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Microplastics effects on wettability, pore sizes and saturated hydraulic conductivity of a loess topsoil

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ABSTRACT

Environmental contamination with microplastics (MP, 0.1 μm – 5 mm diameter) potentially threatens various soil functions and agricultural production. In this study we evaluated the effects of MP on physical soil parameters (saturated hydraulic conductivity, water retention and water repellency) at MP concentrations (0.5 to 2 % w/w) that have been reported for farmland soils. Polyethylene terephthalate (PET) and polystyrene (PS) of three sizes ranging between 0.5 and 3 mm diameter, were mixed with loess topsoil material from an agriculturally used Luvisol. Results show that increasing MP concentration decreased the saturated hydraulic conductivity (k_{sat}) compared to the control soil (without MP), irrespective of MP type. The highest reduction of k_{sat} was found for the highest concentration (2 %) and the largest size MP (approx. 3 mm diameter). Compared to the control, MP addition significantly decreased soil water retention with increasing concentration. In contrast, air capacity was increased with MP addition where strongest effect was found for largest PET particles at the highest concentration. Soil water repellency (measured as Wilhelmy Plate contact angles) was increased at a concentration of 2 % and for MP sizes > 1 mm, while no effect was observed for lower concentrations and smaller MP. In conclusion, MP type, size, and concentration did affect key soil physical parameters, likely to negatively influence plant growth in contaminated soils.

1. Introduction

Microplastics (MP) is a ubiquitous material that originates from consumer and industrial environmental products such as water bottles, plastic plates and packaging (Wang et al., 2021). The properties of MP can vary strongly. According to Kumar et al. (2020) and Marrone et al. (2021) it can have different sizes (0.1 μm –5 mm) and shapes (fragment, foam, line, pellet, fiber, film), can consist of various polymer types (polyethylene, polystyrene, polyethylene terephthalate, polypropylene, polyvinyl chloride), and range in densities between 0.89 and 1.58 g cm^{-3}. The United Nations Environment Program has recognized that environmental contamination with MP is a challenging global issue (UNEP, 2018). As reported by Plastic Europe (2021), the estimated global production of plastic was 367 Tg in 2020. Due to the limited recovery of discarded plastic materials and their environmental persistence, plastic residues accumulate dramatically in the soil environment, despite growing recycling efforts (Zhou et al., 2020).

Agricultural soils are one of the primary environments that is polluted by MP (Nizzetto et al., 2016; Qi et al., 2018). Surprisingly, despite that the amount of MP released into farmland by far exceeds the MP load in the worldwide ocean layer it does so far not get as much attention (van Sebille et al., 2015; Windsor et al., 2019). A global examination of agricultural and horticultural soils exposed to sewage sludge showed that they exhibit concentrations of 1200 MP particles and 1000 MP particles per kg of soil, respectively (Büks and Kaupenjohann, 2020).

Polyethylene terephthalate (PET) and polystyrene (PS) are among the two most widely used plastic types found as MP in agricultural soils (Piehl et al., 2018, Weber et al., 2022). PET (density 1.38 g cm^{-3}, Polymer properties database, 2022) and PS (density 1.05 g cm^{-3}, Polymer properties database, 2022), mainly in fragment shape, have also been recognized as prevalent MP particles in Germany from a long-term soil monitoring site (Weber, 2022).

Over time, large plastics will degrade in farmlands due to mechanical breakdown during tillage, biochemical decomposition, thermal degradation, agricultural activities, and UV irradiation (Shafea et al., 2022). This can result in secondary MP of varying size fractions, shapes, surface charges, and density (Yu and Flury, 2021). In contrast to large plastic

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particles (>5 mm), MP can be incorporated into soil aggregates to a higher degree and affect soil's physical, chemical, and physicochemical properties due to its small size compared to macro-sized plastics (Zhang et al., 2019; Zhou et al., 2020). MP concentrations vary at different soil depths due to various processes of translocation, such as wetting–drying cycles (O'Connor et al., 2019), tillage and ridge cultivation (Zhang et al., 2020), bioturbation (Zhu et al., 2019), rhizosphere hyphae (Yadav et al., 2022), and convective–dispersive transport (Astner et al., 2020).

Notably, direct and indirect effects of MP on the pore size distribution (Zhang et al., 2019), soil aeration (Yu et al., 2022), as well as on water and nutrient uptake by plant roots (de Souza Machado et al., 2020) were observed. Soil water dynamics and retention determine soil fertility and plant nutrient use efficiency, which is essential for plant production and viable harvest (de Souza Machado et al., 2018).

In recent years, a growing number of studies investigated the soil chemical and biological alteration caused by MP. However, much less is known on the impact of MP contamination on soil physical properties, such as hydraulic conductivity and soil water retention function (Guo et al., 2022). Hydraulic conductivity is a crucial physical soil property that affects fluid flow and hence also the spatial distribution of MP with depth (Monkul and Özhan, 2021). Furthermore, MP can affect soil hydraulic properties due to the MP size and its proportion in the soil. With increasing MP amounts in soil, the soil micropores and the number of coarse pores decrease, reducing the soil's hydraulic conductivity (Kumar et al., 2020; Guo et al., 2022). Chia et al. (2022) indicated reduced saturated hydraulic conductivity due to clogging soil pore space. Microplastics can block soil pores and prevent the transport of nutrients and water to plants (Sajjad et al., 2022). However, it is still unclear how plant available water, field capacity, and permanent wilting point are affected by MP and how this will impact plant growth (de Souza Machado et al., 2020). Furthermore, the hydrophobicity of MP particles presents an intense repulsion to water molecules and water availability in soil (Kumar et al., 2020). This implies that there are still open questions about the MP impact on soil physical and physiochemical properties (e.g., how can alterations in soil wettability by MP impact saturated hydraulic conductivity and soil water retention? Or how can MP affect water retention of soils in highly contaminated areas?). To fill this knowledge gap is the motivation of our study.

