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Effects of tire wear particles on the water retention of soils with different textures in the full moisture range

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ABSTRACT

Tire wear particles (TWPs) are significant contributors to microplastic pollution in the environment, yet there is limited scientific information concerning their impact on soil hydraulic properties. This study aimed to investigate the impact of TWPs at different concentrations (1, 4, 8, and 16% of the air-dried mass of packed soil samples, w/w) on the water retention curves (WRC) of southern California soils with five different textures (clay, clay loam, silt loam, sandy loam, and loamy sand). The concentrations of 8% and 16% were selected to represent extreme pollution scenarios that might occur near highway corridors. High-resolution water retention data, spanning from saturation to oven dryness, were generated using HYPROP™ and WP4C dew point meter instruments. We also developed WRC scaling equations based on the quantity of TWPs. The bulk density of the samples decreased as the TWP concentration in soils increased. The inclusion of very high concentrations of TWPs (8% and 16% w/w) led to a significant reduction in soil moisture content in the intermediate and dry ranges across various soil textures. However, at the same moisture range, adding 1% TWPs had a minimal impact on soil moisture reduction, while the influence of the 4% TWPs concentration treatment was noticeable only in loamy sand and partially in clay loam soils. Additionally, the overall plant available water decreased with increasing TWP concentrations, except for the clay soil. The texture-specific scaling models exhibited promising performance, with RMSE values ranging from 0.0061 to 0.0120 $cm^3\ cm^{-3}$. When bulk density was included as an additional input predictor to construct a single scaling model for all textures, the RMSE increased. Nevertheless, it still indicated a good fit ranging from 0.007 to 0.024 $cm^3\ cm^{-3}$, highlighting the suitability of simple scaling for identifying WRC in TWPs-polluted soils, particularly for practical purposes. The findings of this study can contribute to a better understanding and quantification of the impact of TWPs on soil hydrology.

1. Introduction

Microplastics (MPs) are defined as plastic particles with an effective diameter of <5 mm (Frias and Nash, 2019). They are usually formed from polymeric products serving a range of purposes, such as textiles within the fashion industry, food packages and vehicle tires (Jadhav et al., 2021; Periyasamy and Tehrani-Bagha, 2022). The broad application and simple spreading of MPs have resulted in their presence in diverse ecosystems, from air to marine and terrestrial environments (Horton et al., 2017; Scheurer and Bigalke, 2018).

Depending on their polymeric substances and formation process, MPs can have a variety of forms and shapes, ranging from microbeads used in cosmetic products (Guerranti et al., 2019) to films and fibers generated by processes such as fragmentation, weathering, and degradation (Julienne et al., 2019; Tian et al., 2022; Wang et al., 2015). Their base polymeric substance and chemical additives have given them versatile characteristics such as toxicity, long environmental lifetime, and interactions with other toxic compounds (Padervand et al., 2020; Wang et al., 2018; Wang et al., 2023; Wik and Dave, 2009). These characteristics have arguably placed microplastic pollution, along with climate change, as one of the most significant anthropogenic environmental concerns in human history. Following the global concern, research on the detection and analysis of MPs dates back to the beginning of the century when they were reported in marine environments (Thompson et al., 2004) and later in terrestrial ecosystems (Horton et al., 2017). The pollution of agricultural soils by MPs is also of emerging concern which requires dedicated investigation into the impact of these pollutants on soils (Guo et al., 2020; Wang et al., 2019).

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Soil systems are recognized as long-term sinks for MP particles (Bläsing and Amelung, 2018; Scheurer and Bigalke, 2018). Among the primary sources of MPs pollution, especially in agricultural soils, are sewage sludge or treated wastewater application as soil amendments (Corradini et al., 2019; Wang et al., 2019), plastic mulches or greenhouse covers, microplastic-containing fertilizers used in agriculture (Guo et al., 2020), and tire wear particles (TWPs) resulting from the erosion of tire treads on urban or rural roads and subsequently deposited into soils by wind or rainfall (Luo et al., 2021; Wik and Dave, 2009). TWPs stand out as having the largest portion of MPs in the environment, with reported values nearly fifty times higher than other MPs (Goßmann et al., 2021; Rasmussen et al., 2023). They are known to accumulate in soils at high volumes, with dry weight concentrations varying from 0.04% to 15.8% (w/w) (Baensch-Baltruschat et al., 2020). The concentration of the TWPs in soils depends on the distance from the highways and the traffic volume of the road (Goßmann et al., 2021). A recent study revealed exceptionally high TWP concentrations (up to 2.6% in dry-weight of soil) even in the soils of rural areas with low-traffic roads in Norway (Rødland et al., 2023).

Studies have shown that the chemical, physical, and biological composition and characteristics of the soils are influenced by the presence of MPs such as TWPs (de Souza Machado et al., 2018). However, the influence of TWPs on soil hydraulic properties (SHPs), specifically the water retention curve (WRC) and hydraulic conductivity curve (HCC), is still under question and requires further research. SHPs are essential inputs for solving the Richards equation and studying the flow and transport properties of saturated and unsaturated soils. SHPs depend mainly on the structure and texture of the soils and vary depending on any changes imposed on them. However, research on the impacts of MPs on SHPs is very scarce, and do not fully agree. For instance, while some studies indicate that MPs reduce the water-holding capacity (WHC) of soils, others demonstrate an enhanced WHC with low concentrations of MPs (Wang et al., 2023; Zhou et al., 2021). Nevertheless, among the few available studies, data on the impact of different concentrations of TWPs on the hydraulic properties of soils with different textures are neglected. Guo et al. (2022) studied the influence of polypropylene MPs on the SHPs of three soils with loam, clay, and sand textures. They applied three particle sizes (20, 200, and 500 μm) and different concentrations (up to 6%, w/w) of MPs in their experiments and observed a reduction in the water retention capacity of soils by the added MPs. Their results showed the influence of MPs on the available soil pore space depending on the soil texture. This effect was more pronounced in clay soils compared to loam and sandy soils. In a similar study, Jing et al. (2023) extended the range to larger MPs and explored the effects of Polyethylene MPs with different sizes (25, 150, 550, and 1000 μm) and concentrations (up to 5%, w/w) on the SHPs of a silt loam soil. Their findings also highlight a significant reduction in the WHC of the soil depending on its MP concentration. However, Wang et al. (2023) emphasized that the impact of higher concentrations of MPs on the WHC of soil depends highly on soil texture rather than the size and concentration of MPs. In their study, the van-Genuchten parameters obtained for different soil textures followed different trends depending on the MPs concentrations and their impact on the porosity, surface area, and pore volume of each soil texture. A substantially reduced WHC of the MPs contaminated soils, even at lower concentrations (i.e., 2%, w/w) depending on the soil texture, was reported in similar studies (Shafea et al., 2023; Wang et al., 2023; Yu et al., 2023). These studies, however, mostly neglected the role of soil texture and did not consider TWPs.

