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RESEARCH ARTICLE

Photodegradation modifies microplastic effects on soil properties and plant performance

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Abstract

1. Microplastics (MPs) in soil affect plant–soil systems depending on their shape and polymer type. However, previous research has not yet considered the effects of degraded plastics, which are the plastic materials actually present in the environment.
2. We selected eight MPs representing different shapes (fibres, films and foams) and polymer types, and exposed them to UV-C degradation. Each MP was mixed with soil at a concentration of 0.4% (w/w). The phytometer *Daucus carota* grew in each pot. At harvest, soil properties and plant biomass were measured.
3. Photodegradation altered MP physical and chemical properties, impacting plant–soil systems. MP degradation effects on plant and soil were observed with fibres and foams, but there were negligible effects with films. The latter could be explained by the polymer structure of films and manufacturer's additives, potentially delaying their degradation.
4. Degraded fibres increased soil respiration more than their non-degraded counterparts, as photodegradation increased the positive effects of fibres on soil water retention. The emergence of oxygenated groups during degradation may have increased the hydrophilicity of fibres, enhancing their ability to retain water. Degraded foams increased soil respiration, which could be related to the possible leaching of organic substances with lower partition coefficients, which may promote soil microbial activity.
5. In contrast, degraded foams decreased soil aggregation, likely as degradation produced larger holes increasing their permeability. Also, the increase in hydrophilic molecules could have decreased soil particle cohesiveness. Degraded fibres and foams increased shoot and root mass as a result of MP effects on soil properties. Photodegraded MPs affected root traits, which could be linked to MP effects on soil water status and plant coping strategies.
6. *Synthesis and applications*. Photodegradation can intensify the effects that microplastics (MPs) have on plant–soil systems, which would have frequently been underestimated had we only worked with pristine MPs. Plastic companies, agricultural practitioners and researchers should consider that plastics are being

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degraded as they enter the soil. Policies should promote practices to minimize MP accumulation in soils and ensure their proper disposal.

KEYWORDS
additives, ecotoxicology, microplastic properties, microplastic shape, pollution, polymer type, solar radiation

1 | INTRODUCTION

Microplastics (MPs), polymer-based particles <5 mm occur in many shapes and cover a high physical and chemical diversity (Rillig et al., 2019). As MPs are ubiquitous around the globe, not only in oceans but also terrestrial systems, where it arrives through soil amendments, plastic mulching, irrigation, etc. (de Souza Machado et al., 2018; Piehl et al., 2018), MP pollution has become a recognized global change threat to terrestrial ecosystems (de Souza Machado et al., 2018).

Recent research has shown that pristine (non-degraded) MPs may affect plant species productivity (de Souza Machado et al., 2019; Lozano, Lehnert, et al., 2021; van Kleunen et al., 2020), plant community composition (Lozano & Rillig, 2020) and different soil properties related to soil functionality (Lozano, Aguilar-Trigueros, et al., 2021). Such effects have been linked with MP properties such as shape and polymer type (Lozano, Lehnert, et al., 2021; Zhao et al., 2021). Indeed, pristine fibres can increase plant biomass of *D. carota* by ~27% while pristine foams increase it by ~45% in comparison with soils without MPs (Lozano, Lehnert, et al., 2021). Likewise, depending on the polymer type, MP effects on soil microbial activity may differ; for instance, it may decrease with pristine polyethylene (PE) films while being unaffected with pristine polyamide (PA) fibres (Lozano, Lehnert, et al., 2021). However, these results might capture only part of the truth, as they only account for the effects of pristine MPs (before they are subjected to weathering), and do not consider those of weathered and degraded plastics, which are the plastic materials actually present in the environment, including the soil.

Once plastics enter the environment, mechanical degradation (e.g. abrasion on roads), biological degradation (e.g. waxworms and selected microbes, including fungi) or photodegradation (UV irradiation) comes into play, altering plastic properties. Among these, photodegradation can be considered one of the most common processes of plastic degradation worldwide (Helmberger et al., 2020; Sivan, 2011). Exposure to ultraviolet radiation causes photo-oxidation of plastic, with plastic pieces losing tensile strength, changing colour, roughness, sorption ability and brittleness (Gewert et al., 2015; Waldman & Rillig, 2020). Indeed, heat, sunlight and well-aerated conditions are ideal for generating MPs through iterative fragmentation processes (Sivan, 2011). As plastics are susceptible to photodegradation, resulting in rapid and dramatic change in physical, mechanical and optical properties, a wide range of additives, such as light and thermal stabilizers, UV absorbers and antioxidants, are frequently used to enhance polymer properties and plastic durability (Hahladakis et al., 2018). The application of such additives varies depending on the desired plastic shape (e.g. fibre, films or foams) and the polymer type used, which implies that photodegradation effects on plastic may depend on both MP shape and polymer type.

MP shapes such as fibres, films or foams vary in characteristics like surface area, thickness, flexibility or porosity (Rillig et al., 2019), variables that interact differently with the soil matrix and help explain the different effects that MPs have on plant–soil systems. For instance, fibres improve soil water retention (Lozano, Aguilar-Trigueros, et al., 2021), while films could promote soil evaporation and porosity (Lozano, Lehnert, et al., 2021; Wan et al., 2019) with consequences for plant–soil systems. However, such plastics are commonly exposed to solar radiation and thus to photodegradation. For instance, MP films may enter the soil due to photodegradation of temporary greenhouses, plastic mulching or silage degradation (Piehl et al., 2018), while MP foams could pollute the soil due to the degradation of plastic containers. Therefore, MP effects on plant–soil systems can be potentially modified by photodegradation as this process may alter the physical and chemical structure of MPs. Thus, we aimed to determine (i) whether the effects of MP photodegradation on a plant–soil system differ from those observed with pristine MPs. That is, we aimed to test whether the apparent positive effects that pristine MPs may have on soil properties and plant performance (e.g. de Souza Machado et al., 2019; Lozano & Rillig, 2020) or the less commonly observed negative effects (e.g. van Kleunen et al., 2020) hold up; and (ii) whether such effects vary depending on MP shape and polymer type. To do so, we established a microcosm experiment where a variety of pristine and degraded MPs of different shapes and polymer types were used and their effects on the phytometer *D. carota* were measured.

