Discover Education

Case Study

Research-based learning as an innovative approach for teaching students of environmental engineering: a case study of the emerging field of microplastics in soil

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Abstract
We implemented research-based learning (RBL) as an alternative to traditional frontal classroom lectures and laboratory sessions to impart knowledge on the emerging topic of microplastics in soil to students. The RBL module aimed at studying how microplastics (MPs) affect soil processes. We designed low-cost, small-scale and simple experiments for master's students in Environmental Engineering at the Hamburg University of Technology. Students reported a clear understanding of concepts underlined by their presentation of the results and enthusiasm towards future exploration for their master's or doctoral projects evidenced by a number of students carrying out research projects in the same field after finishing the module. The experiments were consequently published as an online learning module with the Hamburg Open Online University, to make them accessible for other students. The recent push in the education sector to include innovative teaching and learning methodologies offers new opportunities for RBL that are practical and replicable learning experiences that foster students' research and problem-solving skills in areas of chemical, soil physics and environmental engineering fields.

Keywords Research-Based Learning · Soil Health · Microplastics · Environment · Student-Participative Research

1 Introduction

In view of the changes brought about in the educational sector owing to growing demand of innovative teaching and learning approaches, accentuated in particular during the COVID-19 pandemic and recent geopolitical crises, universities have been seeking different innovative means of pedagogy that navigate the existing challenges and achieve intended learning goals. This quest has led to a wider application of already existing effective learning methodologies such as the research-based learning (RBL) [1]. In the core of RBL, students conduct their own research and with guidance by an academic supervisor are encouraged to make their own interpretations and draw conclusions from the observations. This hands-on learning helps students better understand the subject [2, 3] and gain appreciation of assumptions and uncertainty in data. It has variously been described as a participatory form of learning [4], a student-centred learning method [5], and a format that focuses on the research with students actively conducting research and inquiry [1].

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In RBL, students become the focus of knowledge generation rather than serve as recipients of knowledge provided by their teachers (Fig. 1). Hence, students are expected to identify the source of knowledge by conducting their own research and experiments, thus fostering cognitive, behavioural, and affective experiences [1, 6]. Aimed at filling knowledge gaps by making the students active participants in knowledge creation, RBL contributes as well to students' preparation for their dissertation research [7]. As reported by different studies, RBL is associated with long-term career benefits with students participating in RBL having reported a greater interest and having a better chance in pursuing successful scientific career years down the line [6, 8, 9]. It has been argued that an early exposure to research through a format such as RBL can pre-empt any struggles that the students may face in the later stages of their studies when they engage with research [10, 11].

Research-based learning differs from conventional laboratory modules in that students gain active experience in contributing to ongoing research questions instead of repeating the laboratory manual experiments (Fig. 2). Furthermore, this mode of learning lays emphasis on the research process and research problems rather than passive reception of ideas, knowledge, and research results [12]. RBL experiments have the potential for further innovation in laboratory driven teaching and learning, particularly in a post-pandemic academic scenario where practical skills and knowledge gaps could widen due to changes in the educational sector brought about during the pandemic. RBL methodology offers an effective way to inculcate hands-on understanding in smaller laboratory groups, in this regard.

Research-based learning has been widely recognised as a methodology to increase the engagement of students and create an autonomous path for them to co-create and gain knowledge [12–15]. Bowyer and Akpinar (2022) argue that while the nature of RBL makes it challenging for students, the rewards with regard to making the students work ready and helping them shape their professional identity makes the effort worth it. Thiem et al. [15] report a better understanding of the research process among students, including higher tolerance for obstacles in the process [15]. More recently, Pourhejazy and Isaksen [14] explored the design of research-based learning for undergraduate programs. They argue that research-based learning provides the quintessential qualifications to students to make the fit for engaging in the research projects they are perceived to be ready for by the faculty,RBL has the potential to fill the gap that currently exists between perception and reality of the readiness of students [14].

Motivated by the importance of research and innovation skills in students' training and future career and the limitation imposed by the COVID-19 global pandemic on students' practical and research experiences, we employed RBL approaches to investigate the poorly understood effects of microplastics (MPs) on soil processes. The term microplastics is used to describe pieces of plastic broadly between 1 µm and 5 mm in size, although the exact range

