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Microplastics in sandy soils: Alterations in thermal conductivity, surface albedo, and temperature☆

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ABSTRACT

Rapid growth in plastic production has exacerbated disposal of plastic wastes in terrestrial ecosystems. Unfortunately, soils represent large reservoirs for disposal of microplastics (MPs). MPs infiltrate into the soil through various pathways and alter its intrinsic properties. Despite advances in understanding the impact of MPs on soil physical, biological, and hydrological processes, their influence on surface energy balance and soil temperature remains understudied. Such information is more necessary than ever, considering the ongoing changes to soil systems caused by climate variations and extremes. We conducted laboratory experiments on sandy soils to investigate how MPs with different characteristics impact soil temperature dynamics. The changes in the soil thermal conductivity and surface albedo, in the presence of polyethylene (PE) and polyvinylchloride (PVC) particles at various concentrations were measured. The results demonstrate that MPs, and particularly PVC, with amorphous characteristics may decrease effective thermal conductivity of sand by 38%. Moreover, the deposition of MPs at the surface of samples may increase surface albedo by 28% and 77% with addition of 5% PVC and 5% PE, respectively. Such effects are pronounced at higher soil moisture contents, facilitating migration and deposition of MPs on the surface. We ultimately examined the impact of changes in soil thermal and radiative properties on soil temperature dynamics by monitoring the thermal regime in drying sand columns. Our findings indicate that MPs significantly alter evaporative flux and subsurface temperature profile, hence providing insights into understanding the changes in soil energy balance due to the presence of MPs.

1. Introduction

Global plastic production has aggravated disposal of plastic wastes in terrestrial ecosystems where soil serves as a large repository for these wastes (Adhikari et al., 2024; Eze et al., 2021; Grause et al., 2022; Meizoso-Regueira et al., 2024). Microplastics (MPs) as particles smaller than 5 mm infiltrate the soil through various ways including irrigation, plastic mulching, and atmospheric deposition (Heinze et al., 2024; S. Li et al., 2022; Xu et al., 2020). Depending on their type and concentration, MPs change inherent properties and hydrophysical characteristics of soil such as porosity, density, pore size distribution, hydraulic conductivity, and water holding capacity (Amobonye et al., 2021; Yu et al., 2023). Microplastics may further affect a variety of biological and hydrological processes in soil (Qiu et al., 2022). For instance, recent studies have revealed that MPs alter water infiltration and evaporation dynamics by affecting subsurface transport mechanisms in soil and vapor diffusion flux at the surface (Jannesarahmadi et al., 2023; Z. Wang et al., 2023). Additionally, MPs can change soil structure and nutrient availability, further affecting microbial communities and their interactions with plant roots and soil organic matter (Han et al., 2024; Y. Wang et al., 2023).

Despite recent progress in understanding the changes in various processes in soil due to the presence of MPs (Hanif et al., 2024), their impact on surface energy balance, soil temperature, and thermal characteristics has received little attention (Doneva et al., 2023; Routier et al., 2024). This oversight is particularly significant given the importance of these factors in the context of soil-climate interactions. Soil temperature plays a pivotal role in the coupling between land and atmosphere by influencing all components of land energy balance. Shifts

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List of abbreviations

e	Evaporation rate (mm/day)
e_0	Evaporation rate of the pure sand at saturation (mm/day)
K_T	Thermal conductivity (W/mK)
MPs	Microplastics
PE	Polyethylene
PVC	Polyvinylchloride
R_s	Shortwave irradiation (W/m^2)
T	Soil temperature (°C)
T_a	Air temperature (°C)
T_{surf}	Surface temperature (°C)
α	Albedo
α_{MP}	Albedo of sand with microplastics
$\alpha_{pure\ sand}$	Albedo of pure sand

in sensible heat flux raise air temperature as surface temperature increases. Higher air temperature, in turn, accelerates soil desiccation and results in intensified soil warming in the absence of latent heat cooling, thereby creating a feedback loop that amplifies the warming process (Aminzadeh & Or, 2017; Seneviratne et al., 2010). Considering their distinct radiative and thermal properties and filling characteristics, MPs may influence soil temperature regime, partitioning of radiative energy over evaporating terrestrial surfaces, and thus heat and mass fluxes between land and atmosphere. These will impact the ability of soil to absorb, retain, and transfer heat influencing the overall climate-soil feedback mechanisms (Vogelbacher et al., 2024).

