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Saturated hydraulic conductivity in microplastics incorporated soils: Effects of soil texture, polymer type, particle size, and concentration

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Abstract
The present study investigated the saturated hydraulic conductivity (K_s) of two distinct textured soils (loam and sandy loam) in the presence of three different types of plastic polymers [polyethylene terephthalate (PET), polyvinyl chloride (PVC), and polyethylene (PE)] of two different sizes (0.5 to < 1 mm and < 0.5 mm). The K_s was measured in this experiment using the constant-head approach, which follows the concept of Darcy's law. In sandy loam soils (sand 62%), PET particles ranging from 0.5 mm to < 1 mm had the highest K_s (2.1 cm/h). Since PET particles are more hydrophobic than PVC, as seen in prior investigations, the highest K_s in the presence of PET reflects the impact of the hydrophobicity of the resulting particles on water repellency. Additionally, the average trend of K_s is PET > PVC > PE. The effect of increased pore dimensions might represent the mechanism underlying the greater K_s in sandy loam soils than in loamy soils. Two mechanisms, pore dimension increase, and pore-clogging influence the K_s value at low and high concentrations, respectively. However, significant variations in the effects of MP size on K_s were not detected. In this investigation, regardless of particle size, the pore dimension mechanism often increased the K_s at low concentrations. In contrast, the pore-clogging effects prevailed at higher concentrations, affecting and decreasing the K_s value. In addition, the K_s value in the presence of PE particles in loam and sandy loam soils decreased as the concentration increased, and the K_s value was higher for smaller PE particles than for larger PE particles. Due to the limited data on the effects of MP polymer type and size on the K_s of soil within a narrow range of contamination inputs, it might reveal substantial implications for nutrient and pollutant transport in soil. The authors designed to examine the paucities in MP investigation in this unlikely polluted condition of soil environments.

Keywords PET · PVC · PE · Saturated hydraulic conductivity · Soil texture

1 Introduction

Concerns about the extent of plastic pollution worldwide are increased by the identification of microplastics (MP < 5 mm) in some soil and water environments. Estimates suggest that the amount of MP on land could be four to twenty-three times greater than that in the ocean [22, 25]. MP have recently been identified in cultivated soils and were identified as an increasing source of concern regarding soil contamination [10]. Polyethylene (PE), polypropylene

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(PP), and polystyrene (PS) are the three primary forms of soil MPs and are found mainly as fibres and fragments [12, 24, 32], but the scenarios could be different for background MP concentrations. In addition to direct entry, there are other methods by which MPs can enter soils, such as the application of plastic agricultural film [7, 12, 32]. Large plastic particles on agricultural land eventually degrade due to various factors, including mechanical breakdown caused by tillage, biochemical breakdown, thermal degradation, agrarian practices, and UV exposure [32, 33]. This degradation of MP could lead to the formation of secondary MPs with various densities, surface charges, morphologies, and size fractions [38]. Smaller secondary MPs can be incorporated into soil aggregates and have a stronger impact on soil's physical, chemical, and physicochemical properties because of their smaller size fractions [40]. Recently, Hakim et al. [17] reported the effects of polymer type on particle aggregation and adhesion behavior and how the heteroaggregation of MP is influenced by plastic polymer type. On the other hand, a recent study on conventional and biodegradable MP with varying particle sizes reported that the macroaggregate percentage decreased from 84% to 65–71%, and the aggregate size decreased from 1.4 mm to 1.0–1.1 mm [18].