There is a need for a systematic study that addresses the influence of TWP accumulation on the water retention characteristics of soils across a wide range of concentrations. Therefore, we investigated the influence of TWPs, the most common MPs, on the WRC of soils with different textures. The WRC of five soil materials mixed with four concentrations of TWPs were measured in an experimental setup. The amount of TWPs varied from very low to very high concentrations. Our objective was to investigate the impact of TWPs on the WRC of soils with different textures in the full moisture range and to develop a straightforward scaling model for estimating the WRCs of contaminated soils in the intermediate to dry range. The high-resolution WRC data were obtained through the combination of evaporation and chill-mirror techniques, which assisted us in providing a more detailed description of the impact on the full moisture range of the WRCs. This study stands as a pioneering effort to obtain high-resolution water retention data of soils with different textures contaminated with low to very high concentrations of TWPs. Two simple linear scaling models were developed to assess the impact of TWPs on the WRC of the soils within the range of field capacity (FC, pF = 1.8) to permanent wilting point (PWP, pF = 4.2). For that purpose, two modeling cases were explored. In the first case, distinct models were established for each soil texture, utilizing TWPs as the sole input predictor. In the second case, a universal model was created by adding the dry bulk density of soil as an additional input predictor.

Table 1
Some physical and chemical properties of the soil materials used in the current study.

Texture	Sand (%)	Clay (%)	Silt (%)	ρ_b (g cm^{-3})	EC (ds m^{-1})	TOC (%)	TN (%)
Sandy loam	62	6	32	1.47	1.68	0.78	0.14
Loamy sand	80	3	17	1.61	1.97	0.65	0.13
Clay loam	29	35	37	1.33	6.02	1.87	0.14
Silt loam	24	20	57	1.38	7.42	1.65	0.09
Clay	18	48	34	1.38	8.06	1.88	0.13

EC: Electrical conductivity, TOC: Total organic carbon, TN: Total nitrogen, and ρ_b: Bulk density of the control samples.

2. Materials and methods

2.1. Soil material preparation

Soil materials were collected from two distinct sites situated in southern California. The coarse-textured soils were obtained from landscape irrigation plots located at the University of California Riverside Agricultural Experiment Station in Riverside, California. A total of 72 samples from depths of 0–50 cm and 50–100 cm of 36 research plots were gathered. The fine-textured soil materials were obtained from a 60-ha commercial alfalfa field situated in the Imperial Valley, Southern California. A collection of 144 disturbed soil samples was obtained across 36 sampling locations, with sampling increments of 0.3 m, extending down to 1.2 m depth. Soil materials were air-dried, cleaned of the fine roots, and sieved through a 2 mm sieve. Particle size distributions of the soils were determined using the PARIO™ device (METER Group, Inc., Pullman, WA, USA) and the hydrometer soil particle size analysis method. As a concluding step, samples of similar textures from each site were mixed to create a composite soil material for the purpose of this study. Finally, five major soil textures – clay (C), clay loam (CL), silt loam (SiL), sandy loam (SL), and loamy sand (LS) – were specifically selected for the experiments. The physical and chemical properties of the soil materials used in this study are outlined in Table 1. The bulk density (ρ_b, g cm^{-3}) of the control samples ranged from 1.33 for the clay loam to 1.61 for the loamy sand soil textures. The total soil organic carbon content was found to be <1% for the coarse-textured and below 2% for the fine-textured soils. Fig. 1 depicts a schematic illustration of the sample preparation, laboratory measurement, and data processing and modeling steps.

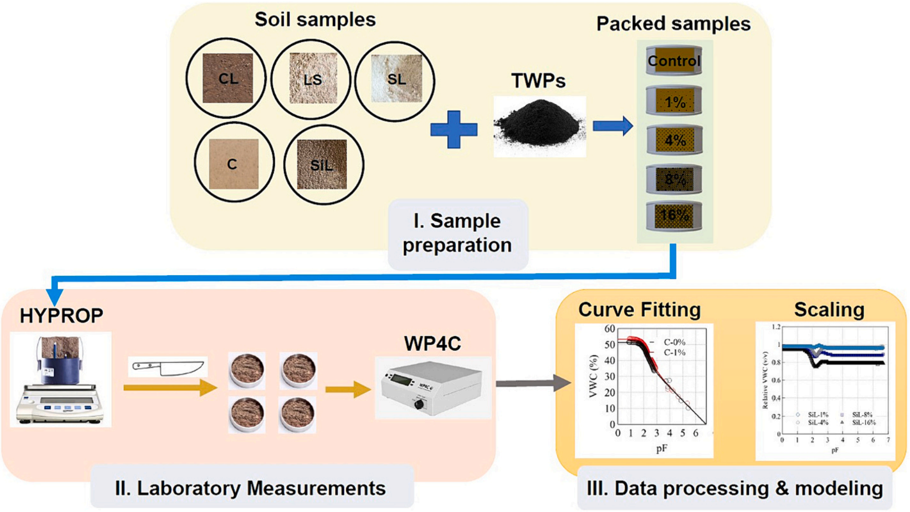

Fig. 1. Schematic illustration of the sample preparation (step I), laboratory measurement (step II), and data processing and modeling steps (step III). Step I included sieving air-dried soil samples, mixing them with tire wear particles at four different concentration levels ranging from 1% to 16% (w/w) and then packing them inside HYPROP™ cylinders. Step II involved wet and intermediate water retention measurements using HYPROP™ and then subsampling each packed sample for dry-end water retention measurement using the WP4C instrument. Step III involved fitting the Peters-Durner-Iden variant of the van Genuchten model using HYPROP-FIT software and then using linear regression to scale the water retention curves between field capacity and permanent wilting point. C: Clay, CL: Clay loam, SilL: Silt loam, LS: Loamy sand, and SL: Sandy loam.