The coupling between soil, climate, and microplastics has significant implications for ecosystem functions (X. Li et al., 2022; Wei et al., 2024). Altered soil temperatures, intensified by the presence of MPs and a warming climate, influence the habitat and metabolic rates of soil microorganisms which are important factors for soil health and fertility. Changes in microbial activity influence organic matter decomposition and the balance of carbon and nitrogen cycles, therefore impacting soil quality and the emission of greenhouse gases (Wu et al., 2024; Xiang et al., 2024). The ongoing climate challenges and improper disposal of MPs in soil pose serious interconnected risks that could significantly alter soil thermal regimes, with serious implications for soil biodiversity and ecosystem functioning. This ultimately affects nutrient cycling, soil organic carbon stock (Hassani et al., 2024), and organic matter decomposition, which in turn influence soil aeration, root growth, and plant health (Aralappanavar et al., 2024; Boots et al., 2019; Chia et al., 2022; Domeignoz-Horta et al., 2023; Rillig et al., 2021; Tian et al., 2023; Zhou et al., 2024).

Motivated by the importance of soil thermal characteristics for a wide range of soil services and functions, the specific goal of the present study is to investigate how the presence of MPs alters soil temperature dynamics and its inherent thermal and radiative properties. Specifically, we seek to quantify changes in thermal conductivity and surface albedo across a wide range of particle sizes and water content in the presence of MPs with distinct chemical and physical characteristics. Understanding these alterations is crucial for predicting the broader impacts on soil health, ecosystem services, and the feedback mechanisms between soil and climate.

2. Materials and methods

2.1. Materials

The measurements were conducted on fine-, medium-, and coarse-textured sand samples with respective particle size of 0.1–0.4 mm, 0.4–0.8 mm, and 0.7–1.2 mm, and density of 2.6 g/cm^3. We used ultra-high molecular weight polyethylene (PE) with particles of 34–50 μm and density of 0.94 g/cm^3, and low molecular weight polyvinylchloride (PVC) with 80–200 μm particles and 1.4 g/cm^3 density (Sigma-Aldrich).

We conducted our experiments using 2% and 5% (by mass) concentrations of PE and PVC to assess the impact of microplastics on soil thermal and radiative properties. These concentrations are consistent with some of the microplastic levels detected in contaminated soils. For instance, Fuller & Gautam (2016) reported microplastic (mass) concentrations ranging from 0.03% to 6.7% in an industrial area. This range of concentrations was also opted in previous studies investigating the impact of MPs on various soil properties and processes (e.g., Guo et al., 2022; Jannesarahmadi et al., 2023; Shafea et al., 2023; Z. Wang et al., 2023). In each experiment, microplastic particles were carefully mixed with sand to make uniform mixtures. Table 1 summarizes the porosity of the sand samples in the presence of MPs determined based on the volumetric saturation method (Missimer & Lopez, 2018).

2.2. Measurements of thermal conductivity and albedo

The effective thermal conductivity of the samples was determined using a thermal properties analyzer (Meter, THEMPOS TR-3) with an accuracy of ±10%. The sensor uses a transient line heat source to measure thermal responses along a needle probe inserted into the sample. Each test was repeated three times at 30 min intervals to ensure replicability of the results.

Surface albedo of sand samples were measured using a light sensor (ML-02, EKO Instruments) with a stated spectral range of 400–1100 nm. To mimic shortwave radiation over the samples, a 300-W halogen lamp was used to illuminate the surface at 45° providing a radiation flux of 430 W/m^2. Tungsten-halogen lamps resemble sunlight with a spectrum peak at 0.9 μm. Reflected radiation flux was measured at four distinct angles of 90° (directly above the sample), 60°, 45°, and 30°, using the light sensor. The albedo of each sample was determined by averaging the measured reflectance coefficients at these four angles (Couradeau et al., 2016). Each measurement was repeated four times to ensure the reliability of the results.

2.3. Evaporation experiments from sand samples

To investigate the impact of MPs on soil temperature dynamics, a series of evaporation experiments were conducted on the sand samples, shown in Fig. 1. Glass columns with 8 cm diameter and 20 cm height were filled with medium-textured sand and were initially fully saturated with water. Tungsten-halogen lamps with varying intensities were used to mimic an incoming shortwave radiation of 300 W/m^2 over the samples. A constant wind flow of 1 m/s was kept over the surface of sand columns using a fan. We used a hotwire anemometer (VOLTCRAFT, PL-135HAN) with 5% accuracy to measure the mean wind speed above the surface of samples (see Fig. 1). The values of air temperature and relative humidity, continuously monitored in the lab (Testo 174H), were in the range of 22.1 ± 1.6 °C and 39 ± 5%, respectively. Vertical temperature profiles within the soil columns, at depth of 0, 1, 2, 4, 7, 11, 15, and 19 cm, were measured at 5 min intervals using arrays of thermocouples. The samples were insulated with polyurethane foam to minimize lateral heat exchange with the surrounding air and to ensure effective one-

Table 1
Porosity of sand samples at different concentrations of polyethylene (PE) and polyvinylchloride (PVC).