One of the primary determinants of soil fertility is the physical characteristics of the soil. The ability of healthy soil to absorb, hold, and release water while minimizing water erosion is one of its most important properties. Soil structural dynamics significantly alter the hydraulic characteristics of soil [2, 20, 30]. The soil's hydraulic conductivity reflects the ability of the soil to transport water, solutes, and chemicals. It is one of the major physical features of soil that influences water infiltration, how irrigation and drainage works, the loss of fertilizers due to soil erosion, and how substances move through leaching and transport, which in turn impacts all soil and water management practices [26]. Nonetheless, there is still a lack of information about how MP affect the physical characteristics of soil while considering water and nutrient transport. Since hydraulic conductivity is one of the important properties of soil affecting water and nutrient transport, the present study focused on the saturated hydraulic conductivity (K_s) of soil in the presence of different MP polymer types. An increasing amount of research has examined the chemical and biological changes that MP cause in the soil in recent years [18, 27]. On the other hand, very little is known about how MP pollution affects the physical characteristics of soil, such as hydraulic conductivity [16]. Depending on the soil textural class, K_s is affected by MP, and with increasing MP concentration, K_s decreases [33]. Recent investigations have focused on the effects of the type and concentration of MP on K_s without considering their concentration in a pristine environment [33] within a low-concentration window. Due to the lack of data regarding the ways K_s behave in soil environments with an MP concentration below the contaminated agricultural soils [33], we strive to fill these gaps.

To shed light on these less-studied effects of MP pollution, this study investigated the effects of three different types of MP [polyethylene terephthalate (PET), polyethylene (PE), and polyvinyl chloride (PVC)] mixed with topsoil collected from an undisturbed site to observe the K_s. It was hypothesized that (i) as the particle size increases, MPs will have an impact on and reduce K_s. (ii) K_s will be impacted by various polymer types depending on the polymer properties. (iii) K_s will be impacted by the soil textural class. Given these assumptions, the present research investigates the K_s of two distinct soil types in a scenario where MP contamination by three different plastic polymers was unlikely. This investigation is one of the few that examines the effect of MP at low concentrations on a crucial soil physical property, K_s, to the best of the author's knowledge.

2 Materials and methods

2.1 Collection and processing of soil samples

The study soils were collected from two undisturbed sites on the Chittagong University (CU) campus with notable differences in soil texture. Loamy soil was collected from the field beside Ansar camp (22° 27′ 56″ N, 91° 46′ 46″ E), and sandy loam soil was collected from the experimental field of the Soil Science Department, CU (22° 27′ 58″ N, 91° 46′ 49″ E) (Fig. S1 A and S1 B, supporting information). Soil samples were collected from 0 to 15 cm depths following the methods described in Chia et al. [7, 8] and the collection was adjusted depending on field conditions. After collection, the samples were air-dried and broken through a wooden hammer. The broken soil samples were sieved through a 2 mm stainless steel sieve. The sieved samples were stored to analyse the physical and chemical properties of the soil [13].

2.2 Collection of MP materials

The investigation focuses on the microplastic polymers PET, PVC, and PE, which are the major forms of soil microplastics and are reported in different soil/environmental conditions. These polymers of MP are relatively recalcitrant and cause serious environmental problems [1, 12, 24]. These most used plastic materials of three different polymer types [polyethylene terephthalate (PET), polyvinyl chloride (PVC), and polyethylene (PE)] were collected from the local market based on their availability, use, and environmental exposure. We used sharp scissors to cut the collected plastics into small, micro-sized particles, which we then sieved. We first used the scissors to create thin flakes of plastic, which we then further cut down into micro-sized particles. Next, we used two sieves to separate two different size fractions (0.5 to < 1 mm and < 0.5 mm), defining them as microplastic size. The MP particles were stored at room temperature after passing through sieves of 1 mm and 0.5 mm. A picture of three different types of plastic particles is presented in the supporting information (Fig. S2).

2.3 Experimental setup

Microplastics (PET, PVC, and PE) of 0.5 to < 1 mm and < 0.5 mm were incorporated with previously sieved 2 mm soil samples at rates of 1 mg, 5 mg, 10 mg, and 15 mg per 100 g of soil (on a dry weight basis, Wt/Wt%). After the incorporation of different sizes of MP at four different rates, soil samples with different textures were filled with aluminum cores, maintaining a uniform bulk density of approximately 1.20 g cm^{-3}. There were 144 sets of cores for treatments (soil type × MP type × MP size × MP rate × replication = 2 × 3 × 2 × 4 × 3) along with 6 (2 × 3) controls. These cores were used for the investigation of K_s. The number of cores were 48 for each of the MP types, i.e., for PET (MP-PET × PET size × PET rate × soil type × replication: 1 × 2 × 4 × 2 × 3 = 48), PVC (MP-PVC × PVC size × PVC rate × soil type × replication: 1 × 2 × 4 × 2 × 3 = 48), and PE (MP-PE × PE size × PE rate × soil type × replication: 1 × 2 × 4 × 2 × 3 = 48), including 6 control (3 for each of the soil types). Therefore, the treatment arrangement resulted in a total number of 150 cores.

