct influence on plant root growth (Ma et al., 2009), their precise determination is crucial.

Soil health is assessed, among other factors, using indicators for water movement and storage (Bagnall et al., 2022). For water movement, both saturated and near-saturated hydraulic conductivity (K_{sat} and K_{ns}, respectively) are important factors, but also the volumetric water content at field capacity (θ_{FC}), the permanent wilting point (θ_{WP}), and the plant-available water (PAW). Furthermore, the retention characteristics can be related to the soil pore size distribution (B. Liu et al., 2021). In general, total soil porosity can be differentiated and characterized by the macroporosity (P_{mac}), which indicates the volume of pores larger than 0.03 mm. This information is crucial as it defines the soil's capability to drain excess water (Reynolds et al., 2009). Second, the air capacity (AC) serves as a quantitative measure of the soil's capacity of both storing and providing soil gases (Topp et al., 1997). and the PAW quantifies the soil's ability to retain and provide plant-accessible water. All three parameters play a pivotal role in maintaining optimal physiological functions in plant roots.

The mentioned soil parameters can be significantly impacted by the presence of MPs in soil, although so far only demonstrated for concentrations well above the average occurrence of MPs in soil, as shown, for instance, in studies on the influence of PET microfibers on water-holding capacity, aggregate stability, and bulk density. For example, de Souza Machado et al. (2018) reported an increase in water-holding capacity and aggregate stability of a loamy-sandy soil due to elevated concentrations of PET microfibers (0.4 weight-% [%-w]). Conversely, at a lower concentration of 0.1%-w, no discernible effects were detected in the same study. Ingraffia et al. (2022) demonstrated that the contamination with PET microfibers reduced aggregate formation by 32%, 47%, and 33% for a Vertisol, Entisol, and Alfisol, respectively, accompanied with altered soil bulk density. In a complementary study, a notable reduction in the volume of meso- and micropores along with an increase of macropores was observed at a concentration of 0.3%-w of PET microfibers in clayey loam soils (G. S. Zhang et al., 2019). Furthermore, fibers added at 0.1% and 0.3%-w significantly increased water-stable macroaggregates (>2 mm). However, no discernible effects on soil bulk density or K_{sat} were found at the applied concentration of PET microfibers. This highlighted the strong dependence of the effect of PET microfibers on soil texture.

Another study established an inverse relationship between PP MP concentration and soil infiltration capacity (Z. Guo et al., 2022). Addition of PP MPs to loamy, clayey, and sandy soils significantly reduced K_{sat}, whereas larger MP particles had a weaker effect on K_{sat}. Furthermore, Z. Guo et al. (2022) reported that PP with increasing particle sizes (from 20 to 500 µm) reduced water retention, especially in clayey compared to sandy- and loamy-textured soils. This reduction affected both saturated (θ_s) and residual water content (θ_r). Finally, Xie et al. (2023) found that in compacted silty-sandy soil, different low-density polyethylene (LDPE) particle sizes had opposing effects on hydraulic properties. Particles of 500 µm increased K_{sat}, whereas particles of 150 and 50 µm reduced K_{sat}. In contrast, LDPE particles decreased θ_r of compacted silty sand soil independently of particle size or concentration added. This pattern of changes in K_{sat} and θ_r was explained by a reduction in pore size and number of macropores in case of K_{sat} changes.

Core Ideas

- Soil texture is a critical factor for the effects of microplastic (MP) on soil hydraulic properties.
- Soil hydraulic properties of soil-MP mixtures vary depending on soil texture and saturated soil water content.
- MP fibers changed soil water characteristics more substantially than MP particles, for example, affecting porosity and macropore volume or impacting water retention either positively (in sand) or negatively (in silt loam).
- MP fibers increased plant-available water in sand but decreased it in silt loam.
- MP particles potentially clogged soil pores in silt loam and sand and adversely affected water flow paths.

As shown above, MPs can lead to changes in soil porosity and soil pore distribution, which in turn can have significant effects on soil hydraulic characteristics, such as water retention and conductivity. However, the mechanisms underlying the effects of MPs on soil hydraulic properties have not been systematically explored and are not yet fully understood. Moreover, ambiguous findings are reported in the literature. This ambiguity might stem from the study design itself, as either the same MP type is used in combination with different soils, or one soil is used in combination with different MP types. Focusing solely on the effects of MPs on one soil (or one soil texture) may result in an incomplete assessment, as the soil hydraulic properties are closely linked to the soil pore size distribution and, therefore, to soil texture (Ingraffia et al., 2022; Z. Wang et al., 2023). To gain a better understanding of the effects of MPs on soils, it is imperative to study the interplay between different MP particles and/or microfibers (types, size, and concentrations) and different soils with different textures (de Souza Machado et al., 2018; Xie et al., 2023; G. S. Zhang et al., 2019).

In the present study, we conducted experiments with three soil types with contrasting texture (Luvisol: silt loam, Albic Luvisol: sand, and Chernozem: silt loam) and four different MPs (LDPE, PP, PS, and PET microfibers) at a fixed concentration (0.4%-w). Furthermore, we measured the full

TABLE 1 Characteristics of the experimental soils.

Soil type	WRB soil class	pH (in $CaCl_2$)	C_{org}	Sand (%) 63–2000 µm	Silt (%) 2–63 µm	Clay (%) <2 µm
Luvisol	Silt loam	6.5	1.01	8	77	15
Albic Luvisol	Sand	5.1	0.50	87	10	3
Chernozem	Silt loam	7.5	2.06	11	68	21

Abbreviation: WRB, world reference base, the international system for classification of soil.

soil water retention and hydraulic conductivity characteristics rather than only one soil characteristic such as K_{sat}. As MPs are known to be hydrophobic (Prajapati et al., 2022), we also measured the near-saturated hydraulic conductivity (K_{ns}). We hypothesized that the MP types would affect the soil characteristics differently, as they differed in size and shape. We also hypothesized that the different soil textures would be affected differently by the different MPs as the pore size distribution differed between the soils.

2 | MATERIALS AND METHODS

2.1 | Soils

Three soil types according to IUSS Working Group WRB (2022) were used in the study: (i) a Luvisol with a silt loam texture, (ii) an Albic Luvisol with a sandy texture, and (iii) a Chernozem with a silt loam texture. The basic soil characteristics of the three different soils are listed in Table 1. The two soils of the same texture class, that is, Chernozem and Luvisol, differed in their organic carbon (C_{org}) content (Chernozem = 2.06%, Luvisol = 1.01%). The Luvisol soil was taken from an agricultural field at the agricultural research station Campus Klein-Altendorf of the University of Bonn, Germany (50.613614° N, 7.000713° E). The Albic Luvisol soil was taken from an agricultural field of the Albrecht Daniel Thaer Institute for Agriculture and Horticulture Sciences of the Humboldt University of Berlin located in Thyrow, Germany (52.254674° N, 13.236030° E). The third soil type, Chernozem, was collected from the agricultural research station of the Helmholtz Centre for Environmental Sciences (UFZ), located in Bad Lauchstädt, Germany (51.393447° N, 11.875048° E). All soil types were taken from 0- to 20-cm depth, air-dried, and sieved to 2 mm. Soil texture was measured by wet sieving and the pipette method according to DIN ISO 11277 (2002). Organic carbon content (C_{org}) was measured by combustion (TOC-V CPH, Shimadzu), and pH was measured in $CaCl_2$ solution at a ratio of 5 g soil to 40 mL of $CaCl_2$.

2.2 | Microplastics

Based on results on MP pollution reported in the literature (de Souza Machado et al., 2019; Piehl et al., 2018), the following MPs were selected: (i) LDPE as powder with particle size 300–600 µm, (ii) PP as 4 mm beads, (iii) PS as 3–5 mm beads, and (iv) PET microfibers used as pillow filling with 2.88 ± 0.17 mm in length and 0.74 ± 0.01 in diameter. Microfiber length was determined by manually measuring individual microfibers ($N = 50$), while the diameter was determined by analyzing scans (EPSON, Expression, 12000XL) of microfibers via the software tool WinRHIZO (Regent Instruments Inc.). The LDPE, PP, and PS were purchased from Goodfellow GmbH, and the PET from JYSK Nordic A/S.

PS and PP plastic beads were shredded in a conventional high-performance kitchen blender (BlendTec classic 575, Luba GmbH) and sieved to 100–1000 µm particle size with stainless steel analyzing sieves. All particle types (LDPE, PP, and PS) were measured with a laser diffraction particles size analyzer (HORIBA LA-950) by dispersing the respective MP powder in ethanol.

The particle size distributions of the different particulate MPs are displayed in Figure S1 and show that the LDPE powder had the narrowest particle size distribution compared to the PP and PS powders, which had been sieved to 100–1000 µm. The PET microfibers used consisted of PE terephthalate, which was determined via Raman spectroscopy (Figure S2, Table S1). A piece of a PET plastic bottle was cut out as a reference material for PET and its spectrum was compared with the spectrum of the microfibers. See further MP characteristics in Table 2.

2.3 | Soil preparation

For the experiments, the four MP types were added separately to each air-dry soil type at 0.4%-w and mixed thoroughly. According to de Souza Machado et al. (2018), the applied mass concentration was the upper limit of MP concentration at which the MP-amended soils show only minor total volume changes. The LDPE, PP, and PS particles were mixed with the soil manually in closed plastic bottles. The control was treated in the same way, but without MP addition. Since the synthetic microfibers were strongly entangled, the PET microfibers were torn apart by hand and added to the soil step by step while shaking the soil. As all experiments were performed in quadruplicate, 60 samples (three soils × (four MP + 1 control) × four replicates) were prepared for the measurements of the soil hydraulic characteristics (water retention

TABLE 2 Characteristics of the experimental microplastics.

Microplastic	Abbreviation	Size (µm)	Density (g cm^{-3})
Low-density polyethylene	LDPE	444.0 ± 1.0	0.92[a]
Polypropylene	PP	548.0 ± 4.7	0.90[a]
Polystyrene	PS	532.3 ± 4.7	1.05[a]
Polyester microfibers made of polyethylene-terephthalate	PET	2880 ± 170	1.38[b]

[a]Density values were according to the technical datasheet from the supplier (Goodfellow GmbH).
[b]Density value according to the technical data from Reichelt-Chemietechnik GmbH + Co.

and K_{sat}), and another set of 60 samples for the infiltration measurements (K_{ns}).

For the K_{sat} measurements and the evaporation method used to determine water retention and hydraulic characteristics, the air-dry samples were packed into stainless steel cylinders of 250 cm^3 volume (height = 5 cm and diameter = 8 cm) at predefined bulk density (Luvisol = 1.2 g cm^{-3}, Albic Luvisol = 1.6 g cm^{-3}, and Chernozem = 1.4 g cm^{-3}). The bulk density was adjusted according to the bulk densities of the different soils observed in the field. For the infiltration measurements (K_{ns}), the samples were packed into PVC columns of 10 cm height and 10 cm diameter at the same bulk densities as in the 250 cm^3 cylinders. The PVC columns were sealed with a permeable cloth and left on a sand bed. Here, it has to be noted that the raw density of the MPs differs from those of the soil leading to very small differences in theoretical porosity compared to the control of the individual soils.