2.2. Sampling process

This study encompassed four TWP concentration levels to investigate their influence on the WRC of soils. These levels included concentrations in the range of 0 (control), 1, 4, 8, and 16% (w/w) of the air-dried mass of each packed control sample with the specified ρ_b. The all-black rubber powder TWPs (150 µm - 1 mm) were sourced from Entech, Inc. (Middlebury, IN, USA). The air-dried sieved soil materials with different concentrations of TWPs were packed within 250 cm^3 stainless-steel cylinders (inner diameter: 8 cm, height: 5 cm). To ensure homogeneously and uniformly packed samples regardless of their TWP concentrations, the soil material and TWPs underwent a meticulous manual mixing process before being packed in multiple stages. The packing process was similar for all samples and replicates. Target ρ_b for the control soil samples were chosen in accordance with measurements taken at the collection sites. Packed soil cylinders were carefully placed in water containers from the bottom and allowed to naturally saturate before the evaporation experiment.

2.3. Laboratory measurements

Saturated soil cylinders were mounted on HYPROP™ devices (METER Group, Inc., Pullman, WA, USA), positioned on balances, and allowed to evaporate freely from the top. HYPROP™ device uses the simplified evaporation method for the identification of SHPs (Peters and Durner, 2008; Peters et al., 2015). In this method, SHPs are identified through a continuous measurement of the water content and matric potential in two depths of a soil sample. The evaporation method using HYPROP™ has been successfully used to identify the hydraulic properties of soil systems (Haghverdi et al., 2018; Singh et al., 2020) and soil mixtures (Naseri et al., 2019; Naseri et al., 2023). The experimental campaign consisted of five HYPROP™ devices, each placed separately on a scale within an air-conditioned laboratory. That provided us with simultaneous measurement of SHPs for five samples with similar soil texture and different TWP concentrations. Each HYPROP™ measurement campaign was followed by WRC dry-end measurements using the WP4C Dew Point PotentioMeter benchtop instrument (METER Group, Inc., Pullman, WA, USA). For that purpose, four subsamples with an approximate volume of 7 cm^3 were sliced from each soil cylinder after the HYPROP™ measurement campaign. Subsamples were taken from four distinctive depths of the soil cylinder to produce a wider distribution of water retention data points using the WP4C device. After measuring the matric potential of each soil subsample using WP4C, their water contents were measured precisely by oven-drying. Soil subsamples were then added to the original HYPROP™ soil and the total soil samples were oven-dried to obtain their moisture content and dry ρ_b. The HYPROP™-WP4C measurements (repeated two times) yielded high-resolution water retention data over a wide moisture range for all the samples.

2.4. WRC parametrization of soil samples

The Peters–Durner–Iden (PDI) variant (Iden and Durner, 2014; Peters, 2013) of the constrained van-Ghenuchten (VG) (Van Genuchten, 1980) model with four free parameters (hereafter called VG-PDI model) was fitted to the measured water retention data. The VG-PDI model ensures that water content reaches zero at oven-dryness by introducing a linear reduction in water content against the logarithmic transformation of soil matric potential (cm) (i.e., $\mathrm{pF} = \log 10(|\mathrm{h}|)$) within the dry range of the WRC (Iden and Durner, 2014). The VG-PDI model does not require more parameters than the original VG model and is shown to have a more consistent description of the WRC in low moisture contents (Haghverdi et al., 2020).

The general form of the VG-PDI model consists of a superposition of capillary, $\theta^{cap}(h)$ (cm^3 cm^{-3}) and adsorptive retention terms, θ^{ad} (h) (cm^3 cm^{-3}), shown as:

$$\theta(h) = \theta^{cap}(h) + \theta^{ad}(h) = (\theta_s - \theta_r)\, S^{cap} + \theta_r\, S^{ad} \tag{1}$$

where S^{cap} and S^{ad} are capillary and water adsorption saturation functions (−), h is the soil matric potential (cm), and θ_s and θ_r (cm^3 cm^{-3}) are the soil saturated and maximum adsorbed water contents, respectively.

To ensure the physical constraint that the water content reaches zero at oven-dryness ($h = h_0$), the S^{cap} is substituted by a scaled version of the VG model:

$$\theta(h) = (\theta_s - \theta_r)\frac{\Gamma(h) - \Gamma_0}{1 - \Gamma_0} + \theta_r S^{ad} \tag{2}$$

where h_0 (cm) is the matric potential at oven-dryness, $\Gamma(h)$ represents any saturation functions such as Van Genuchten (1980), Fredlund and

Table 2

Parameter bounds for the VG-PDI model imposed during the fitting process by the HYPROP-FIT software.*

Parameters	Min	Max	Unit
θ_s	0.1	1	$cm^3\ cm^{-3}$
θ_r	0	0.4	$cm^3\ cm^{-3}$
α	0.00001	0.5	cm^{-1}
n	1.01	15	–

[*] A pF value of 6.8 was set for all the oven-dried soil samples.