	Pure sand	2% PE	5% PE	2% PVC	5% PVC
Fine sand (0.1–0.4 mm)	0.37	0.34	0.32	0.36	0.35
Medium sand (0.4–0.8 mm)	0.38	0.36	0.33	0.37	0.36
Coarse sand (0.7–1.2 mm)	0.39	0.36	0.34	0.37	0.34

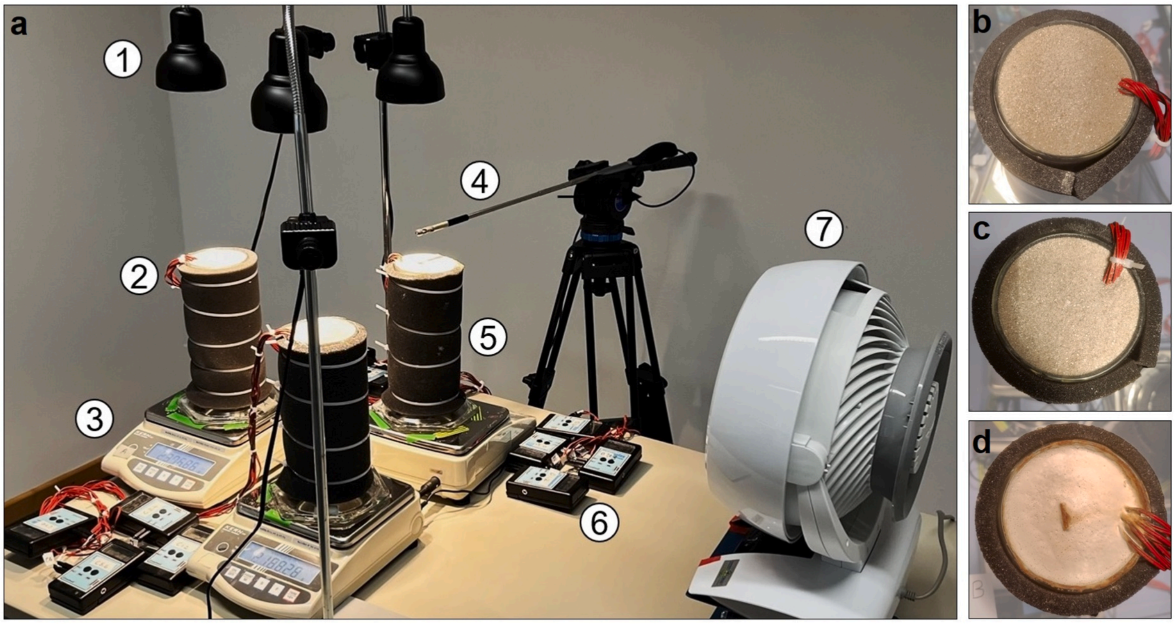

Fig. 1. (a) Setup of the evaporation experiments, including (1) tungsten lights; (2) array of thermocouples; (3) digital balances; (4) hotwire anemometer; (5) sand columns; (6) data loggers; and (7) fan. Surface of the pure sand (b), 5% PVC (c), and 5% PE (d) samples at the end of evaporation experiment.

dimensional heat transfer in the columns. Our evaporation experiments were conducted at 5% concentration of PE and PVC. The experimental design enabled a thorough examination of how MPs influence the thermal behavior of porous media, providing valuable insights into the potential environmental impacts of microplastic pollution on soil health and hydrological processes.

3. Results and discussion

3.1. The impact of microplastics on thermal conductivity of sand columns

Fig. 2 depicts the impact of MPs on thermal conductivity of sand samples at various moisture contents of soil. The increase in the effective thermal conductivity with increase in the moisture content is evident in all samples (Ghanbarian & Daigle, 2016; Ore et al., 2024). Overall, we observe slightly higher thermal conductivity in the sand samples with smaller particle size, indicating the influence of increased contact area between adjacent grains on enhancement of conduction heat transfer in porous media (Zhang & Wang, 2017).