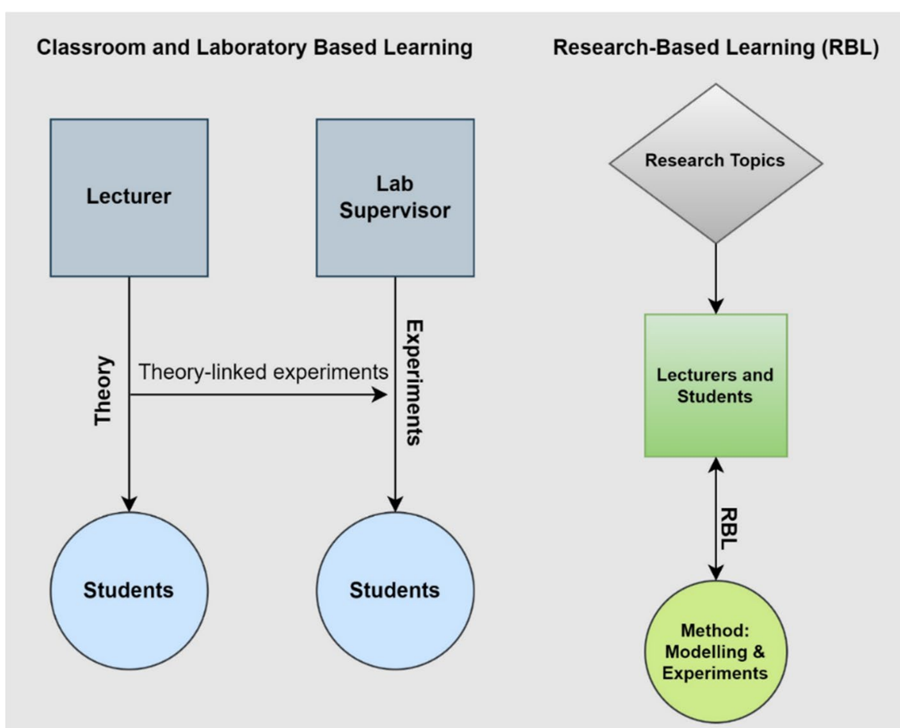

Fig. 1 A schematic description of the research-based learning concept

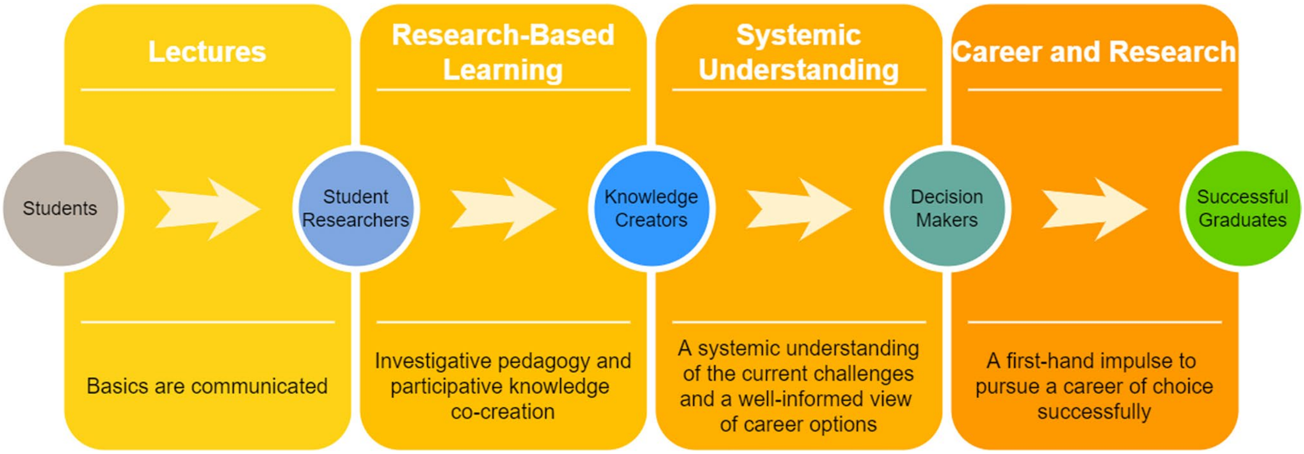

Fig. 2 A schematic description of the different intended impacts of the research-based learning methodology

is still under debate [16]. MPs effects in the environment is an emerging field of study and research, given the recent knowledge on widespread plastic contamination [17, 18]. Microplastics contamination has been reported in water, soil, air, and even in the human food chain, with a recent discovery of microplastics in human blood [19]. Accordingly, this topic has received significant attention from various groups.

Master's degree programs have a broad eligibility criteria for admissions, particularly for environmental engineering programs, where eventually interested students with a bachelors in civil engineering, chemical engineering, environmental engineering, agricultural engineering, petroleum engineering, or even mechanical engineering end up studying together. This diversity of backgrounds was also the case with the current batch of environmental engineering masters. Given the importance of trained environmental professionals to solve the environmental challenges and their dearth, particularly in Europe, it becomes vital to design courses that provide the students opportunity to choose a topic where they want to specialise at an early stage in their degree program. In this regard, having a RBL module can provide the master's students with a hands-on experience necessary to guide them towards the most interesting field of research within the field of environmental engineering, even with varied backgrounds at the bachelor's level.

The choice of "MPs effects on soil processes" in our RBL approach is because although the effects of microplastics in marine environments has been studied extensively, much less is known about how microplastics influence flow and transport processes occurring in soil. This is of particular interest given the dependence of the global food system on the soil and the vital services provided by a healthy soil. Research-based learning applied to this field can open up the possibility to train students with different background such as chemistry, physics, soil science and environmental engineering to devise innovative approaches aiming at tackling the microplastics-related challenges imposed on soil, water, food and the environment. These domains are interconnected, whereby a positive intervention in one domain can lead to simultaneous or subsequent improvements in the other domains [20, 21]. Hence, research-based learning has the potential to promote a better understanding of the Soil–Water-Food nexus among the next generation of scientists, policy makers and engineers.

The presence of microplastics in soil can modify vital physical and chemical soil parameters that influence soil characteristics such as wettability, permeability, and structure. This could in turn impact how fluid flows or plants and crops grow in the soil contaminated by microplastics. To shed new light on this topic, we designed laboratory experiments for master's students in Environmental Engineering at the Hamburg University of Technology aimed at providing the students with the basic understanding and tools to investigate and quantify how MPs influences some of the soil key processes including plant growth, soil water evaporation, cracking in desiccating soils, solute transport in soil, and water infiltration in soil. We could anticipate that not all experiments will show sensitivity to MPs, but this was part of the educational strategy to foster critical thinking and hypothesis formulation with the students. The specific objectives of this module were to provide preliminary understanding of the effects of microplastics on these processes which are vital for sustaining soil ecosystem services. Given that the research on microplastics in terrestrial environment, an emerging threat of great global concern [18, 22], is still in its embryonic stage [17], modules such as this can serve as pointers to inspire further investigative research projects [23], and create a future-ready crop of inspired scientists.

2 Methodology

The different benefits of research-based learning (RBL) notwithstanding, its module design requires more development in academic literature [14, 24]. This study aims to be a contribution towards this discussion. Pourhejazy and Isaksen [14] have summarised the important criteria in the design of RBL modules, in line with a previous study by Mick and Alan (2009), which correspond to the methodology applied in the design of the RBL module that is the subject of this study [14, 25]. The three main criteria they report are: defining learning and skill development goals, defining clearly measurable outputs of the course, and defining the role of students in the course [14]. In our methodology, the learning goals included inculcating interest in a new research field among a batch of students coming from diverse backgrounds at bachelor's level, the measurable outputs were the number of students that would continue working in the field for their master theses and projects, and possible research publications. Lastly, students had a central role in the whole module, whereby they conducted the experiments, collected and analysed the data, interpreted the results, and compiled reports for communication. These correspond to the criteria and tenets of RBL as reported in other recent literature [13, 26, 27].

The RBL module was offered by the Institute of Geo-Hydroinformatics at the Hamburg University of Technology in Germany as a part of a new module titled "Emerging Trends in Environmental Engineering". The designed RBL activities consisted of five experiments focusing on the impact of microplastics on a variety of processes important for soil function and ecosystem services. As a new institute at this university with a clear mandate to drive innovation in the way courses are designed and taught, we aimed to take the first step in this direction with this RBL module. The research-based learning approach trialled in this project aimed at improving the access of the student to new concepts in evolving research fields of environmental engineering. Furthermore, it was aimed to train the students to make them ready to take up detailed Master Project and Master Thesis work in these fields, which are relatively new at this university.

