Effect of plastic pollution in soil properties and growth of grass species in semi-arid regions: a laboratory experiment

Nasrin Gharahi1,2 · Rasool Zamani-Ahmadmoodi1,3

Received: 27 April 2021 / Accepted: 19 February 2022 / Published online: 5 April 2022
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Abstract
Since the year 2020, the use of plastic as a strategy to mitigate the spread of COVID-19 disease has been given substantial attention. Global environmental contamination of plastic creates waste and is a known threat to soil ecosystems as a main sink of microplastics. However, there is still considerable uncertainty about microplastics controlling soil properties alteration. Therefore, we carried out an incubation experiment with soil and Carex stenophylla Wahlenb., which are the dominant soil and grass species in semi-arid regions. We investigated the effect of polymer polyethylene terephthalate (PET) concentrations (0%, 1%, 3%, and 5%) on C. stenophylla growth and soil ammonium-N and nitrate–N, organic matter content, pH, soil aggregates, and soil respiration. When soils were exposed to PET microplastics, fewer seeds germinated (62.8 ± 32%) but not significantly (p value > 0.05) when soils were treated to 0, 1, 3, and 0.5% PET. Shoot height was also not effectively reduced with PET. The soil pH was considerably lower when exposed to higher PET compared to all other treatments with the soil exposed to 5% w/w PET for both unplanted and planted, being 0.84 and 0.54 units, respectively, lower than the controls. The soil microbial respiration under exposure to PET was considerably increased in comparison to control samples. Moreover, the presence of PET resulted in potential alterations of soil stability, and with PET present soil stability increased. In conclusion, PET microplastics cannot significantly affect the development of C. stenophylla but could affect crucial soil properties. In addition, changes occurred with increased variability in soil ammonium-N and nitrate–N, particularly at a high PET ratio.

Keywords Plastic pollution · COVID-19 · Soil respiration · Soil physical properties · Grass species · Semi-arid regions

Introduction
As evidenced by global plastic consumption and following disposal, the use of plastic is endemic in modern society, leading to microplastic pollution as a mounting environmental concern. Since early in the year 2020, the use of plastic has increased due to COVID-19 disease. With the spread of coronavirus, the production and use of surgical masks, gloves, and protective equipment have increased significantly, and governments are working to upgrade their stockpiles of these products. Such products are essential in these conditions, but all this material and plastic waste will be discharged directly to marine and terrestrial ecosystems (de Souza Machado et al. 2018; Rezania et al. 2018). Soil plastic pollution will originate from plastic particles of micro- and nano-size. Soil microplastic pollution is found to be greater than that in the marine environment (Horton et al. 2017; de Souza Machado et al. 2018). Therefore, investigating soil health and impacts of microplastics to soil ecosystems is of high priority.

Recently, limited research studies have yet been shown some soil micro and macroorganisms can feed microplastics, and consequently suffer from health problems (Rodriguez-Seijo et al. 2017; Kim and An 2019). However, there is uncertainty about these mechanisms, and first studies suggest that microplastics in soils could lead to change to soil physico-chemical properties, microbial activities, and plant mature.

Several factors, such as irrigation, plastic mulching, soil amendments, flooding, and diffuse and urban runoff,
may result in penetrating microplastics into soils (Eerkes-Medrano et al. 2015; Dris et al. 2015; Steinmetz et al. 2016; Majewsky et al. 2016; Mahon et al. 2017; Kim and An 2019). Upon their entry into soils, microplastic particles can intersperse inside the soil via soil management methods (Steinmetz et al. 2016), wet-dry cycles (O’Connor et al. 2019), bioturbation (Huerta Lwanga et al. 2017; Maass et al. 2017), and harvesting (Rillig et al. 2017). Physico-chemical characteristics of soil, such as water-holding capacity, soil bulk density, soil structures, and soil pH, can be altered by the decomposition of microplastics in soil aggregates (de Souza Machado et al. 2018, 2019).