Our measurements revealed the decrease in thermal conductivity of the sand samples with addition of MPs. Considering the lower thermal conductivity of PVC, 0.16 W/mK (Choy, 1977), relative to PE, 0.48 W/mK (Huang et al., 2019), we observed more pronounced effect in the PVC samples, which was intensified with increase in the PVC concentration. The decrease in the thermal conductivity with addition of MPs is due to their insulating properties. The amorphous nature of PVC, which lacks a regular molecular structure, hinders efficient transfer of thermal energy and makes PVC an effective thermal insulator. In comparison, the semi-crystalline structure of PE enhances its thermal conductivity relative to PVC (Choy, 1977). However, both polymers exhibit lower thermal conductivity compared to quartz sand, 8.4 W/mK (Zhang & Wang, 2017), which has a predominantly crystalline structure that facilitates more efficient conduction heat transfer. Microplastics further influence the packing of sand samples by changing the arrangement of particles within the soil matrix. This alternation affects the pore geometry and structure, which in turn impacts the connectivity between soil particles. Such changes in pore configuration directly influence the thermal conductivity of soil by modifying heat transfer pathways and affecting the heat conduction through the solid phase. Although the filling effect of MPs, shown in the insets of Fig. 2, decreases the porosity of the sand samples (Jannesarahmadi et al., 2023), their inherently low thermal conductivity does not significantly alter the conductivity of dry samples at concentration levels in the present study (2% and 5%). Their impact on thermal conductivity becomes more pronounced, however, with increase in moisture content, particularly in the samples with PVC. In the wet samples, MPs replace water with higher thermal conductivity (which is about 0.6 W/mK) in the pore space and lead to a decrease in the overall thermal conductivity of the samples.

3.2. Variation of soil albedo with addition of microplastics

To investigate the impact of MPs on alternation of surface albedo, we conducted our experiments on the medium-textured sand with various concentrations of PE and PVC. Fig. 3 shows variation of surface albedo relative to that of pure sand, for samples with 2% and 5% PE and PVC. Overall, the PE samples demonstrate a more significant impact of MPs. The albedo of dry samples with 2% and 5% PE was respectively measured to be 10% and 22% higher than that of the dry pure sand (0.07). The increase in albedo highlights the reflective properties of microplastic particles which enhance the ability of the surface to reflect the incident light. The impact was more pronounced at higher moisture contents. When the sample became fully saturated, PE particles which have a lower density than water tended to float and accumulate on the surface, forming a thin (<0.5 mm) white crust (Jannesarahmadi et al., 2023). Consequently, we observed increases of 39% and 77% in the surface albedo of fully saturated sands with 2% and 5% PE, respectively, relative to the saturated pure sand (0.05). For fully saturated samples containing 2% and 5% PVC, the surface albedo was 16% and 28% higher, respectively, when compared with pure sand.

As surface albedo increases in the presence of microplastics, a larger portion of intercepted shortwave radiation is reflected from the surface thus decreasing the net radiation flux and altering the surface energy balance of soil samples. This limits radiative energy absorption at surface and leads to lower surface temperatures and reduced soil heat flux which thereby influence thermal regime of the subsurface (discussed in the following section).