2 | MATERIALS AND METHODS

2.1 | Plant species and MP selection

We selected *Daucus carota* as a phytometer, which is a herbaceous plant typical of grassland ecosystems (Federal Agency for Nature Conservation, 2019) that shows clear responses to MPs in soil (Lozano et al., 2022; Lozano, Lehnert, et al., 2021). Also, we selected eight secondary MPs widely used in daily life, which represent three MP shapes: fibres, films and foams and six polymer types: PA, polyester fibres made to at least 85% of polyethylene terephthalate (PET; Council Directive, 2011), polypropylene (PP), low density PE, PET, polystyrene (PS) and polyurethane (PU) (Figure 1). Our study did not require ethical approval.

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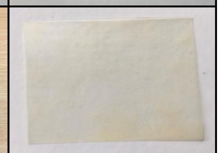
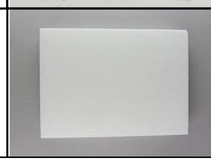
FIGURE 1 Non-degraded (pristine) and degraded plastic types. Plastic was exposed to UV-C degradation for 2 weeks except PET film which was exposed for 4 weeks. Microplastics source is given.

Shape	Polymer type	non-degraded	degraded
Fibers	**Polyethylene terephthalate (PET)** Rope Paraloc Mamutec polyester (20%) and PET (80%) white, item number 8442172, Hornbach.de		
	Polyamide (PA) White fibers Connex, item number 10010166, Hornbach.de		
	Polypropylene (PP) Rope Paraloc Mamutec polypropylene orange, item number, 8442182, Hornbach.de		
Films	**Polyethylene (PE)** Low Density PolyEthylene (LDPE) isilo film black, folien-bernhardt. thickness (0.07 mm)		
	Polyethylene terephthalate (PET) Transparent food container cover Serviceverpackung, W&V Vetreibs-UG thickness (0.2 mm)		
	Polypropylene (PP) Transparent folders of Cast Polypropylene STYLEX		
Foams	**Polyurethane (PU)** Grey foam sheet, item number, 3838930, Hornbach.de		
	Polystyrene (PS) EPS70 Insulation Packing Board SLABS, Wellpack Europe		

2.2 | Microplastic degradation

Plastics were exposed to UV-C degradation (254 nm irradiation) by using a photodegradation chamber with three 36 W UV-C lamps (Figure S1). The average incident energy in the chamber was of 20.98 Wm^{-2} (photometer; item number HD 2302.0, DeltaOHM), which simulated UV-C wavelengths. UV-A (present in solar light) and UV-C (used for shorter photodegradation experiments due to its higher energy) are ranges of the ultraviolet wavelength spectra that produce similar final outputs (e.g. breaking of polymer chains, volatile organic compounds production, reactive oxygen species or surface cracking) (De Freitas et al., 2022; Wu et al., 2023), and therefore could be compared. Each plastic type was photodegraded during 2 weeks; except PET film, which was photodegraded during 4 weeks as these films showed an extremely slow rate of degradation after FTIR analyses. MPs were randomly distributed in the chamber and their position was shifted twice during the photodegradation time. Then, plastic was manually cut with scissors and an upper size of 5.0 mm length for fibres and 5.0 mm^2 area for films and foams was established. Foams were cut by using a Philips HR3655/00 Standmixer (1400 W, ProBlend 6 3D Technologie) and sieved through a 4 mm mesh.

2.3 | Soil preparation

We collected dry sandy loam soil (Albic Luvisol; 0.07% N, 0.77% C, pH 6.66) from a dry grassland plant community located in Dedelow, Brandenburg, Germany (53°37′N, 13°77′W). The soil was sieved (4 mm mesh size), homogenized and mixed with each MP type at a concentration of 0.4% (w/w). Thus, 0.76 g of each MP type were mixed into 190 g of soil for each pot (4 cm diameter, 21 cm height, 200 mL). MPs were manually separated and mixed with the soil during 1 min in a large

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container, before placing it into each pot, to help provide an equal distribution of MPs throughout the soil. The same handling was applied to the control soils (without MPs) to provide the same disturbance level.

2.4 | Experimental design

In September 2020, soil mixed with MPs was pre-incubated without plants for 42 days in a glasshouse with a daylight period set at 12 h, 50 klx and a temperature regime at 22/18°C day/night with a relative humidity of 40%. This incubation time allowed for the interaction between soil microbial communities and MP particles, and the potential leaching of MP chemical substances into the soil. Pots were watered with 50 mL of tap water, and covered to avoid evaporation but allowing aeration. Seeds of *D. carota* were surface sterilized with 4% sodium hypochlorite for 5 min and 75% ethanol for 2 min and then thoroughly rinsed with sterile water. Seedlings of similar size were transplanted into pots 3 days after germination, with one single seedling per pot. Then, plants grew for 43 days and were watered every third day with 40 mL during the first 3 weeks, and then every second day with 30 mL of tap water, to maintain water holding capacity at ~70%. The experimental design consisted of 8 MP types (3 fibres, 3 films, 2 foams) × 2 degradation levels (non-degraded, degraded) × 7 replicates = 112 pots. Twelve additional pots were established as control without MPs. All pots were randomly distributed in the glasshouse chamber, and their position shifted twice during the experiment to homogenize environmental conditions. All plants survived until the end of the experiment. At harvest, plants were separated into above- and below-ground parts; soil was air-dried and stored at 25°C for soil aggregation analyses, while fresh soil samples were used to measure soil respiration.

