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# Minimal preferential transport of microplastics through macropores in irrigated disturbed and undisturbed soil columns

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ABSTRACT

Microplastics are environmentally persistent pollutants. Transport of microplastics away from root zones by infiltrating water is potentially crucial in remediating polluted agricultural soils. However, existing knowledge suggests that microplastics are retained and dispersed within the root zone under typical agricultural water balances. To investigate the underlying mechanisms, we sampled two soil types and conducted experiments in both disturbed and undisturbed soil columns. Microplastics were introduced into the surface, then transported deeper under multiple irrigation-drying cycles. Microplastic concentrations in soil matrices and fracture zones were separately measured, to investigate transport behavior arising from preferential flow. For all disturbed soil columns, even after 120 cm water (before correction for porosity) was applied over seven irrigation-drying cycles, over 80 % of the microplastic mass remained within the shallowest 5 cm. Furthermore, microplastics were detected beneath 40 cm depth only after seven irrigation-drying cycles. The undisturbed columns exhibited slightly greater transport, especially through fractures, but similar overall behavior with disturbed columns. Microplastic concentrations in soil matrices and fractures were highly correlated, suggesting primarily diffusive transport, and that the strong retardation of microplastic transport was similarly dominant within the matrices and fractures. Hence, mechanically remediating microplastic polluted soils by leaching is challenging, and preventing pollution is crucial.

## 1. Introduction

Plastic pollution of the environment threatens at least 12 out of 17 of the United Nations Sustainable Development Goals (Walker, 2021). As a key aspect of the global plastic problem, soil pollution by microplastics endangers multiple cornerstones of sustainable development, including agricultural sustainability, food security, soil health, and terrestrial ecosystem functioning (Baho et al., 2021; Walker, 2021; Wu et al., 2024). Soils may be the largest environmental sink of plastic waste and microplastics, and agricultural soils are particularly affected (Kawecki and Nowack, 2019), due to the widespread use of plastic products in agricultural fertilization, cultivation, and plastic mulching (Wu et al., 2024). However, much of the existing research has focused on microplastic pollution of aquatic and marine environments, whereas microplastic pollution of soils and its effects on the terrestrial ecosystem has not been sufficiently addressed (Surendran et al., 2023). Plastics and microplastics are environmentally persistent, which implies that complete biogeochemical degradation or transformation cannot be relied upon to efficiently remove microplastics from polluted soils, especially root zone soils (Qi et al., 2020). Due to their high environmental persistence and the infeasibility of mechanically removing microplastic particles from soils, microplastic leaching by hydrological transport processes is an important mechanism for remediating polluted agricultural soils at time scales shorter than the environmental lifespan of microplastic particles.

In practice, microplastic transport through soils under environmentally and agriculturally relevant hydrological fluxes may be highly limited under a wide range of environmental conditions, soil types, and microplastic polymer types and particle sizes (O'Connor et al., 2019). This was observed in experiments where microplastics were infiltrated into three different types of soils under continuous rainfall (12.5 h) with light and heavy rainfall intensities (10 mm/24 h and 30 mm/24 h

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respectively) (Zhang et al., 2024), and under simulated rainfall conditions in artificial porous media composed of glass beads (Waldschläger and Schüttrumpf, 2020). This highly limited transport was also observed for various microplastic types and soil types even under high rainfall intensities of 22–35 mm/h (Tehrani et al., 2025). In Zhao et al. (2022), it was observed that microplastics were transported very slowly and ineffectively by infiltrating water, and remained within the top 10 cm of the soil, not only within the soil matrices but remarkably also within fracture zones that conduct preferential flow. Therefore, microplastics are prone to accumulating in shallow soils and root zones (Horton and Dixon, 2018; Li et al., 2022), where potential adverse impacts on terrestrial ecosystems and agriculture are potentially maximized (Yu et al., 2025).

Many studies have addressed microplastics in soils, but there remain knowledge gaps on microplastic fate in soils under the combination of (1) large cumulative infiltration volumes characteristic of agriculturally relevant time scales (i.e., a year), (2) controlled yet realistic conditions with intermittent drying between infiltration events, and (3) distinguishing between microplastic transport in the soil matrix and fracture zones. These knowledge gaps hinder mechanistic understanding and efforts to create process-based models of microplastic transport in soils, which is currently an emerging field of study, especially regarding preferential flow and microplastic transport at spatial scales larger than the laboratory scale (Yang and Tang, 2025).

To address these knowledge gaps, and their underlying mechanisms, we conducted disturbed soil column experiments of microplastic transport using two soil types to ascertain that the observed microplastic transport behavior is not specific to highly water-redistributive natures of particular soils. We applied multiple irrigation-drying cycles to the soil columns, to investigate whether the lack of observed microplastic advection persists under larger cumulative infiltration volumes in controlled settings. We then repeated the experiment on undisturbed soil columns, to ensure that the conclusions are not affected by the homogenization of soil structure and physical properties associated with the disturbed column packing process or other similar soil homogenizing processes such as tillage. The distinction between microplastics in the soil matrix and soil fractures also provides additional insight into the potential influence of soil structure, preferential flow, and processes affecting soil structure such as soil compaction and tillage. Finally, instead of a primarily phenomenological discussion, in our discussions we focus on physical mechanisms, and potential implications for microplastic transport modeling under the commonly-used advection-diffusion-reaction framework (Molnar et al., 2015) for hydrological contaminant transport. Hence, the overall goal of this study is to experimentally investigate and obtain mechanistic insight into the hydrological transport of microplastics in agricultural soils under hydrological conditions representative of agricultural water management.