Limited research studies have been conducted on the general impacts of microplastics on soil physiochemical properties. According to several studies, the existence of microplastics in terrestrial ecosystems may harm plant performance, microbial activities, and soil characteristics (Liu et al. 2017; de Souza Machado et al. 2018, 2019; Zang et al. 2019; Wang et al. 2020). Studies include the effects of aged low-density polyethylene and polyester fibers on forest microbiome composition and activity by Ng et al. (2018) and impacts of microplastics on the soil biophysical environment by de Souza Machado et al. (2018). They observed alterations in the water holding capacity, soil bulk density, and the functional relationship between the microbial activity and water stable aggregates which define the soil biophysical environment.

In a study conducted by Zang et al. (2019), the impacts of microplastics type and content on several parameters, including plant growth, photoassimilate carbon allocation, and soil microorganisms, were assessed. Zang et al. (2020) reported negative effect of microplastics on plant growth influencing in both above and belowground productivity.

One study found that microplastics produced of conventional high-density polyethylene and biodegradable polyactic acid, and synthetic fibers could affect the performance of Lolium perenne L. (perennial ryegrass), health of Aporrectodea rosea (rosy-tipped earthworm), and crucial soil properties (Boots et al. 2019). Nevertheless, since limited studies have been carried out on the effects of microplastics on soil ecosystems and plant performance, the present study status is to be understood for subsequent investigations. In the present research, we investigate interactions between microplastics and soil quality, and the impacts to plant performance as well as the fate of microplastics in soils. Therefore, this experiment was set up to assess the plant performance responses to the microplastic contamination of soil ecosystems by polymer polyethylene terephthalate (PET), using soil sown with Carex stenophylla Wahlenb., the most important grass species in semi-arid regions. C. stenophylla plays an increasingly important role in desert ecosystem in arid and semi-arid regions and its shortage is an important cause of desertification which increases wind and water erosion (Pajouhesh et al. 2020).

Materials and methods

Soil sampling, microplastic production, and material characterization

Soil samples were collected from the top 0.3 m of a loam inceptisol soil (Soil Survey Staff. 2010), and the samples were air-dried for 1 week. The samples were then passed through a 5-mm sieve to remove the shells.

The common polymer polyethylene terephthalate (PET) types existing in the environment were used as microplastics for the analysis. The PET was obtained by cutting transparent PET bags. The density of PET polymers was 0.925 g/cm$^3$. Prior to being added to the soil, these polymers were ground to pass through a 0.5-mm sieve to ensure that each piece dimension was < 5 mm.

Experimental design and setup

All experiments were performed under laboratory environments at Shahrekord University, Iran. The experiment was crossed design with two parameters, “plastic” and “plant.” The factor “plastic” had four levels: concentration of 0, 1, 3, and 5% (w/w), and the parameter “plant” had two levels: planted or unplanted. Microplastics sieved at < 5 mm were mixed with the dry soil particles sieved at < 5 mm at application rates of 0, 0.01, 0.03, and 0.05 kg kg$^{-1}$ and located in a 0.22 m deep by 0.2 m wide pot. C. stenophylla is the dominant grass type in semi-arid regions.

C. stenophylla is a perennial herb in the family of Cyperaceae. The plant has the broad underground stems (rhizomes). This plant is unisexual and the male and female flowers are each located on separate spikes (Kukkonen 1998). This species belongs to the Irano-Turanian flora and is one of the dominant plants of steppe rangelands.

In these experiments, pots in which ryegrass was grown received 200 seeds and were watered daily with 10 ml of tap water using a spray bottle. All pots were incubated in a room at 25 °C for 30 days.

According to Table 1, several microplastics, plants, and soil combinations were analyzed.

Soil moisture content was kept constant throughout incubation by wetting daily and returning them to their primary weight by adding water equivalent to the weight variation for weight loss from evapotranspiration.

The seeds were monitored for germination, which was recorded daily. The length of the shoots at 10 random places within each pot was also recorded to determine the growth of C. stenophylla.
At the end of the experiment (after 30 days), the pots were destructively sampled manually and soil samples for analyzing soil ammonium-N and nitrate–N, pH, organic matter content (OC), and soil aggregates were collected.