2.5 | Microplastic characterization

We measured the water absorption capacity of MP pieces of $6 \times 6\,cm^2$ following the UNE EN ISO 62:2008 standard. Plastic was immersed in distilled water for 24 h and the changes in weight and thickness were determined. Water absorption was measured on films and foams. Due to the flexibility and brittleness of single fibres after degradation, it was not possible to assess their water absorption capacity. Identity of the plastics (i.e. polymer type) was confirmed by using a FTIR Jasco ATR-FTIR-4100 (Jasco International Co. Ltd.), reflection mode, from 4000 to $600\,cm^{-1}$, an average of 32 scans performed with the resolution of $4\,cm^{-1}$. For each plastic type, we measured two samples three times.

2.6 | Soil measurements

2.6.1 | Soil aggregation

We measured water-stable soil aggregates (WSAs) following a protocol by Kemper and Rosenau (1986), modified by Lehmann et al. (2019). Briefly, we placed 4.0 g of dried soil (<4 mm) on sieves with a mesh size of 250 µm. Soil was rewetted with deionized water by capillarity and inserted into a sieving machine (Agrisearch Equipment, Eijkelkamp) for 3 min where the agitation and re-wetting caused the treated aggregates to slake. Then, we dried and weighed the water-stable fraction (dry matter) and subsequently, we extracted the coarse matter, which was also dried at 60°C for 24 h. Soil aggregation was calculated as: WSA (%) = (dry matter − coarse matter)/(4.0 g − coarse matter).

2.6.2 | Soil respiration

We measured soil respiration via infrared gas analysis. We placed 25 g of fresh soil in individual 50 mL centrifuge tubes (Sarstedt AG & Co. KG, item number 62.548.004) whose lids were modified to control gas exchange via a rubber septum (Supelco, item number 27235 U). We measured CO_2 concentration (ppm) at two time points: First, we flushed the tubes with CO_2 free air for 5 min to measure CO_2 concentration at time zero. Then, soil samples were incubated at 20°C for 24 h and we measured CO_2 concentration for the second time. At both times, we took a 1-mL air sample and injected it to an infrared gas analyser (LiCOR-6400XT photosynthesis system; Li-Cor Biosciences). Measurements were obtained every ~2 s. The difference between the maximum and the minimum value (peak) was converted to ppm using the calibration equation (ppm = −467 + 195.18 peak).

2.7 | Plant measurements

2.7.1 | Plant biomass and root morphological traits

At harvest, roots were carefully removed from the soil and gently washed by hand in order to measure morphological traits of fine roots (i.e. <2 mm in diameter which included mostly first to third order roots). We measured length, surface area, volume and root average diameter (RAD) on a fresh sample (random portion of the middle part of the root system) using the WinRhizoTM scanner-based system (v.2007; Regent Instruments Inc.). We calculated different root morphological traits: specific root surface area (SRSA; $cm^2\,mg^{-1}$), specific root length (SRL; $cm\,mg^{-1}$), RAD (mm) and root tissue density (RTD; root dry weight per volume mg cm^{-3}). Shoot and root mass were measured after drying samples at 60°C for 72 h.

2.8 | Statistical analyses

We performed principal component analysis (PCA) on our response variables for each MP shape either degraded or non-degraded, using the function 'prcomp' and 'fviz_pca' from the R package 'factoextra' (Kassambara & Mundt, 2017). Ellipses in the graph grouped the

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treatments with a confidence level of 0.95. To validate differences between treatments we used the function 'manova' from the R package 'MASS' (Venables & Ripley, 2002). We tested the null hypothesis by means of the Pillai trace statistic, which is robust to violation of multivariate normality and homogeneity of the variance–covariance matrix (Quinn & Keough, 2002).

We performed linear models to test the effect of MP degradation on plant–soil variables. MP shape, polymer type and degradation were considered as explanatory variables. Polymer was nested within MP shape as each shape had different polymer types, and was included as a random factor in the model (Schielzeth & Nakagawa, 2013) as follows: $\sim A \times B + (1|A/C)$, with A representing 'Shape', B 'Degradation' and C 'Polymer'. Response variables were log-transformed to fulfil linear model assumptions. The function 'lmer' from the 'lme4' R package was used in the mixed models. Then, we implemented the function 'emmeans' from the eponymous R package to define pairwise comparisons. 'Tukey' tests were used to compare each degraded MP type (shape and polymer) with its non-degraded counterpart, while the 'Dunnett' test was used to compare each of them with the control. Second, polymer and degradation were considered as fixed factors in the linear model. Residuals were checked to validate assumptions of normality and homogeneity and when necessary, we implemented the function 'varIdent' from the 'nlme' R package (Pinheiro et al., 2021) to account for heterogeneity in the treatment. Then, we implemented the function 'glht' and the 'Tukey' or 'Dunnett' test from the 'multcomp' R package to compare among treatments (Bretz et al., 2011). Statistical analyses were done in R 4.2.3 (R Core Team, 2023).

3 | RESULTS

3.1 | Photodegradation changes physical and chemical properties of MPs

Brittleness, surface microcracks, roughness and yellowing in MPs increased with photodegradation (Figure 1). Water absorption in films increased by 472% after degradation. Specifically, PE, PET and PP films increased it by 177%, 112% and 2484% respectively (Figure S2). Foams exhibited a contrasting pattern depending on the polymer type. Polystyrene (PS) increased water absorption by 113% while PU decreased it by 98% (Figure S2). MP chemical structure was affected by photodegradation, as measured using Fourier transform infrared (FTIR). Specific chemical modifications (areas of interest) are in Figure 2 (entire spectra are in Figure S3). As expected, appearance, broadening or increasing of hydroxyl and carbonyl bands indicated the development of the degradative process and the increase in the degradation level (Chamas et al., 2020; Miranda et al., 2021). PP and PET fibres, PP film, PS and PU foam (Figure 2) showed both the formation or broadening of the hydroxyl band (3700 to 3250 cm^{-1}) (Curcio et al., 2018) and appearance, increase or broadening of the carbonyl band (1850 to 1550 cm^{-1}) (Rouillon et al., 2016). Condensation polymers (PET and PA fibre, PET film; Figure 2b,c,e) showed an increase in intensity of the hydroxyl band, and the change of baseline close to the carbonyl band (Figure 2b,c) showed the formation of a different carbonyl group.