## 2. Materials and methods

### 2.1. Experimental materials

Two commonly cultivated soils (0–30 cm, from Yangling and Ansai farmland), not subject to prior plastic mulching, were collected in Shaanxi, China. The soil from Yangling is a clay loam soil (Nachtergaele et al., 2000) with bulk density between 1.25 and 1.48 g·cm$^{-3}$, saturated water content of 39.3 %, field capacity of 25 %, saturated water conductivity of 1.33 mm·min$^{-1}$, mean weight diameter between 0.7 and 1.0 mm, geometric mean diameter between 0.5 and 0.9 mm, with 55–80 % of aggregate particles larger than 0.25 mm (measured with the dry sieving described by Leys et al., 2002), and organic carbon content of 7.62 g·kg$^{-1}$ (measured with the method of Nelson and Sommers, 1996). The soil from Ansai is a sandy loam (Nachtergaele et al., 2000) with bulk density between 1.2 and 1.3 g·cm$^{-3}$, saturated water content of 36.2 %, field capacity of 28 %, saturated water conductivity of 1.85 mm·min$^{-1}$, mean weight diameter between 0.3 and 0.8 mm, geometric mean diameter between 0.4 and 0.7 mm, with 30–60 % of aggregate particles larger than 0.25 mm, and organic carbon content of 1.23 g·kg$^{-1}$. After the removal of plant matter residues, the soil was air-dried and sieved to 10 mm, then set aside. Low-density polyethylene (LDPE) ground microplastics were purchased from Jiangmen Zhonglian Plasticizing Technology, with a density of 0.96 g·cm$^{-3}$. The size distribution of the microplastics was 0.5–1 mm (12.5 %), 0.25–0.5 mm (62.5 %) and 0.05–0.25 mm (25 %), representative of actual field distributions observed in our previous study (Chen et al., 2022). The soil column experiments were conducted in a climate-controlled greenhouse (25 ± 10 ℃).

### 2.2. Synthetic soil columns

Synthetic soil columns were constructed by connecting five plexiglass rings of height 10 cm and two rings of height 5 cm, to form cylinders with 20 cm inner diameters, 0.5 cm thicknesses, and 60 cm heights. The connections were sealed with waterproof tape to prevent leakage. The bottom of each column was supported by a porous metal plate (gap size 1 cm), covered from above with a sheet of 80-mesh polyester fabric. Sieved dry soil was filled into the columns, layer by layer according to the soil bulk densities observed in the field: 1.25 g·cm$^{-3}$ (1.20 g·cm$^{-3}$) at 0–20 cm depth, and 1.40 g·cm$^{-3}$ (1.30 g·cm$^{-3}$) at 20–50 cm depth in Yangling (Ansai) soil. Then, 5 % w/w microplastic was thoroughly mixed into the uppermost 1 cm of soil to create a microplastic pollution source layer. Five treatments to simulate various irrigation regimes were performed: control (CK), and 1, 3, 5 and 7 irrigation-drying cycles. Four replicates were constructed for each treatment. As two soil types were studied, 40 synthetic soil columns were prepared in total.

The control treatment (CK) was to irrigate the initially completely dry soil column to 40 % of field capacity (irrigating Yangling and Ansai soil to 10 % and 11.2 % volumetric water content respectively). Each irrigation-drying cycle consisted of irrigating to full saturation, then natural drying to 11 % volumetric water content over approximately 30 days, during which soil water content was monitored by weighing the columns twice daily. Irrigation rates were pre-calibrated to ensure no ponding occurred. Perforated balloons maintained at constant hydraulic pressure were used to apply constant irrigation rates yielding approximately 18 cm (Yangling soil) or 16 cm (Ansai soil) of cumulative infiltration (not corrected for porosity) over 2 h (i.e., 20 cm·h$^{-1}$ mean porewater velocities). After 7 irrigation-drying cycles, which spanned a total duration of 8 months, the cumulative infiltration would be around 120 cm water (around 300 cm corrected for porosity). Under field conditions, cumulative infiltrations of 100 cm water correspond to time scales of around a year, ±0.5 orders of magnitude depending on climate zone. The infiltration rate applied in this study (120 cm cumulative infiltration in 8 months) is representative of precipitation levels in Northwest China where the studied soils were obtained, and other similar semi-arid zones (Li et al., 2016).

After each irrigation-drying cycle, soil samples were separately collected from soil matrices and fracture zones, sequentially from the 0–2 cm, 2–5 cm, 5–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, and 40–50 cm soil layers. Small steel scratchers and brushes were used to obtain soil samples along visually identified soil fracture zones, by abrasively removing a 1 mm layer from the soil around each fracture; these samples constitute the soil fracture samples of the experiment. The rest of the soil is considered to be part of the soil matrix.

### 2.3. Undisturbed soil columns

Undisturbed soil columns of 30 cm depth were excavated from Yangling and inserted into identical cylinders as above, subject to only a single treatment, 3 irrigation-drying cycles, with three replicates. Other experimental procedures are identical to those of the synthetic soil columns. These undisturbed soil columns have physical structures and properties that reflect the native state of the soil in the field, with bulk densities of 1.25 ± 0.02 g $cm^{-3}$ and 1.43 ± 0.05 g $cm^{-3}$ in the 0–5 cm and 5–30 cm soil layers, respectively, in contrast to the synthetic soil columns which have spatially homogenized physical structures and properties and are thus more representative of tilled soils (Priori et al., 2024).