2.4 Methods of analysis

The percentages of sand, silt, and clay in the soil samples were determined via the hydrometer method described in Bouyoucos [4, 5], and the textural class was determined from Marshall's triangular coordinates. The amount of organic carbon was determined via the Walkley and Black wet oxidation method [9, 34], and organic matter was estimated indirectly by multiplying the organic carbon content by the *Van Bemmelon factor* of 1.724 [29]. The soil K_s was determined via the constant head method [13]. Before the experiments were conducted, the soils were analysed for the physicochemical assay; the pH, CEC, Ca^{2+}, and Mg^{2+} were measured [23] (Table S1). The pH was measured with a pH meter after the suspension was prepared at a 1:5 soil-to-water ratio (w/v) [23]. See the supporting information for the chemical and physical parameters (Table S1).

3 Results and discussion

3.1 Effects of microplastic polymer type on saturated hydraulic conductivity

In the present study, three types of MPs; PET, PVC, and PE, 0.5 to < 1 mm and < 0.5 mm, significantly affected the K_s of loam and sandy loam textured soils, respectively, even within a very narrow range of MP concentrations between 0.001 and 0.015% (Wt/Wt) (Fig. 1; Table S2). The highest K_s (2.1 cm/h) was observed in sandy loam soils in the presence of PET at sizes ranging from 0.5 to < 1 mm at a concentration of 0.015% (Wt/Wt). This highest K_s in the case of sandy loam soils at high particle concentrations manifested the mechanism of pore dimension increase in larger size particle fractions of the soils [39]. In contrast, the lowest K_s (1.02 cm/h) was detected in the loam soils at the highest concentration of PET particles at sizes ranging from 0.5 to < 1 mm, which indicated that the pore-clogging effect at high PET particle concentrations in the lower pore fractions in loam soils. This lowest K_s could be due to the dominance of fine particle fractions over those in sandy loam soils. The hydrophobic behavior of MP also determines their water repellency, and subsequently, water flows through porous media. Güney et al. [15] reported that the contact angle values of PVC were smaller than those of PET, which indicated that the greater hydrophobicity of PET than that of PVC could lead to greater water flow and K_s in the presence of PET. It has also been reported that the hydrophobicity of PET particles is greater than that of PVC [37].