Xing (1994) and Kosugi Kosugi (1996) and Γ_0 is the basic function at $h = h_0$:

$$\Gamma(h) = \left[\frac{1}{1+(\alpha h)^n}\right]^{1-1/n} \tag{3}$$

where α (cm^{-1}) and n (–) are the van Genuchten shape parameters. The water adsorption saturation function, $S^{ad}(x)$ is given by (Iden and Durner, 2014):

$$S^{ad}(x) = 1 + \frac{1}{x_a - x_0}\left\{x - x_a + b\ln\left[1 - exp\left(\frac{x_a - x}{b}\right)\right]\right\} \tag{4}$$

where x_a and x_0 are pF (–) values at suctions equal to h_a and h_0 (cm), respectively. h_a is the suction at air entry for the adsorptive retention and b is the shape parameter (–):

$$b = 0.1 + \frac{0.2}{n^2}\left\{1 - exp\left[-\left(\frac{\theta_r}{\theta_s - \theta_r}\right)^2\right]\right\} \tag{5}$$

Table 2 shows the parameter bounds used for the VG-PDI model parameters during the non-linear parameter optimization. The fitting algorithm minimized the sum of squares deviations between measured

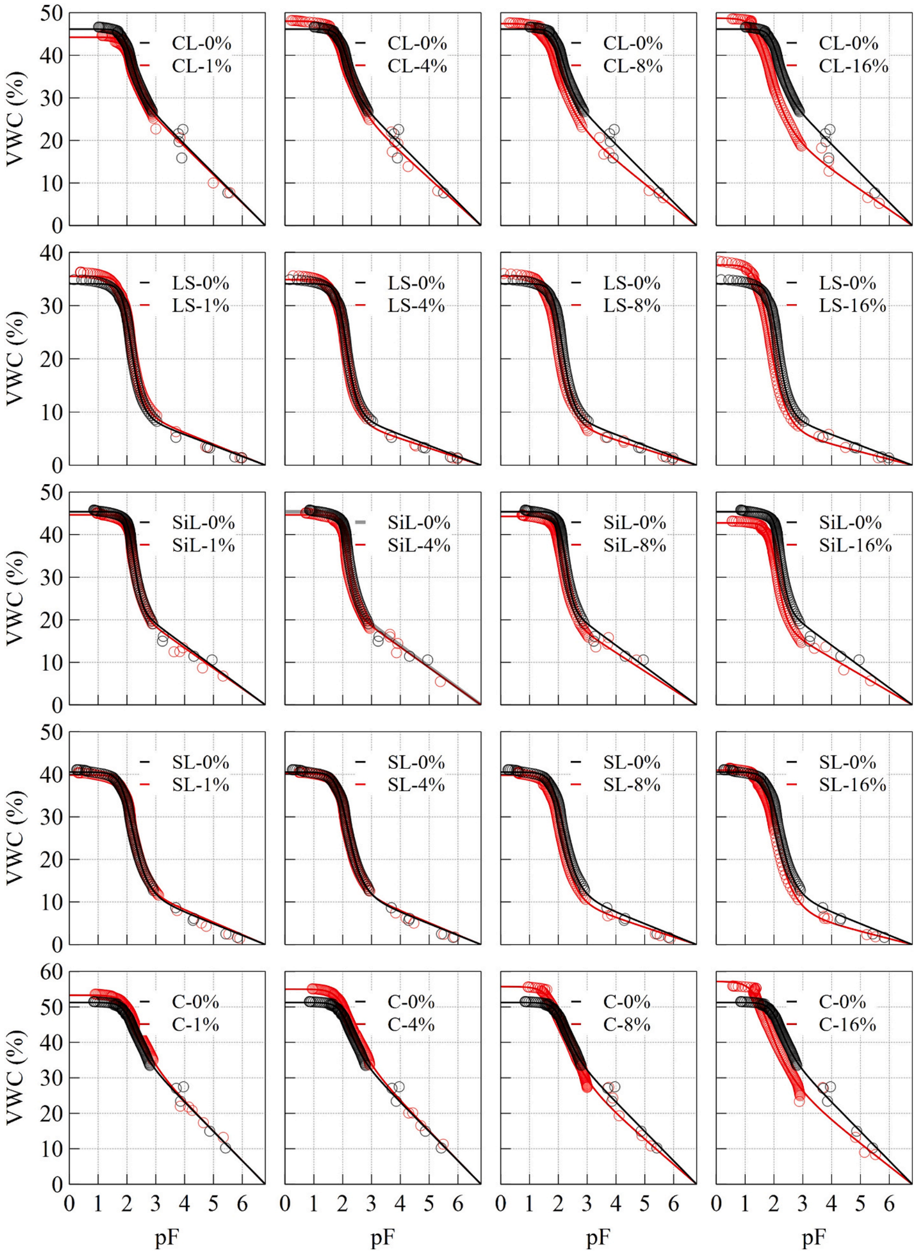

Fig. 2. The measured soil water retention data (circles) and the fitted VG-PDI model (solid lines). Control samples are shown in black and samples with different TWPs concentrations ranging from 1 to 16% are shown by red color codes. C: Clay, CL: Clay loam, SilL: Silt loam, LS: Loamy sand, and SL: Sandy loam. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3

Fitted VG-PDI model parameters for the five soil textures with different concentrations of TWPs (Wp), fitting RMSE values and soil volumetric water contents at FC (pF = 1.8) and PWP (pF = 4.2).

Texture	W_p (w/w)	α (cm^{-1})	n (–)	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	RMSE (cm^3 cm^{-3})	θ_{FC} (cm^3 cm^{-3})	θ_{PWP} (cm^3 cm^{-3})
C	0%	0.0083	2.287	0.390	0.513	0.006	0.498	0.215
	1%	0.0076	1.936	0.389	0.533	0.004	0.517	0.218
	4%	0.0094	1.891	0.400	0.550	0.004	0.527	0.211
	8%	0.0132	1.762	0.346	0.557	0.009	0.507	0.186
	16%	0.0305	1.691	0.335	0.572	0.012	0.450	0.164
CL	0%	0.0083	2.773	0.321	0.461	0.006	0.443	0.177
	1%	0.0082	2.962	0.312	0.442	0.005	0.431	0.172
	4%	0.0129	2.019	0.302	0.480	0.005	0.436	0.161
	8%	0.0178	1.895	0.274	0.474	0.004	0.403	0.142
	16%	0.0243	1.866	0.241	0.487	0.006	0.373	0.122
SiL	0%	0.0063	3.700	0.230	0.454	0.006	0.448	0.129
	1%	0.0065	3.426	0.220	0.446	0.007	0.439	0.124
	4%	0.0077	3.560	0.227	0.446	0.009	0.434	0.126
	8%	0.0082	2.916	0.207	0.443	0.004	0.422	0.114
	16%	0.0094	3.002	0.188	0.427	0.004	0.398	0.102
LS	0%	0.0088	2.844	0.098	0.341	0.005	0.315	0.054
	1%	0.0092	2.624	0.104	0.355	0.005	0.324	0.057
	4%	0.0102	2.627	0.086	0.349	0.005	0.307	0.046
	8%	0.0145	2.330	0.084	0.356	0.004	0.276	0.04
	16%	0.0201	2.148	0.071	0.376	0.005	0.249	0.037
SL	0%	0.0090	2.292	0.129	0.405	0.005	0.369	0.071
	1%	0.0080	2.494	0.137	0.398	0.006	0.373	0.076
	4%	0.0093	2.441	0.135	0.402	0.005	0.366	0.074
	8%	0.0116	2.235	0.11	0.398	0.004	0.339	0.059
	16%	0.0144	1.951	0.086	0.410	0.005	0.325	0.047