### 2.4. Microplastic extraction

Two separate samples were obtained from each replicate, yielding 8 (6) data points for each result reported for the synthetic (undisturbed) soil columns. The experimental soils were also tested before microplastic addition, and no microplastics were detected. Microplastics in the soil samples were extracted as follows: (1) 50 mL of saturated $CaCl_2$ solution was poured into a beaker containing a 5 g soil sample. (2) The suspension was filtered 6 times through 3 μm filter paper. (3) The filter paper was folded up and oven-dried at 45 °C until it reached a constant weight. (4) The filtrate was transferred onto a 600-mesh nylon gauze, which was soaked into 30 % $H_2O_2$ and 10 % $H_2SO_4$ solutions for 10 h each to remove organic impurities. (5) The gauze was rinsed with deionized water and then oven-dried at 45 °C. (6) The filtrate was transferred onto weighing paper. (7) Microplastic counts, concentrations, and masses within the filtrate were identified, calculated, and processed in the ImageJ software using the methods described in Zhang et al. (2018).

## 3. Results

### 3.1. Microplastic distribution and concentration profiles in the soil

Despite the large cumulative infiltration, and large pore-water

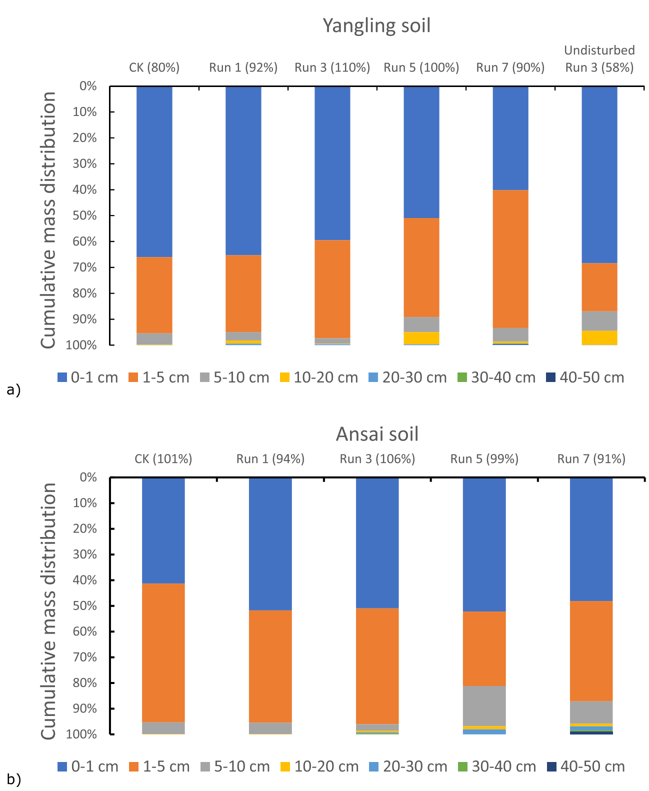


**Fig. 1.** Cumulative microplastic mass distributions (proportionally normalized to 100 % per treatment, to correct for imperfect recovery rates during microplastic extraction), and how they vary with the number of irrigation-drying cycles, in the (a) synthetic and undisturbed Yangling soil columns and in the (b) synthetic Ansai soil column. The numbers in the brackets are the absolute recovery rates of the total input microplastic mass for each treatment.

velocities during irrigation, almost all microplastics, > 98 % for the synthetic Yangling soil column (Fig. 1a), and > 95 % for the synthetic Ansai soil column (Fig. 1b), remained in the uppermost 10 cm of soil. In the synthetic Yangling (Fig. 1a) and Ansai (Fig. 1b) soil columns, microplastics were detected no deeper than 10–20 cm under CK. After one irrigation-drying cycle, microplastics were detected in Yangling (Ansai) soils down to 20–30 cm (10–20 cm) depth. For both types of synthetic soil columns, only after the seventh irrigation-drying cycle were microplastics detected at the bottom of the columns, and even then only at very small concentrations. Microplastic concentrations in the soil matrix of the pollution source layer did not significantly change regardless of the number of irrigation-drying cycles (Table 1a) for all disturbed soil columns, but did significantly change with the number of cycles in the soil fractures (Table 1b). At intermediate depths between 1 cm to 10 cm, the microplastic concentrations changed significantly with the number of cycles in both the soil matrix and soil fractures. At deeper depths beneath 10 cm, the microplastic concentrations generally did not change significantly with the number of cycles in both the soil matrix and soil fractures. This suggests that the irrigation-wetting cycles had the effect of spreading microplastics from the source layer to the shallow soil, and that the effects were similar in both the soil matrix and soil fractures.