2.4 | Soil hydraulic characterization

2.4.1 | Saturated hydraulic conductivity (K_{sat})

The filled 250 cm^3 cylinders were placed in boxes and saturated stepwise from the bottom for 7 days using tap water. The KSAT device (Meter Group AG) was used to measure K_{sat} using the falling head method. K_{sat} values were normalized to 20°C. Each sample was measured three times, and the mean as well as the standard deviation of K_{sat} was calculated.

2.4.2 | Soil water retention and other soil characteristics

After the K_{sat} measurements, the soil water characteristics were determined by the evaporation method using the HYPROP system (Meter Group) as described by Schindler et al. (2010) in combination with the WP4 Dewpoint Potentiometer (Decagon Devices). Finally, the Mualem–van Genuchten (van Genuchten, 1980) model was fitted to the HYPROP data (retention and conductivity data), where the actual water content θ can be expressed as a function of pressure head h (cm) by:

$$\theta(h) = \frac{(\theta_s - \theta_r)}{\left(1 + (\alpha \cdot |h|)^n\right)^m} + \theta_r, \tag{1}$$

with θ_s and θ_r as the saturated and residual volumetric water contents (cm^3 cm^{-3}), and n and α as shape parameters, where n (-) can be related to the pore size distribution and α (cm^{-1}) is a scaling factor related to the air entry value. Van Genuchten (1980) related m is defined as $m = 1 - 1/n$.

The hydraulic conductivity function was described by:

$$K_r(h) = \left[\frac{[1 - (\alpha h)^{mn}[1 + (\alpha h)^n]^{-m}]^2}{[1 + (\alpha |h|)^n]^{m\lambda}}\right], \tag{2}$$

where $K_r(h)$ (-) is the relative hydraulic conductivity at a given pressure head h and λ is the tortuosity factor (-). To obtain the actual hydraulic conductivity, $K_r(h)$ has to be multiplied with the saturated hydraulic conductivity K_{sat}. It has to be noted that K_{sat} was not fitted and set as a matching point during the fitting process.

The four replicates were measured individually by the evaporation method and were also fitted individually. For the mean van Genuchten parameters of one soil/MP combination, the individual data points from the evaporation method were combined and simultaneously fitted. The corresponding van Genuchten parameters as well as further soil characteristics are listed in Table 3. For analyzing the effect of MPs on the soil hydraulic characteristics, the fitted van Genuchten soil hydraulic parameters (α, n, θ_s, and θ_r) were used. Additionally, the water content at field capacity (θ_{FC}, cm^3 cm^{-3} measured at $\log_{10} h = 1.8$ or $h = -63$ cm), water content at wilting point at $\log_{10} h = 4.2$ ($h = -15{,}848$ cm) (θ_{WP}, cm^3 cm^{-3}) and the PAW (θ_{PAW}, cm^3 cm^{-3}) were calculated based on the soil hydraulic parameters.

Finally, some basic soil characteristic, that is, the macroporosity (P_{mac} [cm^3 cm^{-3}]) (Equation 3) according to Reynolds et al. (2009), AC (cm^3 cm^{-3}) (Equation 4) according to Topp et al. (1997), and water-filled pore space (WFPS [%]) (Equation 5), were calculated.

$$P_{mac} = \theta_s - \theta_{@h=10\text{ cm}}, \tag{3}$$

$$AC = \theta_s - \theta_{@h=100\text{ cm}}, \tag{4}$$

TABLE 3 Van Genuchten parameters for the three soil types used according to the user's manual of the MDI (Decagon Devices) as well as calculated *A* values.

Soil type	WRB soil class	A (cm^{-1})	n	A @ $h = -2$ cm
Luvisol	Silt loam	0.02	1.41	7.9299
Albic Luvisol	Sand	0.124	2.28	2.4286
Chernozem	Silt loam	0.01	1.23	8.5112

Abbreviations: MDI, mini-disk infiltrometer; WRB, world reference base, the international system for classification of soil.

$$\text{WFPS} = \frac{\theta_{@\text{given } h}}{\theta_s} \times 100. \tag{5}$$

Thereby, the ratio between the WFPS for the control and that of a soil/MP mixture was calculated for predefined pressure heads (here at $\log_{10} h = 0$, 0.6, 1.2, 1.8, 2.4, 3, 3.6, 4.2, 4.8, 5.4, and 6). Negative differences mean that the WFPS was reduced compared to the control, whereas positive differences indicate that the MP amendment increased the WFPS with potential positive impacts on water availability for plant growth.

2.4.3 | Near-saturated hydraulic conductivity (K_{ns})

The mini-disk infiltrometer (MDI, Meter Group AG) with a disk diameter of 4.5 cm was used to measure the water infiltration into dry soils. The MDI has a small water reservoir, from which the water can infiltrate into the soil, and a Mariotte compartment, which controls the suction of the infiltration. For the infiltration, a suction of $h = -2$ cm was set, and the water reservoir was filled to its maximum volume of 95 mL with brilliant blue for coloring food (FCF), (E133) stained tap water to facilitate the reading of the reservoir level. For the measurements, the MDI was placed on the soil surface of the soil-packed polyvinyl chloride (PVC) columns (10 cm height, 10 cm diameter). During the infiltration process, a webcam installed in front of the infiltrometer recorded pictures of the scene every 10 s, which was facilitated by a custom-made software. The photos were stored as JPEG files along with a timestamp and were used to record the infiltrating water after the infiltration had been finished (Figure S3). Each soil column was measured three times after being dried for 7 days at 60°C to ensure reproducible starting conditions in water content.

To calculate K_{ns} from the raw infiltration data, Equation (6) was fitted to the infiltration data, where C_1 (cm s^{-1}) is related to the hydraulic conductivity, and C_2 (cm s$^{-1/2}$) is related to the soil-specific absorption–desorption process (Rojas et al., 2022). For the estimation of the hydraulic conductivity, the method proposed by R. Zhang (1997) was used, where C_1 reflects the slope of the cumulative infiltration curve versus the square root of time.

$$I = C_1 t + C_2 \sqrt{t}. \tag{6}$$

In a second step, K_{ns} can be calculated by:

$$K_U = \frac{C_1}{A}. \tag{7}$$

where A is related to the suction h (cm) imposed during infiltration by:

$$A = \frac{11.65 \cdot \left(n^{0.1} - 1\right) \cdot e^{[a(n-1.9)\alpha h]}}{\left(\alpha r_o\right)^{0.91}}, \tag{8}$$

where r_o is the radius of the MDI (here $r_o = 2.25$ cm) and α and n are the van Genuchten parameters α and n, respectively. Parameter a is variable depending on the van Genuchten n: a is equal to 2.92 for $n \geq 1.9$ and equal to 7.5 for $n < 1.9$. The corresponding van Genuchten α and n values were selected from a look-up table provided by the user's manual (version 3) of the MDI (Decagon Devices) and are listed for the three soil types used (Table 3). K_{ns} measurements were performed on all four sample replicates three times to be in-line with K_{sat} measurements.

2.5 | Data analysis

To assess the contribution of both the independent variables of soil and MP type on the dependent variables, such as K_{sat} and K_{ns}, the effect size η^2 (%) was calculated (Richardson, 2011). The η^2 for each main effect, that is, the effects of soil type ($\eta^2(A)$) and MP type ($\eta^2(B)$) on the soil hydraulic characteristics, as well as the interaction of both (η^2(AB)), was calculated in a two-way analysis of variance (ANOVA) with replication using Equations (9–11). The effect size for the error ($\eta^2(E)$), which resembles the unknown variance, was calculated according to Equation (12).

$$\eta^2(A) = \frac{\text{SSA}}{\text{SST}} \times 100, \tag{9}$$

$$\eta^2(B) = \frac{\text{SSB}}{\text{SST}} \times 100, \tag{10}$$

$$\eta^2(AB) = \frac{\text{SSAB}}{\text{SST}} \times 100, \tag{11}$$

$$\eta^2(E) = \frac{SSE}{SST} \times 100, \quad (12)$$

where SSA is the sum of squares for soil type, SSB is the sum of squares for MP type, SSAB is the sum of squares for the interaction between soil type (A) and MP type (B), SST is the total sum of squares, and SSE is the sum of squares for the error.

For the K_{ns} and K_{sat} measurements, the standard deviation (SD) was calculated for the four sample replicates, with an error propagation according to Equation (13).

$$SD = \sqrt{\frac{1}{4}\left(SD_1{}^2 + SD_2{}^2 + SD_3{}^2 + SD_4{}^2\right)}. \quad (13)$$

To test for significant differences between the different soils mixed with MP and the corresponding control, one-sided heteroscedastic t-tests were performed at a significance level of $p \leq 0.05$, indicating a significant MP effect, and $p \leq 0.001$, indicating a highly significant MP effect.

3 | RESULTS

3.1 | Saturated hydraulic conductivity (K_{sat})

K_{sat} greatly differed between the soils (Figure 1) and was lowest for the Chernozem (mainly below 14 cm day^{-1}), slightly higher for the Luvisol (10–50 cm day^{-1}) and highest for the Albic Luvisol (250–730 cm day^{-1}). For both finer textured soils, the addition of PET microfibers significantly increased K_{sat} by 91 ± 47% ($p = 0.02$) in Luvisol and by 67 ± 43% ($p = 0.03$) in the Chernozem compared to the control. In contrast, in the coarse-textured Albic Luvisol, the addition of PET microfibers resulted in a highly significant reduction of K_{sat} by 58 ± 2% ($p < 0.001$). In this Albic Luvisol soil, not only the PET microfiber amendment, but also the addition of PP and PS resulted in a significant reduction of K_{sat} compared to the control soil, with 25 ± 11% ($p = 0.007$) lower K_{sat} for PP-amended soil and 34 ± 13% ($p = 0.002$) lower K_{sat} values for PS-amended soil (Figure 1).

3.2 | Near-saturated hydraulic conductivity (K_{ns})

The results of the K_{ns} measured at $h = -2$ cm in initially air-dried soil (Figure 1) revealed in general a different pattern as found for K_{sat}, with the lowest K_{ns} for the Luvisol (below 16 cm day^{-1}), higher K_{ns} for Chernozem (14–70 cm day^{-1}), and much higher K_{ns} for the Albic Luvisol (45–230 cm day^{-1}). The same trend of reduced K_{ns} as for K_{sat} was found for the MP-amended Albic Luvisol, where LDPE, PS, and PET reduced K_{ns} significantly by 32 ± 13% ($p = 0.01$), 44 ± 23% ($p = 0.005$), and 62 ± 4% ($p < 0.001$), respectively, compared to the control. Surprisingly, in the Chernozem the same relative change in K_{ns} was observed with addition of LDPE, PS, and PET, significantly reducing K_{ns} by 32 ± 14% ($p = 0.02$), 44 ± 24% ($p = 0.006$), and 62 ± 4% ($p = 0.01$). In contrast, the addition of LDPE, PP, and PS in Luvisol significantly increased K_{ns} by 120 ± 73% ($p = 0.01$), 40 ± 17% ($p = 0.001$), and 27 ± 13% ($p = 0.04$), respectively. However, PET in Luvisol did not significantly change K_{ns} compared to the control.