Microplastics usually display high hydrophobicity and unique structural properties (e.g., surface charge, density and shape) that make them distinct from soil minerals (Campanale et al., 2020; Zou et al., 2020). Water repellency is a transient property of soil particle interfaces affecting physical, chemical, and biological functions (Sepehrnia et al., 2020). This, in turn, can affect the ability to create and stabilize soil aggregates, and thus may also have drawbacks on the natural soil organic matter sequestration potential (Bachmann et al., 2008; Vogelmann et al., 2013).

To shed light on these understudied physical and physico-chemical aspects, this study aims to simultaneously evaluate the effects of two different MP types (polyethylene terephthalate, PET and polystyrene, PS) mixed with topsoil loess material (derived from a Luvisol as a common agricultural soil) on soil hydraulic conductivity, soil water retention, and wettability. We hypothesized that i) PET compared to PS will change in their impact on saturated hydraulic conductivity (k_{sat}) and soil water retention and will change the soil wettability stronger than PS due to their respective properties (e.g., higher density of PET compared to PS), ii) with the increase of MP concentration, the saturated hydraulic conductivity and soil water retention will decrease because of soil pore clogging, and iii) that soil water repellency (SWR) will increase with increasing MP concentration and decreasing MP particle size.

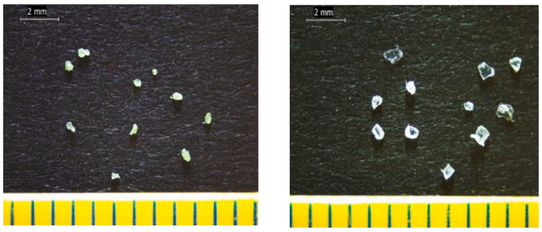
2. Materials and methods

2.1. Materials

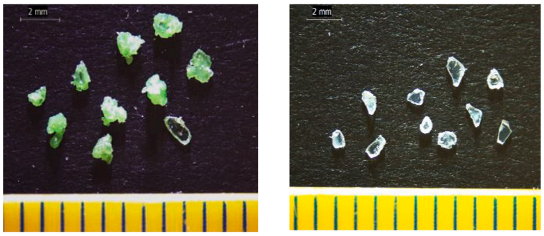
Soil material was collected in winter 2020 from the plow layer (0–20 cm soil depth) of a Luvisol at the experimental site of the University of Kassel (Neu-Eichenberg, Germany, 51°23′N 09°53′E). Soil texture is classified as silt loam (27 % sand, 53 % silt, 20 % clay) with 4 % organic matter and a pH ($CaCl_2$) of 6.2. The soil was air-dried, homogenized, and passed through a 2 mm sieve before mixing with MP.

Macro-sized plastic particles were produced by manual cutting PET plastic bottles and PS disposable plates into 10 mm^2 plates. A high-speed rotor pulverizer (Fritsch, Idar-Oberstein, Germany) was used to produce MP. Plastics were frozen first with liquid nitrogen and then the powders were produced by grinding with different filters (0.5 and 1 mm). In total, three MP size fractions were obtained: S: polyethylene terephthalate and polystyrene (both 0.6 mm); M: polyethylene terephthalate (1.4 mm); polystyrene (1.3 mm); and L: polyethylene terephthalate (2.5 mm), polystyrene (2.4 mm). Particle sizes were determined by microscopy (Leica EZ4 W; Metzlar, Germany) and ImageJ software (Schneider et al., 2012). The shape of the finally manufactured MP can be considered as fragments in all size classes (Fig. 1).

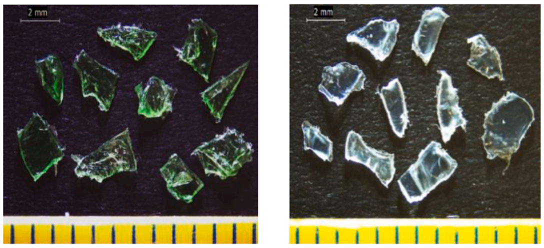
The three MP size fractions were added to the sieved soil at concentrations of 0.5, 1 and 2 wt - % of dry soil, respectively. Soil without plastic was used as a control. It is important to state that since microplastics are ubiquitous, it is next to impossible to tell if a given soil is truly free of (especially nano-sized) plastics. However, we subjected our samples to a rigorous visual inspection before using them. The selected concentrations reflect realistic MP concentrations found in highly contaminated agricultural soils and were chosen based on previous studies (de Souza Machado et al., 2018; Qi et al., 2020). Soil and MP was mixed by 10 min stirring with a metal spoon. Although no MP was added



S) Polyethylene terephthalate (0.6 mm), Polystyrene (0.6 mm)



M) Polyethylene terephthalate (1.4 mm), Polystyrene (1.3 mm)



L) Polyethylene terephthalate (2.5 mm), Polystyrene (2.4 mm)

Fig. 1. Particle sizes; (S): polyethylene terephthalate and polystyrene (both 0.6 mm); (M): polyethylene terephthalate (1.4 mm); polystyrene (1.3 mm); and (L): polyethylene terephthalate (2.5 mm), polystyrene (2.4 mm).

Table 1

Investigated treatments and used abbreviations: types, sizes and concentrations. S: polyethylene terephthalate and polystyrene (both 0.6 mm); M: polyethylene terephthalate (1.4 mm); polystyrene (1.3 mm); and L: polyethylene terephthalate (2.5 mm), polystyrene (2.4 mm).