In the undisturbed Yangling soil column, microplastics were detected down to 20–30 cm depth, and > 94 % microplastics remained in the uppermost 10 cm of soil after 3 irrigation-drying cycles (Fig. 1a). Furthermore, the microplastics that were able to leach out of the source layer were transported more efficiently across the rest of the undisturbed soil columns (Fig. 1a). In all columns but especially the synthetic columns, the mobility of microplastic particles is very low, and microplastic concentrations in the soil matrix decreased exponentially with depth regardless of the number of irrigation-drying cycles (Table 1a). Amongst the synthetic soil columns, beneath 10 cm depth, there is no clear difference between soil types in the microplastic concentrations in the soil matrix (Table 1a) and in the spatial partitioning of microplastic mass (Fig. 1). Therefore, the overall transport behavior of microplastics in the Ansai and Yangling soil columns, both disturbed and undisturbed, are essentially similar.

### 3.2. Microplastic concentrations in soil fracture zones are typically larger than in the soil matrix

In both the synthetic Yangling and Ansai soil columns, for all treatments the mean microplastic concentrations in soil fractures at all depths was consistently higher than in soil matrices (Fig. 2a), except in the source layer of the synthetic Yangling soil column after 7 irrigation-drying cycles. Unlike in the synthetic Yangling and Ansai soil columns (Fig. 2a), microplastic concentrations within the fracture zones of the uppermost 5 cm (including the source layer) of the undisturbed Yangling soil columns were substantially (4x) larger than within the soil matrix (Fig. 2b). Nevertheless, overall microplastic transport behavior in the undisturbed soil columns appears in general similar to that observed in the synthetic soil columns: most microplastic mass is concentrated in the uppermost 10 cm of soil (Fig. 1a), and microplastic concentrations decrease monotonically and exponentially with depth in both the soil matrix and fractures (Fig. 2b).

Within the synthetic soil columns of both soil types, Spearman's correlation analyses (Table 2) show that microplastic concentrations have no significant correlations with soil type (correlation coefficient $r = -0.016$, $p < 0.05$), but concentrations in soil matrices and fractures are very significantly correlated ($r = 0.893$, $p < 0.01$) with each other. Different soil types and soil structural properties (i.e. matrix versus fractures) are associated with substantially different contaminant advection behavior (Tang and van der Zee, 2022), but such differences did not materialize in this experiment. Therefore, the similar observed microplastic concentrations across soil types and across matrices and fractures implies that the transport behavior of microplastic was

**Table 1**
Microplastic concentrations in the various soil depths after the various number of irrigation cycles, for both Yangling and Ansai soil.

Table 1a Microplastic concentration (mg $g^{1}$) in soil matrix

| Soil type | Soil layer | Irrigation times CK | Run 1 | Run 3 | Run 5 | Run 7 | Undisturbed soil-Run 3 |
|---|---|---|---|---|---|---|---|
| Yangling | 0–1 cm | 39.34 ± 3.26 aA | 39.15 ± 5.18 aA | 39.92 ± 4.60 aA | 39.17 ± 3.89 aA | 40.49 ± 2.90 aA | 17.72 ± 4.17 aB |
| | 1–5 cm | 2.51 ± 0.25 bBC | 2.99 ± 0.76 bBC | 7.89 ± 4.68 bA | 4.09 ± 2.19 bB | 6.40 ± 1.49 bA | 1.14 ± 0.25 bC |
| | 5–10 cm | 0.27 ± 0.17 cB | 0.25 ± 0.08 cB | 0.07 ± 0.06 cB | 1.49 ± 0.08 cA | 0.42 ± 0.04 cB | 0.36 ± 0.21 bB |
| | 10–20 cm | - | 0.05 ± 0.001 cA | 0.01 ± 0.00 cA | 0.20 ± 0.03 cA | 0.03 ± 0.02 cA | 0.14 ± 0.00 bA |
| | 20–30 cm | - | - | 0.02 ± 0.01 cA | 0.04 ± 0.01 cA | 0.01 ± 0.01 cA | - |
| | 30–40 cm | - | - | - | - | 0.001 ± 0.00 c | - |
| | 40–50 cm | - | - | - | - | 0.005 ± 0.00 c | - |
| Ansai | 0–1 cm | 37.98 ± 6.13 aA | 33.09 ± 6.69 aA | 37.66 ± 4.52 aA | 32.48 ± 6.24 aA | 32.89 ± 5.49 aA | |
| | 1–5 cm | 8.60 ± 1.09 bA | 4.29 ± 1.88 bB | 8.42 ± 1.55 bA | 7.43 ± 6.10 bA | 8.584 ± 4.69 bA | |
| | 5–10 cm | 0.39 ± 0.30 cA | 0.35 ± 0.23 cA | 0.12 ± 0.12 cB | 1.21 ± 0.58 cB | 1.26 ± 1.10 cB | |
| | 10–20 cm | - | - | 0.02 ± 0.01 cB | 0.05 ± 0.04 cB | 0.02 ± 0.01 cB | |
| | 20–30 cm | - | - | 0.01 ± 0.00 cB | - | 0.03 ± 0.02 cB | |
| | 30–40 cm | - | - | 0.003 ± 0.00cA | - | 0.02 ± 0.01 cA | |
| | 40–50 cm | - | - | - | - | 0.04 ± 0.03 c | |