One key criterion considered in the design of our RBL activities was to focus on research theme that can be studied using low overhead cost experiments. The students conducted the experiments following a given template and were asked to do a review of literature and draw inferences from there. With this methodology, the students first performed experiments on a given topic to gain a first-hand experience of the process and then did a basic literature review in order to make sense of the results. Based on this, the students drew their own conclusions from the data collected in the experiments and compared them with literature, which have been included in the following sections. This could potentially enable many teachers in other parts of the world to employ similar approaches in their teaching and learning experiences. The details of each experiment are summarised in Table 1 and explained in the following sections. The microplastics used in the experiments were supplied by Sigma-Aldrich Chemie GmbH, Germany, with polyethylene (PE) having a particle size of 34–50 µm and even smaller polyvinyl chloride (PVC) in powder form. The concentration of microplastics used in the different experiments were decided by the students based on a preliminary literature review.

2.1 Microplastics effects on plant growth

This experiment was conducted to study the effect of MPs on plant growth. In this series of experiments, MPs were mixed with dry soil at 5%, 10% and 15% concentration by mixing 2.5, 5 and 7.5 g of MPs with 50 g of dry soil, respectively. Two types of microplastics were used in the experiments conducted by the students including polyvinyl chloride (PVC) and polyethylene (PE) to evaluate effects of the chemical structure and properties of MPs on plant growth. The mixture of soil and microplastics was placed in a cylindrical pot of 5 cm in diameter and 8 cm in height. Common garden cress (*Lepidium sativum*) was chosen as the plant in this experiment mainly because it grows in a relatively short period of time (less than a week). The cress seeds were sown by adding 1 g of the seeds per pot and the pot was placed in a Smartwares (Smartwares Europe, Netherlands) LED Grow station (Fig. 3). The pots were irrigated 2 times (each 30 mL) once at the start of the experiment and then at 3 days from the onset of the measurement. The plants were harvested after one week. The surface of the pot was photographed once per day during the experiment.

The size and shape of the leaves together with the total fresh mass of the plants was quantified using a digital balance having an accuracy of 0.01 g. In total, 10 pots were used, corresponding to the following distribution:

- 2 pots: Soil without microplastics (control treatment).
- 3 pots: Soil with microplastics at 5, 10 and 15% concentration of polyvinylchloride (PVC).
- 3 pots: Soil with microplastics at 5, 10 and 15% concentration of polyethylene (PE).
- 2 pots: Soil without microplastics and soil with microplastics (15% PVC).

Table 1 Details of the different experiments conducted in the RBL module

Experiment	Setup & dimensions	Learning focus	Treatments & replications	Microplastic types	Microplastic concentrations
Plant growth	Pots: 5 cm diameter and 8 cm height	The effect of microplastics on plant growth	6 treatments, 2 control	Polyethylene (PE) and Polyvinyl chloride (PVC)	5%, 10 %, 15 %
Desiccation cracking	Petri dish: Diameter of 145 mm	The effect of microplastics on soil cracking	4 treatments, 3 replications,1 control	Polyethylene (PE) and Polyvinyl chloride (PVC)	6%, 10%
Water infiltration	Mini Disk Infiltrometer (Meter Group) and soil column of diameter 51 mm	The effect of microplastics on the infiltration of water into soil and fitting the data to Philip's equation	2 treatments, 2 control	Polyethylene (PE) and Polyvinyl chloride (PVC)	10%
Soil water evaporation	Memmert HPP750eco climate chamber and glass column of 80 mm diameter and 200 mm height	The effect of microplastics on the evaporation of water from soil	3 treatments, 1 control	Polyethylene (PE)	0.75%, 1.5%, 4.5%
Solute transport	Cylinder of diameter 8.25 cm, length 20.2 cm.	The effect of microplastics on solute transport in soil	1 treatment, 1 control	Polyethylene (PE)	5%

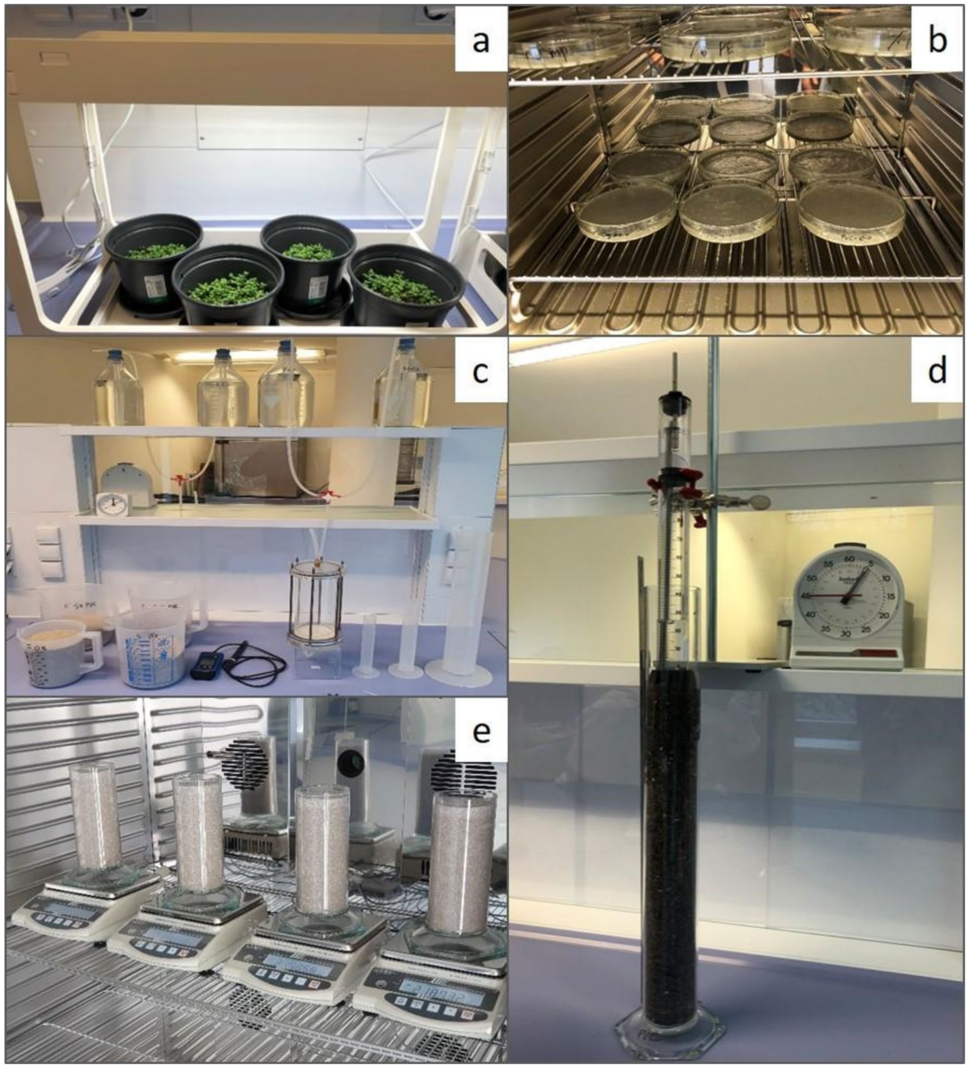

Fig. 3 Photographs of the different experimental setups used to investigate effects of microplastics on **a** plant growth, **b** desiccation cracking, **c** solute transport, **d** water infiltration and **e** water evaporation