Soil pH was measured with a pH meter (Watson and Brown 1998). Ammonium-N and nitrate–N were determined following Bowman et al. (2006) procedure. Soil OC was determined according to the Walkley and Black method (Haldar and Sarkar 2005). Aggregate size stability (MWD) was calculated as $MWD = \sum_{k=1}^{n} X_k \times M_k$ where $k$ is aggregate size; $X_k$ (mm) is the mean diameter of the sized aggregate; and $M_k$ (%) is the mass proportion of the sized aggregate.

Laboratory experimental conditions for soil microbial respiration

Soil microbial respiration was measured only for the unplanted treatment. The soil sample treatments (A, B, C, and D in Table 1) in three replicates were incubated separately in the laboratory in tubes of 2.6 cm diameter, 9 cm height, and 47.78 cm³ volume. The measured field bulk density ($\rho_b$) with the known volume ($\rho_b = \text{mass of dry soil} / 47.78 \text{ cm}^3$) was used to calculate the mass of the required dry soil. The initial soil moisture content was kept constant during the incubation time.

Airtight sealed glass containers with a volume of 1200 ml were used for the incubation tubes. The analysis of CO₂ gases was conducted at day 2, 4, 6…, and 30 (2-day intervals) upon 30 days’ pre-incubation. Measurement of headspace concentration of CO₂ of each incubation tube sample was repeated four times (0, 40, 80, and 120 min after closing the glass containers) each analysis day. Gas chromatography using Agilent 7890A with 3 detectors was utilized to determine CO₂ concentration of the headspace.

Data analysis

The differences in germination and shoot length of C. stenophylla were analyzed using one-way analysis of variance (Webster 2007) with the factor plastic, via SPSS 20 for Windows. For mean differences, $p < 0.05$ was considered significant for the treatments. The plastic influence on the soil properties was assessed using an LSD analysis to assess the effect of several treatments on soil ecosystem.

Results

Change to germination and growth of C. stenophylla.

In soils not treated with PET (controls), on average, 62.8 ± 32% of the seeds germinated over the 30 days, with minimum and maximum of 0.0% and 85.6%, respectively. Fewer seeds germinated but not significantly ($p$ value > 0.05), when soils were treated with 1, 3, and 5% PET, which led to a 2.8, 10.6, and 18.6% reduction in comparison to the controls, respectively (Table 2). The daily seed germination was lower in soils treated with 1 and 3% PET and was lowest in soils treated with 5% PET in comparison to the controls (Fig. 1a).

| Combinations of microplastic PET, plant, and soil | Letter code |
|-------------------------------------------------|-------------|
| Soil                                            | A0          |
| Soil + mixing with 0.01 kg kg⁻¹ PET              | A1          |
| Soil + mixing with 0.03 kg kg⁻¹ PET              | A3          |
| Soil + mixing with 0.05 kg kg⁻¹ PET              | A5          |
| Soil which received 200 seeds                   | B           |
| Soil which received 200 seeds + mixing with 0.01 kg kg⁻¹ PET | B1 |
| Soil which received 200 seeds + mixing with 0.03 kg kg⁻¹ PET | B3 |
| Soil which received 200 seeds + mixing with 0.05 kg kg⁻¹ PET | B5 |

Table 1

| Combinations | Mean ± SD | Minimum | Maximum |
|--------------|-----------|---------|---------|
| Germination success (%) of the soil (control, B) and soil under three different rates of microplastic (B1–B5) | 62.80 ± 32.00a | 85.67 | 51.08 ± 28.00a | 70.50 |
| Shoot length (cm) of the soil (control, B) and soil under three different rates of microplastic (B1–B5) | 9.40 ± 4.80a | 14 | 7.80 ± 3.80a | 11 |

The letters in bold denote the tested combinations listed in Table 1. Small letters behind values refer to a meaningful variation ($p < 0.05$) between treatments. The values shown are mean ± standard deviation values of three replicates.
The mean shoot length of *C. stenophylla* over 30 days ranged between 9.4 ± 4.8 and 7.8 ± 3.8 cm and was not significantly (*p* value > 0.05) different with soils treated with 0, 1, 3, and 5% PET (Table 2, Fig. 1b). The maximum shoot length was on average 14, 13, 14, and 11 cm for soils treated with 0, 1, 3, and 5% PET, respectively (Table 2). In general, adding microplastics had no significant impact on germination and shoot length of *C. stenophylla* (Table 2, Figs. 1a and b).