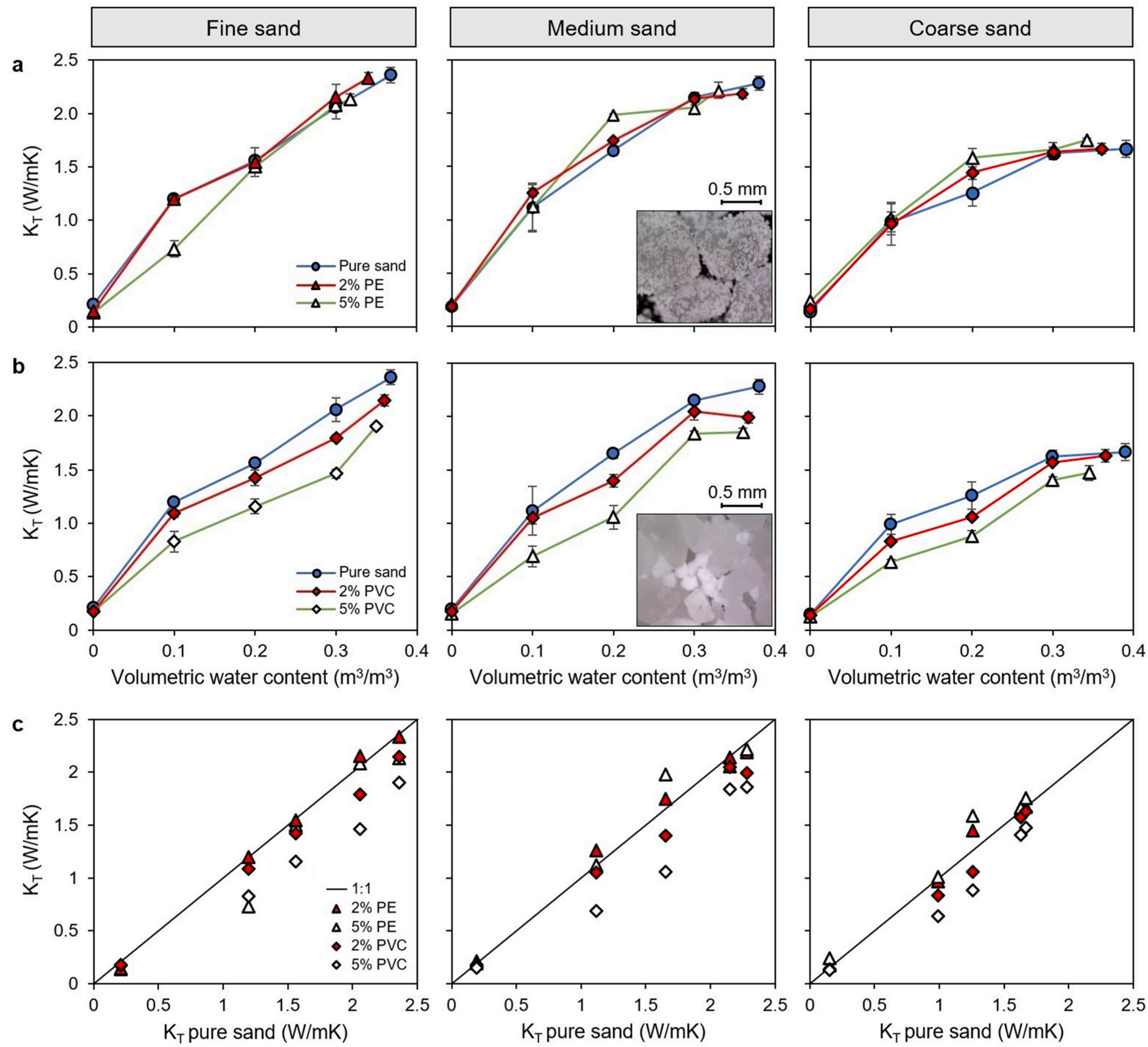

Fig. 2. Variations of effective thermal conductivity (K_T) in fine, medium, and coarse sands with various concentrations of PE (a), and PVC (b). The insets show microscopic images of dry sand with 5% concentration of PE (top) and PVC (bottom). (c) Comparison of the thermal conductivity of the sand samples including PE and PVC (vertical axis) with thermal conductivity of pure sand (horizontal axis).

3.3. Temperature dynamics during evaporation process

Our measurements revealed significant influence of microplastics on thermal conductivity and surface albedo of the sand. To understand the impact of changes in such intrinsic soil physical properties on soil temperature dynamics, we conducted evaporation experiments on sand columns under controlled environmental conditions in the presence of wind (1 m/s) and radiation flux (0 and 300 W/m^2). As illustrated in Fig. 4, the addition of PE increases the evaporation rate relative to the pure sand sample during the so-called stage 1 evaporation, which is characterized by capillary supply to the vaporization plane at the surface (Or et al., 2013). The increase in evaporation rate from the PE samples is attributed to the enhancement of vapor diffusion in the overlying air with deposition of MPs at the surface and formation of small active pores (see the inset in Fig. 3) (Haghighi & Or, 2013; Shahraeeni et al., 2012). The enhancement of evaporation rate (relative to pure sand) was less at radiation flux of 300 W/m^2, suggesting that the increased surface albedo with the formation of the PE crust reduces the available energy at the vaporization plane.

Consistent with measurements of Jannesarahmadi et al. (2023), duration of stage 1 evaporation increased with the addition of MPs. This is attributed to the filling effect of MPs and the resulting changes in the pore structure. During stage 1, formation of narrower capillary pathways extends the water supply from the drying front that recedes into the porous medium to the vaporization plane at the surface (Jannesarahmadi et al., 2023; Or et al., 2013; Shokri & Sahimi, 2012). The impact of increased and prolonged evaporation rates from samples with MPs can be seen in their lower water content relative to the pure sand (Fig. 4c and d). Water content was determined at the end of evaporation experiments by oven drying (24 h at 105 °C) of samples