2.2 Microplastics effects on cracking in desiccating soil

This experiment was conducted to study the effect of microplastics on cracking morphology formed as a result of water evaporation following the general methodology used in DeCarlo and Shokri [28] and Shokri et al. [29]. Desiccation cracking are important to study various flow and transport processes in soil as they act as preferential pathways for rapid water and nutrients flow. Cracking behavior in agricultural soils can be influenced by different biotic and abiotic factors, and the effect of microplastics in this regard is a field of study yet to be fully explored [30]. To investigate how type and concentration of MPs influence cracking morphology in soil during evaporation, MPs were mixed with a mixture of sand and sodium montmorillonite clay (referred to as bentonite). The soil medium was prepared by mixing 16 g of clay with 8 g of sand mixture (2:1 ratio of clay to sand). Polyethylene (PE) and polyvinyl chloride (PVC) were used as the microplastics at concentration of 6% and 10% (by weight), mixed with the 24 g of the soil mixture. A control sample without microplastics was used as a reference. Three repetitions were prepared for each treatment to ensure reproducibility of the data. The total number of samples hence was 13 (two treatments for two microplastics, each repeated three times (2 × 2x3), and one control).

At the start of the experiment, water was added to the dry mixture (sand + clay + microplastics) in a weight ratio of 4 (water):1 (dry solid) in a container. The final paste was prepared by mechanically stirring to ensure a mixture as much homogenous as possible. After thorough mixing, the material was poured into petri dishes (inner diameter of 145 mm). The dishes were placed in an oven (Model UN110, Memmert GmbH, Germany) for evaporation experiments and kept at a temperature of 30° C. The samples were kept in the chamber for 4 days (Fig. 3). At the end of this period, the surface of the clay was imaged using a digital camera to analyze the cracking patterns and the influence of the type and concentration of microplastics on the formed cracks as a result of water evaporation.

2.3 Microplastics effects on water infiltration in soil

This experiment was conducted to study the effect of microplastics on the rate of water infiltration in soil. An important class of flow events involves water entry through soil surface in a process known as infiltration [31]. The rate of this process relative to the rate of water supply to the surface determines how much water enters the soil, and how much, if any, will pond (maintain on the surface) and create overland flow (runoff). The rate of water infiltration indicates the ability of soil to supply water required for the growth of vegetation among other things. The primary objective of this experiment was to conduct a series of infiltration experiments to quantify how the presence of MPs influences soil water intake properties. The experiments were conducted using measurement devices known as infiltrometers. A Mini Disk Infiltrometer (manufactured by Meter Group) was used in this experiment (Fig. 3). The measurements included vertical infiltration experiments in dry soil in the absence and presence of PE and PVC MPs (10% concentration by mass in both cases).

2.4 Microplastics effects on soil water evaporation

Water evaporation from soil influences many hydrological processes and it is a key component of the water cycle. How evaporation from soil is influenced by the presence of MPs is poorly understood. Although water evaporation from soil have been extensively studied in literature at different scales and boundary conditions [32–34], there are only a few papers discussing MPs effects on soil water evaporation [30]. Thus, the aim of this experiment was to provide new insights on how the presence and concentration of microplastics influence water evaporation from soil. Quartz sand ('*Filtersand*' manufactured by Min2C GmbH, Germany) with the average particle size of 0.4–0.8 mm was used in the evaporation experiments. Four cylindrical glass columns (200 mm in height and 80 mm in diameter) were used in the evaporation experiments. One column was packed with sand without microplastic but the other three were packed with mixture of sand and microplastic at concentrations of 0.75% polyethylene (PE), 0.75% polyvinyl chloride (PVC) and 1.5% PE. Concentration in this case refers to the dry mass ratio of MPs to sand. In each column, a total solid dry mass of 1450 g was used to pack the column. Each sample was manually mixed with 450 g of water. The mixture was used to pack the glass columns following the procedure explained in [35]. The columns were placed in a climate chamber (Memmert HPP750eco) on digital balances (Kern EW 6200-2NM) with an accuracy of 0.01 g connected to a computer to record the evaporative mass losses automatically every 5 min. The mass loss data was used to quantify the evaporation dynamics and to investigate the influence of microplastics concentration on the same. Both relative humidity and ambient temperature were kept constant during the experiment at 30% and 25 °C, respectively.

2.5 Microplastics effects on solute transport in soil

Experiments were conducted to study MPs effects on solute transport in soil which is important in a variety of applications including but not limited to contaminant transport, nutrient distributions or fertilizer applications in soil. Under steady-state flow condition, transport and distribution of non-volatile dissolved chemicals that neither react nor adsorb to solid surface in a homogenous porous medium can be quantified using Advection–Dispersion Equation (ADE) expressed as:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - V\frac{\partial C}{\partial x} \tag{1}$$

where; C is the solute concentration (g/mm^3), D is the diffusion–dispersion coefficient (mm^2/s), V is the advective transport velocity (mm/s), t is time in seconds and x is the dimension along length of the column (mm).

As can be seen in Eq. (1), one of the key parameters affecting solute transport in soil is the diffusion–dispersion coefficient $D(\frac{cm^2}{s})$. Very little is known about how the presence of MPs influences transport properties of soil including D which motivated this experiment. Within this context, the students investigated the diffusion–dispersion coefficients of soil in the presence and absence of MPs. A series of column breakthrough curve (BTC) experiments was conducted with NaCl as the solute. For this purpose, NaCl solution with the concentration of 20 g/L was passed through a column filled with soil using the setup illustrated in Fig. 3. The effluent concentration of NaCl was measured at the outflow using an electrical conductivity meter (Scanntronik Mugrauer GmbH, Germany) over time and the analytical solution of ADE was fitted on the measured data to determine D in the absence and presence of MPs (more details on the analytical solution are presented in Sect. 3.5).