3.2 | Photodegraded fibres and foams increased soil respiration while photodegraded foams decreased soil aggregation

Ordination by PCA based on plant performance and soil properties responses showed a clear separation between control soils and soil mixed with any MP shape either degraded or non-degraded (Figure 3; Table S2). Likewise, a clear separation was found between degraded and non-degraded fibres and foams, opposite to films. The first two axes of the PCA explained 71.5% of the total variance. Overall, we observed that soil respiration was higher with degraded fibres than with their non-degraded counterparts or control soils (see variation in the PC1 axis). In contrast, soil aggregation was higher with non-degraded foams than with their degraded counterparts, and with any MP shape compared to control soils (see variation in PC2 axis).

MP shape and degradation affected soil respiration (Figure 4a; Table S3), which increased with degraded MP and was higher in soil with degraded fibres and foams than with their non-degraded counterparts. Overall, the observed effects of MP shape were driven by PA, PP fibres and PU foams. No differences were found between degraded and non-degraded films. Also, soil respiration was higher with degraded fibres, films and foams, and with non-degraded films in comparison to control soils. In terms of polymer type, it was higher with degraded PA and PP fibres, PE films and PU foams, and to some extent with degraded PET films and PS foams compared to control soils, while their non-degraded counterparts did not affect soil respiration, except for PE and PET films. The non-degraded PET fibres also increased soil respiration compared to control soils while no effect was registered for their degraded equivalent (Figure 4a; Table S4).

Contrary to soil respiration, soil aggregation was higher with non-degraded foams than with their degraded counterpart. Such MP-shape effects were particularly driven by PU (Figure 4b; Tables S3 and S4). No differences were found between degraded and non-degraded fibres and films or between other polymer types, except for PET fibres which showed a marginal difference. Also, soil aggregation increased with degraded and non-degraded fibres and films compared to control soils, while only non-degraded foams followed such pattern. In terms of polymer type, soil aggregation was higher with degraded PA and PET fibres, as well as with PE and PET films (both degradation levels) compared to control soils. In contrast, it was higher with non-degraded PS and PU foams and to some extent with PP films.

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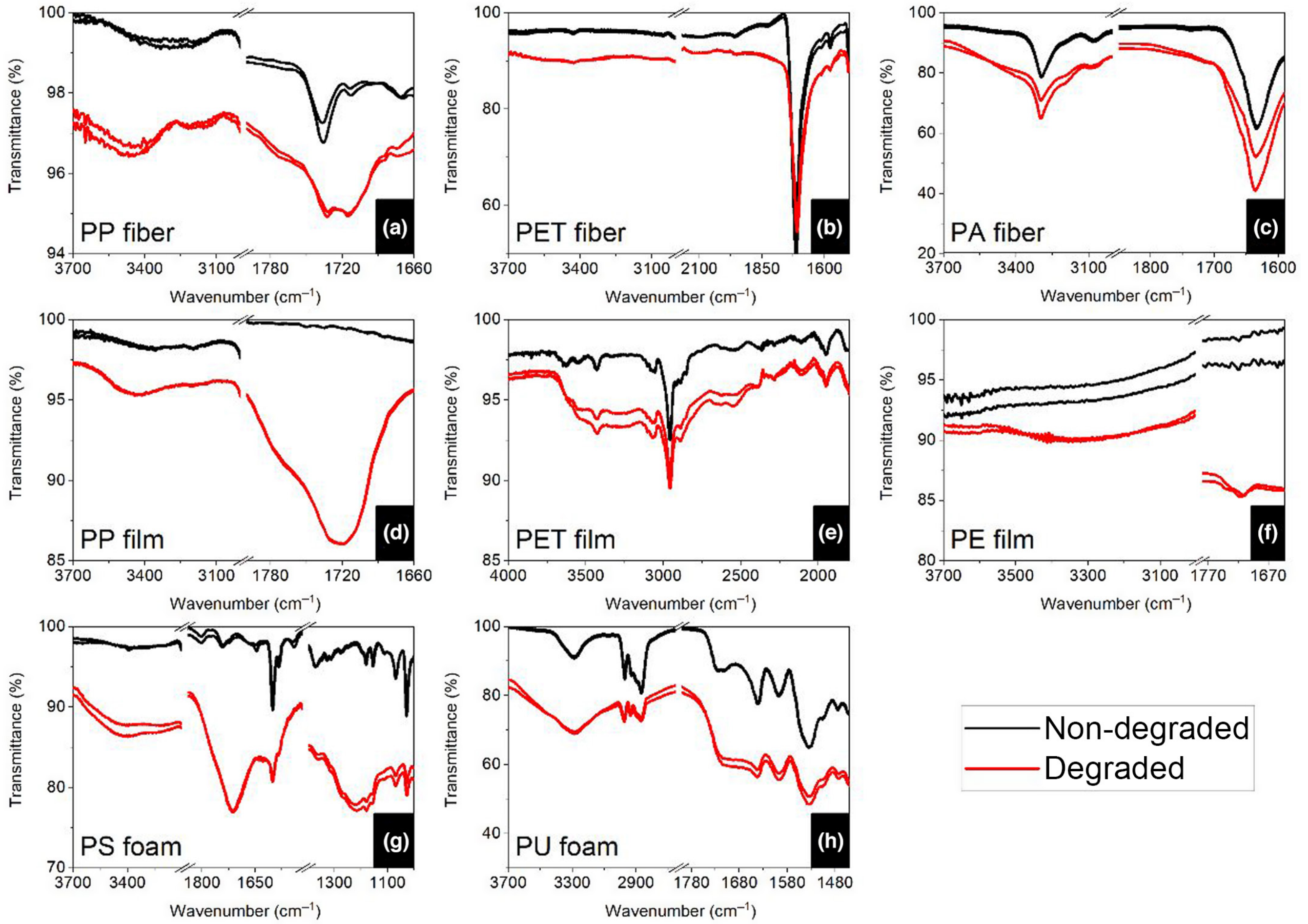

FIGURE 2 FTIR spectra of non-degraded and degraded plastic. Each polymer has a different axis set and breaks for better visualization of different degradation outputs. The entire spectra for each polymer are available in Figure S3.