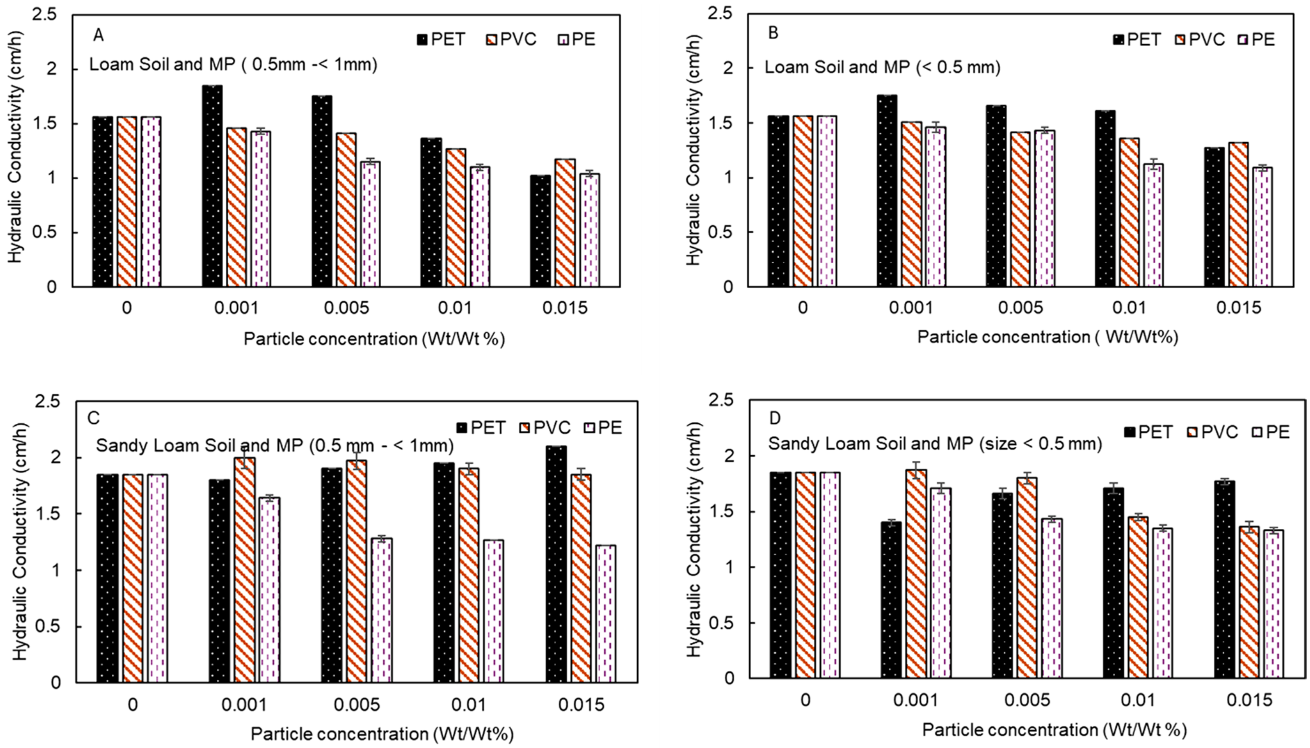


Fig. 1 Effects of microplastic polymer type on soil K_s

Regardless of the variation in soil texture, among the three types of MPs, the addition of both PVC and PE resulted in a gradual decrease in K_s with increasing concentrations, except for some variations that were observed in the case of larger-sized (0.5 to < 1 mm) PVCs in sandy loam soils (Fig. 1). Owing to pore-clogging effects, the K_s of loam and sandy loam soils decreases with increasing concentrations of MP [33, 35]. However, the effects of PET on K_s were not identical in loam and sandy loam soils (Fig. 1). A recent investigation reported a significant increase in K_s with increasing size and MP concentration in black clay soils due to the increase in pore diameter in black clay soils [36]. In addition, a similar study reported an increase in K_s with increasing pore dimension [39].

Adding the lowest 0.001% (Wt/Wt) concentration of PET MP to the loamy soil raises the K_s value by 1.12 times compared to the control soil (Fig. 1A and B). Later, the K_s of loam soils decreased gradually with increasing concentrations of PET (Fig. 1A and B). Loam soils generally have a balanced distribution of soil particles, with approximately half of the porous space in soils. At low concentrations, PET particles cannot clog pores and cannot reduce water flow; however, the increased water flow in loam soils in the presence of PET might be due to the hydrophobic nature of PET [37]. In contrast, the PET particles at higher concentrations clog the soil pores and reduce the K_s of loam soils, which indicated that the hydrophobic repulsion of water molecules at low concentrations of PET could not overcome the effects of the PET particle concentration at higher PET levels (Fig. 1A and B). The decrease in K_s at higher concentrations of PET is supported by the mechanism of pore dimension and/or pore diameter increase due to the dominance of smaller size fractions of particles compared with those of sandy loam soils [36, 39]. On the other hand, irregular changes in the K_s of sandy loam soils after the addition of PET particles (0.5 to < 1 mm) were observed due to variations in the sizes and concentrations of those MP (Fig. 1D). However, a gradual increase in K_s in sandy loam soils with larger particles (0.5 to < 1 mm) indicated the repulsion of water molecules from hydrophobic PET surfaces (Fig. 1C). Muñóz et al. [28] reported a decrease in the drag reduction percentage due to the application of a hydrophobic coating to the inner wall of the pipe under fluid flow conditions, which also reduced the energy required to transport fluid in a pressurized pipe. The presence of hydrophobic particles in a soil matrix can generate moderate repellency to water molecules in the presence of naturally occurring hydrophobic sand, but a surface coating on individual soil particles causes more extreme repellency from water [3], which can induce water flow and increase K_s in the soil. A gradual decrease in K_s with increasing PVC concentration was observed in the sandy loam soils, this gradual decrease is explained by the pore-clogging effects of the increased concentrations of MP in loam and sandy loam soils [33, 35].