Table 1b Microplastic concentration (mg $g^{1}$) in soil fractures

| Soil type | Soil layer | Irrigation times CK | Run 1 | Run 3 | Run 5 | Run 7 | Undisturbed Soil-Run 3 |
|---|---|---|---|---|---|---|---|
| Yangling | 0–1 cm | 35.46 ± 7.77 aE | 46.35 ± 0.93 aB | 45.90 ± 10.88 aB | 39.53 ± 8.62 aD | 42.70 ± 15.73 aC | 66.58 ± 5.88 aA |
| | 1–5 cm | 4.36 ± 0.47 bD | 5.43 ± 2.15 bD | 7.60 ± 2.27 bD | 12.28 ± 0.72 bC | 20.41 ± 6.83 bB | 26.28 ± 16.58 bA |
| | 5–10 cm | 0.38 ± 0.23 cC | 1.43 ± 0.46 cC | 4.20 ± 2.77 cB | 3.27 ± 1.39 cBC | 1.96 ± 0.86 cC | 8.94 ± 2.10cA |
| | 10–20 cm | - | 0.26 ± 0.16 cA | 0.49 ± 0.19 dA | 1.26 ± 0.47 dA | 0.67 ± 0.52 cA | 1.17 ± 0.13 dA |
| | 20–30 cm | - | 0.27 ± 0.15 cA | 0.32 ± 0.13 dA | 0.24 ± 0.18 dA | 0.60 ± 0.56 cA | 0.70 ± 0.05 dA |
| | 30–40 cm | - | - | - | - | 0.009 ± 0.003c | - |
| | 40–50 cm | - | - | - | - | 0.003 ± 0.001 c | - |
| Ansai | 0–1 cm | 51.78 ± 8.22 aA | 43.69 ± 5.04 aB | 44.26 ± 5.87 aB | 41.54 ± 8.37 aC | 45.68 ± 11.84 aB | |
| | 1–5 cm | 4.65 ± 1.55 bD | 17.93 ± 4.81 bA | 9.80 ± 0.95 bC | 13.94 ± 4.98 bB | 12.90 ± 6.00 bB | |
| | 5–10 cm | 0.36 ± 0.11 dB | 0.79 ± 0.28 cB | 4.59 ± 1.11 cA | 3.36 ± 1.31 cA | 2.83 ± 0.43cA | |
| | 10–20 cm | 1.10 ± 0.57 cdA | 0.52 ± 0.06 cB | 2.21 ± 1.23 dA | 1.22 ± 1.02 dA | 0.97 ± 0.42 dA | |
| | 20–30 cm | - | - | 1.16 ± 0.30 dA | 0.04 ± 0.03 dA | 0.94 ± 0.36 dA | |
| | 30–40 cm | - | - | 0.63 ± 0.37 dA | - | 0.75 ± 0.10 dA | |
| | 40–50 cm | - | - | - | - | 0.08 ± 0.01 d | |

Note: Different small letter means significant difference among different soil layers ($p < 0.05$); Different capital letter means significant difference among irrigation runs ($p < 0.05$); empty entries with '-' imply no microplastic detected.

predominantly diffusive. Hence, the movement of water through the soil during the multiple wetting-drying cycles has had the primary effect of spreading the microplastics closely around the source layer, while not significantly transporting them directionally along with the flow of water.

In the experiment, all of the calculated microplastic mass recovery rates were close to 100 % (Fig. 1), except for one case, which is the undisturbed soil column after 3 irrigation-drying cycles. This low calculated recovery rate possibly occurred because the undisturbed soil column has a highly heterogeneous structure that was not fully characterized by the 6 samples obtained (3 replicates and two samples per replicate). The larger heterogeneity in the structure of the undisturbed soil is corroborated by the larger variations in the observed concentrations in the undisturbed soil column compared to the disturbed soil column (Fig. 2). Furthermore, as discussed above, despite the low mass recovery rate in the undisturbed soil columns, the overall observed microplastic distributions and transport are similar in the disturbed and undisturbed soil columns (Fig. 2).

## 4. Discussion

### *4.1. Microplastic transport in fracture zones*

In the undisturbed Yangling soil columns, the substantially larger microplastic concentrations in the fracture zones than in the soil matrix suggest that more preferential transport of microplastics through fractures occur in the undisturbed soil than in the synthetic soils. This is likely because the process of constructing the synthetic soil columns may have homogenized soil physical structures and destroyed extensive interconnected networks of fracture zones. Such homogenization or tillage would result in lower pore connectivity and spatially isolated fractures that are unable to efficiently channel water and microplastics towards deeper depths (Wardak et al., 2022; Pires et al., 2017). This instead facilitates mixing between fracture zones and the soil matrix, thereby homogenizing microplastic concentrations between fracture zones and the soil matrix (Tang and Van der Zee, 2022). In contrast, the undisturbed soil column would have retained more of the heterogeneous physical structures that occur in the field (Pires et al., 2017), which are better able to conduct large water and microplastic fluxes (Tang and Van der Zee, 2022). This would facilitate the accumulation of microplastics within fracture zones, while enabling microplastics to more effectively bypass the soil matrix. Similarly, compared to the synthetic Yangling soil columns, preferential flow and transport may be more prevalent in Ansai soil, which is evidenced by the larger concentration of microplastics in fractures in Ansai soil. Nevertheless, the overall microplastic transport behavior is similar between the undisturbed and both types of synthetic soil columns.