3.3 | K_{ns} to K_{sat} ratio

To obtain deeper insights into the relative differences between K_{ns} and K_{sat} across the different soil types in response to MP additions, the mean K_{ns} to K_{sat} ratio (K_{ns}/K_{sat}) for all MP amendments was calculated (Table 4). For the Luvisol and Albic Luvisol controls, K_{ns} was approximately one-third of K_{sat}, whereas in the Chernozem soil, K_{ns} was 10 times higher than K_{sat} without the addition of MP. However, these ratios were differently influenced due to different MP amendments.

The presence of LDPE in the Luvisol increased the K_{ns}/K_{sat} by 172% ($p = 0.02$), primarily due to a significant increase in K_{ns} without altering K_{sat} substantially. Furthermore, the addition of PP to the Luvisol resulted in a significant 30% increase in K_{ns}/K_{sat} ($p = 0.02$) caused by higher K_{ns} compared to the control and only smaller increase in K_{sat}, while the addition of PET decreased the ratio by 50% ($p = 0.03$), attributed to substantial increase in K_{sat}, while K_{ns} stays relatively unaffected.

In the coarser textured Albic Luvisol, only the introduction of LDPE significantly affected the K_{ns}/K_{sat} ratio with a decrease of 27% ($p = 0.03$) compared to the control, as LDPE notably reduced K_{ns} while leaving K_{sat} unchanged. As the other MP types show significant decreases in both K_{ns} and K_{sat}, the ratio of both parameters is not significantly affected.

In the case of the fine-textured Chernozem, both PS and PET reduced the K_{ns}/K_{sat} by 39% ($p = 0.02$) and 76% ($p = 0.002$), respectively. The PET microfibers in particular caused a significant shift in hydraulic conductivity, with a significant reduction in K_{ns} and increase in K_{sat}.

3.4 | Effect sizes of soil type versus microplastic type

The results of the ANOVA indicated that the differences for both K_{sat} and K_{ns} were mainly caused by the differences in soil type and not by MP type, whereby the effect of soil type was more pronounced for K_{sat} (Figure 2a) than for K_{ns} (Figure 2b). The calculated $\eta^2(A)$ for K_{sat} was 77%–97%, while for K_{ns}, it

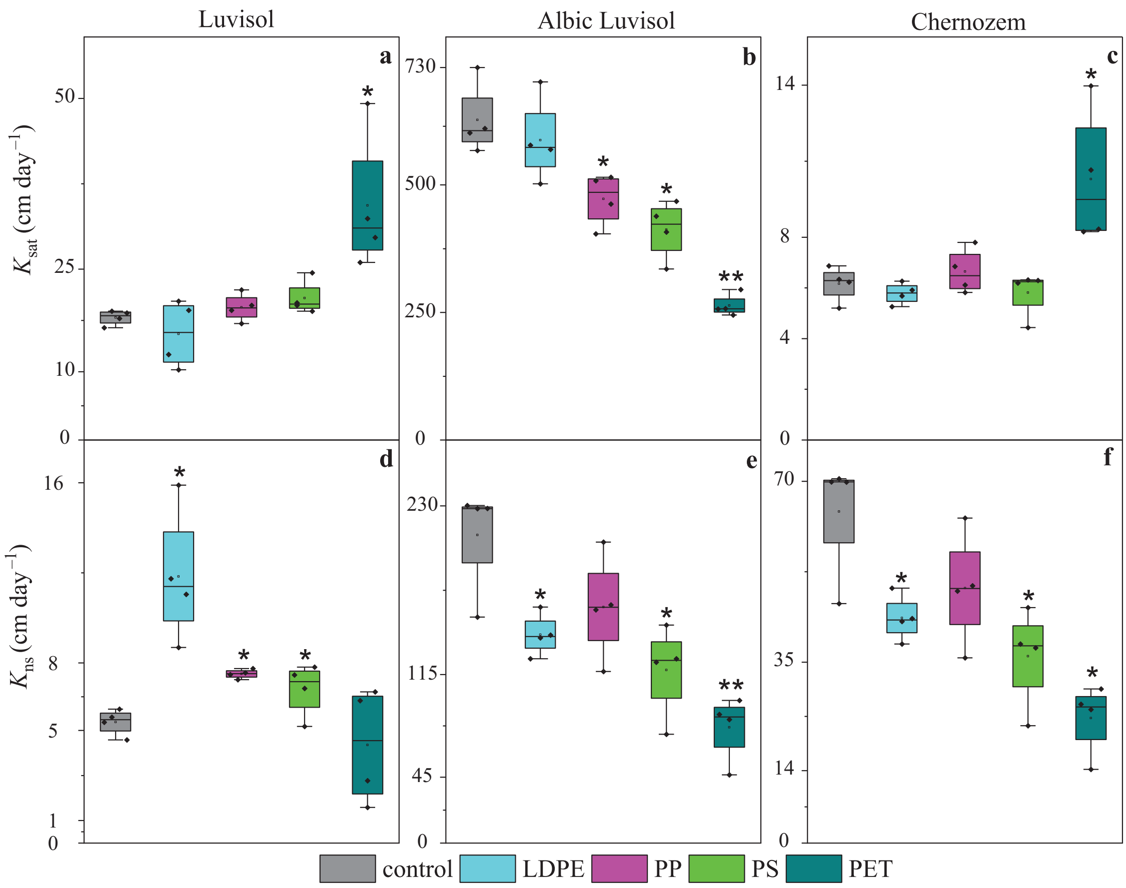

FIGURE 1 Boxplot diagram of saturated hydraulic conductivity (K_{sat}, cm day^{-1}) for (a) the Luvisol, (b) Albic Luvisol, and (c) Chernozem and near-saturated hydraulic conductivity (K_{ns}, cm day^{-1}) for (d) the Luvisol, (e) Albic Luvisol, and (f) Chernozem mixed with the four different microplastic (MP) types at 0.4%-w, and the respective soil types without the addition of MP. Boxes are the interquartile range (IQR) from the 25th to 75th percentile, lines inside boxes indicate the median, open squares indicate the mean values, upper and lower whiskers are 1.5 times the IQR, and markers are individual data points. Asterisks (*) mark significant differences in K_{sat} or K_{ns} between MP treatment and control, which was tested via one-sided, heteroscedastic *t*-test ($p \leq 0.05$). Double asterisks (**) mark highly significant differences at $p \leq 0.001$. Note that the *y*-axis are scaled differently for better visualization. LDPE, low-density polyethylene; PET, polyester microfiber; PP, polypropylene; PS, polystyrene.

TABLE 4 Mean K_{ns} to K_{sat} ratio for the three soils mixed with low-density polyethylene (LDPE) particles, polypropylene (PP) particles, polystyrene (PS) particles, and polyester (PET) microfibers at 0.4%-w or no microplastics (control).

Soil type	Control	LDPE	PP	PS	PET
Luvisol	0.30 ± 0.03	0.82 ± 0.28[a]	0.39 ± 0.04[a]	0.33 ± 0.05	0.15 ± 0.09[a]
Albic Luvisol	0.34 ± 0.06	0.25 ± 0.04[a]	0.34 ± 0.06	0.29 ± 0.09	0.30 ± 0.07
Chernozem	10.56 ± 2.24	7.59 ± 1.05	7.63 ± 2.05	6.39 ± 1.80[a]	2.57 ± 0.98[a]

[a]Significantly different from control ($p \leq 0.05$).

was slightly lower (52%–84%). The soil type effect was generally less pronounced in the K_{ns} measurements and also when PET microfibers were present.

The results for the calculated $\eta^2(B)$ showed that the MP influence was much more pronounced for the K_{ns} measurements based on infiltration into the dry soil, with the highest effect for PS (13%) and PET (28%), whereas for K_{sat} in the saturated soil, no (0% for LDPE) to only a minor MP effect (6% for PET) was observed.

The interactive effect of soil type and PET on K_{sat} was 2.5 times greater than that of the microfibers alone ($\eta^2(AB) = 15\%$ and $\eta^2(B) = 6\%$). In contrast, the interactive effect of soil type and PET on K_{ns} was less than half as high ($\eta^2(AB) = 13\%$ and $\eta^2(B) = 28\%$). Notably, PS particles had a greater effect on

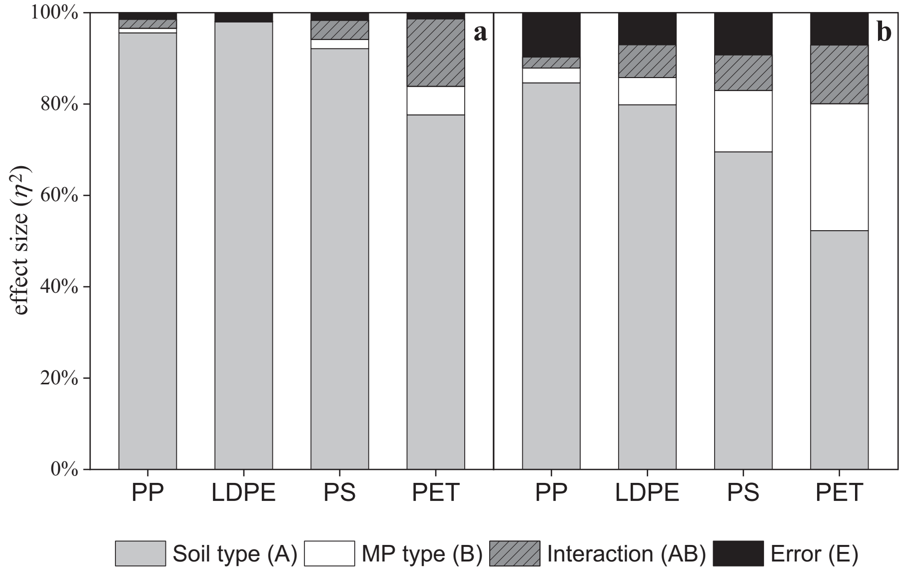

FIGURE 2 Size of the effect (η^2) of soil and microplastic (MP) type on (a) K_{sat} (cm day^{-1}) and (b) K_{ns} (cm day^{-1}). $\eta^2(A)$ is the effect size of soil type, $\eta^2(B)$ of MP type, $\eta^2(AB)$ of the interaction of soil and MP type, and $\eta^2(E)$ is the error. LDPE is low-density polyethylene, PP is polypropylene, PS is polystyrene, and PET is polyester microfibers made of polyethylene terephthalate.

K_{ns} than the interactive effect ($\eta^2(B) = 13\%$, $\eta^2(AB) = 8\%$,), but this effect was relatively small.