In addition to size and concentration variations, the hydrophobicity of plastic surfaces is related to the physicochemical and electrochemical properties of the MP. These properties depend on the chemical composition of the polymer, the type of plasticizer used, the degree of polymerization, the surface structure, the crystallinity, and the polarity [11, 14, 31]. However, hydrophobic repulsion cannot be the only factor influencing the wettability mechanism of plastic particles [19]. The wettability of MP depends on the nature and density of the chemical functional groups on their surface [19].

3.2 Effect of microplastic particle size on saturated hydraulic conductivity

Regardless of their size, the PET particles applied in loam soils increased the K_s at lower concentrations but decreased the K_s at higher concentrations (Fig. 2A). At lower concentrations, the hydrophobicity of the PET particles dominated the pore-clogging effect in the loam soils. Later, at higher concentrations, the PET particles clogged the pores of the loam soils and reduced the K_s. In contrast, larger sized (0.5 to < 1 mm) PET particles gradually increase the K_s with increasing concentration in the sandy loam soils (Fig. 2B). The larger-sized PET particles showed no pore-clogging effects on the sandy loam soils at low concentrations. The larger PET particles could be well-arranged in large pores due to the low structural stability of sandy loam soils, which had 62% sand particles (Table S1). However, those increases in K_s at high concentrations in sandy loam soils could be explained by the high pore fractions and larger pore dimensions (Fig. 2B). The addition of PET particles (0.5 to < 1 mm) could increase the number of macropores in sandy loam soils [33, 35, 39]. Additionally, the hydrophobicity of PET particles might be greater at higher concentrations. On the other hand, the smaller-sized PET particles could not clog the pores to significantly reduce the K_s of the sandy loam soils compared with that of the control soil (Fig. 2B). The smaller-sized PET particles, even at high concentrations, seemed to be distributed homogeneously in both macro- and micropores in sandy loam soils [33]. However, the highest K_s (2.1 cm/h) was detected for the PET particles (0.5 to < 1 mm) in the sandy loam soil at the highest concentration applied in this investigation. On the other hand, the lowest K_s (1.02 cm/h) was observed in loamy soils with similar PET sizes, which indicated that pore-clogging occurred at higher concentrations at lower pore dimensions and lower pore fractions in loamy soils than in sandy loam soils.

Regardless of size, the PVC particles gradually reduced the K_s of loam soils with increasing concentrations (Fig. 2C) because of their pore-clogging effects. However, only the smaller-sized PVC particles reduced the K_s of the sandy loam soils at the highest concentration (Fig. 2D). At the lowest concentration of the larger-sized PVC particles, the K_s of the sandy loam soils increased due to the hydrophobic repulsion of PVC with water molecules (Fig. 2D). However, the K_s of the sandy loam soil returned to that of the control soil due to pore-clogging effects [16, 33] when larger PVC particles were used at high concentrations.

Like PVC, PE particles, regardless of their size, gradually reduced the K_s of both loam and sandy loam soils with increasing concentrations (Fig. 2E and F). The PE particles gradually clog the pore spaces of loam and sandy loam soils at relatively high concentrations, reducing the K_s. At a specific concentration, the smaller-sized (< 0.5 mm) PE particles presented higher K_s values in sandy loam soils than the larger-sized (0.5 to < 1 mm) PE particles (Fig. 2F). This higher K_s for smaller-sized particles could be explained by greater surface area and hence greater hydrophobic repulsion to water molecules by PE. In contrast to PE, the addition of smaller particles of both PET and PVC resulted in lower K_s in sandy loam soils than did the addition of larger (0.5 to < 1 mm) particles (Fig. 2B and D). Furthermore, in loam, the addition of both PVC and PE particles (0.5 to < 1 mm and < 0.5 mm) resulted in a decreasing trend in K_s with increasing particle concentration, except for PVC in sandy loam soils (Fig. 2C, D, E and F). The irregular trend of K_s in sandy loam soil in the presence of PVC could be explained by the greater interaction of water molecules and PVC particles due to the lower hydrophobicity of PVC than that of PE [21]. Accordingly, the two different sizes of MP particles have no significant effect on the K_s in our investigation, in contrast to the kind of polymer type of MP particles (Table S2).