C: Clay, CL: Clay loam, SilL: Silt loam, LS: Loamy sand, and SL: Sandy loam.

data points and the VG-PDI model output.

2.5. Developing regression models of scaling WRC

Two simple linear scaling models were developed to assess the impact of TWPs on the WRC of the soils within the range of FC (pF = 1.8) to PWP (pF = 4.2). For this purpose, two modeling cases were explored. In the first case, distinct models were established for each soil texture, utilizing TWPs as the sole input predictor:

$$\theta_P(h) = \left(aW_p + b\right)\theta_c(h) \tag{5}$$

where $\theta_P(h)$ is the volumetric soil water content at matric potential h of the soil containing TWPs (cm^3 cm^{-3}), W_p (%) is the weight percent of the TWPs in the sample and $\theta_c(h)$ is the volumetric water content of the soil at matric potential h of the control soil (cm^3 cm^{-3}) ($W_p = 0$).

In the second case, a universal model was created, including $\theta_c(h)$ of all the five investigated soil textures used in this study. The simple scaling model uses W_p and the dry bulk density, ρ_b (g cm^{-3}) of the soil as input predictors:

$$\theta_P(h) = \left(aW_p + b\rho_b + c\right)\theta_c(h) \tag{6}$$

where a, b and c are fitting parameters (–).

The goodness of fit was assessed using the root mean square error (RMSE) between the soil moisture content fitted by the VG-PDI model (θ_{fit}) and the estimated soil water contents by the regression scaling models (θ_{reg}):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(\theta_{fit} - \theta_{reg}\right)^2}{N}} \tag{7}$$

where N is the number of water retention data points.

3. Results & discussion

3.1. Impact of TWPs on the soil WRC

The bulk density of the samples decreased as TWP concentration increased. Overall, samples with the highest TWP concentration (16%, w/w) had approximately 16% lower ρ_b compared to control samples with zero TWPs. This decrease is attributed to the lower specific densities of plastic particles compared to soil particles, as they are both lighter and occupy more volume than soil particles (Yu et al., 2023). The decline in ρ_b indicates a change in the pore structure of the soil, transitioning to a looser soil structure. This alteration, coupled with the hydrophobic surface of microplastics, affects the WHC of the soils (Wang et al., 2022; Yu et al., 2023).

Water retention data of the soils mixed with different concentrations of TWPs (0, 1, 4, 8, and 16%, w/w) were measured in an experimental setup using the extended evaporation method. The measured water retention data points, as well as the fitted VG-PDI model to them, are shown in Fig. 2. The VG-PDI model parameters and calculated values of RMSE are also given in Table 3. According to the table, the values of RMSE ranged from 0.004 to 0.012 cm^3 cm^{-3}, representing the satisfactory fitting accuracy of the WRC on the measured retention data by the applied methodology. The table also includes the calculated water contents of the soils at FC (pF = 1.8) and PWP (pF = 4.2).

As anticipated, the influence of TWPs on the WRC is evident even in a short timescale, regardless of the texture of the soils. The degree of impact depends on the concentration of TWPs included in the soil and is more visible in high volumes of TWPs. This corresponds with the findings of Guo et al. (2022), who indicated a correlation between various concentrations of MPs in the soil and their impact on soil moisture. The degree of impact varies among different soil textures. While clay (C) and clay loam (CL) soils are influenced the most by the existence of TWPs, the impact is less pronounced for silt loam (SiL) and sandy loam (SL), especially in low concentrations of TWPs. However, the impact of TWPs on the WRC of clay loam (C) and clay (C) soils is evident across the full range of moisture content from saturation to oven dryness, even at lower TWP concentrations. Additionally, while lower concentrations of TWPs slightly influence the WRCs of these soils in the mid-range of moisture