3.3 | Photodegraded fibres and foams led to increased shoot and root mass

MP shape and degradation affected shoot mass (Figures 3 and 4c; Table S3), which was higher with degraded fibres and foams than with their non-degraded counterparts. Overall, the observed effects of shape were driven by PA fibres and PU foams. No differences were found between degraded and non-degraded films. Also, shoot mass tended to increase with degraded fibres compared to control soils (Figure 4c). In terms of polymer type, shoot mass was higher with degraded PA fibres, but lower with non-degraded PP films compared to control soils. Also, shoot mass was slightly lower with non-degraded PE films and degraded PET films than with control soils.

Root mass was affected by MP shape and degradation (Figure 4d; Table S3). It was higher with degraded fibres than with their non-degraded counterparts, an effect mainly driven by PA (Figure 4d; Table S4). Likewise, root mass tended to be higher with non-degraded fibres compared to control soils. Regarding polymer type, it was higher with degraded and non-degraded PA fibres and with non-degraded PP films compared to control soils.

3.4 | Photodegraded MPs did affect root morphological traits

Root trait expression was affected by MP degradation depending on MP shape (Table S5; Figure S4). SRL and SRSA tended to be higher with non-degraded fibres and films compared to control soils. In contrast, RTD tended to be lower with degraded and non-degraded fibres and films respectively. Root traits were also marginally affected by polymer type. SRL was higher with degraded PET films than with their non-degraded counterparts or control, while root diameter showed the opposite pattern. SRSA increased with PA fibres compared to control soils (Table S6). RTD was lower with non-degraded PA fibres, PET and PP films, and degraded PP fibres and films compared to control soils.

4 | DISCUSSION

Overall, weathering can modify MP properties, which in turn may affect plant–soil systems. In our study, photodegradation influenced the effects various MP types had on soil and plants. In many cases,

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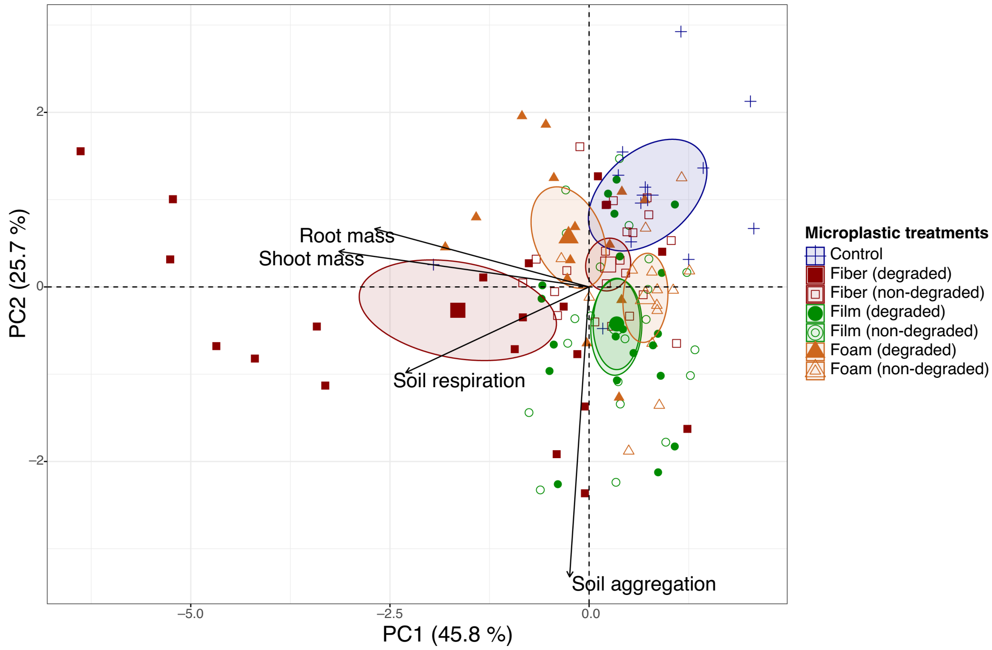

FIGURE 3 Principal component analysis of the soil properties and plant biomass response to degraded and non-degraded microplastics of different shapes (fibres, films and foams) $n=7$. Control without microplastics was also included, $n=12$. Arrows indicate response variables. Ellipses grouped the different treatments with a confidence level of 0.95.

data on pristine MPs would have underestimated the effects we observed for the degraded particles. Our research demonstrates that the effects that pristine MPs may have on plant–soil systems (e.g. de Souza Machado et al., 2019; Lozano & Rillig, 2020), may hold up after plastic photodegradation, but only in the case of plastic films, probably as their molecular structure makes them highly resistant to photodegradation. However, this may not hold true for fibres and foams. Our findings indicate that the apparent neutral effects of pristine fibres and foams on plant biomass and soil respiration (Figure 4) transitioned to positive effects following photodegradation, which does not signify desirable outcomes, but simply a deviation from their original natural conditions. Foam degradation showed negative effects on soil aggregation. Plastic companies, agricultural practitioners and researchers should thus consider that MPs are being degraded as they enter the soil, resulting in shifts in their effects on various responses.