3.3 Effect of soil texture on saturated hydraulic conductivity

Regardless of the size variation of all MPs, soil texture strongly affects the saturated hydraulic conductivity of soils (Fig. 3). For any type of MP polymer, the K_s in the sandy loam soil was relatively greater than that in the loamy soil,

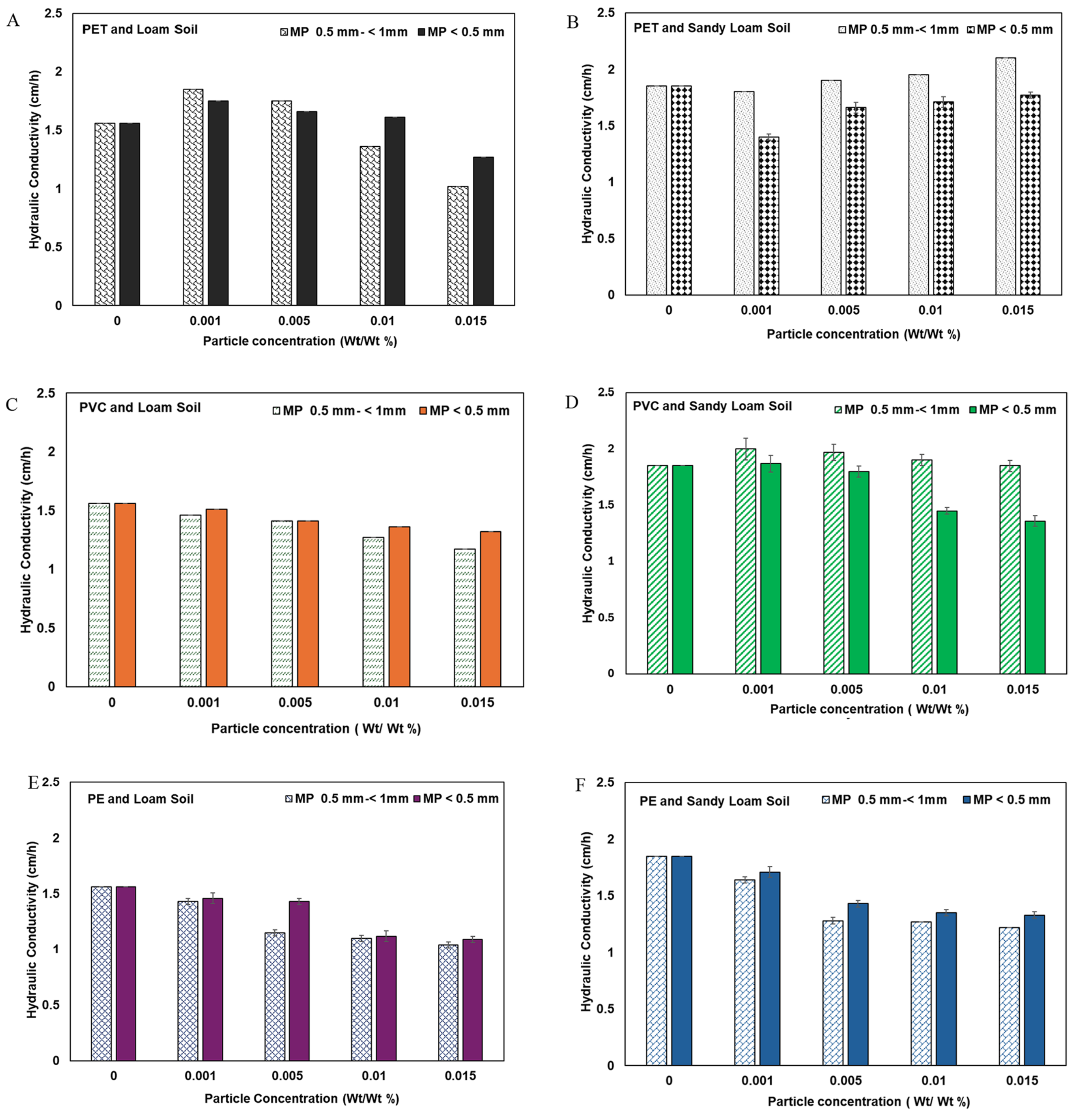
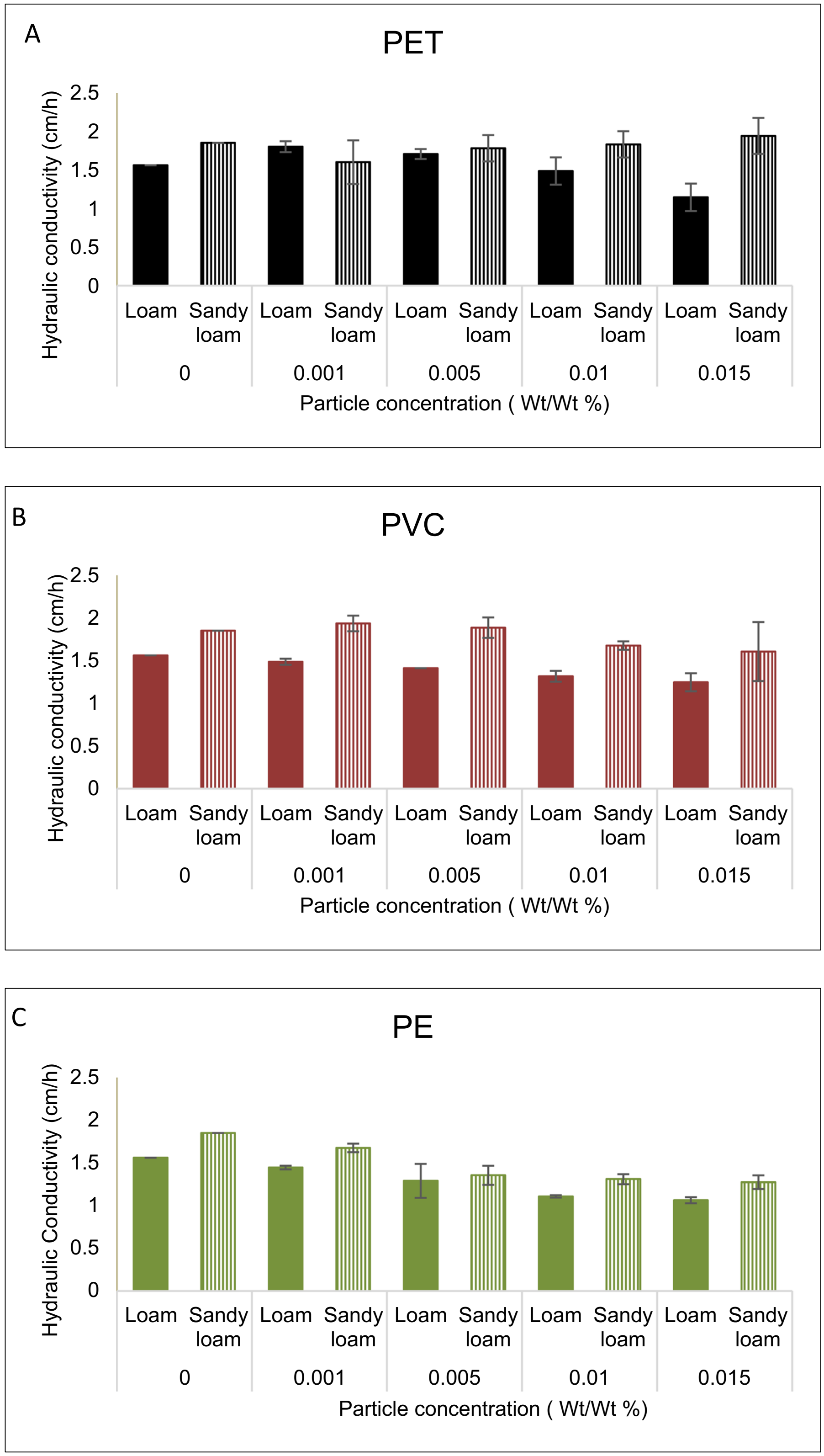