3 Results and discussion

The section sums up the results of the experiments conducted in the research-based learning module. The results presented here are derived from the student reports and the main findings highlighted by the students are presented as quotes under each experiment. Furthermore, the process of a typical RBL module as detailed by Bowyer and Akpinar (2022) has been put into the context of these experiments towards the end of this section [12].

The following is an overview of the experimental results obtained by the students in the module including a discussion on how the students presented and interpreted their findings. The graphical representation of the results of the RBL experiments is included in the appendix of this manuscript and not as part of the main text as the main aim of the manuscript is to present the idea of RBL as an effective learning tool rather than presenting the research results. Furthermore, the experiments are also explained in step by step detail in the online learning module published at https://lernen.hoou-tuhh.de/course/view.php?id=11.

3.1 Experiment 1: plant growth

In the first batch, plant growth comparison was made between soils with no microplastics, 5% PVC, 10% PVC, and 15% PVC. In the second batch, plant growth comparison was made between soils with no microplastics, 5% PVC, 10% PVC, and 15% PE. A third additional batch was performed with two pots (one with no microplastics and one with 15% PVC) to support the findings of the first batch.

The results suggest less biomass production as MPs were added to the soil. Further increase of the concentration of MPs (even up to 15% by mass) resulted in relatively minor changes in the total biomass produced under the boundary conditions employed in our experiments. As a result, the students reported that

"no general trend can (sic) be concluded",

however it was acknowledged that

"the experiments were helpful to understand the possible effect of microplastics on the plants."

Considering the reported data in Appendix, one may suggest that the negative effect of MPs on plant growth was lessened as concentration increased. To interpret the obtained results, the students referred to literature [36] in their discussions that the MPs at higher concentrations could potentially stimulate plant growth. The effect of microplastics on plant growth cycle has also been reported in other studies [22, 37].

3.2 Experiment 2: desiccation cracking

The recorded images at the end of the evaporation experiments in the Petri dishes were used to investigate the desiccation cracking in the absence and presence of MPs. Students used MATLAB software to analyse the data via segmentation of the image into black and white images. Black and white images were used to determine the crack area and crack density using a script developed in MATLAB software following the procedure explained in Shokri et al. [31].

The results suggest that addition of polyethylene (PE) resulted in a general decreasing trend for crack density and crack area ratio in the experiments conducted by the students. However, in the case of polyvinyl chloride (PVC), the crack density was found to generally follow an increasing trend with an increase in the MPs concentration. Moreover, while the crack area increased with an increase in the PVC MPs concentration from 0 to 6%, it decreased as the concentration increased to 10%. This series of experiments highlight the importance of type of MPs on cracking patterns and morphology as MPs with different chemical properties (PE vs PVC in our studies) could induce very different effects on soil processes.

The students concluded that more repetitions are necessary for more conclusive results about MPs effects on the cracking patterns and morphology. It was stated in the student reports that *"the number of samples should be more to have (sic) a conclusion and perform statistical analysis."*

It was also reported that the crack lengths observed in the experiments in control treatments were in the range as reported in literature [29]. Note that MPs effects on desiccation cracking patterns and morphology is an active field of research with many open questions on how the type, concentration and other internal (e.g. type of soil) and external boundary conditions (e.g. drying conditions) influence the cracking dynamics which have been the focus of a number of recent studies [30, 38, 39].

3.3 Experiment 3: infiltration

Water infiltration into soil is affected by several factors including water content, hydraulic conductivity, and the presence of heterogeneities in soil. The classical approach commonly used to quantify water infiltration in soil is Philip's model [40] expressed for the case of vertical infiltration as:

$$I = St^{\frac{1}{2}} + At \tag{2}$$

where, I is the cumulative infiltration (*mm*), t is the time (seconds), S *(mm/s*$^{1/2}$*)* is the sorptivity and A *(mm/s)* is a constant whose value depends on the soil properties and water content. The students used this model to investigate how the presence of MPs influence cumulative infiltration in soil.

The obtained results by the students suggest that

"the *addition of microplastics to soil increased the water infiltration in both cases of PE and PVC compared to the infiltration in soil in the absence of MPs."*

This trend could be due to a decrease in the water retention capacity of soils contaminated with MPs, a consequence that is detrimental for normal functioning of agricultural soils. The students found that the trend of increasing infiltration rates with increased microplastics in soil was consistent with previously reported studies [41]. Xing et al. [41] have attributed the increased infiltration to the increase in hydraulic conductivity due to inhibition of soil particle aggregation, increased soil porosity, and the hydrophobic nature of the microplastics particles [41] which could explain the observed higher water infiltration in the case of soil contaminated with MPs in our experiments.

3.4 Experiment 4 Evaporation

The mass data recorded by the digital balances were used to quantify how water evaporation was influenced by the presence of MPs and its concentration. The so-called stage-1 and stage-2 evaporation [42] was observed in all cases. At the early stage of the evaporation from porous media, water evaporation occurs at the surface which is supplied by the capillary induced liquid flow transporting water from the wet zone toward the surface. This results in a relatively constant evaporation rate (stage-1 evaporation). When the resistive gravitational and viscous forces are balanced by the upward capillary forces, the liquid continuity with the surface is disrupted marking the end of stage-1 evaporation and the onset of a transition period. When all continuous liquid pathways are disconnected from the surface, a new vaporization plane forms below the surface which marks the onset of stage-2 evaporation [43]. The subsequent evaporation is governed by the liquid transport via capillary liquid pathways to this new vaporization plane, evaporation at this level and then vapor diffusion through the overlying dry layer. Our results suggest a longer stage-1 evaporation as the MPs concentration increases. The conclusions drawn by the students were as follows:

"The cumulative mass loss increases by adding microplastics to the sample. With the exception of the 4.5 % concentration, an increase in the microplastics concentration from 0% to 0.75% to 1.5% led to an increase in the evaporation rate. The apparent inverse effect at higher concentration (4.5%) needs to be studied in detail."

Similar trends have been observed in a few recent studies [30]. Wan et al. [30] attributed this phenomenon to an increase in the creation of water channels due to the presence of microplastics [32]. Wang et al. [44] highlighted the effect of microplastics on the alteration of soil porosity and soil aggregate properties affecting evaporation dynamic [44]. To fully understand the effects of MPs on the evaporative fluxes, one would need to investigate how exactly their presence influences transport properties of porous media (e.g. wettability, porosity, pore size distribution, aggregation of particles, etc.) which plays an important role on the evaporation dynamics.