4.1 | Photodegradation increases water absorption for films, decreases it for foams and affects the chemical structure across MPs

Water absorption was affected by photodegradation depending on MP shape and polymer type. It increased for degraded films, while the opposite was true for degraded foams (Figure S2). The increase in microcracks, roughness and oxygen-containing groups on film surfaces due to degradation, probably contributed to increasing their water absorption. We observed this pattern for any film regardless of the polymer type. On the contrary, water absorption decreased with degraded PU foams which would be linked to an increase in permeability as they had larger holes than their non-degraded counterparts; PS foams followed a similar behaviour to that of films. After degradation carbonyl and hydroxyl groups appeared for every MP, evidence of oxidative degradation pathways (Chamas et al., 2020). Hydroxyl and carbonyl groups form hydrogen bonds with water (Chamas et al., 2020), making the molecule more hydrophilic. Simultaneously, MPs decrease in molar mass as a result of degradation (Chamas et al., 2020). These MP alterations can facilitate the migration of molecules of potential toxicity to water and/or soil (Ren et al., 2021), helping explain the subsequent effects that degraded MPs have on plant–soil systems.

4.2 | Photodegradation effects on MPs have consequences for plant–soil systems depending on MP shape

Photodegradation effects on MPs only affected the soil and plants when fibres or foams were mixed with soil (Figure 3). Although films also experienced change in physical and chemical structure with degradation, such changes did not appear strong enough to affect plant–soil systems. This can be attributed to the film polymer structure, and additives, potentially delaying degradation compared to other MP shapes. For instance, PE films possess backbone chains constructed exclusively from C-C single bonds that resist photo-oxidative degradation due to the lack of UV–visible chromophores (Chamas et al., 2020). Moreover, as most films are used in agriculture, and are therefore highly exposed to

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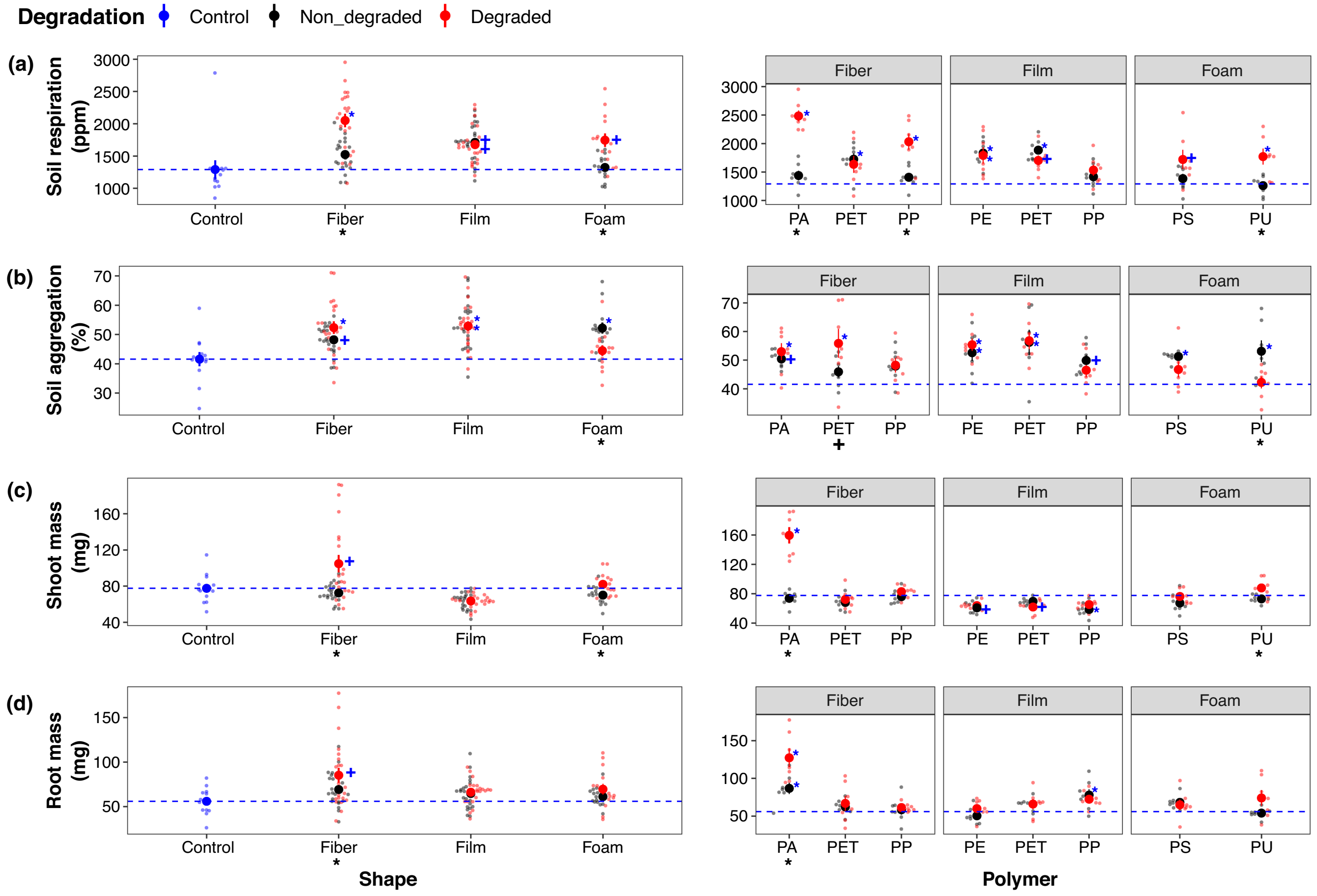

FIGURE 4 Soil respiration (a), soil aggregation (b), shoot mass (c) and root mass (d) responses to non-degraded and degraded microplastic shapes (left panels) and polymer types within shapes (right). Mean and standard error are represented. Data points are shown as circles. Soil aggregation was expressed as the percentage of water-stable aggregates. Horizontal dotted lines indicate the mean value in the control soils. Polymers: PA (polyamide), PET (polyethylene terephthalate), PP (polypropylene), PE (low density polyethylene), PS (polystyrene) and PU (polyurethane). Significance was established at 0.05 (*) and 0.1 (+). Black asterisks under the name of each microplastic indicate differences between the soils with degraded and non-degraded microplastic. Blue asterisks next to error bars indicate differences between the soil with microplastics and the control soils. $n=7$ for polymer type; $n=12$ for control samples.