Plastic type	Size (mm)	Concentration (%)
No plastic added	–	–
Polyethylene terephthalate	0.6 mm (S)	0.5
		1
		2
	1.4 mm (M)	0.5
		1
		2
	2.5 mm (L)	0.5
		1
		2
Polystyrene	0.6 mm (S)	0.5
		1
		2
	1.3 mm (M)	0.5
		1
		2
	2.4 mm (L)	0.5
		1
		2

to the control, it was also subjected to the same stirring. The MP-soil mixtures and the control were filled into steel cores (diameter: 5.63 mm, height:4 mm, volume:100 cm^{-3}) and compacted under standardized conditions with a material testing machine (ZwickRoell, Ulm, Germany) to a bulk density of 1.4 g cm^{-3}.

In addition to the control, a total of 9 combinations for both PET and PS were prepared. PS and PET were used in three size classes, each: small (S), medium (M) and large (L) in different concentrations of 0.5, 1 and 2 % resulting in 19 treatments in total, and each treatment was replicated four times (Table 1).

2.2. Measurement of soil parameters

2.2.1. Saturated hydraulic conductivity

Saturated hydraulic conductivity (k_{sat}) was determined by a falling head permeameter (Eijkelkamp, Giesbeek, the Netherlands), under transient flow conditions (DIN EN ISO 17892–11:2019). Samples were saturated with tap water for 24 h, and k_{sat} was measured for four replicate samples per treatment. For each sample, three repeated measurements were conducted, and the derived k_{sat} values were averaged (mean). The saturated hydraulic conductivity of each sample was calculated by applying a modified Darcy equation to account for transient flow conditions according to Hartge and Horn (2016):

$$k_{sat} = (a^*l/A^*t)^*\ln[h1/h2]$$

where a is the area (m^2) of the water supplying capillary, A is the area (m^2) of the sample, l is the length (m) of the sample, t is the time (s) elapsing during the infiltration measurement, and ln ($h1/h2$) is the natural logarithm of the quotient of the water column's height in the capillary at the beginning ($h1$) and the end ($h2$) of the measurement.

2.2.2. Soil water retention

Soil water retention was measured as desorption curves at matric potentials of −6 (~pF 1.8), −15 (~pF 2.2), −30 (~pF 2.5), −50 (~pF 2.7), −100 (~pF 3), −500 (~pF 3.7), and −1500 kPa (~pF 4.2) by applying pressure, using suction plates (DIN-EN-ISO 11508, 2014). From the water retention function, field capacity (FC) at pF 2.5, air capacity (AC), plant available water (PAW), and permanent wilting point (PWP) were calculated. Total pore volume (TPV), was calculated from bulk density ρ_b and mean particle density $\bar{\rho}s$ as

$$TPV = 1\text{-}\frac{\rho_b}{\bar{\rho}_s}$$

Mean particle density was calculated accounting for the fraction of MP that was added to the mineral soil, assuming a density of 1.05 g cm^{-3} for PS and 1.38 g cm^{-3} for PET.

2.2.3. Contact angle

Contact angles were measured by the Wilhelmy plate method (Bachmann et al., 2003) using 100 g of soil. The air-dry sample material was fixed in an ideally single-grain-layer on a microscopic glass slide by double-sided adhesive tape, covering the slide from all sides (Woche et al., 2005).

Advancing and receding contact angles were determined with a precision contact angle tensiometer (DCAT 11, DataPhysics, Filderstadt, Germany). The dynamic contact angles are calculated after correction for the buoyancy force from the wetting force as;

$$cos\theta = F_w/(\sigma_{lv}{}^*l_w)$$

where F_w is the wetting force measured during immersion of the slide (N), σ_{lv} (N m^{-1}) is the surface tension of the test liquid (H_2O), and l_w (m) is the wetted length of the 4 mm immersed sample.

2.3. Statistical data analysis

A one-way analysis of variance (ANOVA) was used to test for the significance of differences between the average values of four replicates, using the Tukey test at $P < 0.05$. The measured factors (saturated hydraulic conductivity, water retention parameters, and contact angle) were analyzed as a function of MP type, size, and concentration. All statistical procedures were carried out with the R Software, version 4.0.3. (R Core Team, 2020).

3. Results

3.1. Effects of microplastic type, size, and concentration on saturated hydraulic conductivity

At the same bulk density (1.4 g cm^{-3}), the addition of plastic reduced k_{sat}, independently of MP type (Fig. 2, Table 2). Saturated hydraulic conductivity was significantly decreased with increasing MP particle size and concentration for both MP types ($p < 0.05$, Fig. 2). The effect of MP concentration was most pronounced for the small MP, while the medium and large MP particles did not exhibit such a strong difference in k_{sat} for the three concentrations (Fig. 2).

When the two MP types are compared with respect to sizes and concentrations (Fig. 3, A&B), the saturated hydraulic conductivity was reduced stronger for PET with increasing particle size and concentration, and the strongest effect was found for the largest PET particles (L) at 2 % concentration. For PS, only the variability of k_{sat} decreased with increasing particle size, but the median stayed the same (Fig. 3, A).

3.2. Effects of microplastic type, size fraction, and concentration on soil water retention parameters

When compared to the control, soil water retention was decreased with increasing MP concentration for each type and size fraction at each matric potential ψ_m, (Fig. 4, A) also with increasing MP sizes for each type and concentration (Fig. 4, B).

However, the reduction in water retention was more apparent between the control and the treatments, and among the treatments only at high suction (-1500 kPa). The greatest impact was found for the biggest PET and PS particles ($\geq$2 mm) that reduced water content at all matric potentials compared to the other size fractions and the control (Table 3).