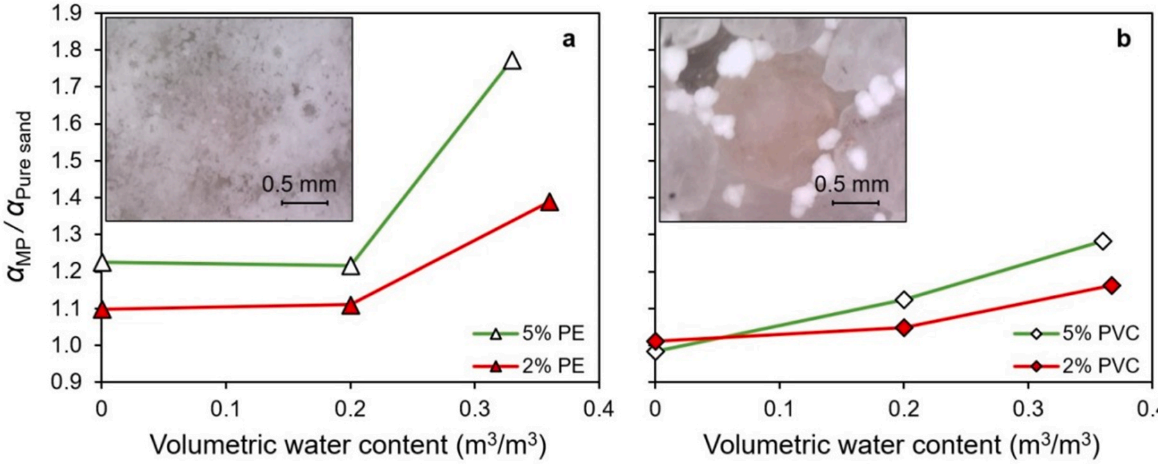

Fig. 3. Changes in albedo of sand samples including PE (a) and PVC (b) with 2% and 5% concentration (α_{MP}) relative to the albedo of pure sand ($\alpha_{Pure\ sand}$). The insets depict microscopic images of the surface of saturated (medium) sand with 5% PE (left) and 5% PVC (right).