### *4.2. Microplastic transport behavior is overall strongly diffusive in the root zone*

From 0–7 irrigation-drying cycles, microplastic concentrations monotonically decreased with depth in both studied soils (Fig. 2). Such concentration profiles are characteristic of predominantly diffusive (i.e., redistributive) transport behavior, instead of the advection-dominant advective-diffusive Gaussian pulses or contaminant fronts typical for other solute and colloidal contaminants in both soil matrices and fractures (Pang and Šimůnek, 2006; Molnar et al., 2015; Tang et al., 2023, 2024). This is consistent with other findings in the literature. In agricultural fields continuously plastic mulched over 32 years, the peak

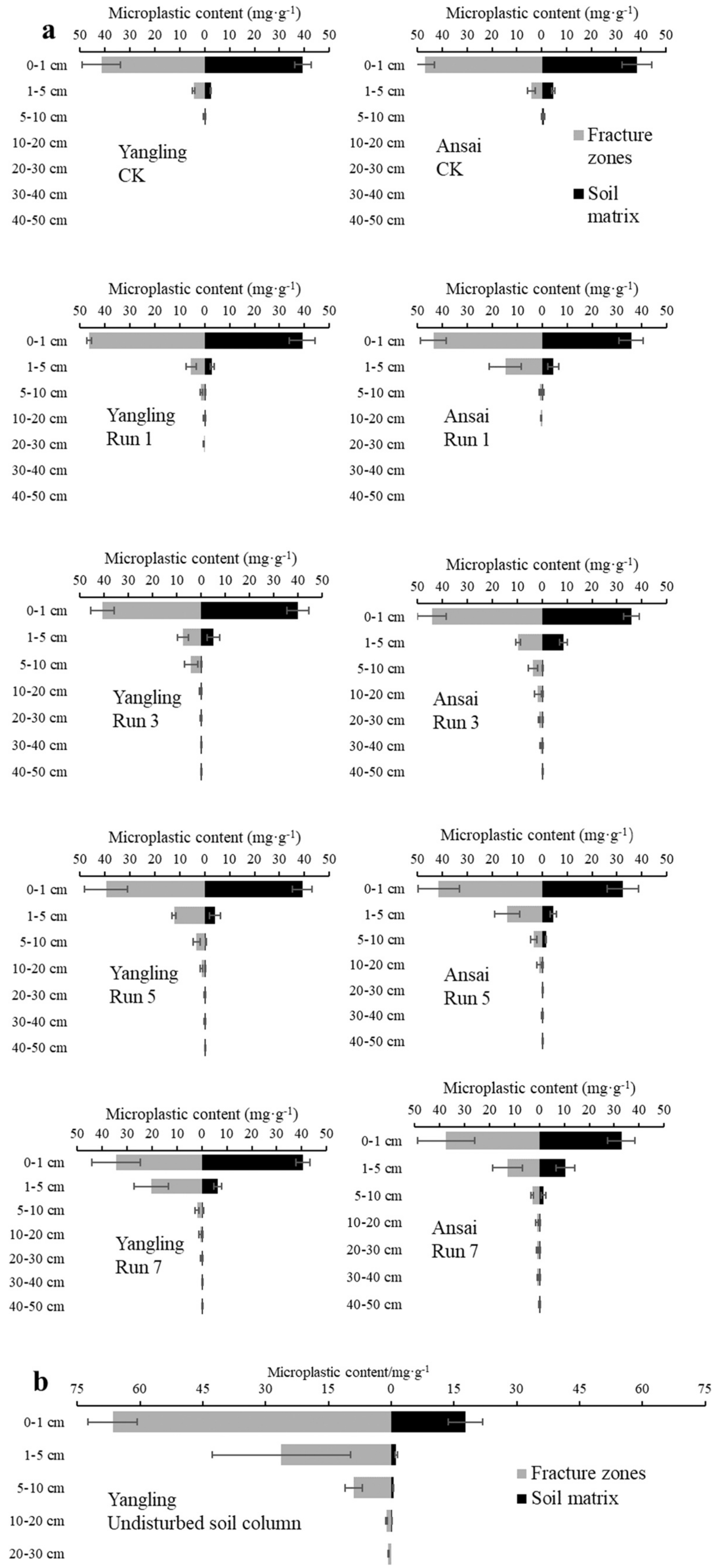


**Fig. 2.** Microplastic concentrations across the various soil depth bins in the soil matrix and in fracture zones in the (a) synthetic soil columns after 0,1,3,5,7 irrigation-drying cycles and (b) undisturbed soil columns after 3 irrigation-drying cycles.

**Table 2**
Correlation analysis between microplastic distributions, irrigation cycles, and soil related parameters.

| | Soil types | Irrigation runs | Soil depth | Microplastic content in fractures | Microplastic content in soil matrix |
|---|---|---|---|---|---|
| Soil type | 1 | | | | |
| Irrigation run | 0.000 | 1 | | | |
| Soil depth | 0.000 | 0.000 | 1 | | |
| Microplastic content in fractures | 0.036 | 0.232** | −0.909** | 1 | |
| Microplastic content in soil matrix | −0.016 | 0.295** | −0.863** | 0.893** | 1 |

Note:
* $p < 0.05$.
** $p < 0.01$.

microplastic concentration depth remained within the soil's uppermost 20 cm (Li et al., 2022). Similar results were observed after 24 years of (microplastic-containing) sewage sludge application (Heinze et al., 2024). A recent literature review (Kedzierski et al., 2023) of data from 442 field soil samples across 43 studies, including 20 studies focusing specifically on agricultural soils, also showed that microplastics were predominantly concentrated in the top soil. That literature review, which is representative of a wide range of soil properties and environmental conditions, showed that peak microplastic concentrations were mostly within the uppermost 15 cm of the soil, and there was no observed migration of peak concentrations to depths deeper than 25 cm at all. Similarly, another review on microplastics in soils across four different land-use types (Qiu et al., 2023) found that peak microplastic concentrations were always at approximately 5 cm depth. All these observations imply that microplastics do not experience substantial downwards advection in soils.