3.5 Experiment 5: solute transport

The main aim of this experiment was to provide the student with the basic tools required to study solute transport in soil and determine how this process is influenced by the presence of MPs. One could use Eq. (1) to describe solute transport through the sand column used in our experiments. The analytical solution of Eq. (1) under the boundary conditions applied in our experiments can be expressed as (Jury & Roth, [45]):

$$\frac{C(L,t)}{C_0} = \frac{1}{2}[erfc(\frac{L-Vt}{\sqrt{4Dt}}) + expexp\left(\frac{VL}{D}\right)\left(\frac{L+Vt}{\sqrt{4Dt}}\right)] \quad (3)$$

where erfc (x) is the complementary error function defined as 1-erf(x), $C(L,t)$ (g/mm^3) is the solute concentration at a given length L (mm) and time t (seconds), C_0 is the initial solute concentration (at $L=0$; $t>0$), V (mm/s) is the advective transport velocity (defined as $=q/\theta$; q being Darcy velocity and θ being the water content), and D (mm^2/s) is the diffusion–dispersion coefficient. Equation 3 was fitted to the measured concentrations at the outflow to determine D and porosity (ε). In our measurement $C_0=20$ g/L, L = 20.2 cm, q = 0.0018 cm/s (in the absence of MPs) and q = 0.0021 cm/s (in the presence of MPs). Note that since the sand columns were fully saturated with liquid during the experiment, θ remained constant and equal to the porosity of the sand. For the curve fitting, the students used Microsoft Excel to fit Eq. (3) on the experimental data with the results presented in the Appendix. The calculated D and ε in the absence of MPs were 0.000244 cm^2/s and 0.5 and they were 0.00489 cm^2/s and 0.35 in the presence of MPs, respectively. Addition of MPs filled the pore spaces in the sand columns which could have resulted in reduction of porosity. Regarding the MPs effects on solute transport, the students concluded that

"The effect of microplastic (PE) in a coarse sand sample is the increase of the dispersion."

The students argued that.

"The reasons for the higher dispersion coefficient are the change in pore size and flow pathways due to the added microplastics."

The reported experimental data suggest that the sand column containing MPs arrived at the breakthrough point earlier than the sand column without MPs. This is consistent with the observations reported in recent papers. For example, Ren et al. [46] reported that MPs may co-transport with solutes in soil by serving as vectors, which might be an explanation of the early breakthrough in the case of soils with MPs [46]. Additionally, Li et al. [47] reported earlier breakthrough of oxytetracycline due to increased concentration of MPs in soil, which was attributed to the reduced sorption of the solute [47].

In these experiments conducted under the research-based learning (RBL) mode, a common thread that was observed across the experiments was that students were able to follow the process of framing research questions, reviewing the literature, collecting and analysing the data, proposing answers and explanations, and communicating the results which has been presented as a defining feature of RBL [12]. This is further evidenced from the fact that at least one of the participating students went into doctoral research in this field, after publishing a research paper on one of the topics of the module. Furthermore, at least four students proceeded to do their master theses in the same field. The presence of a tangible output in the form of research publications or theses is a defining feature of RBL when compared to other learning approaches, and this was achieved in this module [14]. These tangible results conform with the reported aims of RBL courses in other recent studies including improving students' work readiness, inculcating research mindset, and fostering deep learning [13, 26, 27].

This encouraging response points to the efficacy of the RBL approach as an innovative teaching and learning method, in particular for a new field of study, to attract students to pursue their immediate and long term research goals in the field. In this regard, Pourhejazy and Isaaksen (2024) report that students participation plays the central role in the success of a RBL module, thus aligning with studies that found that students' learning improves by up to 80% with active experience of the process [14]. Ahel and Schirmer (2022) also reported higher ratings for different examined dimensions among students that experienced the RBL-based format compared to students that experienced the conventional format [48]. In order to achieve this, Bowyer and Akpinar (2022) report about the different possibilities RBL can be integrated into the curriculum: as a compulsory synthesis project, as an elective project, as a summer research programme, as a thesis project, or a compulsory research-based course [12].

4 Conclusions

These experiments provided a basic descriptor to the students about the wide-reaching effects of microplastics pollution in the environment that go beyond water pollution. The five experiments generated results that give a basic yet solid idea about the effect of microplastics on different soil processes under consideration. As a result, the students were able to understand with hands-on participative research the potential effect microplastics can have on soil processes and functioning. The conclusions drawn by the students from their experimental findings resonate with the results reported in peer reviewed literature on microplastics research.

The potential shown by these small-scale, low-overhead, student-participative laboratory experimental studies is promising in a post-pandemic education system. The RBL module gave the students hands-on knowledge and experience about a wide range of environmental impacts of microplastics. The students hereby actively took part in knowledge co-creation, which is an encouraging sign for the post-COVID education strategy, where the focus is on filling the knowledge gaps arising out of long unexpected breaks. Our study provides an example of innovative teaching in the field of microplastics in soil which proved to be an effective way of enhancing students' learning experiences and pedagogy in higher education. These can further serve to imbibe research interests in the students and hence diversify their prospects after the completion of their studies.

On the other hand, such modules also contribute to improving didactics by engaging academic and research staff actively in open research questions, given that detailed studies on the effects of microplastics on soil processes have been initiated in the Institute of Geo-Hydroinformatics at the Hamburg University of Technology after the completion of the discussed RBL module. They can potentially spur ideas about extensive future research projects and proposals on topics that have not yet been explored by the research institute or the university.

Author contributions NS, SSK, and DO designed the experiments and the study. SJ performed the experiments and analyzed the data. TMS analyzed, interpreted, and contextualized the data, and was the lead author of the manuscript. DE and AB contributed to the research-based learning aspect of the manuscript and revised the draft of the manuscript. TMS and NS revised the manuscript. All authors read and approved the final manuscript.

Data availability Data sets generated during the current study are available from the corresponding author on reasonable request.

Competing interests The authors declare no competing interests.

Appendix

Graphs describing the results of the five student experiments.