3.5 | Soil water retention and other soil characteristics

Using the van Genuchten parameters (α, n, θ_s, and θ_r) obtained by fitting the van Genuchten function to the retention and hydraulic conductivity data from the evaporation experiment, it was possible to infer how the tested MPs affected the soil water characteristics. The measured soil retention data of the different soils including the replicates as well as the fitted van Genuchten model are shown in Figures S4–S6. Additional characteristics, such as the water content at field capacity at $\log_{10} h = 1.8$ (θ_{FC} [cm^3 cm^{-3}]), water content at the permanent wilting point at $\log_{10} h = 4.2$ (θ_{WP} [cm^3 cm^{-3}]), and the PAW (θ_{PAW} [cm^3 cm^{-3}]) were also calculated and are shown in Table 5. Based on the fitted mean soil hydraulic parameters (based on the four replicates) for the different soil/MP combinations, the retention curves were plotted in Figure 3. For better visualization, the near-saturated part (0–10 cm suction) was plotted along the entire curve. As can be seen, the mean soil water retention curves showed in general only minor differences for the MP amendments, and significant differences to the control were detectable only at pressure heads $<\log_{10} h = 1$ (Figure 3).

For the Luvisol at full saturation, θ_s ranked PET > control > LDPE > PP > PS, with the PET-amended Luvisol ($\theta_s = 0.513$ cm^3 cm^{-3}) able to store 3 ± 1.5% more and significantly the most water among the treatments ($p = 0.02$). In contrast, the Luvisol mixed with PP and PS showed significantly decreased θ_s ($p = 0.05$ for PP and $p = 0.002$ for PS), meaning that the porosity of the Luvisol was significantly enhanced due to addition of microfibers, whereas due to addition of PP and PS particles, the soil porosity was significantly decreased. It should be noted, though, that the fitted θ_s values are uncertain because the evaporation method fails to provide data in the near-saturated region ($h > -10$ cm), and therefore the interpretation of the θ_s values should be done with caution.

In the range of the steep decline of the retention curve, where soil drainage shifted from large pores to medium and small pores, no influence of MP particles on the retention curve could be detected. Only the Luvisol with added PET microfibers led to significantly elevated water contents at the wilting point at $\log_{10} h = 4.2$ (+7 ± 4%, $p = 0.02$). However, the water content at field capacity and the PAW were not significantly affected by MPs at all. Furthermore, the PET-amended Luvisol exhibited 76 ± 62% less and, therefore, the smallest θ_r among the treatments, statistically slightly above the critical p-value of 0.05 ($p = 0.056$).

The retention curve of the Albic Luvisol mixtures showed a later air entry compared to the loamy silt, and also a steeper slope in the mid-pressure head range ($\log_{10} h = 1.2$–2.4), which can also be seen in the larger van Genuchten n values for the Albic Luvisol (mean n value for the control = 2.894) compared to the Luvisol (mean n value for the control = 1.229).

The water stored in Albic Luvisol therefore drained across a very narrow range of pressure heads, due to the uniform pore size distribution in this sandy soil. The mixture of sandy soil with microfibers enabled a higher water storage, characterized

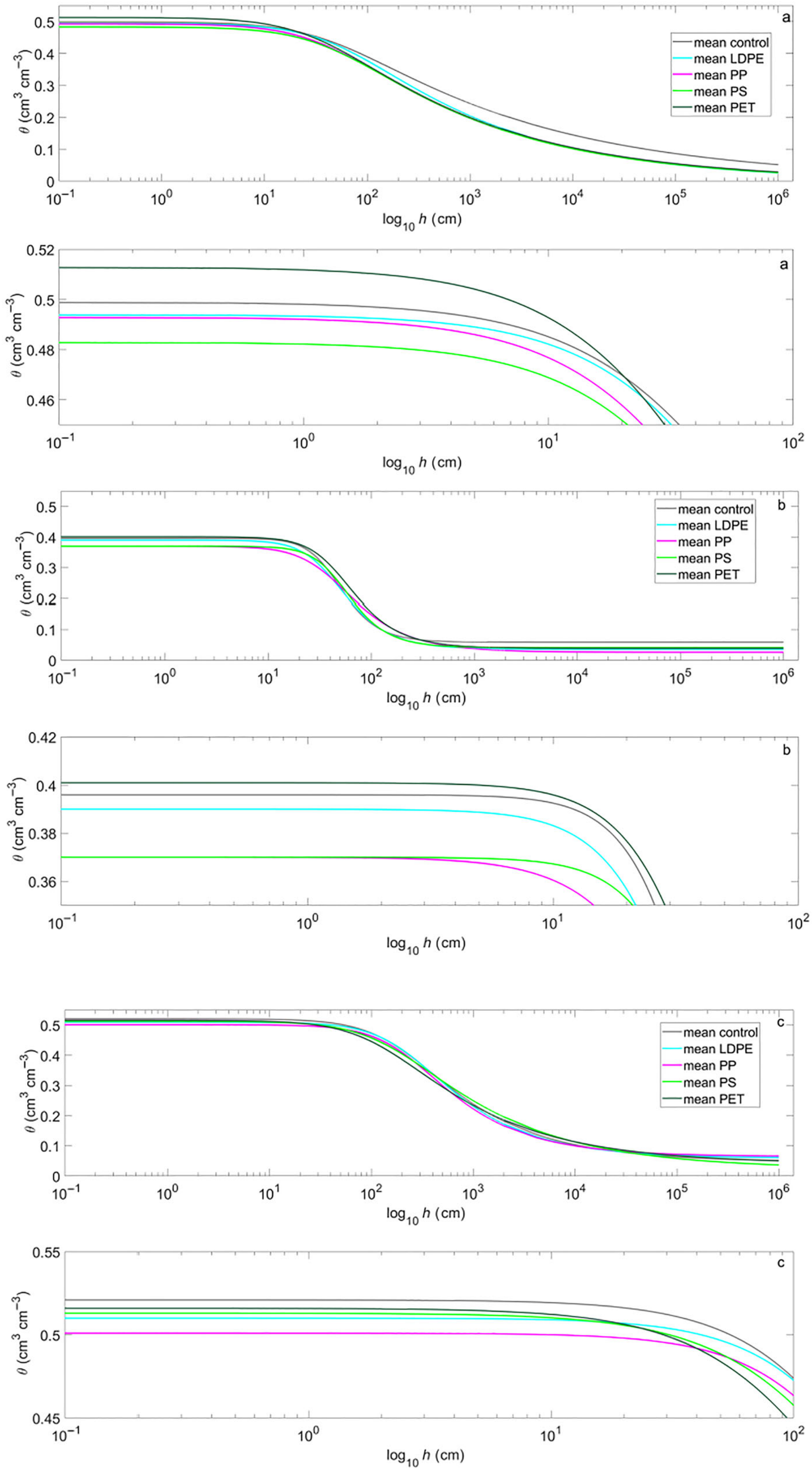

FIGURE 3 Mean soil water retention curves for the (a) Luvisol, (b) the Albic Luvisol, and (c) the Chernozem mixed with the four different microplastic (MP) amendments at 0.4%-w. LDPE is low-density polyethylene, PP is polypropylene, PS is polystyrene, and PET is polyester microfiber comprised of polyethylene terephthalate. The control is lacking the addition of MP. Significant differences in water content at given pressure heads from the control are marked with an asterisk (*) and were tested via one-sided, heteroscedastic *t*-test ($p \leq 0.05$).

TABLE 5 van Genuchten parameters fitted on the four replicates used in the evaporation method, and calculated water content at saturation (θ_s), which is equivalent to total porosity, residual water content (θ_r), tortuosity (λ) water content at field capacity (θ_{FC}), water content at wilting point (θ_{WP}), and plant-available water (θ_{PAW}) for the three different soils and four different microplastics (LDPE = low-density polyethylene, PP = polypropylene, PS = polystyrene, and PET = polyester microfiber comprised of polyethylene terephthalate) added at 0.4%-w.

Soil	Treatment	α (kPa^{-1})	n	θ_s (cm^3 cm^{-3})	θ_r (cm^3 cm^{-3})	λ	θ_{FC} (cm^3 cm^{-3})	θ_{WP} (cm^3 cm^{-3})	θ_{PAW}
Luvisol	Control	0.023	1.229	0.499 ± 0.007	0.004 ± 0.003	−3.351	0.400 ± 0.012	0.086 ± 0.003	0.314 ± 0.011
	LDPE	0.018	1.300	0.493 ± 0.012	0.007 ± 0.006	−2.351	0.409 ± 0.021	0.089 ± 0.008	0.320 ± 0.017
	PP	0.024	1.287	0.492 ± 0.005[a]	0.002 ± 0.003	−5.204	0.394 ± 0.006	0.090 ± 0.007	0.304 ± 0.011
	PS	0.022	1.289	0.481 ± 0.007[a]	0.005 ± 0.005	−0.171	0.394 ± 0.011	0.087 ± 0.005	0.307 ± 0.009
	PET	0.029	1.280	0.513 ± 0.010[a]	0.001 ± 0.002	−4.239	0.399 ± 0.010	0.092 ± 0.004[a]	0.307 ± 0.009
Albic Luvisol	Control	0.024	2.894	0.385 ± 0.009	0.034 ± 0.014	0.414	0.193 ± 0.012	0.034 ± 0.014	0.160 ± 0.018
	LDPE	0.025	2.453	0.392 ± 0.002	0.036 ± 0.006	0.959	0.190 ± 0.010	0.036 ± 0.006	0.154 ± 0.015
	PP	0.025	2.060	0.378 ± 0.009	0.035 ± 0.020	2.451	0.204 ± 0.013	0.037 ± 0.017	0.167 ± 0.029
	PS	0.021	2.739	0.374 ± 0.008	0.041 ± 0.005	0.455	0.202 ± 0.002	0.041 ± 0.005	0.161 ± 0.007
	PET	0.022	2.388	0.401 ± 0.007[a]	0.039 ± 0.009	0.678	0.223 ± 0.007[a]	0.039 ± 0.009	0.184 ± 0.013
Chernozem	Control	0.005	1.541	0.517 ± 0.002	0.056 ± 0.010	−0.138	0.497 ± 0.003	0.087 ± 0.012	0.409 ± 0.015
	LDPE	0.004	1.638	0.509 ± 0.007	0.059 ± 0.006	−0.133	0.490 ± 0.006	0.089 ± 0.006	0.401 ± 0.009
	PP	0.004	1.668	0.501 ± 0.007[a]	0.064 ± 0.007	0.197	0.481 ± 0.008[a]	0.090 ± 0.003	0.391 ± 0.008
	PS	0.006	1.410	0.505 ± 0.013	0.035 ± 0.024	−0.139	0.479 ± 0.010[a]	0.099 ± 0.021	0.380 ± 0.026
	PET	0.008	1.428	0.520 ± 0.007	0.026 ± 0.013[a]	−1.600	0.470 ± 0.005[a]	0.102 ± 0.012	0.368 ± 0.014[a]

[a]Significantly different form control ($p \leq 0.05$).

by a significantly increased porosity (+4 ± 2%, $p = 0.03$), increased water content at high pressure heads (<$\log_{10} h = 1$), and at field capacity at $\log_{10} h = 1.8$ (+15 ± 4%, $p = 0.008$), in combination with a positive effect on the PAW (+15 ± 8%, $p = 0.05$).