Calculated air capacity was higher for both plastic types compared to

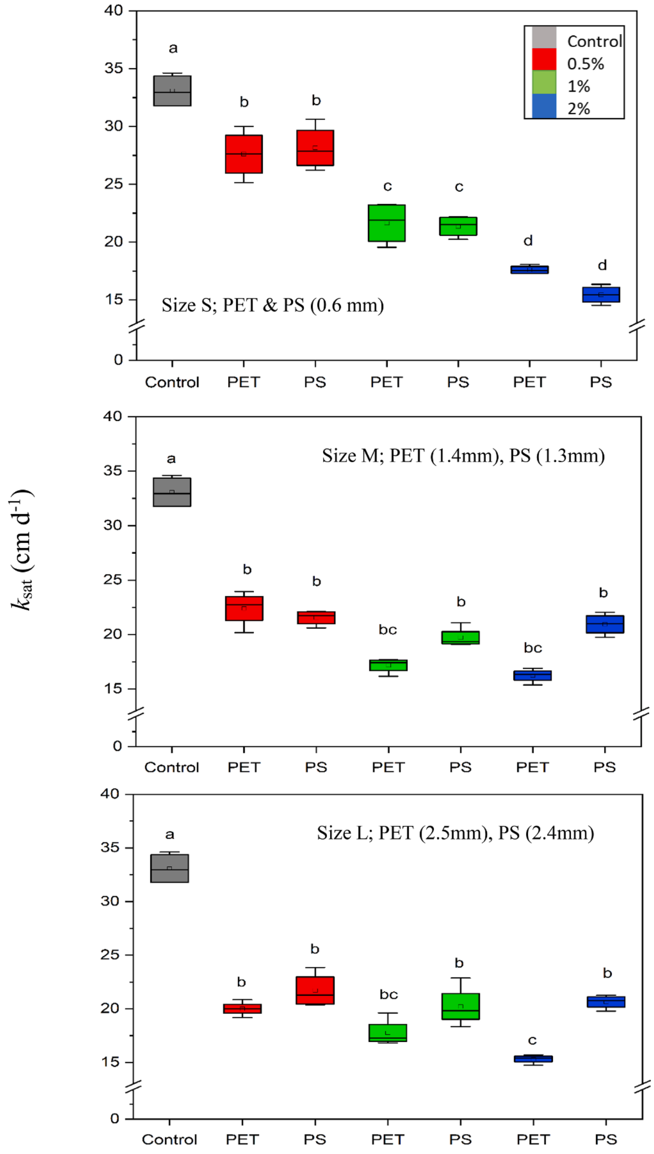


Fig. 2. Effects of various microplastic (MP) concentrations (0.5%, 1% and 2%) at different size fractions on saturated hydraulic conductivity (k_{sat}). Different letters indicate significant differences ($p < 0.05$) ($n = 4$).

the control with the strongest increase for the PET-treatment at 2 % concentration and a size ≥ 2 mm (L; Table 3). At the same time field capacity of the control was about 4 vol-% higher than for the PET-treatment (≥2 mm size and 2 % concentration).

Microplastic decreased plant available water by about 5 vol-% compared to the control, with the strongest effect found for the highest concentration. The highest MP concentration and size M (≥1 and < 2 mm) showed the most pronounced reduction of plant available water. The water content at the permanent wilting point was reduced by about 3 vol-% in samples treated with MP of size L (≥2 mm) and at 2 % concentration (Table 3).

MP in trend also affected total soil pore volume in all MP treated samples compared to the control, however, differences were < 1% (Table 3). The changes were due to reducing the mean particle density of the soil-MP mixtures compared to the control with mineral particles only.

No significant difference was observed between the particle sizes and concentrations (Fig. 4; A&B). Microplastic type was not found to impact the effects of MP addition on soil water retention.

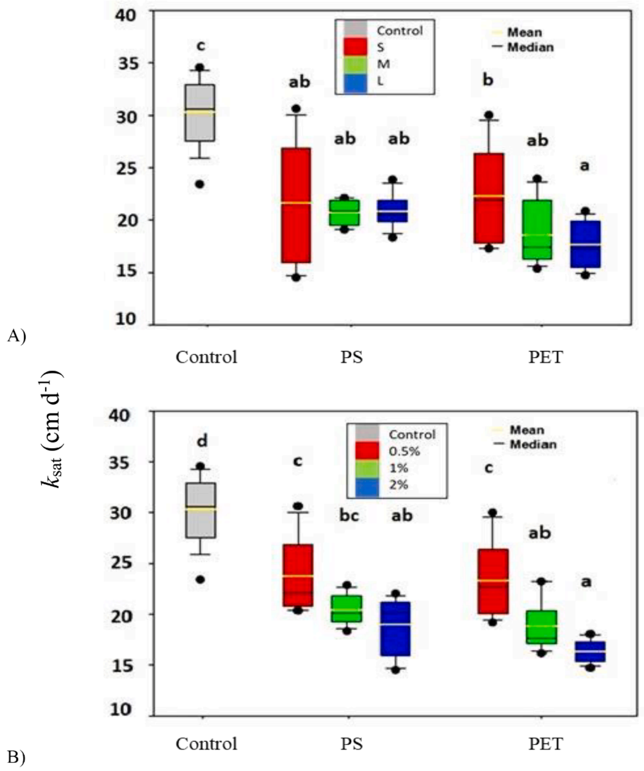


Fig. 3. Effect of microplastic particle size (A) and concentration (B) on saturated hydraulic conductivity (k_{sat}) for the two microplastic types (polystyrene, PS and polyethylene terephthalate, PET) in relation to the Control. Different letters indicate significant differences ($p < 0.05$) ($n = 4$).

Table 2

Statistical tests of the impact of added microplastic (MP) type, particle size, and concentration on saturated hydraulic conductivity and soil water retention parameters for fixed parameters and the combined factors *F*-value (*p*-value).