See Figs. 4, 5, 6, 7, 8

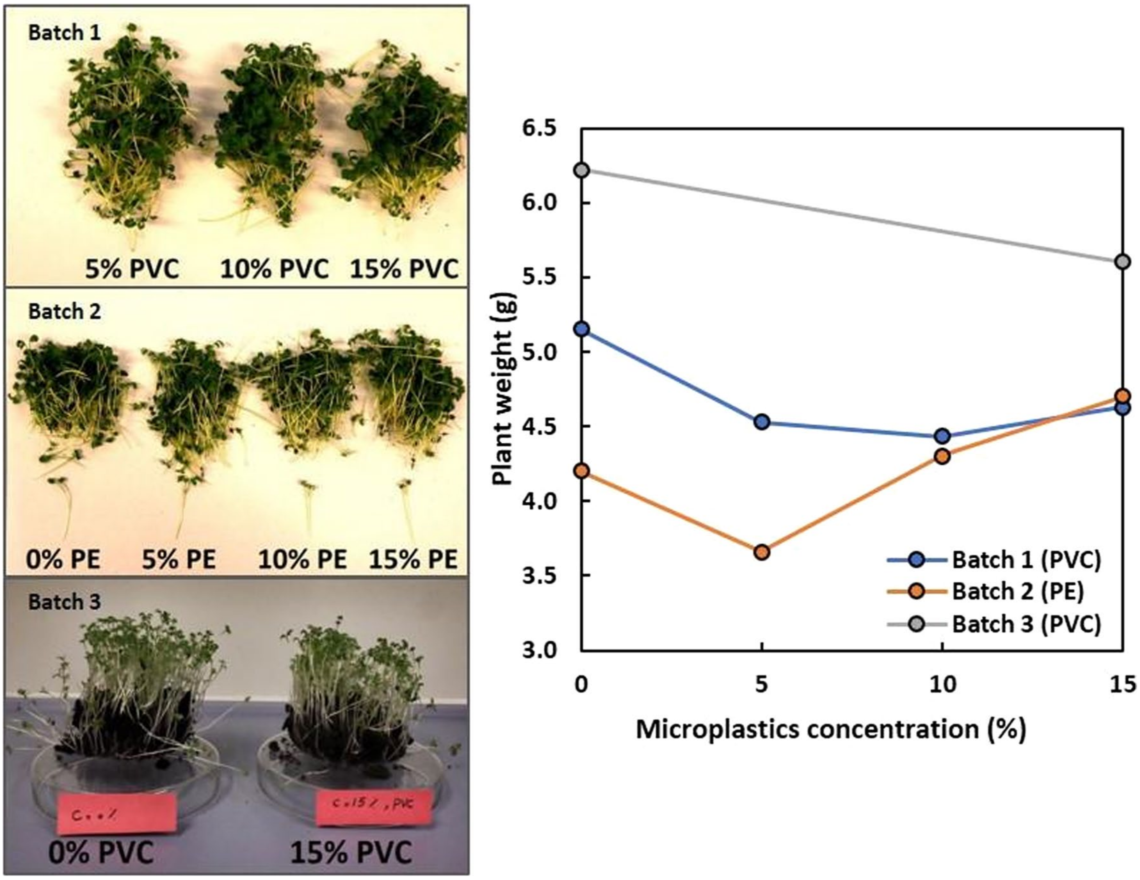

Fig. 4 Visual representation of the results of the three batches and a plot of plant weight versus microplastics concentration

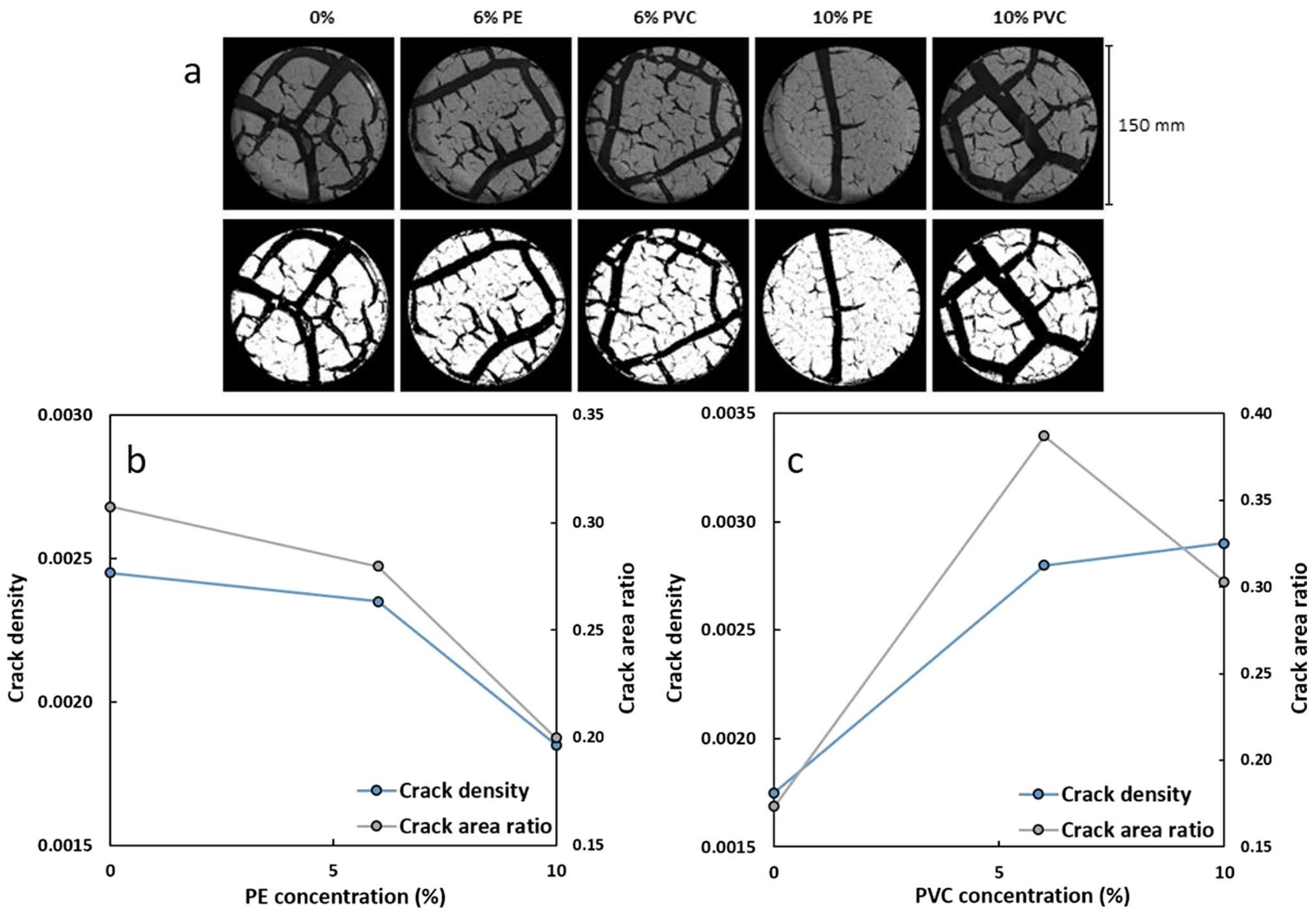

Fig. 5 **a** Typical examples of the crack patterns formed at the end of the evaporation experiments in the absence and presence of different MPs with the grey value and black and white images presented on top and bottom, respectively. The title above each photo indicates the type and concentration of MPs. Crack density and crack area ratio with (**b**) polyethylene (PE) and (**c**) polyvinylchloride (PVC) microplastics