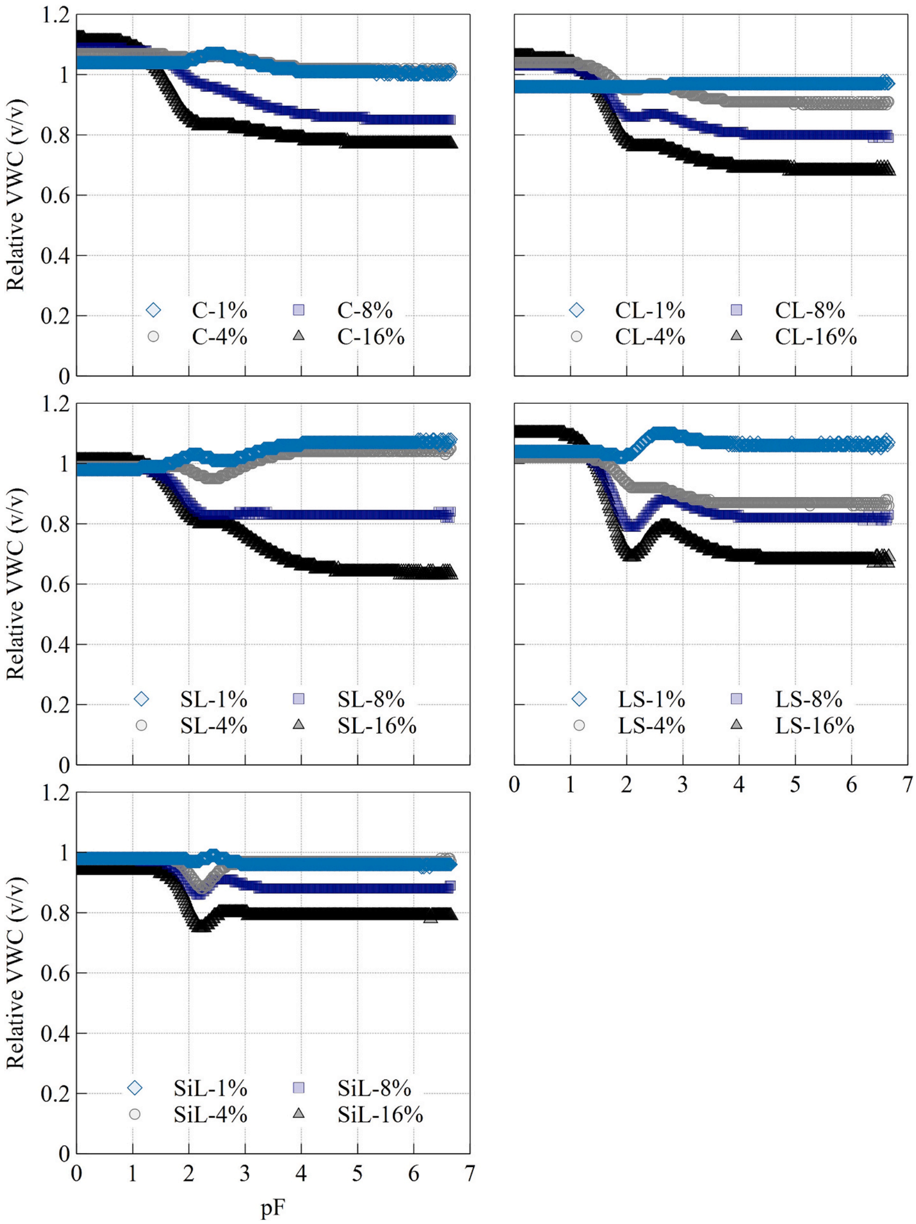

Fig. 3. Relative volumetric water contents (v/v) of five soil textures due to TWPs concentrations from saturation to oven-dryness ($0 < pF < 6.8$) for all soil textures. Different concentrations are shown by color codes. C: Clay, CL: Clay loam, SilL: Silt loam, LS: Loamy sand, and SL: Sandy loam.

content, in other soil textures, low amounts of TWPs do not significantly alter the WRC up to pF = 3.

TWPs change the density of soil samples, with a direct impact on the θ_s and water content of the soils near saturation. The influence rises with the concentrations of the TWPs, followed by a reduction of the air-entry point. Although the shape parameter α (−) did not change significantly in low concentrations of TWPs (1% and 4%, w/w) in all soils, higher values of α were observed for higher concentration levels of TWPs. The amount of change depended on the soil texture.

For instance, the increase in parameter α for the 16% TWPs treatment was the highest for clay soil ($\alpha = 0.0222$) and lowest for the silt loam soil ($\alpha = 0.0031$). For the 8% treatment, the highest increase in parameter α was observed for clay loam (0.0095) and the lowest was observed for silt loam (0.0019). The shift towards larger macropores in the wet range of WRC filled by TWPs depends on the increased density of contaminated soils based on the amount of TWPs. Moreover, higher amounts of TWPs decreased parameter n for all the textures and concentration levels except for clay loam 1% and sandy loam 1% and 4%. The highest difference was for clay loam and the lowest was for sandy loam for the 16% TWPs concentration level.

Additionally, the influence of TWPs within intermediate and dry ranges of WRC of all soils is more pronounced at higher concentration values of TWPs. Shafea et al. (2023) also reported a decrease in soil water retention of a silt loam soil with increasing microplastics (polyethylene terephthalate and polystyrene), which was more noticeable at a high soil matric potential of −1500 kPa. The existence of TWPs reduces soil volumetric moisture content in the intermediate to dry ranges of the WRC. This is related to the alteration of the pore volume by TWP concentrations, in a way that small TWPs in the μm scale reduce the pore volume in the intermediate to dry range of WRC. That corresponds to the reduction of θ_r and lower soil water contents at both FC and PWP in all soil textures supported by their values presented in Table 3. The reduction in θ_r for the 16% TWPs concentration level was more pronounced for fine-textured soils than coarse-textured soils. Values of θ_r differ from 0.055 ($cm^3\ cm^{-3}$) for clay and 0.080 ($cm^3\ cm^{-3}$) for clay loam to 0.027 ($cm^3\ cm^{-3}$) and 0.043 ($cm^3\ cm^{-3}$) for loamy sand and

Table 4
Linear regression models to estimate volumetric water contents of soils containing TWPs ($\theta_P(h)$) by scaling the volumetric water content of the control soil ($\theta_c(h)$).

Soil texture	Scaling model	Scaling case	RMSE (cm^3 cm^{-3})
Clay	$\theta_P(h) = (-0.0159\,W_p + 1.0786)\theta_c(h)$	I	0.012
Clay Loam	$\theta_P(h) = (-0.0154\,W_p + 0.9871)\theta_c(h)$	I	0.008
Silt Loam	$\theta_P(h) = (-0.0118\,W_p + 0.9863)\theta_c(h)$	I	0.007
Loamy Sand	$\theta_P(h) = (-0.0202\,W_p + 1.0325)\theta_c(h)$	I	0.006
Sandy Loam	$\theta_P(h) = (-0.0168\,W_p + 1.0334)\theta_c(h)$	I	0.008
Clay	$\theta_P(h) = (-0.0160\,W_p - 0.0597\rho_b + 1.1092)\theta_c(h)$	II	0.024
Clay Loam	$\theta_P(h) = (-0.0160\,W_p - 0.0597\rho_b + 1.1092)\theta_c(h)$	II	0.013
Silt Loam	$\theta_P(h) = (-0.0160\,W_p - 0.0597\rho_b + 1.1092)\theta_c(h)$	II	0.009
Loamy Sand	$\theta_P(h) = (-0.0160\,W_p - 0.0597\rho_b + 1.1092)\theta_c(h)$	II	0.007
Sandy Loam	$\theta_P(h) = (-0.0160\,W_p - 0.0597\rho_b + 1.1092)\theta_c(h)$	II	0.008