Factors and Interactions	DF	log10(*ksat*)	AC (vol-%)	FC (vol-%)	PAW (vol-%)	WP (vol-%)	TPV (vol-%)
MP Type	2	223.96***	57.46***	4.62*	16.10***	58.90***	1.57e + 26 ***
MP particle Size	2	12.33***	36.82***	1.15	0.69	25.15***	0.00e + 00
Concentration	2	52.07***	12.39***	4.57*	2.56	6.70**	1.85e + 26 ***
Type: Size	2	5.59**	0.10	0.24	1.27	7.76***	0.00e + 00
Type: Concentration	2	1.70	0.79	1.37	0.93	1.93	0.00e + 00
Size:Concentration	4	11.33***	1.05	0.29	0.30	5.77***	0.00e + 00
Type:Size:Concentration	4	2.41	0.32	0.48	0.22	0.86	0.00e + 00

DF: degree of freedom for the *T*-test; k_{sat}: saturated hydraulic conductivity; AC: air capacity; FC: field capacity; PAW: plant available water; WP: wilting point; TPV: total pore volume. The asterisks indicate that the values are significantly different (*$p < 0.05$, **$p < 0.01$ and ***$p < 0.001$).

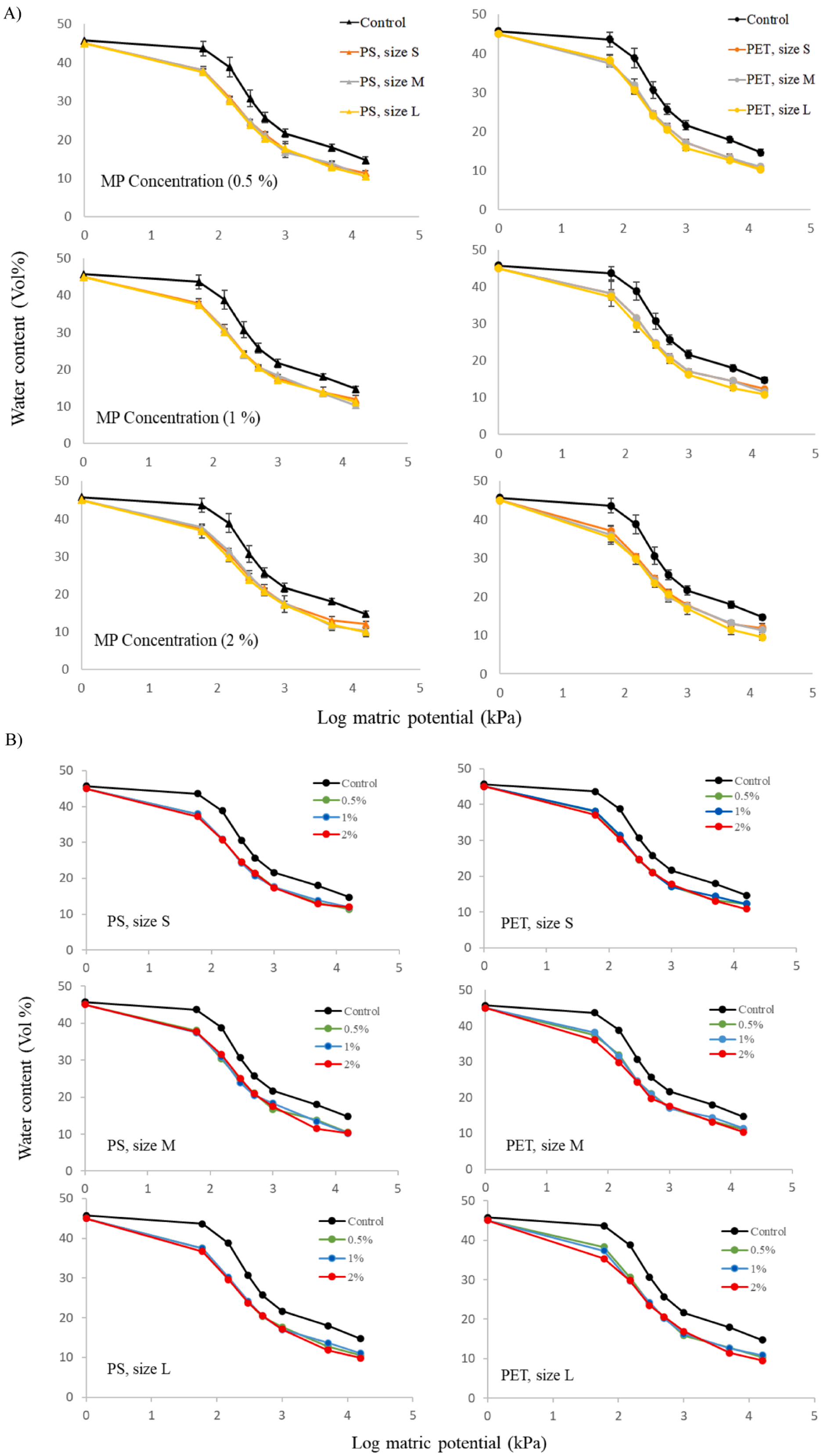


Fig. 4. Effect of microplastic addition (left: Polystyrene; right: Polyethylene terephthalate) on the soil water retention curve at concentrations (w/w) of 0.5%, 1% and 2% for different microplastic particle sizes (A), and for different particle concentrations, and effects of various concentrations (B) of PET and PS MP for different particle sizes; (S): polyethylene terephthalate and polystyrene (both 0.6 mm); (M): polyethylene terephthalate (1.4 mm); polystyrene (1.3 mm); and (L): polyethylene terephthalate (2.5 mm), polystyrene (2.4 mm). Concentrations; 0.5%, 1% and 2% (w/w). Error bars represent the standard deviation of replicates (*n* = 4).

Table 3
Calculated soil hydraulic parameters for the Control and soil/microplastic variants and statistical analysis with respect to microplastic (MP) size fraction and concentration k_{sat}: saturated hydraulic conductivity; AC: air capacity; FC: field capacity; PAW: plant available water; WP: wilting point; TPV: total pore volume. Particle sizes; (S): polyethylene terephthalate (PET) and polystyrene (PS) (both 0.6 mm); (M): polyethylene terephthalate (1.4 mm); polystyrene (1.3 mm); and (L): polyethylene terephthalate (2.5 mm), polystyrene (2.4 mm). Concentrations; 0.5%, 1% and 2% (w/w), ($p < 0.05$).