**Change to soil microbial respiration**

In the 2-day interval over 30 days, CO₂ flux was approximately two-fold higher in unplanted soils treated with 3% PET, in comparison to other treatments. The daily CO₂ flux was two- to three-fold higher in unplanted soils exposed to high PET (5% w/w PET), in comparison to other treatments (Fig. 2). This showed a high cumulative CO₂ in unplanted soils treated with 3% and 5% w/w PET compared to control soil (0% w/w PET) (*p* value < 0.05; Table 3).

**Influence on soil physical and chemical characteristics**

After 30 days of exposure to PET, the soil pH ranging between 7.03 ± 0.15 and 7.87 ± 0.06 (Table 3) was significantly different between the unplanted-soil PET treatments and control (A) (*p* value < 0.05). With the presence of *C. stenophylla*, soil pH was significantly affected by the PET treatments. Planted-soil pH, ranging between 7.41 ± 0.03 and 7.93 ± 0.10 (Table 3), was significantly different between the planted-soil PET treatments and control (B) (*p* value < 0.05). The pH of the soil, particularly when exposed to higher PET, was significantly lower than all other treatments, with the soil exposed to 5% w/w PET for both unplanted and planted soil being 0.84 and 0.54 units, respectively, lower than the controls (Table 3).

Soil OC was on average 0.67 ± 0.2% and was slightly greater in the soil of pots by adding *C. stenophylla*. Nevertheless, OC except for 5% w/w PET treatments was not significant compared to control soil (0% w/w PET) and was not measurably influenced by PET treatments (Table 3).
At day 30, ammonium–N and nitrate–N varied broadly from 19 to 40 mg·kg⁻¹ and 56 to 94 mg·kg⁻¹, respectively, for PET-treated unplanted soils (Table 3). Ammonium–N and nitrate–N varied from 10.7 to 40.7 mg·kg⁻¹ and 44.3 to 83.3 mg·kg⁻¹, respectively, over PET-treated planted soils. Soils that received PET showed significantly greater ammonium–N and nitrate–N compared to controls (Table 3).

**Effect of microplastic on soil aggregation**

Table 4 and Fig. 3 demonstrate the influence of the four PET applications on aggregate size distribution after 30 days' incubation. Compared to the control, the proportion of the >1 mm and 0.1–0.5 mm fractions for unplanted soils increased with the use of PET (A1, A3, A5) in comparison to the control (A), albeit this increase was significant only for the A3 and A5 treatments. The proportion of the 0.5–0.2, 0.2–0.1, 0.1–0.05, and <0.01 mm fraction decreased after 30 days, for all A1, A3, and A5 in comparison to the control (A), but this decrease was only considerable for the proportion of the 0.1–0.05 mm fraction.

Regarding the planted soils, Table 4 shows that incubating the four PET applications for 30 days significantly decreased the proportion of the <0.5 mm fraction in comparison with incubating the control (B) for 30 days. It can also be seen that the proportion of the >1 mm and 0.1–0.5 mm fractions increased significantly using PET (B1, B3, B5) compared with the control (B).

In addition, both unplanted and planted soils under 3% and 5% PET treatments had a greater proportion of the >1 mm and 0.1–0.5 mm fractions compared with 1% and 0% PET treatments.