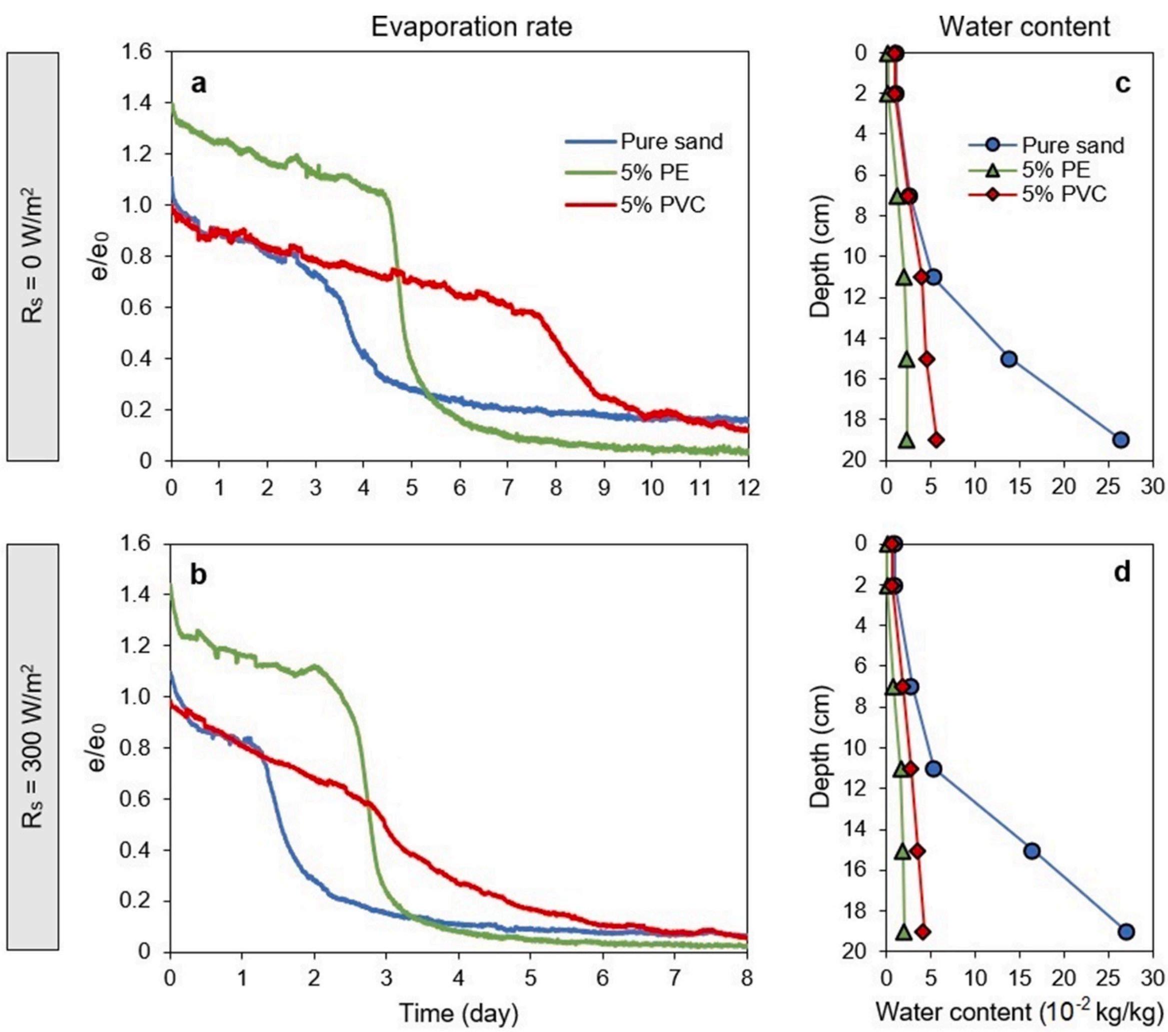

Fig. 4. Normalized evaporation rates (the ratio of evaporation rate, e, to the evaporation rate of the pure sand at saturation, e_0, with similar boundary conditions) from the sand samples under shortwave irradiation of $R_s = 0$ W/m^2 (a) and $R_s = 300$ W/m^2 (b); gravimetric soil moisture profile measured at the end of evaporation experiment for $R_s = 0$ W/m^2 (c) and $R_s = 300$ W/m^2 (d).

collected layer-by-layer at different depths. This careful sampling ensured the minimum mixing between layers by step-wise removal of upper layers.

Fig. 5 shows dynamic evolutions of temperature in the sand columns, measured at 5 min intervals, under two contrasting radiation conditions. In the absence of radiation flux, latent heat cooling due to evaporative

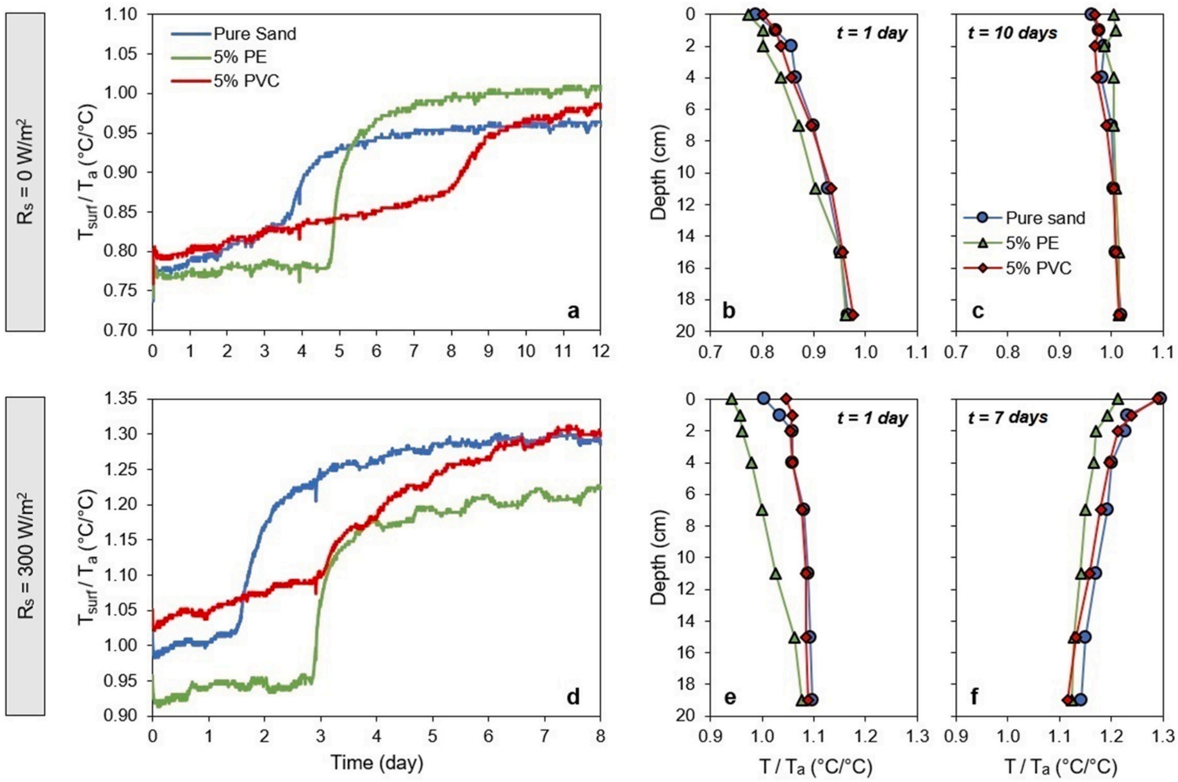

Fig. 5. Dynamic evolution of surface temperature, T_{surf} (a) & (d) and subsurface temperature profile, T (b & c-e & f), normalized with air temperature, T_a, for pure sand and samples with 5% PE and 5% PVC under $R_s = 0$ W/m^2 (top) and $R_s = 300$ W/m^2 (bottom) radiation flux.