UV radiation, the plastic industry uses additives (UV absorbers, light stabilizers and antioxidants) to delay photodegradation and prolong product lifetime (Hahladakis et al., 2018). Among these additives, bisphenol A, benzophenones and other phenolic compounds (Hahladakis et al., 2018; Sait et al., 2021) exhibit toxic effects in aquatic systems (Pillard et al., 2001; Zhao et al., 2020), animals and other organisms (Michałowicz, 2014) with potential negative consequences on plant–soil systems. Thus, our results suggest that short-term photodegradation of films does not clearly affect plant–soil systems, but strong negative effects could be expected after prolonged exposure to UV radiation (e.g. sunlight on mulches for years), as these toxic additives may eventually enter the soil matrix. Regarding the other shapes, soil respiration and plant biomass were higher with degraded fibres than with their non-degraded counterparts or other shapes; while soil aggregation was lower with degraded foams than with their non-degraded counterparts or other shapes. Finally, shoot and root masses increased with degraded fibres and foams compared to other MP shapes. See specific discussion on these aspects in the following sections.

4.3 | Photodegraded fibres and foams increase soil respiration more than their non-degraded counterparts

Non-degraded MPs increased soil respiration compared to control soils, which may be linked to MPs as an important carbon source for soil microorganisms (Rillig et al., 2021). Degraded fibres and foams modified these responses, as they increased soil respiration more than their non-degraded counterparts (Figure 4a). Among the different shapes, soil respiration was higher with fibres than with foams. Through a physical mechanism, non-degraded fibres could create small pores within aggregates helping to retain water (Lozano, Aguilar-Trigueros, et al., 2021), which stimulates soil microbial activity (Six et al., 2004). However, with photodegradation a chemical

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mechanism is also involved. The emergence of oxygenated groups may increase MP hydrophilicity (Waldman & Rillig, 2020), which enhances the polymer's ability to absorb and retain water (Andry et al., 2009). This helps explain the higher soil respiration with degraded fibres, as well as with fibres compared to foams. In contrast, degraded foams (PU) did not retain more water than their non-degraded counterparts, due to the increase in permeability after photodegradation. Increased soil respiration with degraded foams may rather be due to the increased leaching of organic substances into the soil, especially those with a lower partition coefficient (Gewert et al., 2015) that could promote soil microbial activity (Rillig et al., 2021). Nonetheless, among those substances are also some with potential ecotoxicological risk that could affect soil microbial respiration (Ren et al., 2021).

4.4 | Photodegraded foams decrease soil aggregation more than their non-degraded counterparts

Soil aggregation was lower with degraded foams than with their non-degraded equivalents, degraded fibres or films (Figure 4b). Foams have a sponge-like structure that in a non-degraded stage allows them to soak up water promoting soil aggregation, likely explaining their increase compared to control soils (Six et al., 2004; but see Lozano, Lehnert, et al. (2021) for a different perspective). However, such positive effects were counteracted as photodegradation increased permeability. In addition, the increase in hydrophilic molecules with photodegradation may decrease soil particle cohesiveness, decreasing soil aggregation. Also, as foams are made of highly toxic monomers (Lithner et al., 2011) and may contain organic pollutants (Zhang et al., 2018), photodegradation, can increase the leaching of hazardous substances of ecological risk (Lithner et al., 2011) that could harm soil biota (Ren et al., 2021) with potential negative effects on soil aggregation. In contrast, fibres can help retain water and entangle soil particles promoting soil aggregation (Lozano, Aguilar-Trigueros, et al., 2021).

4.5 | Photodegraded fibres and foams led to an increase in shoot and root mass while films had the opposite effect

Among the different shapes, fibres and foams led to the highest shoot and root mass. Likewise, both degraded fibres and foams led to an increased shoot and root mass in comparison with their non-degraded counterparts (Figure 4c,d). Fibre effects on plant biomass may be related to the discussed positive effect they had on soil properties. Soil aggregation promotes rooting, enhancing rhizodeposition and mycorrhizal associations (Smith & Read, 2008), promoting plant biomass. These cascading effects were particularly evident with PA fibres, probably as they photodegraded more easily than the other fibre types, evidenced by their higher yellowing (Figure 1), which is a defining characteristic of photodegradation (Andrady, 2003). Similarly, the positive effects that degraded foams, in particular PU foams may have on soil respiration (proxy of soil microbial activity) could contribute to explain the increased plant biomass (Hortal et al., 2013). In contrast, films tended to decrease shoot mass compared to the control soil, which can be linked to films creating soil channels that increase soil evaporation rate (Wan et al., 2019), decreasing water availability for plants. Also, as mentioned, the plastic film industry uses specific additives with potential toxic effects on soil microorganisms (Pillard et al., 2001; Zhao et al., 2020), and seed germination (Lozano et al., 2022), that may affect plant performance. Finally, we observed that plants growing with degraded and non-degraded foams (PU) differed from each other in terms of shoot biomass, but neither group differed from the control. This is due to the low variability of MP effects on plant performance compared to control samples, which implies that our predictions on the effects of MPs on plant–soil systems can be considered consistent and reliable.

4.6 | Photodegraded MPs affected root morphological traits

Films and fibres affected root traits. SRL and SRSA (root fineness) increased with degraded films compared to control soils, which allow plants to uptake water and nutrients under diminishing water conditions, as those created by films (Wan et al., 2019). A similar root strategy has been found under drought (Lozano et al., 2020). We observed a higher root fineness and smaller diameter with degraded PET films than with their non-degraded counterparts. This particular polymer is widely used in the food industry, as their toxicity is relatively low compared to other MPs. However, they appear to contain many unclassified substances (Lithner et al., 2011) that could stress the plant to the point of altering root trait expression. Likewise, degraded PET and PP fibres led to a decrease in RTD compared to control soils, which is potentially indicative of a strategy to support faster nutrient acquisition (Lozano et al., 2020). However, further research is needed to support this idea.