The retention curve of the Chernozem exhibited a smoother curve progression, generally indicating higher θ_s (0.50–0.52 cm^3 cm^{-3}), higher θ_{FC} (0.47–0.50 cm^3 cm^{-3}), and higher θ_r (0.03–0.07 cm^3 cm^{-3}) than the other two soil types. This suggests greater water retention compared to the Luvisol and Albic Luvisol, due to a higher proportion of fine particles. The retention characteristics of the various MP-Chernozem mixtures diverged at high pressure heads up to $\log_{10} h = 2.4$, after which they converged to a similar curve progression. The saturated water content of the Chernozem control soil (0.52 cm^3 cm^{-3}), and at the same time the soil porosity, was slightly reduced by 2 ± 1% due to the addition of LDPE and PS, and significantly reduced by 3 ± 1% by the addition of PP ($p = 0.01$). Furthermore, the PP-amended Chernozem contained less water at suctions < $\log_{10} h = 1$. This can also be seen in the lower water content at field capacity (−3 ± 1%, $p = 0.01$) and a slight reduction in PAW by 5 ± 2% ($p = 0.07$). Additionally, in the Chernozem, the PS particles affected θ_{FC} (−4 ± 2%, $p = 0.02$) and PAW (−7 ± 6%, $p = 0.08$) similarly negative. The addition of PET had no effect on θ_s of the Chernozem and therefore, on its porosity. However, PET microfibers in the Chernozem markedly reduced soil water retention at FC but also at the dry end. As a result, this adversely impacted θ_{FC} (−5 ± 1%, $p = 0.009$) and θ_{PAW} (−10 ± 3%, $p = 0.04$). Moreover, at the very dry end, θ_r was 54 ± 23% lower compared to the control ($p = 0.03$).

3.6 | Water-filled pore space and pore volume

To analyze the effect of the different MPs on the WFPS, the difference between the WFPS of the control and of the MP-amended soil was calculated (Figure 4). As can be seen from Figure 4, the largest relative difference in WFPS in the Luvisol was not found at full saturation or at low pressure heads, but in the range of field capacity at $\log_{10} h = 1.2$–2.4. Here, the WFPS for the PET and PS treatments deviated the most from the control, whereas PS showed significantly higher ($p = 0.05$) and PET nonsignificantly lower values compared to the control. Most strikingly, the course of WFPS over the entire pressure head range differed due to the addition of PET and PS in opposite ways. Parallel to the increase in the percentage of WFPS in the PS treatment, the proportion of WFPS in the PET treatment decreased, while both curves approached each other, converged in the area of the wilting point at $\log_{10} h = 4.2$ and then followed a similar course up to $\log_{10} h = 6$. At lower pressure heads, for example, at $\log_{10} h = 4.8$ and 5.4, PET-amended soil had a significantly increased WFPS ($p = 0.05$). In contrast, LDPE- and PP-amended soil showed no statistical differences to the WFPS in the control.

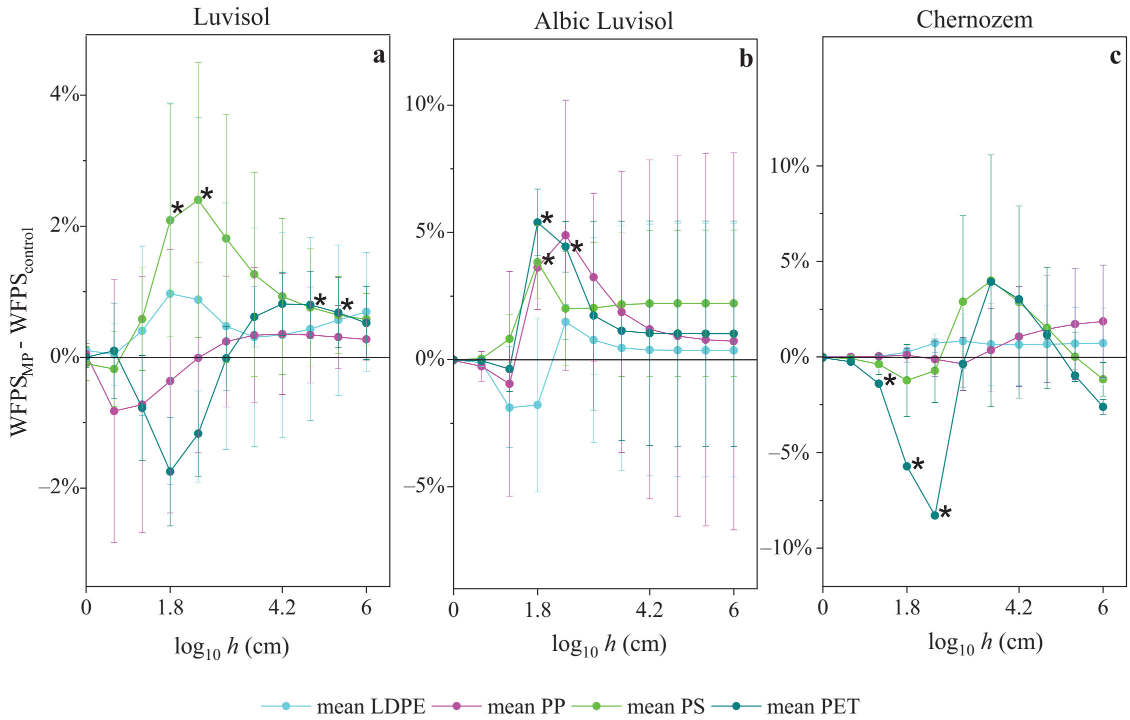

FIGURE 4 Differences between the water-filled pore space (WFPS [%]) calculated between volumetric water contents at saturation and given pressure heads ($\log_{10} h = 0$, 0.6, 1.2, 1.8, 2.4, 3, 3.6, 4.2, 4.8, 5.4, and 6 cm) for the control and the microplastic-amended (a) Luvisol, (b) Albic Luvisol, and (c) Chernozem. LDPE is low-density polyethylene, PP is polypropylene, PS is polystyrene, and PET is polyester microfiber comprised of polyethylene terephthalate. Solid line marks 0, representing the control. Significant difference ($p \leq 0.5$) from the control is marked with an asterisk (*) and was tested via one-sided, heteroscedastic *t*-test. Note that the *y*-axis are scaled differently for better visualization.

Unlike the declining trend of WFPS observed in PET-amended Luvisol, as described above, the addition of PET to the Albic Luvisol notably increased WFPS at field capacity ($\log_{10} h = 1.8$) by 11 ± 3% ($p = 0.008$), reaching its peak. Similarly, PS in the Albic Luvisol led to a similar trend in WFPS, with significantly increased WFPS compared to the control (+8 ± 2%, $p = 0.02$), and reaching its peak at field capacity. Interestingly, these two MP types evoked a similar trend in WFPS as a function of pressure head, unlike that of the Luvisol. Particularly, in the drier regions at lower pressure heads, PS in the Albic Luvisol effected a more pronounced increase in WFPS compared to the other MP species.

The WFPS in the Chernozem was most strongly influenced by the presence of PET microfibers. Compared to the control, WFPS was strongly reduced with decreasing pressure head up to $\log_{10} h = 2.4$, with significantly lower (−16 ± 2%) WFPS at field capacity ($p = 0.03$). Above $\log_{10} h = 2.4$, WFPS in the Chernozem containing PET increased rapidly with decreasing pressure head, reaching its maximum at $\log_{10} h = 3.6$, thereafter dropping again and showing comparable values to the control around the wilting point at $\log_{10} h = 4.2$. In contrast, addition of the other MP species did not change the WFPS significantly.

Total porosity, macroporosity, AC, and the PAW were calculated for the three soil types tested. The AC constituted 10%–16%, 22%–28% and 7%–10% of the soil volume in the Luvisol, Albic Luvisol, and Chernozem, respectively, while the macroporosity ranged from 0.3% to 2.8% in the Luvisol, 0.2%–2% in the Albic Luvisol, and 0.4%–0.8% in the Chernozem. The PAW was the highest in the Chernozem (0.34–0.39 cm^3 cm^{-3}), followed by the Luvisol (0.27–0.28 cm^3 cm^{-3}), and the lowest in the Albic Luvisol (0.09–0.11 cm^3 cm^{-3}). Adding the different MP species to the individual soil types significantly affected pore volumes with consequences for soil porosity, AC, and PAW (Figure 5).

PS and PP particles significantly decreased the total porosity of the Luvisol by 4 ± 1% ($p = 0.002$) and 1.4 ± 0.9% ($p = 0.05$), respectively. Additionally, PS in the Luvisol reduced the AC (−10 ± 9%, $p = 0.04$). Addition of LDPE particles led to a slight reduction of both AC and macroporosity. Oppositely, PET microfibers in the Luvisol significantly enhanced total porosity (+3 ± 1.5%, $p = 0.02$), AC (+11 ± 9%, $p = 0.02$), and macroporosity (+33 ± 23%, $p = 0.01$). Nonetheless, none of the MP types tested significantly affected PAW.

Similarly, PET microfibers led to a significant enhancement of total porosity in the Albic Luvisol (+4 ± 2%, $p = 0.03$), paired with a significantly reduced AC (−5 ± 2%, $p = 0.04$) and significantly higher PAW (+29 ± 11%, $p = 0.04$).

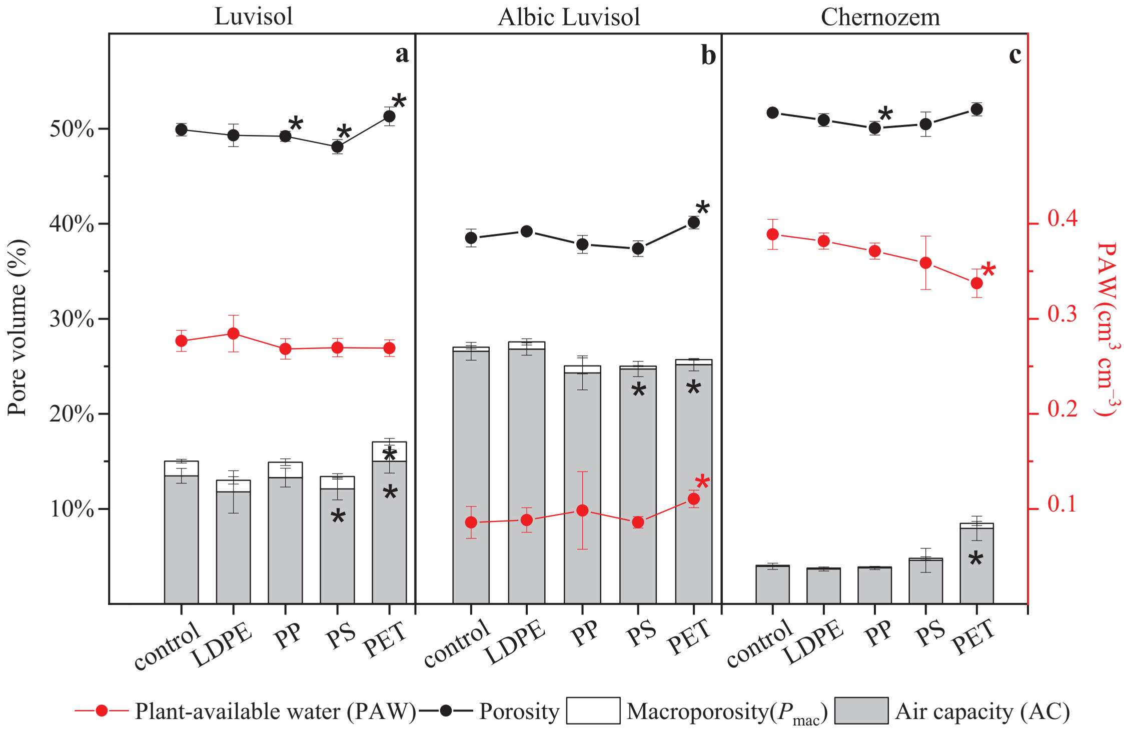

FIGURE 5 Total porosity (assuming that total porosity equals θ_s), macroporosity, air capacity (all in %), and plant-available water (cm^3 cm^{-3}) without (control) and with the addition of different microplastic types in (a) the Luvisol, (b) Albic Luvisol, and (c) the Chernozem. LDPE is low-density polyethylene, PP is polypropylene, PS is polystyrene, and PET is polyester microfibers comprised of polyethylene terephthalate. Significant differences from the control are marked with an asterisk (*) and were tested via one-sided, heteroscedastic *t*-test ($p \leq 0.05$).