TYPE-Size-Concentration	k_{sat} (cmd $^{-1}$)	TPV (Vol %)	AC (Vol %)	FC (Vol %)	PAW (Vol %)	PWP (Vol %)
Control	30.31 ± 3.18a	45.66 ± 0.00 d	7.04 ± 1.39d	45.26 ± 2.03b	34.01 ± 2.05b	14.74 ± 0.69a
PET-S-0.5%	27.61 ± 2.1 ab	45.53 ± 0.00c	7.89 ± 0.34c	44.84 ± 1.61ab	32.76 ± 1.64ab	12.08 ± 0.06c
PET-S-1%	21.64 ± 1.86 bc	45.40 ± 0.00b	7.97 ± 0.58c	44.87 ± 1.13ab	30.41 ± 1.10a	14.46 ± 0.04 ab
PET-S-2%	17.6 ± 0.37c	45.13 ± 0.00 a	9.63 ± 0.98 ac	43.68 ± 1.34ab	29.67 ± 2.31a	14.00 ± 1.35 ab
PS-S-0.5%	28.15 ± 1.95ab	45.50 ± 0.00c	8.02 ± 0.77bc	44.62 ± 0.53ab	31.23 ± 0.96a	13.39 ± 0.73b
PS-S-1%	21.37 ± 0.93bc	45.33 ± 0.00b	9.29 ± 0.48ac	44.64 ± 1.28ab	30.68 ± 2.58a	13.96 ± 1.33b
PS-S-2%	15.44 ± 0.8 d	45.00 ± 0.00 a	9.23 ± 1.61ac	43.77 ± 1.19ab	29.61 ± 0.46a	14.16 ± 0.74 ab
PET-M−0.5%	22.4 ± 1.61bc	45.53 ± 0.00c	8.90 ± 1.33bc	44.09 ± 1.21ab	31.09 ± 1.24a	13.00 ± 0.07b
PET-M−1%	17.18 ± 0.7c	45.40 ± 0.00b	9.76 ± 0.99ac	44.87 ± 1.13ab	31.37 ± 1.24a	13.50 ± 0.26b
PET-M−2%	16.23 ± 0.63c	45.13 ± 0.00 a	10.63 ± 0.56ab	42.42 ± 2.76ab	29.04 ± 2.73a	13.38 ± 0.13b
PS-M−0.5%	21.54 ± 0.71bc	45.50 ± 0.00c	9.44 ± 0.74ac	44.71 ± 1.08ab	32.39 ± 1.09ab	12.32 ± 0.15c
PS-M−1%	19.72 ± 0.93c	45.33 ± 0.00b	10.03 ± 1.68ab	44.03 ± 0.38ab	31.96 ± 0.47ab	12.06 ± 0.11c
PS-M−2%	20.94 ± 1 bc	45.00 ± 0.00 a	10.62 ± 1.06ab	44.37 ± 0.74ab	32.29 ± 0.37ab	12.08 ± 0.75c
PET-L-0.5%	20.01 ± 0.68 bc	45.53 ± 0.00c	10.81 ± 0.30ab	45.01 ± 1.63ab	32.86 ± 1.65ab	12.14 ± 0.05c
PET-L-1%	17.75 ± 1.27c	45.40 ± 0.00b	10.76 ± 1.13ab	43.87 ± 1.14ab	31.08 ± 1.10a	12.78 ± 0.09c
PET-L-2%	15.32 ± 0.41 d	45.13 ± 0.00 a	13.25 ± 1.06a	41.58 ± 1.43a	30.38 ± 1.96a	11.20 ± 0.83d
PS-L-0.5%	21.7 ± 1.63 bc	45.50 ± 0.00c	11.27 ± 0.70ab	44.11 ± 0.83ab	31.74 ± 0.85a	12.37 ± 0.22c
PS-L-1%	20.21 ± 1.91 bc	45.33 ± 0.00b	10.83 ± 0.41ab	44.10 ± 0.93ab	31.08 ± 0.78a	13.02 ± 0.18b
PS-L-2%	20.74 ± 0.66 bc	45.00 ± 0.00 a	12.84 ± 0.64a	43.21 ± 2.19ab	31.61 ± 3.10a	11.60 ± 1.20d

3.3. *Impact of MP on soil wetting properties*

The mean contact angle (CA) for the largest size (L) of the pure MP (without soil) was 137.6° (PS) and 157.1° (PET), while the medium size range (M) MP showed the highest degree of water repellency with 166.8° and 168.1° for PET and PS, respectively (Fig. 5, A). Contact angles of soil samples mixed with MP showed a statistically significant increase compared to the control in all treatments (MP type and size) only at 2 % concentration (Fig. 5, B), while lower concentrations (0.5 and 1 %) had no clear effect (data not shown). Contact angles increased with MP size from small to large. The size fraction < 1 mm increased CA of the soil, but less than the fraction > 1 mm that changed soil wettability from subcritically water repellent (i.e., CA > 0ˆand < 90°) to hydrophobic (i.e., CA ≥ 90°; Fig. 5, C). In contrast to the pure MP, the largest size fraction (L) of both MP types resulted in higher CA compared to the smallest fraction (S) when mixed with the soil. The largest effect on soil wetting properties was observed in the mixture of soil with MP > 1 mm (M, L; Fig. 5, C). No measurable impact was found with respect to MP type.

4. Discussion

4.1. *Hydraulic implications*

Several key findings of this study support the impact of MP particles on transport and retention of water in soil: (i) Both types of MP tested (PET and PS) affected soil water parameters, while there was no significant difference between MP types with respect to water retention and CA. For saturated hydraulic conductivity a stronger impact of PET was indicated. (ii) Tested sizes and concentrations of MP caused a notable reduction in soil water retention and k_{sat} compared to the control. (iii) The impact of MP on k_{sat} was connected to MP type, size, and concentration.