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**Table 3** Mean of soil physicochemical properties of the soil under three different rates of microplastics at day 30 of incubation times

| Combinations of microplastic PET and soil | pH     | OC    | Ammonium-N (mg/kg) | Nitrate–N (mg/kg) |
|------------------------------------------|--------|-------|--------------------|------------------|
| A                                       | 8.1 ± 0.60 | 7.87 ± 0.06 | 0.67 ± 0.2 | 19.0 ± 1.7 | 56.0 ± 3.6 |
| A1                                      | 7.6 ± 0.16 | 7.53 ± 0.06* | 0.70 ± 0.0 | 36.7 ± 2.9* | 85.3 ± 8.2* |
| A3                                      | 9.8 ± 0.43* | 7.27 ± 0.06* | 0.58 ± 0.1 | 39.3 ± 0.6* | 93.7 ± 14* |
| A5                                      | 11.8 ± 0.5* | 7.03 ± 0.15* | 0.52 ± 0.1* | 40.0 ± 3.5* | 94.3 ± 16.7* |
| Combinations of microplastic PET, plant, and soil |        |       |                    |                  |
| B                                       | –      | 7.93 ± 0.10 | 0.95 ± 0.0 | 10.7 ± 1.2 | 44.3 ± 2.9 |
| B1                                      | –      | 7.73 ± 0.00* | 0.93 ± 0.2 | 35.0 ± 3.5* | 81.3 ± 7.1* |
| B3                                      | –      | 7.60 ± 0.06* | 0.77 ± 0.1 | 39.7 ± 4.0* | 81.3 ± 17.2* |
| B5                                      | –      | 7.41 ± 0.03* | 0.68 ± 0.1* | 40.7 ± 1.2* | 83.3 ± 5.7* |

The letters in bold denote the tested combinations listed in Table 1. * refers to a meaningful variation (p < 0.05) in comparison to the control. The values shown are mean ± standard deviation values of three replicates.
Discussion

Microplastics’ effect on seed germination and growth of *C. stenophylla*.

Plant growth could be altered by microplastic contamination of soil, as observed by microplastic-induced variations in the germination and shoot length of *C. stenophylla*. Several parameters, such as (1) direct toxicity of microplastic on plant, (2) indirect effect on plant growth via variations in soil characteristics, and (3) microbial communities, can be described as the influence of microplastics on plant growth (Gu et al. 2017; Rillig et al. 2019; Qi et al. 2018; Zang et al. 2020). Our findings revealed that the response to the effects of microplastics on germination rate and plant growth depends on the amount of microplastics within the soil; however, it did not show a significant response.

Prior studies expressing the capability of microplastics to decrease the rate of plant growth reaffirmed by our findings (Boots et al. 2019) have been confirmed. For instance, the reduced seed germination and reduced shoot height of *L. perenne* with microplastic of biodegradable polylactic acid. Bosker et al. (2019) illustrated that polystyrene microplastics decreased germination of the dicotyledon *Lepidium sativum* L.

The analyses of the findings of microplastics in soil are consistent with the results of Qi et al. (2018), Boots et al. (2019), Bosker et al. (2019), Mašková and Herben (2018), Hayes et al. (2017), Martin-Closas et al. (2017), and Dimkpa et al. (2013). In all the mentioned studies, the capacity of microplastics to reduce the germination rate and plant growth was reported. We observed that the reduction in seed germination and growth of *C. stenophylla* was most acute (not significantly) at high microplastic additions. Furthermore, microplastics may damage plant tissues (Navarro et al. 2008), although the phenomenon is still under investigation. In contrast to the above studies, Zang et al. (2020) stated that plant biomass was improved under high microplastics addition rates. They illustrated that the variations in soil