PS amendment also led to significantly reduced AC (−7 ± 3%, $p = 0.02$), but did not affect total porosity.

Particularly the PET microfibers in the Chernozem significantly enhanced AC by 100 ± 33% ($p = 0.02$), which significantly reduced PAW by 13 ± 4% ($p = 0.03$). However, the increase in macroporosity by 384 ± 202% was only slightly significant due to the high variability between replicates ($p = 0.06$). Moreover, a reduced total porosity due to the presence of PP particles in the Chernozem was observed (−3 ± 1%, $p = 0.01$), while macroporosity or AC was not significantly affected. Nevertheless, PP in the Chernozem showed a significantly reduced PAW by 5 ± 2% ($p = 0.08$).

4 | DISCUSSION

We found that at the given mass concentration of 0.4%-w our tested MPs significantly affected the hydraulic conductivity of the three soil types, not only as a function of soil type itself but also depending on whether the soils were initially dry, as characterized by K_{ns}, or saturated, as indicated by K_{sat}. Through the calculation of the effect size η^2, the diverse effects on water flow arising from either soil type, MP type, or the interaction between MP and soil type could be discerned and ranked according to their extent in each soil condition, whether dry or saturated.

In general, the effect size η^2 clearly showed that soil type had the greatest influence on K_{sat} and K_{ns}. This is in line with the findings of Z.Wang et al. (2023), who found that the impact of soil texture on hydraulic properties was significantly higher than that of MP concentrations or sizes. However, the soil type effect was generally smaller for K_{ns} than K_{sat} (Figure 2). The relatively stronger MP effect on K_{ns} was likely because the hydrophobicity of the dry MP particles and microfibers was higher than that of the wet MP particles and microfibers, and the greater interaction effect of PET microfibers and soil type on K_{sat} suggests that the wet microfibers alter water flow by interacting with the particular soil structure. These marked differences in the influence of MPs, in particular of PS and PET, on soil pore structure and thus on hydraulic properties of the investigated soils are discussed in more detail for each soil type in the following sections.

4.1 | Microplastic effects in the Luvisol

In the Luvisol, the addition of PS particles and PET microfibers seemed to have antagonistic effects on soil hydraulic characteristics. While the addition of PET microfibers increased the porosity of the Luvisol to hold significantly more water and increased the percentage of air-filled pores, which are critical for root gas exchange, the addition of PS particles reduced the Luvisol's field capacity and the available air-filled pore volume (Figure 5a).

The fact that PET microfibers at a concentration of 0.4%-w would increase the water-holding capacity of a soil was already demonstrated by de Souza Machado et al. (2019). Presumably, the loamy silt texture of the dry Luvisol prevented a thorough compaction of the fiber–soil mixture, consequently leading to better aeration, water infiltration, and increased water-holding capacity. The widening of the fine pore structure likely led to the creation of new pathways for the water through the saturated soil matrix, positively affecting K_{sat} (Figure 1a). As reported previously, PET microfibers in soil led to altered physical soil properties (de Souza Machado et al., 2019; Ingraffia et al., 2022). In these two studies, it was shown that the incorporation of PET microfibers led to an increased formation of newly formed aggregates. While Ingraffia et al. (2022) reported this for a clay-rich Vertisol (−32%), a loamy Entisol (−47%), and an Alfisol (−33%), in de Souza Machado et al. (2019), it remained unclear which soil type was used. As a result, the addition of PET microfibers to soil could promote the aggregation of soil particles into larger aggregates with larger pores between them. This increases the overall permeability of the soil, allowing water to percolate faster through the saturated soil matrix, which is in alignment with the increased K_{sat} values of the Luvisol in our experiment. However, it should be noted that this effect is most probably caused by the soil type-specific pore structure, as this phenomenon was not observed in our coarse-textured sandy Albic Luvisol (Figure 1b). In addition, the Luvisol amended with PET microfibers held more water at the permanent wilting point ($\log_{10} h = 4.2$), but at complete dryness, the PET-treated Luvisol contained significantly less residual water within its pore space compared to all other MP treatments and the untreated control Luvisol (Table 5). This also provides evidence for a more permeable soil structure in which water can be released more easily from soil pores at higher suction pressures.

In contrast, the presence of PS particles in the Luvisol reduced its porosity and thus its water-holding capacity and air-filled pore space (Figure 5a), most probably due to blocking pores within the loamy silt soil structure, as also stated by Tötzke et al. (2024). These authors used X-ray tomography and neutron imaging to show that clogging macropores or blocking effective water pathways with film fragments can significantly affect water transfer in the soil, resulting in uneven water distribution. By blocking pores, the soil's ability to absorb and to drain water is impaired, as reflected in the significantly enhanced proportion of water-filled soil pores in PS-amended Luvisol (Figure 4a). The fact that PS in the Luvisol markedly decreased the soil porosity may have exerted the dominant influence on water infiltration into the dry Luvisol, as porosity and soil particle arrangement are critical factors affecting the interconnectedness of pores, determining the flow path of water, known as tortuosity (Gan et al., 2022). With decreased porosity, the impact of tortuosity on water flow becomes more pronounced (Gan et al., 2022). As porosity decreases with PS particles in the Luvisol, the pore-clogging effect of PS in the Luvisol may have positively affected tortuosity, resulting in reduced water pathways and enhanced near-saturated conductivity (Figure 1d). Additionally, LDPE and PP particles in the Luvisol also increased K_{ns} (Figure 1d), while also reducing the Luvisol's porosity compared to the control (Figure 5a).

This antagonistic behavior of MP particles and fibers affecting the hydraulic conductivity and consequently the hydraulic properties of the loamy silt is also reflected in the K_{ns} to K_{sat} ratio. While the PET microfibers significantly reduced the K_{ns} to K_{sat} ratio, MP particles significantly enhanced it (Table 4). As MP particles in the Luvisol tended to block the soil pores, their effects were most pronounced in dry soil, while the pore-expanding properties of the microfibers were only effective under saturated conditions.

4.2 | Microplastic effects in the Albic Luvisol

The presence of PS particles and PET microfibers in the loamy sand Albic Luvisol increased the WFPS but reduced the AC. However, the considerable enhancement in porosity induced by the PET microfibers contrasts with the marked reduction caused by PS particles.

In the case of PET microfiber-amended Albic Luvisol, the increased porosity likely increased water storage within the pore volume, associated with increased water retention and PAW. The PET microfibers added to the Albic Luvisol obviously altered the soil structure in a beneficial way in terms of PAW. Conversely, the reduction in air-filled pore volume indicates a decrease in the available volume for root gas exchange and gas diffusion, which would negatively influence potential root respiration and soil microbial activity in the rhizosphere.

Interestingly, the presence of PET microfibers in the saturated Albic Luvisol affected K_{sat} negatively (Figure 1b), completely opposite to the effect observed in the finer textured Luvisol and Chernozem (Figure 1a,c). Moreover, K_{ns} was impaired as well in the PET microfiber-amended Albic Luvisol (Figure 1e). The effect size η^2 revealed that when interacting with soil texture at water saturation, PET microfibers had the largest impact on K_{sat} (Figure 2a). Conversely, in dry soils, the presence of PET microfibers alone exerted the greatest influence on K_{ns} (Figure 2b).

On the one hand, it is conceivable that the PET microfibers interact with the soil structure, and therefore, with soil particles, likely due to soil aggregation (Lozano, Aguilar-Trigueros, et al., 2021), resulting in the formation of soil clods and impacting soil structure (Maddela et al., 2023).

This would promote the upward movement of water during saturation, as reflected in the significantly increased WFPS (Figure 4b) and increased water-holding capacity (Figure 3b). Moreover, it seems that due to addition of PET microfibers and subsequent soil aggregation, pores not only hold more water but also reduce water flow along the gravitational potential within the saturated soil pores by blocking potential pathways. On the other hand, the intertwining of hydrophobic microfibers in the expanded pore space could lead to a finer subdivision of the pores, increasing capillary forces in the dry Albic Luvisol. As a result, capillary rise increases, which counteracts the gravitational flow of water (Mantoglou & Gelhar, 1987), possibly leading to lower K_{ns} values for the Albic Luvisol.

In contrast, the Albic Luvisol containing PS particles exhibited reduced water-holding capacity compared to both the PET microfiber-amended and control Albic Luvisol, but also showing reduced drainage, as demonstrated by the increased residual water content (Table 5) and enhanced WFPS (Figure 4b). This phenomenon is likely attributed to obstruction of water flow paths by the MP particles, impeding water flow by acting as physical barriers both affecting water storage and drainage. The reduced water storage also suggests reduced soil porosity, that is, reduced pore volume and therefore enhanced attractive forces between water molecules and pore walls, thereby reducing K_{sat}, as observed for PS and PP.

However, PS particles in sandy soil not only reduced the K_{sat} but also K_{ns} (Figure 1b). The effect size η^2 revealed that the effect of PS on K_{ns} ranked highest amongst the three MP particle types (Figure 2b). PS differed from the other particle types due to its higher density than water (1.05 g cm^{-3}, Table 2), which probably makes this MP type less buoyant during water infiltration compared to the other particle types (Table 2). This density variance could have allowed PS acting even more as a physical barrier against gravitational water flow.

In the sandy Albic Luvisol, only the LDPE particles influenced and reduced the K_{ns} to K_{sat} ratio (Table 4). This effect can be attributed to the fact that LDPE was the only particle type that did not impede water flow through the water-saturated soil matrix, probably due to its relatively narrow particle size distribution, which had no influence on the coarse texture. In addition, the Albic Luvisol amended with LDPE exhibited greater water-holding capacity compared to the control or the PS-amended Albic Luvisol (Figure 3b), which reduced water storage and porosity.