In our study, at 2 % concentration of both PET and PS, k_{sat} was reduced by a factor of two compared to the control, which may have

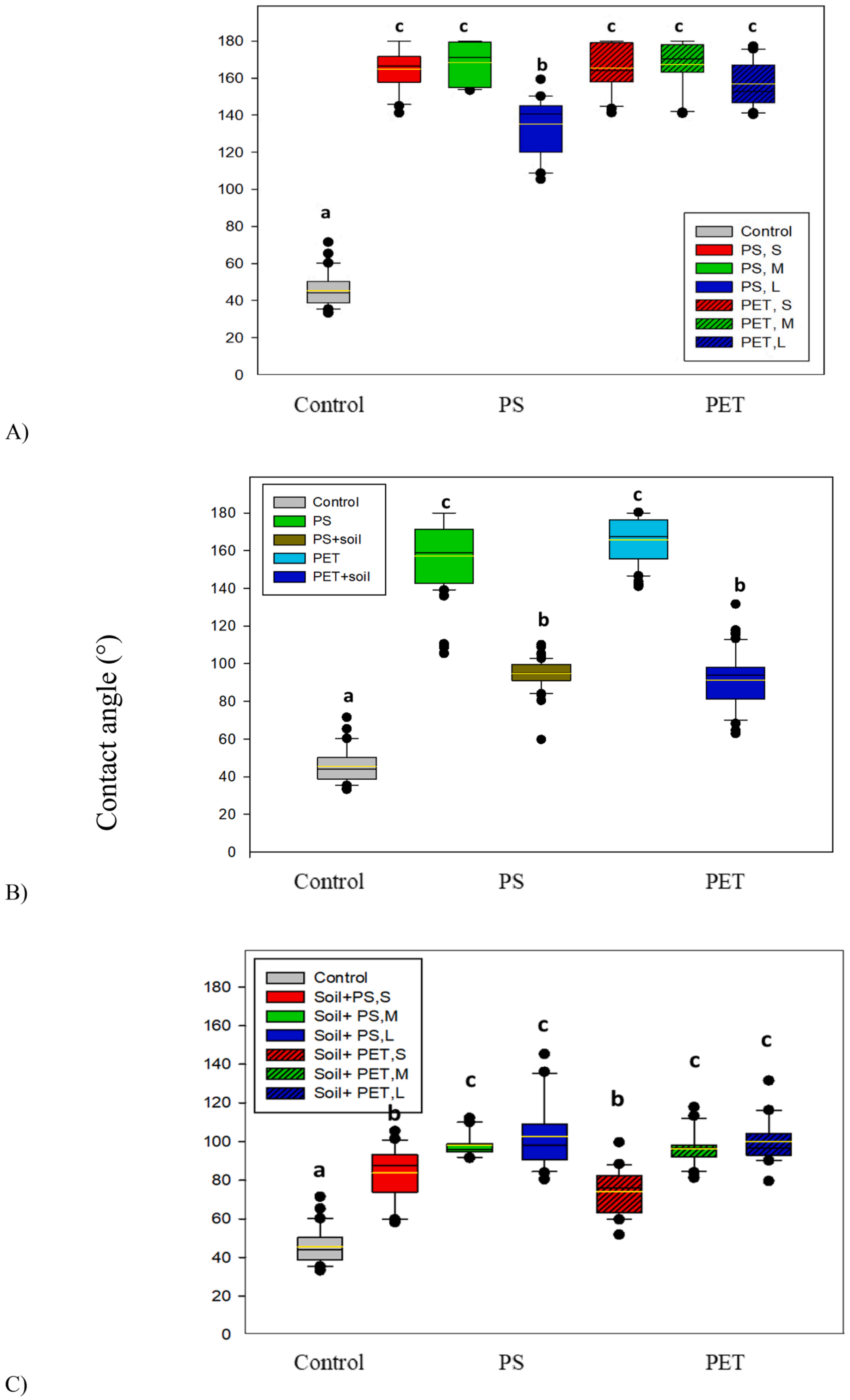


Fig. 5. Advancing contact angle (CA) as determined with the Wilhelmy plate method ($n = 20$). A: CA of the three size fractions of the pure polymers (Polyethylene terephthalate, PET and Polystyrene, PS). B: Microplastic (MP)-treated soil at 2 % concentration irrespective of MP size compared to pure MP and control. C: CA of MP-treated soil samples for different MP sizes at 2 % MP concentration. Control was soil without MP addition. Particle sizes; (S): polyethylene terephthalate and polystyrene (both 0.6 mm); (M): polyethylene terephthalate (1.4 mm); polystyrene (1.3 mm); and (L): polyethylene terephthalate (2.5 mm), polystyrene (2.4 mm).

been caused by clogging of soil pores as suggested by Guo et al. (2022). We observed a stronger reduction for concentrations ≥ 1 % as they used the concentrations of 0.5%,1%, 2%, 4% and 6% of polypropylene fragment and with larger particle sizes (Fig. 2). Our findings support the importance of MP effects on soil water characteristics in highly contaminated soils. Similar k_{sat} values for 1 and 2 % addition may indicate a threshold concentration of 1%. However, the impact of higher concentrations, i.e., >2%, remains to be tested. These results generally confirm our second hypothesis but do not support our first hypothesis (Fig. 2). At the same concentration, smaller particle sizes seemed to have resulted in a more homogeneous distribution of MP particles in the soil and thus a stronger pore-clogging effect (Fig. 2, A). Microplastics decreased soil water retention in general, while at high matric potential (pF 4.2) an additional impact of larger MP size and higher concentration is indicated (Fig. 4). These results agree with the results of Guo et al. (2022), who showed a reduction in water retention at larger MP size 20 µm- 500 µm (size S in our study), and are also supported by the results of a study by de Souza Machado et al. (2019). The authors explain this reduction with decreasing soil porosity and the hydrophobic characteristics of MP with strong repulsion of water molecules.