flux decreases surface temperature below the ambient air temperature (Aminzadeh & Or, 2013). As seen in Fig. 5a, the higher evaporation rate of the PE sample relative to pure sand (and the PVC sample) during stage 1 evaporation yielded lower temperature at the surface, and in depth of the PE column shown in Fig. 5b. Despite similar evaporation rates from the samples with PVC and pure sand in day 1, when samples are well within stage 1 evaporation, the lower effective thermal conductivity of the PVC sample (depicted in Fig. 2) resulted in a slightly lower temperature in depth of the PVC column relative to the pure sand sample (shown in Fig. 5b). This slightly lower temperature is also observed in the temperature profile of day 10 during stage 2 evaporation, when the PVC and the pure sand samples exhibit similar evaporation rates (see Fig. 5c).

The impact of MPs on changing temperature dynamics is more pronounced in the presence of radiation flux. Comparing temperature profiles of PE sample with and without radiation flux suggests higher temperature difference between the PE and the pure sand sample. This higher difference is attributed to the increased surface albedo due to the deposition of PE particles on the surface of the sand column (see Fig. 3a), resulting in a lower net shortwave radiation flux at the surface of the PE sample. Notwithstanding slightly lower evaporation rate of the PE sample relative to pure sand and the PVC sample during stage 2 evaporation (Fig. 4b) and thus less latent heat cooling, its temperature at the surface and in depth of soil column remains lower than pure sand and the sample with PVC due to its higher surface albedo. The influence of the higher surface albedo of the PE sample is evident in its lower surface temperature (relative to pure sand and PVC) towards the end of the experiment, when evaporation from the sand columns is negligible and the interception of radiative flux causes surface temperatures to be higher than the air temperature (Aminzadeh & Or, 2014).

Such changes in soil temperature, driven by alterations in surface albedo and thermal conductivity due to the presence of microplastics may impact soil microbiomes and their metabolic processes, thereby affecting overall soil health and biodiversity (Knight et al., 2024; Sáez-Sandino et al., 2023; C. Wang et al., 2021). Variation of soil temperature further affects seed germination rate, root development, and the efficiency of water and nutrient uptake by plants which are critical to plant growth and crop productivity (Aminzadeh et al., 2023; González-García et al., 2023). Understanding and mitigating these impacts is essential to preserving soil functions and food security, and ensuring sustainable land management practices.

4. Summary and conclusions

We investigated the influence of microplastics on soil temperature dynamics by studying their impact on thermal and radiative properties of soil. A series of laboratory experiments was conducted on sand samples with a wide range of particle sizes and water contents, in order to quantify variation of thermal conductivity and albedo in the presence of PE and PVC particles with various concentrations.

Our results demonstrated that effective thermal conductivity of sand samples decreases with addition of MPs. The impact was pronounced at higher moisture contents, particularly in samples with PVC, where MP particles with inherently lower thermal conductivity relative to water fill the pore space and suppress conduction heat transfer in the porous medium. Addition of MPs further altered surface albedo of sand samples. Overall, deposition of MPs at the surface of samples increased surface albedo relative to pure sand. Our experiments indicate that PE particles which have lower density relative to water deposit over the surface and form a thin white crust over the samples, yielding a considerable increase in surface albedo. The impact of the change in thermal conductivity and surface albedo on temperature dynamics was assessed by investigating the dynamic evolution of surface temperature and subsurface thermal regime in columns of evaporating sands under various atmospheric conditions. Our measurements show that under similar evaporative conditions, the decrease in thermal conductivity and the increase in surface albedo in the presence of MPs result in a colder temperature profile in sand columns relative to pure sand.

Our findings have significant implications for various environmental and ecological processes. The changes in thermal conductivity and surface albedo due to the presence of MPs alter the surface energy balance, potentially affecting soil temperature and surface evaporative fluxes. Variation of soil energy content and distribution further influences temperature-dependent processes such as moisture availability, microbial activity, nutrient cycling, seed germination, and plant growth (Aminzadeh et al., 2023; Jia et al., 2015). Our experiments focused on sandy soils; however, further investigations are needed to explore the impact of microplastics on soil thermal and radiative properties and heat transfer processes across diverse soil types with different mineral compositions. In particular, conducting long-term experiments under natural environmental conditions, especially in soils rich in organic matter, will be essential to identify the influence of microplastics on a variety of biological and hydrological processes. Understanding such impacts is crucial for maintaining soil health and developing strategies for mitigating the adverse consequences of microplastics on terrestrial ecosystems.

CRediT authorship contribution statement

Milad Aminzadeh: Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Tanmay Kokate:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Nima Shokri:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, 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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