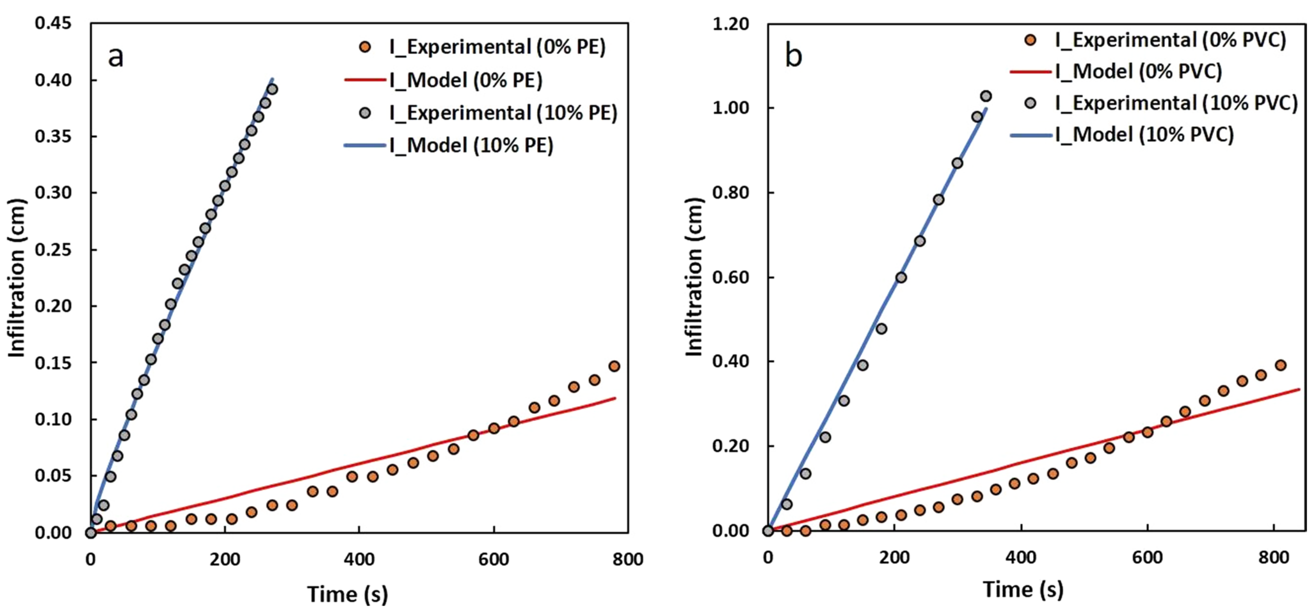

Fig. 6 Measured infiltration into soil samples in the case of (**a**) Polyethylene (PE) and (**b**) Polyvinylchloride (PVC)

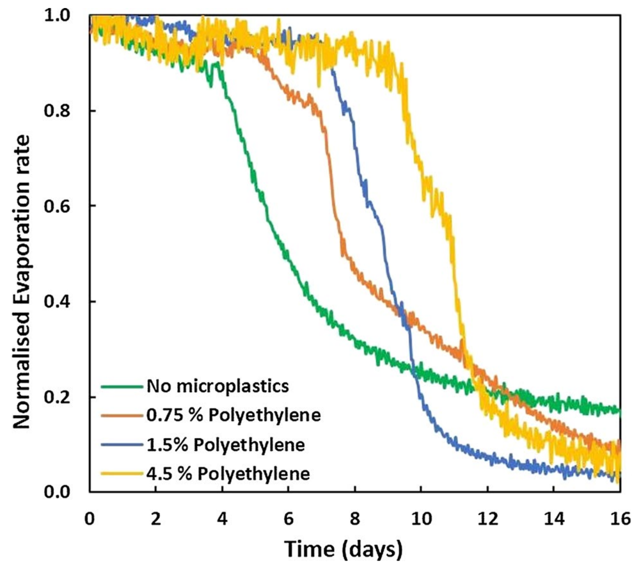

Fig. 7 The normalised evaporation rates (defined as the ratio of evaporative flux to the flux from the fully saturated surface) measured during evaporation from soil samples containing PE with different concentrations

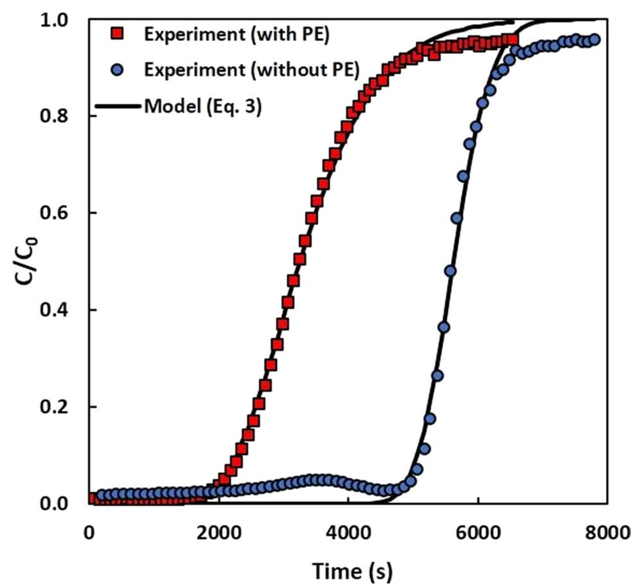

Fig. 8 Breakthrough curves for soil with and without PE microplastics together with the analytical solution of ADE (Eq. 3) fitted on the measured data. C_0 indicates the initial NaCl concentration which was 20 g/L in our experiments

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