This trend persisted even when microplastic concentrations were differentiated between the soil matrix and fracture zones, in both the synthetic soil (Fig. 2a) and undisturbed soil columns (Fig. 2b). Each additional irrigation-drying cycle spatially redistributes the microplastics further, in similarly diffusive manners. Shifts of concentration peaks to lower depths, which signifies downwards advection, were observed in neither soil matrices nor fracture zones of any soil column. Microplastic redistribution was slightly more efficient within fracture zones than soil matrices (Fig. 2). The strong correlations between microplastic concentrations in soil matrices and fractures of each soil layer suggest that microplastics are continuously and effectively redistributed between matrices and fractures regardless of soil type. Hence, the diffusive nature of microplastic transport dominate similarly regardless of soil type or macroporosity. Altogether, this suggests that although specific spatial patterns in water fluxes such as preferential flow may affect microplastic transport in soils, the overall effect is minimal compared to the mean transport behavior, which is predominantly diffusive. This highly contrasts with the classical case of solute transport, as solutes can substantially bypass the soil matrix and move downwards rapidly in the soil through preferential flow (Tang et al., 2024), as they can more closely follow the water flux streamlines.

### 4.3. *Mechanisms of the apparent diffusive hydrological transport of microplastics*

Microplastic advection may be suppressed by the substantial retention and retardation processes that immobilize or slow particle trajectories, leading to the observed predominantly diffusive nature of microplastic transport. Trapping in dead-end pores, filtering by size-exclusion, and attachment onto soil grains due to DLVO interactions are some of the mechanisms responsible that may retain and immobilize microplastics in the soil (Tang and Raoof, 2024), while retardation may be due to processes such as attachment-detachment cycles or aggregation-fragmentation cycles between microplastic particles and soils, or amongst microplastic particles (Horton and Dixon, 2018; Rillig et al., 2017).

Advective transport may become apparent only after very large amounts of cumulative infiltration occurs relative to the spatial scale of the observation. In field soils free from regular large quantities of plastic inputs, the peak concentration depth has been observed to eventually migrate downwards into the soil (Zhang et al., 2023). In studies involving soil column experiments with very short columns, some advective transport behavior becomes apparent in the microplastic breakthrough curves (after 5–10 total pore volumes of infiltration in 8 cm columns) (Gui et al., 2022), and in 10 cm columns (Guo et al., 2024). These studies are consistent with our study, where substantial amounts of microplastics were transported down to 10 cm depth within 7 irrigation-drying cycles (i.e., approximately 7 total pore volumes) (Fig. 2). Under the contextually small cumulative infiltration volumes of this study, relative to the spatial scales of laboratory soil columns, unsaturated zones, and root zones (e.g., 0.3 m – 2 m), the emergent continuum-scale microplastic transport behavior falls within the predominantly diffusive regime.

The direction of microplastic advection may oscillate, further reinforcing the observed diffusive macroscopic transport behavior. During the irrigation-drying cycles, water fluxes point downwards during the irrigation phase, and upwards during the drying phase due to capillary rise. Furthermore, the LDPE microplastics used in this experiment are buoyant in water, thus even when the kinetic energy of infiltrating water drives microplastic particles downwards towards deeper soil, the buoyancy of LDPE microplastics may move them upwards under sufficiently small infiltration rates or dry conditions. In practice, crop transpiration would cause the annual root zone water balance to be even closer to zero (i.e., total infiltration minus actual evapotranspiration becomes even smaller) than under our experimental setup, causing microplastics to be further retained and diffused within the root zone. Furthermore, plant roots can absorb water from deep in the subsurface, further reducing the magnitudes of oscillating downwards-upwards fluxes during the wetting-drying cycles. This would further decrease microplastic advection through the soil, and should be investigated in future studies that extend the experiments of this study with crop cover.

It is also important to consider that microplastic particles are unique individual entities. Unlike solute molecules or relatively fungible colloids such as physically homogeneous sand grains, 'microplastics in soils' in common parlance refers to a large and heterogeneous collection of particulate matter. The collective term of microplastics in soils refers to particles with various geometries, sizes, polymer chemistries, weights, degrees of weathering, and other physicochemical properties. Note that although we have experimented with pristine microplastics of a single polymer type, their initial sizes were heterogeneous. Additionally, physicochemical interactions with the soil environment and organic matter would have led to additional divergences in the physicochemical properties of individual microplastics over the course of the experiment (Ranjan et al., 2023). Such changes in microplastic physico-chemical properties may occur within hours of exposure to the soil environment (Wang et al., 2023), which is much shorter than the 8 month duration of our 7 irrigation-drying cycles. Hence, the trajectories and transport behavior (e.g., adsorption, retardation, filtration, buoyancy) of each individual microplastic particle would differ in many ways (Yang and Tang, 2025). For the collective entity of soil microplastics, the macroscopically observed diffusive transport behavior may thus be explained by the combination of spatio-temporally heterogeneous transport conditions, and spatio-temporally heterogeneous physico-chemical properties unique to each individual microplastic particle.