Our study did not find a decrease in porosity but an increase in coarse pores (Fig. 4), which is consistent with a study by Zhang et al. (2019). The mentioned study showed an increase in the volume of > 30 µm pores and a reduction in the volume of < 30 µm pores by adding PS-MP fibers. As suggested by Guo et al. (2022), MP can reduce the number of soil micropores (i.e., <0.2 µm diameter) by interfering with the agglomeration of small soil particles and reducing soil water retention. Furthermore, we found that with increasing MP concentration from 0.5 to 2 %, field capacity, plant available water, and permanent wilting point were reduced similarly for both MP plastic types tested (Table 3). Our study also showed an enhancement in soil air capacity with increasing MP size and concentration for both, PET and PS (Table 3), which concurs well with a study by Lozano et al. (2021). The extent to which MP affects soil hydraulic properties seems to depend on soil texture and soil porosity changes in the presence of MP particles (Chia et al., 2022). For example, polyester fibers (8 µm × 5.000 µm, 0.4 % [w/w]) in a loamy sand soil increased porosity, water holding capacity, and evapotranspiration (de Souza Machado et al., 2018). In contrast, Zhang et al. (2019) observed a reduction in water holding capacity by incorporating polyester fibers (5 µm × 2.650 µm, 0.3% [w/w]) into clayey soil. However, saturated hydraulic conductivity was not affected by polyester MP addition in a clayey soil (Zhang et al., 2019) and a loamy sand soil (de Souza Machado et al., 2018), despite the significant changes in soil bulk density. Our study, adding MP to a silty loamy soil, showed a reduction in k_{sat} compared to the control depending on MP concentration assumedly due to clogging of micropores and a reduction of water retention parameters due to an increase in the amount of the macropores. This is consistent with previous results reported by Wang et al. (2015). In general, the effect of MP on soil hydrological parameters is associated with a shift in pore distribution, thus affecting the availability of water and nutrients in the agroecosystem (Wang et al., 2022).

4.2. *Soil wetting properties*

The MP-soil mixtures with MP particles > 1 mm showed a higher degree of water repellency than the control and treatments with particles < 1 mm, which was similar for both polymer types and was in contradiction to our third hypothesis as it indicates more significant interactions between larger MP particles and air molecules compared with smaller MP size fractions (Fig. 4). Cramer et al. (2022) as well found a relation between MP particle size and CA, however, they used much smaller MP particles (20–125 µm), not allowing a direct comparison with our results. The highest advancing CA in our study were found at 2 % MP addition (Fig. 5, C), which supported our third hypothesis, while previous studies reported the strongest water repellency to occur between 1 % and 2 % of MP addition (Qi et al., 2020). Cramer et al. (2022), however, also found increasing soil water repellency with increasing MP concentration, which agrees with our results. Furthermore, MP could reside in soil pores for longer periods of time, thus potentially reducing water infiltration due to its hydrophobic properties (Liu et al., 2022). The impact of hydrophobic particles on soil water infiltration depends on MP particle size (Cramer et al., 2022).Smaller MP particles can accumulate in soil pores and decrease the amount of coarse pores, thereby impeding water movement (de Souza Machado et al., 2019).

This study evaluated the impact of pristine MP on saturated hydraulic conductivity, water retention, and wetting properties. However, the hydrophobic properties of the different MP types are not fixed over time but can change as the MP ages. Different aging processes can reduce hydrophobicity, which increases MP migration into deeper soil layers (Ren et al., 2021). For example, size reduction, surface alteration, and formation of polar functional groups due to environmental effects, e.g., by UV irradiation, thermal and biological degradation, and biofilm formation; (Kublik et al., 2022) and oxidation and mechanical abrasion (Ding et al., 2020; Ghatge et al., 2020; Sørensen et al., 2021), modify the physicochemical properties of MP particles, accelerating transport of MP in porous soil media and groundwater systems (O'Kelly et al., 2021). The aspect of changing surface properties of MP due to aging therefore should be a key focus of future research on the topic. Further, the possible impact of MP shape (e.g., particles, flakes, fibers) on the tested parameters remains to be tested.

5. Conclusions

Soils as a crucial part of agroecosystems are increasingly affected by MP pollution. So far, little was known about the effect of MP on soil's physical (hydraulic) and physicochemical properties. The present study provided clear evidence that MP pollution reduces saturated hydraulic conductivity in highly contaminated soils. The combined effect of MP size and concentration was also observed to impact plant available water, with a maximum reduction of this parameter at 2 % MP concentration. Our study shows the effect of pore clogging by MP on saturated hydraulic conductivity and hence serves as an indicator for losses in pore connectivity and infiltration capacity especially during near saturated soil conditions. However, flow under unsaturated conditions may be affected differently which should be considered in future research e.g. by measuring unsaturated hydraulic conductivity functions of MP contaminated soils. Summarized, the observations of this study clearly confirmed an impact of MP on soil hydraulic properties. The soil contact angle was increased when MP concentration reached 2 % of dry soil weight, which corresponds to a typical concentration under field conditions. It highlights the potential effect of accumulated hydrophobic MP on soil water relations (retention and dynamics) at agricultural fields. Overall, the presented experimental setup is indicated to be a straightforward setting to simulate the consequences of MP addition in farmland soil due to the usage of plastic materials (e.g., plastic greenhouse and mulches). We conclude that our research underlined the importance of MP concentration and size for alterations in agroecosystems' natural hydraulic functioning and soil–plant interaction with consequences for root water uptake and plant production in general in farmlands. Addressing the effect of MP surface modification due to aging as well as various MP shapes on soil physical properties is suggested for future research. Moreover, future studies should consider the impact of soil texture on the effects due to MP addition.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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