| Table 4 | Percentage of aggregate at six size fractions after dry sieving of soil treated with PET. The values shown are average values of three replicates, supplementing the results of Fig. 3 |
|---|---|---|---|---|---|---|
|   | > 1 mm | 1–0.5 mm | 0.5–0.2 mm | 0.2–0.1 mm | 0.1–0.05 mm | <0.05 mm |
| Combinations of microplastic PET and soil |   |   |   |   |   |   |
| A   | 27.7 ± 3.5 | 19.5 ± 5.1 | 29.8 ± 1.3 | 12.8 ± 1.9 | 8.4 ± 0.9 | 1.7 ± 0.2 |
| A1  | 27.2 ± 0.5 | 26.6 ± 0.7 | 26.6 ± 2.1 | 10.9 ± 2.3 | 6.1 ± 0.4* | 1.4 ± 0.3 |
| A3  | 30.3 ± 6.4 | 29.3 ± 1.4* | 29.1 ± 1.3 | 9.6 ± 3.4 | 4.6 ± 1.9* | 2.0 ± 0.4 |
| A5  | 31.1 ± 0.3 | 27.6 ± 3.5* | 28.0 ± 2.4 | 11.4 ± 3.6 | 4.3 ± 0.1* | 1.5 ± 0.3 |
| Combinations of microplastic PET, plant, and soil |   |   |   |   |   |   |
| B   | 17.4 ± 2.6 | 24.6 ± 2.5 | 38.9 ± 4.5 | 14.7 ± 5.8 | 3.8 ± 0.6 | 0.5 ± 0.2 |
| B1  | 20.4 ± 8.0 | 23.8 ± 8.1 | 38.9 ± 4.3 | 10.2 ± 1.4 | 5.7 ± 1.1* | 0.78 ± 0.1 |
| B3  | 30.4 ± 8.7* | 34.8 ± 7.5* | 23.1 ± 8.2* | 4.9 ± 1.5* | 5.1 ± 0.2 | 1.6 ± 0.2* |
| B5  | 23.3 ± 5.9* | 32.5 ± 7.4* | 15.4 ± 4.4* | 11.3 ± 1.4 | 6.1 ± 0.6* | 2.6 ± 0.6* |

The letters in bold denote the analyzed combinations listed in Table 1. * refers to a meaningful variation (*p* < 0.05) in comparison to the control.

**Fig. 3** Distribution of percentage of aggregate size–fraction under microplastic for planted and unplanted soils

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**Table 4** Percentage of aggregate at six size fractions after dry sieving of soil treated with PET. The values shown are average values of three replicates, supplementing the results of Fig. 3
characteristics caused by microplastics make a major contribution to increased plant growth (Zang et al. 2020).

**Microplastics’ effects on physico-chemical soil properties**

Our results showed that soil pH decreased with increasing amounts of microplastics in the pot experiment, which could account for the increase in the soil aggregate size, soil porosity, and aeration when the microplastics were added into the soil and altered soil microorganism and soil pH. This is consistent with findings by Bandow et al. (2017) and Boots et al. (2019), who stated that increasing soil microplastics in general resulted in a reduction in soil pH. However, the initial soil pH for both planted and unplanted soils was slightly alkaline and above the optimal range (pH 6.4–7.3) reported to produce many crops (Moebius-Clune et al. 2016).

Furthermore, recent researches indicated that the presence of plant species and soil type may influence microplastics’ effects on soil pH (Boots et al. 2019; Yu et al. 2020; Lozano et al. 2021b). In addition to the soil type and presence of plant species, the microplastic shape in the system may also influence microplastics’ effects on soil pH (Zhao et al. 2021) as polyethylene foams increased soil pH more than polyethylene films.

The addition of microplastics resulted in significantly greater ammonium-N and nitrate-N in soil. Based on the report by Liu et al. (2017), it is assumed that adding microplastics to soil significantly increases the levels of nitrogen in soil. Therefore, the nutrient cycling processes in soil ecosystems may be affected by accumulation of microplastics.

Bacterial respiration was generally increased by adding microplastics to the soil; however, this is very serious when soil is exposed to 3% and 5% PET microplastics. This increasing effect may be due to PET loose flexible structure that may increase soil aeration.

Nevertheless, studies found that increasing microplastic concentrations significantly changed soil enzymes (Liu et al. 2017, 2018; Awet et al. 2018; de Souza Machado et al. 2018, 2019).

However, recent research indicates that polypropylene microplastics added at 7 to 28% w/w of soil dry weight significantly increased soil microbial activity (Liu et al. 2017), whereas polyacrylic and polyester particles added at 0.05–0.4% of soil dry weight had a reduction effect on soil microbial activity (Liu et al. 2017; de Souza Machado et al. 2018).