Microplastics in soils may also be subject to non-hydrological transport processes that are similarly diffusive. An important example for agricultural root zone soils is bioturbation. While bioturbation may accelerate the microplastic movement into deeper soil, bioturbation of soil colloids has been observed to often conform to diffusive random-walk behavior (i.e., 'biodiffusion') (Michel et al., 2022). The tendency for microplastics to accumulate within the shallow soil, as observed in long term field experiments (Li et al., 2022), and in all soil columns of this study, suggests that the predominantly diffusive nature of microplastic transport may also apply under realistic environmental conditions that combine hydrological and non-hydrological transport processes.

### 4.4. Environmental implications

Environmental microplastics are thus transported relatively quickly through the atmosphere and open water, but in soils they are relatively immobilized (Büngener et al., 2023) and diffused (Kedzierski et al., 2023) within the root zone. If microplastics enter soils through other pathways (e.g. subsurface irrigation), they potentially accumulate and clog soils around the entry points (Tang et al., 2023). The propensity for microplastics to be diffused, trapped and retained in soils has led to soils and other porous materials being used as microplastic filters (Büngener et al., 2024). Nevertheless, the strong retention of microplastics in the uppermost layers of the soil also renders them susceptible to overland transport by soil erosion (Yang et al., 2025). This means that microplastics in the soil environment may be significantly less immobilized in landscapes vulnerable to soil erosion, but this increases the potential for overland spreading and surface water pollution of microplastics.

Apart from environmental ecotoxicity and crop contamination risks, microplastic accumulation and spreading may also substantially alter soil hydraulic properties and damage the agricultural utility of soils, as microplastics are primarily hydrophobic particulate matter that fill pore spaces (Guo et al., 2022). The alteration of soil hydraulic properties by hydrophobic particulate matter at agriculturally relevant spatial scales (i.e., beyond representative elementary volumes) may materialize only after some discrete threshold of pollutant concentration is crossed (Steenhuis et al., 2005), potentially cumulating in abrupt, unforeseen, and irreparable soil function collapse. Soil management practices such as tillage may also cause existing microplastics to be further diffused and distributed in soils, potentially causing a larger volume of soil to be degraded (Zhang et al., 2024). Hence, the feasibility of remediating microplastic polluted soils is uncertain, and prevention is arguably crucial. This reinforces the notion that further research to develop agricultural techniques, land management practices, and waste disposal methods that reduce the input of microplastics into soils is urgently needed (Surendran et al., 2023).

## 5. Conclusions

Seven irrigation-drying cycles were applied to soil columns initially containing 5 % microplastics by weight in a pollution source layer comprising the uppermost 1 cm of the soil. For both types of synthetic soil columns, microplastics were detected at 40–50 cm depth only after the seventh irrigation-drying cycle (0.1 % of total input mass for Yangling soil, and 0.9 % for Ansai soil). The seven irrigation-drying cycles applied around 120 cm of total cumulative infiltration (around 300 cm if corrected for porosity), yet over 80 % of the input microplastics remained in the top 5 cm of the synthetic soil columns of both soil types at the end of the experiment. Although microplastic concentrations in the fracture zones beneath the pollution source layer increased faster with irrigation volume than in the soil matrix, the fracture zones and soil matrix both exhibited exponentially decreasing concentrations with depth. The strong retardation of microplastic transport even in the fracture zones, and the overall similarity in microplastic concentrations in the fractures and matrices, together suggest that advective transport of microplastics in soils is weak even under preferential flow. The same was observed in two types of synthetic soil columns, and also undisturbed soil columns. Hence, microplastic transport in soils may generally be predominantly diffusive, such that microplastic redistribution between fractures and matrices is stronger than advection by water flow.

The diffusion-dominant regime of microplastic transport, with an effective absence of advection, implies that infiltrating water merely redistributes the microplastics within the root zone soil, but does not efficiently remove them towards deeper soil. In the long term, microplastics may thus accumulate and spread within shallow soils. Consequently, merely ceasing plastic inputs may have little short-term mitigating effects on soil microplastic accumulation and redistribution. We show that remarkably, microplastic transport is also highly limited not only within the soil matrix, but also within soil fracture zones, for all experimental scenarios. Therefore, microplastic leaching is unlikely to significantly contribute towards groundwater pollution. Combined with the long persistence of microplastics in the environment, this implies that microplastic pollution of soils and the accumulation of microplastics in shallow soil layers and the root zone is persistent and difficult to remediate. This is because microplastics are not effectively removed from the soil by biogeochemical processes. Furthermore, as shown in this study, neither are hydrological infiltration and leaching processes effective at removing microplastics from soils. Hence, although other soil contaminants such as solutes and salt may be flushed and leached by infiltrating water in excess of evapotranspiration, it is unlikely that microplastic contamination can be remediated through such means. This strongly implies that microplastic input reduction will play a much larger role than soil remediation in future efforts to reduce microplastic pollution of soils.

## CRediT authorship contribution statement

**Xiaomei Yang:** Writing – original draft, Supervision, Funding acquisition, Conceptualization. **Ronglong Chen:** Investigation. **Tang Darrell:** Writing – original draft, Funding acquisition, Conceptualization.

## 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.

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## Data Availability

Data will be made available on request.

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