$\theta_c(h)$ *and* $\theta_p(h)$: Soil volumetric water contents at soil matric potential h of the control soil ($W_p = 0$) and soils containing TWPs respectively (cm^3 cm^{-3}), W_p: Weight percent of TWPs (w/w), ρ_b: Bulk density of the control soil (g cm^{-3}). CI: Case I, in which texture-specific scaling models were developed, and CII: Case II, where a universal scaling model was developed using the data of all five soil textures. Scaling models were developed for soil matric potentials ranging from FC (pF = 1.8) to PWP (pF = 4.2).

sandy loam soils, respectively. A similar difference between fine and coarse-textured soils can be observed for 8%, but not for 4% TWPs concentration level. The decrease in the values of θ_r due to the exitance of MPs in soils has also been reported by Xie et al. (2023).

The reduction in θ_{FC} for the highest concentration level of TWPs (16%) compared to the control samples varied between 0.044 cm^3 cm^{-3} for sandy loam and 0.074 cm^3 cm^{-3} for clay loam soils with no clear distinction between fine and coarse textured samples. For the lower TWP concentration levels, the reduction in θ_{FC} was less pronounced. Differences between θ_{FC} values varied between 0.001 cm^3 cm^{-3} to 0.044 cm^3 cm^{-3} for soils with the 8% TWPs concentration and between 0.004 cm^3 cm^{-3} and 0.029 cm^3 cm^{-3} for soils with the 4% TWPs concentration. The role of MPs in diminishing soil pore space and creating a new soil pore structure has also been observed by (Guo et al., 2022; Wang et al., 2023). The reduction in θ_{PWP} (similar to θ_r) for the highest TWP concentration level (16%) was more pronounced for fine-textured soil (0.051 cm^3 cm^{-3} for clay and 0.055 cm^3 cm^{-3} for clay loam soils) than for coarse-textured soils (0.017 cm^3 cm^{-3} for loamy sand and 0.025 cm^3 cm^{-3} for sandy loam soils). The same difference between fine and coarse-textured soils can be observed for the 8% TWPs treatment, but the reduction in θ_{PWP} was less notable. For the 4% TWP concentration level, the changes in θ_{PWP} were minimal and inconsistent between soil textures.

Overall, the plant available water (AWC = θ_{FC} - θ_{PWP}) (cm^3 cm^{-3}) decreased with an increase in the concentration of TWPs, except for the clay soil. The plant available water for the highest TWPs concentration (16%) was 93% of that for control soil for clay loam, silt loam, and sandy loam soils, while the difference was more marked (81%) for loamy sand soil. For lower TWP concentrations up to 4%, however, no substantial reduction in the plant available water was observed (up to a 3% reduction for silty loam soil), and in some cases, there was an increase in plant available water, such as a 9% and 2% increase for clay and clay loam soil, respectively.

3.2. Evaluation of the scaling models

Fig. 3 provides an explicit visualization of the relative water contents in matric potentials ranging from 1.0 to 6.8 on the pF scale for the five soil textures and concentrations of TWPs. These values are obtained by dividing the volumetric water content of soils with different TWPs concentrations by that of the control soil with zero TWPs at each pF value. As depicted in the figure, the reduction of soil water content due to TWPs in the wet range is non-linear and varies across the soil textures. However, a linear reduction in water content attributed to TWPs across soil textures is notably evident at higher tire-wear concentration levels in intermediate and dry parts of the curve. These results were then used as a practical basis for developing scaling models to identify the volumetric water content of soils contaminated by TWPs, depending on the percentage of TWPs present.

Table 4 presents the regression models developed for scaling WRC of soils containing TWPs for five soil textures, as well as the universal scaling model developed using the data of all five soil textures. The goodness of fit of each scaling model is evaluated by the calculated values of RMSE. Additionally, Fig. 4 displays the comparison of measured and estimated water content data using the regression models developed in this study, covering the range between FC and PWP. The texture-specific models (Case I), which solely utilize the TWPs concentration (W_p) as input, exhibited notable accuracy for all textures, with RMSE values ranging from 0.006 to 0.012 cm^3 cm^{-3} for loamy sand and clay textures, respectively. The performance of the general model, which incorporated ρ_b as an additional input predictor across all soil textures, was less strong but still yielded satisfactory accuracy, with RMSE varying between 0.007 and 0.024 cm^3 cm^{-3}. Fig. 4 also indicates the robust fit of the linear regression models, with the data points distributed well around the 1:1 line for all textures and TWPs concentrations. However, the observed deviations from the identity line (1:1) at higher water contents indicate the need for further development of the model for wetter soil conditions.

Our results suggest that incorporating ρ_b as an input parameter when developing texture-specific scaling models is not feasible. A general scaling model also can be implemented for a broader range of soil textures. However, studies have shown that the morphology of MPs in the soil can vary significantly depending on the sampling location and the source of MPs (Wang et al., 2022). Additionally, environmental conditions (including microorganisms and plants), as well as soil types, influence the overall impact of MPs on soil hydraulic properties (Zhang et al., 2023). Consequently, further studies are needed to investigate whether the scaling models developed in this study are applicable to different types of MPs with varying shapes and morphology, as well as to different soil types and under various environmental conditions.