However, another study found that increasing biodegradable polylactic acid and polyethylene concentrations considerably decreased the level of rosy-tipped earthworm in soil (Boots et al. 2019). Microplastic effect on bacterial respiration may also occur in soil systems with different mechanisms.

Furthermore, Zhao et al. (2021) showed that soil respiration was higher with polyethylene foams than without polyethylene foams. Zhao et al. (2021) and Lozano et al. (2021a) also reported that polyethylene films and fragments had neutral effects on soil respiration, while positive effects have been observed in this property when a plant species was included in the system.

Nevertheless, the effects of microplastics existing in soil-to-soil microorganisms are still under investigation.

In this study, the addition of microplastic generally improved aggregate stability leading to a significant increase in the proportion of macropores in the soils. Hence, the variation of particles with sizes larger than 0.5 mm and significantly fewer 0.05–0.1 μm resulting from microplastic applications resulted in increased soil stability. The aggregation of soil is improved by using microplastics due to increasing microbial activity and forming macroaggregates. This positive effect may be due to the loose spongy structure of microplastics that may increase macropores. This is consistent with findings by Boots et al. (2019), Bosker et al. (2019), Sintim and Flury (2017), Zhang and Liu (2019), and de Souza Machado et al. (2018), who reported that, in general, increased soil plastic content implied increased soil aggregate stability. Variations in soil aggregate size may lead to variations in the soil carbon process and nutrient access in micro- and macroaggregates (Tisdall and Oades 1982; Boots et al. 2019). Furthermore, Souza Machado et al. (2018) reported a negative impact of microplastic on soil water–stable aggregates.

It should be mentioned that in two recent years, the use of plastic due to COVID-19 disease as a strategy to mitigate the spread of coronavirus has been given substantial attention. In the last 12 months, approximately 20% of studies in environmental sciences have studied the impact of COVID-19 disease on waste and plastic pollution (Patrício Silva 2018). To the best of our knowledge, limited research studies have focused on the influences of microplastics on soil physiochemical characteristics; this is the first research addressing the impact of microplastics on soil quality and the impacts on plant performance in soils of semi-arid regions. More work is required to clarify the mechanisms by which microplastics can decrease or increase soil quality and plant performance. Moreover, further studies may address the interactions between soil aggregates and microplastics, and the effects on soil characteristics and destination and transport of microplastics in different soils.

**Conclusion**

This study contributes to a better understanding of the effects that microplastics have on seed germination, the growth of *C. stenophylla*, and soil microbial respiration, which can be
linked, among others, to the changes in soil pH, ammonium-N, nitrate–N, and soil aggregate stability.

The present research reveals the variation in a semi-arid soil and subsequent plant performance after 30 days of exposure to microplastics. When exposed to PET microplastics, fewer seeds germinated. However, shoot height was not effectively reduced in the presence of PET, while with PET present there was a decrease in soil pH. The presence of PET results in potential alterations of soil stability.

The results of the soil aggregate distribution between the treatments reveal the complicated consequences of microplastic in the terrestrial ecosystem. The interaction of microplastics and aggregate stability, especially fine-sized particles, could be influential when considering the potential effect of microplastics on soil structure. In conclusion, PET microplastics do not significantly affect the development of *C. stenophylla* but could affect crucial soil properties. In addition, changes occurred with increased ammonium-N and nitrate–N, particularly at high PET ratio. The differences in the microbial respiration between PET treatments and controls also offered that chemical characteristics of the microplastics can have a major impact on directing the change of the soil micro/macrobiome. Future specific research on this area is needed.

**Author contribution** N. Gharahi and R. Zamani-Ahmadmahmoodi supervised the research, designed the experiments, analyzed data, and co-wrote the paper.

**Funding** The present study was funded by Shahrekord University, Shahrekord, Iran.

**Data availability** The datasets applied and/or analyzed throughout the present research are available from the corresponding author on reasonable request.

**Declarations**

**Ethics approval and consent to participate** Not applicable.

**Competing interests** The authors declare no competing interests.

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