Fig. 2 Effect of microplastic particle size on soil K_s

and the difference in K_s for the sandy loam and loams was statistically significant (Table S2). The extent to which MPs affect the K_s of different textured soils seems to be dependent on the arrangement of soil pores after the addition of MP [6]. The addition of PET particles strongly affected the K_s of both loam and sandy loam soils at any concentration of MPs in this study (Fig. 3A). The addition of PET increased the K_s at low concentrations of particles (0.001 and 0.005%) and decreased with increasing particle concentration (Fig. 3A) in loam soils, whereas the opposite trend was observed for K_s in sandy loam soils. This opposite trend of K_s in the presence of PET could be explained by the particle size distribution and arrangements of pores due to large size fractions of particles in sandy loam soils and smaller size fractions of particles in loam soils. Nevertheless, this significant difference in K_s among the different soil textures indicates the clear effect of the particle size distribution on the soil textural class. The K_s in sandy loam soils

Fig. 3 Effects of soil texture on K_s



in the presence of PVC particles initially increased at low concentrations and then decreased at higher concentrations of PVC particles. The increase at low concentrations might be due to the greater hydrophobic repulsion of water molecules in the presence of hydrophobic PVC in the large size fraction of pores in sandy loam soils, whereas with increasing particle concentration, the clogging of pores decreased the K_s (Fig. 3B). However, the PVC in loam soil showed a continuous decreasing trend in K_s, which indicated an increase in pore clogging with increasing particle concentration in a smaller size fraction of loam textured soils. On the other hand, the K_s of both the loam and sandy loam soils decreased gradually with the addition of increasing concentration (Wt/Wt%) of PE particles in both the loamy and sandy loam soils (Fig. 3C).

In previous studies, K_s was not affected by the addition of polyester MP to loamy sand soil [25] or clayey soil [39], although the soil bulk density significantly changed. Moreover, Machado et al. [25] reported increases in porosity, water-holding capacity, and evapotranspiration in loamy sandy soil at high concentrations (0.4%) of polyester fibres (PSs). In contrast, Zhang et al. [39] reported a reduction in water-holding capacity by incorporating 0.3% PS into clayey soils. Furthermore, the addition of PET and PS to silty loam soil resulted in a reduction in K_s compared with that of the control depending on the MP concentration [33, 35]. Previously, many authors have used high concentrations and larger particle sizes (> 0.5 mm) of MP while showing the effects of MP types on K_s [16, 33]. The findings of this study revealed that very low concentrations of MPs ranging from 0.001 to 0.015%, if present in an unpolluted environment, had insightful effects on K_s depending on the type and size of the MP and the soil texture.

4 Conclusion

The saturated hydraulic conductivity of soil is significantly impacted by the three types of microplastic particles (PET, PVC, and PE). The new laws and regulations governing the plastics industry, as well as the disposal and recycling of plastic products, must consider plastic polymers because of their impact on K_s. This study revealed that the type of plastic polymer significantly affects the K_s of the tested soil, depending on the soil textural class. However, there are no significant variations in K_s based on the size of the microplastic polymer. In addition to environmental limits, this study clearly shows how the K_s of soil is strongly impacted by the concentration of microplastics within a very low concentration range. This research provides an overview of the significant soil property K_s in the presence of MP polymer type and size. It will address the issues associated with the morphology and methods of MP production in the upcoming investigation. The study does not focus on investigating the effect of MP particle morphology, indicating a need for further in-depth investigation.

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Author contributions R.H.: Sample collection, sample preparation, experiment; A.H.: conceptualization, sample collection, sample preparation, data analysis, manuscript drafting, manuscript editing; S.R.: sample collection, sample preparation, experiment, analysis, manuscript editing; F.Z.T.: data representation, manuscript drafting, manuscript editing; M.A.: Supervision of the whole work. All authors have read and agreed to the published version of the manuscript.

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Data availability All data generated or analyzed for this investigation are included in this article. The datasets are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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