4.3 | Microplastic effects in the Chernozem

Only in the fine-textured silty loam Chernozem, an increase in macropore volume with the incorporation of PET microfibers was detectable. Many other studies refer the effects of MP on hydraulic properties to the increase in macropores (Z. Guo et al., 2022; Shafea et al., 2023). While this might be true for some textures, as seen for our Chernozem, this statement cannot be generalized, as no significant changes within our Luvisol or Albic Luvisol were found. The enhanced macroporosity within the microfiber-amended Chernozem was accompanied by an overall increased air-filled pore volume compared to the control (Figure 5c). Although no difference in porosity was determined, the microfibers within the fine-structured Chernozem facilitated an increased drainage with significant negative consequences for PAW. Microfibers notably enhanced the permeability of the Chernozem, with pore water being bound less effectively to the pore walls, underscored by the significantly reduced residual water content (Figure 3c) and WFPS at field capacity (Figure 4c).

Consequently, the presence of PET microfibers likely rearranged soil aggregates, resulting in locally increased pore sizes without affecting overall porosity. As proposed by Nimmo (1997), structural alterations of a soil significantly change not only its hydraulic conductivity but also its water retention. As opposed to smaller pores, enlarged pores have altered physical forces, for example, water surface tension, adhesion, capillary tension, and meniscus formation, governing capillarity, and therefore, water retention. Nonetheless, the alteration of soil structure positively affected K_{sat} due to the enhanced water permeability (Figure 1c). However, water flow through the dry soil matrix was negatively affected (Figure 1f). As K_{ns} also depends on the structure and connectivity of the pore space within the soil matrix (Daneshian et al., 2021), potential explanations must reflect on how the PET microfibers potentially rearranged the structure of the Chernozem, leading to an impaired water flow within the dry soil. In this context, it is plausible that the PET microfibers hindered the formation of coherent pore clusters, which could have increased the tortuosity in the Chernozem with the effect of extended flow paths for water and reduced K_{ns}.

The MP particles tested in this study, in particular PP, influenced the Chernozem's total porosity negatively without affecting the air-filled pore space or the macroporosity (Figure 5c). As a result, the PP- and PS-amended Chernozem could store less water, accompanied by slightly reduced PAW. The MP particles in the Chernozem most probably blocked the pores, preventing water from entering the pore space, especially in the dry matrix. Furthermore, the Chernozem had a relatively high organic carbon content (2.06%), twice that of the Luvisol. As demonstrated by Ivanic et al. (2023), attractive hydrophobic interactions between hydrophobic PS particles (1 µm) and soil organic matter could have induced a more static behavior of MP particles in soil, leading to pore blockage and impeding water flow.

5 | CONCLUSION

The findings pertaining to the impact of various MP types on the hydraulic characteristics of different soil types with various soil textures have provided valuable insights into the diverse effects of MPs on key hydraulic characteristics in the different soils. It is evident that the hydraulic properties of a given soil are not solely influenced by the surface properties of the MP type but also by factors like its shape (fiber or particle), size, and the interaction of the MPs with the surrounding soil structure. Our study highlights the complex interplay between MPs and soil characteristics, with the ecological implications (e.g., for root water uptake and crop growth) to be assessed. However, other MP concentrations and soil textures are likely to have different effects, which could be positive, negative, or insignificant.

To provide more accurate insights and future projections regarding the impact of specific MPs on the hydraulic properties of soils with different textures, we recommend focusing on intact (undisturbed) soils. Regarding the assessment of ecological impacts of MPs, it should be noted that MP concentrations of 0.4%-w or similar used in our and many other studies are extraordinarily high, as much lower MP concentrations have been reported for today's agricultural soils, for example, <0.002%-w for arable land treated with biosolids for 10 years (Corradini et al., 2019). However, higher MP concentrations might be realistic for heavily contaminated soils near disposal sites or at individual hotspots in the soil.

AUTHOR CONTRIBUTIONS

Katharina J. Neubert: Conceptualization; data curation; formal analysis; investigation; methodology; visualization; writing—original draft. **Lutz Weihermüller**: Conceptualization; data curation; formal analysis; methodology; resources; validation; writing—review and editing. **Harry Vereecken**: Resources; validation; writing—review and editing. **Nicolas Brüggemann**: Conceptualization; funding acquisition; project administration; resources; supervision; validation; writing—review and editing.

ACKNOWLEDGMENTS

We would like to express our gratitude to Andres Rodriguez Sañudo, student at the RWTH Aachen, Germany, and Ashley Malenfant, student at the Ohio State University, Columbus, OH, for their assistance with data collection and analysis. We also extend our thanks to Dr. Michael Baumecker, manager of the research station of the Albrecht Daniel Thaer Institute for Agriculture and Horticulture Sciences of the Humbold University of Berlin located in Thyrow, Germany, and Dr. Ines Merbach, manager of the agricultural research station of the Helmholtz Centre for Environmental Sciences (UFZ), located in Bad Lauchstädt, Germany, for making it possible to collect soil from their agricultural fields. Their cooperation and support were essential to having multiple soil types available for this study. Finally, we acknowledge the financial support from the German Federal Ministry of Education and Research (FKZ: 031B0907C), which made this study possible.

Open access funding enabled and organized by Projekt DEAL.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ORCID

Katharina J. Neubert https://orcid.org/0009-0004-8321-2320
Lutz Weihermüller https://orcid.org/0000-0003-1991-7735
Harry Vereecken https://orcid.org/0000-0002-8051-8517
Nicolas Brüggemann https://orcid.org/0000-0003-3851-2418

REFERENCES

Alexiou, V. F., Mathioudakis, G. N., Andrikopoulos, K. S., Soto Beobide, A., & Voyiatzis, G. A. (2020). Poly(ethylene terephthalate) carbon-based nanocomposites: A crystallization and molecular orientation study. *Polymers*, *12*(11), 2626. https://doi.org/10.3390/polym12112626

Bagnall, D. K., Morgan, C. L. S., Bean, G. M., Liptzin, D., Cappellazzi, S. B., Cope, M., Greub, K. L. H., Rieke, E. L., Norris, C. E., Tracy, P. W., Aberle, E., Ashworth, A., Tavarez, O. B., Bary, A. I., Baumhardt, R. L., Gracia, A. B., Brainard, D. C., Brennan, J. R., Reyes, D. B., … Honeycutt, C. W. (2022). Selecting soil hydraulic properties as indicators of soil health: Measurement response to management and site characteristics. *Soil Science Society of America Journal*, *86*(5), 1206–1226. https://doi.org/10.1002/saj2.20428

Bian, W., An, L., Zhang, S., Feng, J., Sun, D., Yao, Y., Shen, T., Yang, Y., & Zhang, M. (2022). The long-term effects of microplastics on soil organomineral complexes and bacterial communities from controlled-release fertilizer residual coating. *Journal of Environmental Management*, *304*, 114193. https://doi.org/10.1016/j.jenvman.2021.114193

Brandes, E., Henseler, M., & Kreins, P. (2021). Identifying hot-spots for microplastic contamination in agricultural soils—A spatial modelling approach for Germany. *Environmental Research Letters*, *16*(10), 104041. https://doi.org/10.1088/1748-9326/ac21e6

Büks, F., & Kaupenjohann, M. (2020). Global concentrations of microplastics in soils—A review. *Soilless*, *6*(2), 649–662. https://doi.org/10.5194/soil-6-649-2020

Carney Almroth, B. M., Åström, L., Roslund, S., Petersson, H., Johansson, M., & Persson, N.-K. (2018). Quantifying shedding of synthetic fibers from textiles; a source of microplastics released into the environment. *Environmental Science and Pollution Research*, *25*(2), 1191–1199. https://doi.org/10.1007/s11356-017-0528-7

Corradini, F., Meza, P., Eguiluz, R., Casado, F., Huerta-Lwanga, E., & Geissen, V. (2019). Evidence of microplastic accumulation in agricultural soils from sewage sludge disposal. *Science of the Total*

Environment, *671*, 411–420. https://doi.org/10.1016/j.scitotenv.2019.03.368

Daneshian, B., Habibagahi, G., & Nikooee, E. (2021). Determination of unsaturated hydraulic conductivity of sandy soils: A new pore network approach. *Acta Geotechnica*, *16*(2), 449–466. https://doi.org/10.1007/s11440-020-01088-3

de Souza Machado, A. A., Kloas, W., Zarfl, C., Hempel, S., & Rillig, M. C. (2018). Microplastics as an emerging threat to terrestrial ecosystems. *Global Change Biology*, *24*(4), 1405–1416. https://doi.org/10.1111/gcb.14020

de Souza Machado, A. A., Lau, C. W., Kloas, W., Bergmann, J., Bachelier, J. B., Faltin, E., Becker, R., Görlich, A. S., & Rillig, M. C. (2019). Microplastics can change soil properties and affect plant performance. *Environmental Science & Technology*, *53*(10), 6044–6052. https://doi.org/10.1021/acs.est.9b01339

DIN ISO 11277. (2002). *Soil quality—Determination of particle size distribution in mineral soil material—Method by sieving and sedimentation (ISO 11277:1998 + ISO 11277:1998 Corrigendum 1:2002)*. https://dx.doi.org/10.31030/9283499

Estahbanati, S., & Fahrenfeld, N. L. (2016). Influence of wastewater treatment plant discharges on microplastic concentrations in surface water. *Chemosphere*, *162*, 277–284. https://doi.org/10.1016/j.chemosphere.2016.07.083

Fuhr, L., Buschmann, R., & Freund, J. (2019). *PLASTIKATLAS—Daten und Fakten über eine Welt voller Kunststoff. B. f. o. t. e. G. Heinrich Böll Stiftung, Appenzeller/Hecher/Sack CC-BY-4.0*. https://www.bund.net/fileadmin/user_upload_bund/publikationen/chemie/chemie_plastikatlas_2019.pdf

Gan, J., Yang, Z., Zhang, Z., Li, C., Yang, Y., Zhu, Y., Guo, Y., Wang, R., Zhang, B., Fang, Y., Yu, D., Zhang, J., Liu, H., & Su, J. (2022). Two-dimensional soil geometric tortuosity model based on porosity and particle arrangement. *Minerals*, *12*(1), 43. https://www.mdpi.com/2075-163X/12/1/43

Guo, J.-J., Huang, X.-P., Xiang, L., Wang, Y.-Z., Li, Y.-W., Li, H., Cai, Q.-Y., Mo, C.-H., & Wong, M.-H. (2020). Source, migration and toxicology of microplastics in soil. *Environment International*, *137*, 105263. https://doi.org/10.1016/j.envint.2019.105263

Guo, Z., Li, P., Yang, X., Wang, Z., Lu, B., Chen, W., Wu, Y., Li, G., Zhao, Z., Liu, G., Ritsema, C., Geissen, V., & Xue, S. (2022). Soil texture is an important factor determining how microplastics affect soil hydraulic characteristics. *Environment International*, *165*, 107293. https://doi.org/10.1016/j.envint.2022.107293

Harms, I. K., Diekötter, T., Troegel, S., & Lenz, M. (2021). Amount, distribution and composition of large microplastics in typical agricultural soils in Northern Germany. *Science of the Total Environment*, *758*, 143615. https://doi.org/10.1016/j.scitotenv.2020.143615