3.3. Novelty and limitations of this study and directions for future research

Available studies on the impact of MPs are very limited in the literature. The novelty of our research is threefold. First, we focused on TWPs that are prominent contributors to environmental MP pollution. However, information about the hydraulic properties of urban soils contaminated with them is lacking in the scientific literature. Second, all the previous studies used traditional methods to measure the impact of MPs on water retention (such as pressure plates and sandboxes), which only generate a limited number of measured data points per soil and typically do not cover the dry end. For the first time, we used more novel approaches, including extended evaporation and dew point techniques, to generate high-resolution data over the entire RWC for all our samples. Third, this is the first study that offers simple, practical, yet accurate models (for five soil textures) to quantify the impact of TWPs on soil water retention based on their concentrations and bulk density of the soil and using the water retention of the noncontaminated soil. The scaling equations developed in this study will be of high practical value

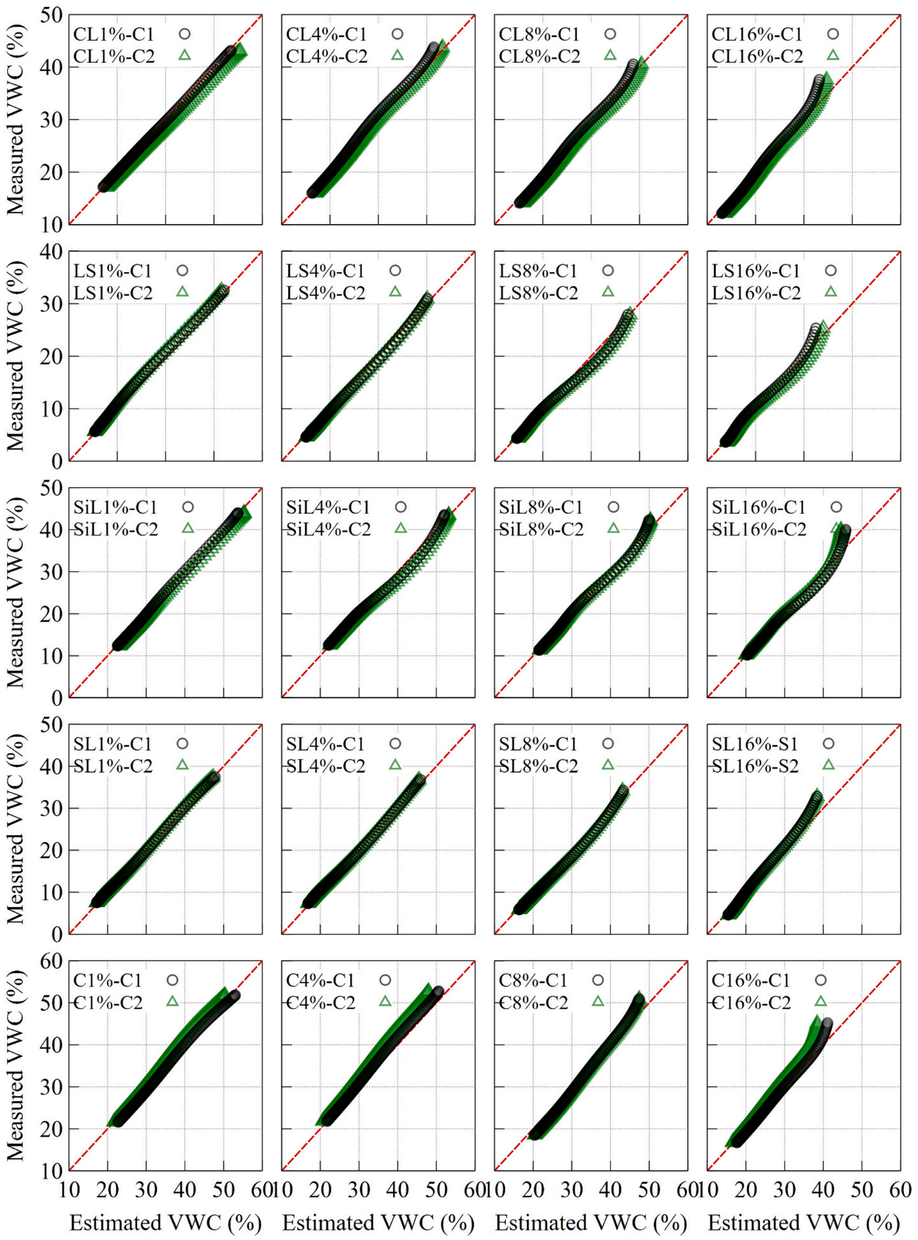

Fig. 4. Performance of the linear regression models to estimate the impact of TWPs on the WRC between FC (pF = 1.8) and PWP (pF = 4.2). C1 is case I, the texture-specific models, shown by blank black circles, and C2 is case II, the universal model developed for all 5 textures, shown by blank green triangles. C: Clay, CL: Clay loam, SiLL: Silt loam, LS: Loamy sand, and SL: Sandy loam. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

to the scientific community to further investigate the impact of TWPs on hydrologic processes using numerical and hydrologic models.

We did not study the effect of TWP size on the WRC, and we leave it to future studies to determine whether that could be a significant factor affecting the soil hydraulic properties as well. Our study was conducted in a controlled laboratory environment using small soil samples. Future research may involve evaluating the performance of our scaling models and verifying the results of our study for different soil types. Additionally, we recommend field-based experimental and modeling studies to understand how TWPs, environmental conditions, and soil types impact root zone soil hydrology, infiltration, and runoff. Our scaling models only cover the plant available water range (between FC and PWP). We recommend further scaling research for the wet end of the RWC. We observed inconsistent impacts of TWP in the wet end, and our scaling models should not be used for wet conditions between saturation and FC.

4. Summary & conclusions

In this study, we investigated the influence of TWP accumulation on the WRC. Our main focus was to assess how varying concentrations of TWPs affect the WRC across different soil textures, covering the entire moisture range from saturation to oven dryness. Using high-resolution measured data, we observed a significant decrease in volumetric soil moisture content within the intermediate to dry range of WRC for soils contaminated with TWPs, even over short periods. Furthermore, we developed a simple scaling model to estimate the impact of TWP concentrations on the WRC of contaminated soils. This model effectively utilizes bulk density and TWP weight percentage to linearly scale the WRC of soils. The developed scaling model, along with our findings, represents an important theoretical advancement with practical implications, particularly for identifying WRC and moisture dynamics in high-risk urban soils, such as those near highway corridors where MPs are likely to be highly concentrated. This research provides a foundation for future practical applications and emphasizes the importance of understanding and mitigating the long-term impact of microplastic contaminants on soil water dynamics. However, further research is needed to accurately measure and model the influence of MPs and TWPs on the unsaturated hydraulic conductivity of high-risk soils across different timescales.

CRediT authorship contribution statement

Amir Verdi: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mahyar Naseri:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no conflict of interest.

Data availability

Data will be made available on request.

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