5 | CONCLUSIONS

Photodegradation increases water absorption for films, decreases it for foams, while affecting chemical structure across MP shapes. Photodegraded fibres and foams increase soil respiration more than their non-degraded counterparts, with positive consequences for shoot and root mass. Photodegraded foams decreased soil aggregation. Overall, photodegradation did not affect root trait expression. As MPs are ubiquitous around the globe and are constantly exposed to photodegradation, their effects on plant–soil systems will likely be found in different ecosystems. Indeed, future research should address the effects of degraded MPs in ecosystems that are highly exposed to solar radiation, such as dryland ecosystems, which cover ~41% of Earth's land surface

(Reynolds et al., 2007), and in addition, have large areas dedicated to agriculture where the use of plastic mulch and temporary greenhouse is a daily practice. Future research on this topic should also include long-term experiments under field conditions further testing our findings on photodegraded MPs and their effects on plant–soil systems.

AUTHOR CONTRIBUTIONS

Y. M. Lozano conceived the ideas and designed methodology with input from W. R. Waldman. H. Gordillo-Rocha and Y. M. Lozano established and maintained the experiment. H. Gordillo-Rocha and W. R. Waldman performed the FI-TR analysis. H. Gordillo-Rocha provided the photos used in the manuscript. Y. M. Lozano analysed the data and wrote the manuscript. M. C. Rillig commented and edited on the first draft. All authors contributed to the document and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

We have no conflict of interest to declare.

DATA AVAILABILITY STATEMENT

Data available from the Dryad Digital Repository https://doi.org/10.5061/dryad.wwpzgmsqn (Lozano et al., 2023).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Figure S1: Photodegradation chamber made of wooden plywood and covered inside with aluminum film (30 μm, ROTH GmbH) to increase degradation performance. Chamber size was of 30 × 50 × 50 cm (height, width, depth). Ventilation was installed to maintain chamber temperature at approximately 50°C and remove the produced ozone (A). Plastic was disposed in trays and randomly distributed twice in the chamber (B).

Figure S2: Water absorption responses to non-degraded and degraded microplastic shapes (left panels) and polymer types within shapes (right). Due to the flexibility and brittleness of single fibers after degradation, it was not possible to assess their water absorption capacity. Mean and standard error are represented. Data points are shown as circles. Polymers: PA (polyamide), PET (polyethylene terephthalate), PP (polypropylene), PE (low density polyethylene), PS (polystyrene) and PU (polyurethane). Significance was established at 0.05 (*). Black asterisks under the name of each microplastic indicate differences between the soils with degraded and non-degraded microplastic of each shape and polymer type. $N = 3$ for each polymer type.

Figure S3: FT-IR entire spectra of non-degraded and photodegraded samples. Each polymer has a different axis set and breaks for better visualization of different degradation outputs.

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Figure S4: Root morphological traits responses to non-degraded and degraded microplastic shapes (left panels) and polymer types within shapes (right). Mean and standard error are represented. Data points are shown as circles. Horizontal dotted lines indicates the mean value in the control soils. Polymers: PA (polyamide), PET (polyethylene terephthalate), PP (polypropylene), PE (low density polyethylene), PS (polystyrene) and PU (polyurethane). Significance was established at 0.05 (*) and 0.1 (+). Black asterisks under the name of PET films indicate differences between the soils with such degraded and non-degraded microplastic type. Blue asterisks next to error bars indicate differences between the soil with microplastics and the control soils. $n = 7$ for polymer type; $n = 12$ for control samples.

Table S1: Shape, polymer type and degradation effects on plastic water absorption. Polymer type was nested within microplastic shape and included as random factor in the model. Results of linear models and multiple comparisons by using the Tukey test. Values in bold denote a significant effect ($p < 0.05$) of the treatment on the dependent variable.

Table S2: Multivariate analysis of variance (MANOVA) of soil properties (soil respiration and soil aggregation) and plant performance (shoot and root masses) in response to degraded microplastics of different shapes based on the Mahalanobis distance. The closer Pillai's trace is to 1, the stronger the evidence that the explanatory variable has a statistically significant effect on the values of the response variables. *F*-values, Pillai trace statistic and *p* values are shown.

Table S3: Microplastic shape and degradation effects on soil respiration, soil aggregation, shoot and root masses. Polymer type was nested within microplastic shape and included as random factor in the model. Results of linear model and multiple comparisons by using the Tukey and Dunnett test. Values in bold and italic denote a significant and marginal effect ($p < 0.05$, 0.1) of the treatment on the dependent variable.

Table S4: Polymer type and degradation effects on on soil respiration, soil aggregation, shoot and root masses. Results of linear model, and multiple comparisons by using the Tukey and Dunnett test. Polyamide (PA); Polyethylenterephthalat (PET); Polypropylene (PP); Low Density Polyethylene (PE); Polystyrene (PS); Polyurethane (PU). Values in bold and *italic* denote a significant and marginal effect ($p < 0.05$, 0.1) of the treatment on the dependent variable.

Table S5: Microplastic shape and degradation effects on root morphological traits. Polymer types was nested within microplastic shape and included ad random effect in the model. Results of linear model and multiple comparisons by using the Tukey and Dunnett test. Specific root length (SRL), specific root surface area (SRSA), root average diameter (RAD) and root tissue density (RTD). Values in bold and *italic* denote a significant and marginal effect ($p < 0.05$, 0.1) of the treatment on the dependent variable.

Table S6: Polymer type and degradation effects on root morphological traits. Results of linear model, and multiple comparisons by using the Tukey and Dunnett test. Specific root length (SRL), specific root surface area (SRSA), root average diameter (RAD) and root tissue density (RTD). Polymers: Polyamide (PA); Polyethylenterephthalat (PET); Polypropylene (PP); Low Density Polyethylene (PE); Polystyrene (PS); Polyurethane (PU). Values in bold and *italic* denote a significant and marginal effect ($p < 0.05$, 0.1) of the treatment on the dependent variable.

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