Heinze, W. M., Steinmetz, Z., Klemmensen, N. D. R., Vollertsen, J., & Cornelis, G. (2024). Vertical distribution of microplastics in an agricultural soil after long-term treatment with sewage sludge and mineral fertiliser. *Environmental Pollution*, *356*, 124343. https://doi.org/10.1016/j.envpol.2024.124343

Huang, Y., Liu, Q., Jia, W., Yan, C., & Wang, J. (2020). Agricultural plastic mulching as a source of microplastics in the terrestrial environment. *Environmental Pollution*, *260*, 114096. https://doi.org/10.1016/j.envpol.2020.114096

Ingraffia, R., Amato, G., Bagarello, V., Carollo, F. G., Giambalvo, D., Iovino, M., Lehmann, A., Rillig, M. C., & Frenda, A. S. (2022). Polyester microplastic fibers affect soil physical properties and erosion as a function of soil type. *SOIL*, *8*(1), 421–435. https://doi.org/10.5194/soil-8-421-2022

IUSS Working Group WRB. (2022). *World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps* (4th ed.). International Union of Soil Sciences. https://wrb.isric.org/files/WRB_fourth_edition_2022-12-18_errata_correction_2024-09-24.pdf

Ivanic, F. M., Guggenberger, G., Woche, S. K., Bachmann, J., Hoppe, M., & Carstens, J. F. (2023). Soil organic matter facilitates the transport of microplastic by reducing surface hydrophobicity. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *676*, 132255. https://doi.org/10.1016/j.colsurfa.2023.132255

Liu, B., Fan, H., Han, W., Zhu, L., Zhao, X., Zhang, Y., & Ma, R. (2021). Linking soil water retention capacity to pore structure characteristics based on X-ray computed tomography: Chinese Mollisol under freeze-thaw effect. *Geoderma*, *401*, 115170. https://doi.org/10.1016/j.geoderma.2021.115170

Liu, M., Lu, S., Song, Y., Lei, L., Hu, J., Lv, W., Zhou, W., Cao, C., Shi, H., Yang, X., & He, D. (2018). Microplastic and mesoplastic pollution in farmland soils in suburbs of Shanghai, China. *Environmental Pollution*, *242*, 855–862. https://doi.org/10.1016/j.envpol.2018.07.051

Lozano, Y. M., Aguilar-Trigueros, C. A., Onandia, G., Maaß, S., Zhao, T., & Rillig, M. C. (2021). Effects of microplastics and drought on soil ecosystem functions and multifunctionality. *Journal of Applied Ecology*, *58*(5), 988–996. https://doi.org/10.1111/1365-2664.13839

Lozano, Y. M., Lehnert, T., Linck, L. T., Lehmann, A., & Rillig, M. C. (2021). Microplastic shape, polymer type, and concentration affect soil properties and plant biomass. *Frontiers in Plant Science*, *12*, Article 616645. https://doi.org/10.3389/fpls.2021.616645

Ma, L., Hoogenboom, G., Saseendran, S. A., Bartling, P. N. S., Ahuja, L. R., & Green, T. R. (2009). Effects of estimating soil hydraulic properties and root growth factor on soil water balance and crop production. *Agronomy Journal*, *101*(3), 572–583. https://doi.org/10.2134/agronj2008.0206x

Maddela, N. R., Ramakrishnan, B., Kadiyala, T., Venkateswarlu, K., & Megharaj, M. (2023). Do microplastics and nanoplastics pose risks to biota in agricultural ecosystems? *Soil Systems*, *7*(1), 19. https://www.mdpi.com/2571-8789/7/1/19

Mahon, A. M., O'Connell, B., Healy, M. G., O'Connor, I., Officer, R., Nash, R., & Morrison, L. (2017). Microplastics in sewage sludge: Effects of treatment. *Environmental Science & Technology*, *51*(2), 810–818. https://doi.org/10.1021/acs.est.6b04048

Mantoglou, A., & Gelhar, L. W. (1987). Effective hydraulic conductivities of transient unsaturated flow in stratified soils. *Water Resources Research*, *23*(1), 57–67. https://doi.org/10.1029/WR023i001p00057

Mintenig, S. M., Int-Veen, I., Löder, M. G. J., Primpke, S., & Gerdts, G. (2017). Identification of microplastic in effluents of waste water treatment plants using focal plane array-based micro-Fourier-transform infrared imaging. *Water Research*, *108*, 365–372. https://doi.org/10.1016/j.watres.2016.11.015

Nimmo, J. R. (1997). Modeling structural influences on soil water retention. *Soil Science Society of America Journal*, *61*(3), 712–719. https://doi.org/10.2136/sssaj1997.03615995006100030002x

Piehl, S., Leibner, A., Löder, M. G. J., Dris, R., Bogner, C., & Laforsch, C. (2018). Identification and quantification of macro- and microplastics on an agricultural farmland. *Scientific Reports*, *8*(1), Article 17950. https://doi.org/10.1038/s41598-018-36172-y

Prajapati, A., Narayan Vaidya, A., & Kumar, A. R. (2022). Microplastic properties and their interaction with hydrophobic organic contaminants: A review. *Environmental Science and Pollution Research*, *29*(33), 49490–49512. https://doi.org/10.1007/s11356-022-20723-y

Rebollar, E., Pérez, S., Hernández, M., Domingo, C., Martín, M., Ezquerra, T. A., García-Ruiz, J. P., & Castillejo, M. (2014). Physicochemical modifications accompanying UV laser induced surface structures on poly(ethylene terephthalate) and their effect on adhesion of mesenchymal cells. *Physical Chemistry Chemical Physics*, *16*, 17551–17559. https://doi.org/10.1039/c4cp02434f

Reynolds, W. D., Drury, C. F., Tan, C. S., Fox, C. A., & Yang, X. M. (2009). Use of indicators and pore volume-function characteristics to quantify soil physical quality. *Geoderma*, *152*(3), 252–263. https://doi.org/10.1016/j.geoderma.2009.06.009

Richardson, J. T. E. (2011). Eta squared and partial eta squared as measures of effect size in educational research. *Educational Research Review*, *6*(2), 135–147. https://doi.org/10.1016/j.edurev.2010.12.001

Rødland, E. S., Lind, O. C., Reid, M., Heier, L. S., Skogsberg, E., Snilsberg, B., Gryteselv, D., & Meland, S. (2022). Characterization of tire and road wear microplastic particle contamination in a road tunnel: From surface to release. *Journal of Hazardous Materials*, *435*, 129032. https://doi.org/10.1016/j.jhazmat.2022.129032

Rojas, J. P., Ruge, J. C., & Carrillo, G. A. (2022). Unsaturated hydraulic conductivity in composite porous media. *Applied Sciences*, *12*(18), 9058. https://doi.org/10.3390/app12189058

Schindler, U., Durner, W., von Unold, G., & Müller, L. (2010). Evaporation method for measuring unsaturated hydraulic properties of soils: Extending the measurement range. *Soil Science Society of America Journal*, *74*(4), 1071–1083. https://doi.org/10.2136/sssaj2008.0358

Shafea, L., Felde, V. J. M. N. L., Woche, S. K., Bachmann, J., & Peth, S. (2023). Microplastics effects on wettability, pore sizes and saturated hydraulic conductivity of a loess topsoil. *Geoderma*, *437*, 116566. https://doi.org/10.1016/j.geoderma.2023.116566

Sharma, N., Allardyce, B., Rajkhowa, R., Adholeya, A., & Agrawal, R. (2022). A substantial role of agro-textiles in agricultural applications. *Frontiers in Plant Science*, *13*, Article 895740. https://doi.org/10.3389/fpls.2022.895740

Topp, G. C., Reynolds, W. D., Cook, F. J., Kirby, J. M., & Carter, M. R. (1997). Physical attributes of soil quality. In E. G. Gregorich, & M. R. Carter (Eds.), *Developments in soil science* (Vol. 25, pp. 21–58). Elsevier. https://doi.org/10.1016/S0166-2481(97)80029-3

Tötzke, C., Kozhuharova, B., Kardjilov, N., Lenoir, N., Manke, I., & Oswald, S. E. (2024). Non-invasive 3D analysis of microplastic particles in sandy soil—Exploring feasible options and capabilities. *Science of the Total Environment*, *907*, 167927. https://doi.org/10.1016/j.scitotenv.2023.167927

van Genuchten, M. T. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal*, *44*(5), 892–898. https://doi.org/10.2136/sssaj1980.03615995004400050002x

Wang, F., Wang, Q., Adams, C. A., Sun, Y., & Zhang, S. (2022). Effects of microplastics on soil properties: Current knowledge and future perspectives. *Journal of Hazardous Materials*, *424*, 127531. https://doi.org/10.1016/j.jhazmat.2021.127531

Wang, Z., Li, W., Li, W., Yang, W., & Jing, S. (2023). Effects of microplastics on the water characteristic curve of soils with different textures. *Chemosphere*, *317*, 137762. https://doi.org/10.1016/j.chemosphere.2023.137762

Weber, C. J., Santowski, A., & Chifflard, P. (2022). Investigating the dispersal of macro- and microplastics on agricultural fields 30 years after sewage sludge application. *Scientific Reports*, *12*(1), Article 6401. https://doi.org/10.1038/s41598-022-10294-w

Xie, Y., Wang, H., Chen, Y., Guo, Y., Wang, C., Cui, H., & Xue, J. (2023). Water retention and hydraulic properties of a natural soil subjected to microplastic contaminations and leachate exposures. *Science of the Total Environment*, *901*, 166502. https://doi.org/10.1016/j.scitotenv.2023.166502

Ya, H., Jiang, B., Xing, Y., Zhang, T., Lv, M., & Wang, X. (2021). Recent advances on ecological effects of microplastics on soil environment. *Science of the Total Environment*, *798*, 149338. https://doi.org/10.1016/j.scitotenv.2021.149338

Zhang, G. S., Zhang, F. X., & Li, X. T. (2019). Effects of polyester microfibers on soil physical properties: Perception from a field and a pot experiment. *Science of the Total Environment*, *670*, 1–7. https://doi.org/10.1016/j.scitotenv.2019.03.149

Zhang, R. (1997). Determination of soil sorptivity and hydraulic conductivity from the disk infiltrometer. *Soil Science Society of America Journal*, *61*(4), 1024–1030. https://doi.org/10.2136/sssaj1997.03615995006100040005x

Zheng, W., Morris, E. K., Lehmann, A., & Rillig, M. C. (2016). Interplay of soil water repellency, soil aggregation and organic carbon. A meta-analysis. *Geoderma*, *283*, 39–47. https://doi.org/10.1016/j.geoderma.2016.07.025

Zubris, K. A. V., & Richards, B. K. (2005). Synthetic fibers as an indicator of land application of sludge. *Environmental Pollution*, *138*(2), 201–211. https://doi.org/10.1016/j.envpol.2005.04.013

SUPPORTING INFORMATION

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

How to cite this article: Neubert, K. J., Weihermüller, L., Vereecken, H., & Brüggemann, N. (2025). Soil texture governs the influence of different microplastics on soil hydraulic properties. *Vadose Zone Journal*, *24*, e70044. https://doi.org/10.1002/vzj2.70044