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Assessing microplastic mobility from soils amended with sewage sludge under different land use and rainfall scenarios☆

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ABSTRACT

Sewage sludge applied in agricultural fields as fertilizer is considered one of the major contributors to microplastic (MP) pollution in soil ecosystems. This study assessed the environmental fate of MPs in soils amended with sewage sludge, using experimental units with uncontaminated soil (control), bare soil amended with sewage sludge (sludge), and soil amended with sludge and cultivated with alfalfa (alfalfa), in a greenhouse experiment. The influence of three high rainfall intensities (137 mm/h, 220 mm/h, and 318 mm/h) on MP mobility by runoff and/or infiltration was evaluated. Results showed that MPs in topsoil (0–5 cm) had a limited mobility over the five-month experimental period. In bare soils, 0.32 % of MPs were transported by runoff and 0.008 % by infiltration, indicating that runoff is a more relevant process than infiltration. In soils planted with alfalfa, the amounts mobilized by runoff and infiltration were significantly lower (0.004 % and 0.002 %, respectively) than in the bare soil treatment. This can be attributed to the crop's ability to stabilize the soil and the plant-mediated capture. Despite higher water runoff volumes generated by increasing rainfall intensities, the MP mobilization rates remained unchanged, indicating a limited influence of water volume at high-to-extreme rainfall intensities. Most MPs detected in the sewage sludge consisted of polyester fibres of varying sizes. Larger fibres were more susceptible to mobilization by runoff, while the smaller ones were more trapped into the topsoil. This study underscores the significant capacity of agricultural soils to retain MPs and highlights the role of crops in conditioning MP mobility.

1. Introduction

The occurrence and accumulation of microplastics (MPs) in agricultural soils have only recently begun to be investigated, revealing that substantial amounts of these particles are already entering and accumulating in these environments (Medyńska-Juraszek and Szczepańska, 2023; Tian et al., 2022; Yang et al., 2021). In addition, prediction models forecast an exponential increase of the actual concentrations (Meizoso-Regueira et al., 2024). MPs found in agricultural fields usually originate from the breakdown of agricultural plastics such as greenhouse covers, mulching films or irrigation pipes, as well as from the application of sewage sludge, compost or coated fertilizers (Briassoulis, 2023; Sa'adu and Farsang, 2023). Among these sources, sewage sludge is recognized as a major contributor to MP pollution due to its high MP content, with a global average of 22.4 MPs per gram of sewage sludge, and concentrations that may range from 0.2 to 1.69 × 10^5 MP/g (Corradini et al., 2019; Harley-Nyang et al., 2023).

The role of sewage sludge in MP pollution is of particular concern in countries where it has been applied to agricultural fields over consecutive years (Zhang et al., 2020; Zhou et al., 2024). In Spain, for example, between 65 % and 82 % of the annually generated sewage sludge is used as agricultural fertilizer, amounting to a yearly soil application of approximately 1.05 million tons (dry weight) (Gregorio, 2015; Eurostat, 2025). With an application rate of 2–2.2 kg of dry sludge per square meter, each application has been shown to increase the average concentration of MPs in soil by approximately 710 particles per kilogram of

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soil (Van Den Berg et al., 2020).

Once sludge is applied to agricultural fields and incorporated into the topsoil, MPs can be transported through surface runoff or infiltration, potentially reaching freshwater ecosystems such as rivers, lakes, or groundwaters (Crossman et al., 2020; Goeppert and Goldscheider, 2021; Schell et al., 2022). The limited studies available indicate that the proportion of MPs transported through runoff or infiltration is very low, with mobilized percentages ranging between 0.1 % and 1 % (Schefer et al., 2025; Schell et al., 2022). Transport processes are complex and are regulated by many different factors that englobe physical, chemical and biological variables (Zhang et al., 2022a,b). For instance, MP transport from soils to aquatic ecosystems largely depends on soil erosion. Factors such as vegetation cover, soil type, and rainfall intensity play a critical role in this process (Han et al., 2022; Rehm et al., 2021). On the other hand, studies focusing on MP infiltration have highlighted the potential risk of MPs penetrating to deeper soil horizons and reaching groundwater resources. This risk is expected to be influenced by factors such as MP size and shape, soil biota, soil type, and the presence and growth stage of vegetation (Luo et al., 2024; Lwanga et al., 2022; Rieckhof et al., 2024; Rillig et al., 2017; Wanner, 2021).

The increasing frequency of extreme weather events driven by climate change such as strong winds, prolonged droughts, and intense rainfall might alter mobilization patterns and the fate of MPs in the environment (Haque and Fan, 2023). Heavy rainstorms have already been linked to an increase in MP emission from agricultural sites polluted with mulching films, primarily due to the increase in plastic breakdown and subsequent runoff (Ling et al., 2023). However, how extreme events such as heavy rainfall events affect areas with sewage sludge application is still unknown. Further studies are needed to elucidate how these events influence the mobilization of MPs contained in sewage sludge amended agricultural soils, with the aim of helping design strategies for mitigating pollution risks.

The main aim of this study was to assess the environmental fate of MPs in soils amended with sewage sludge. The specific objectives were: (1) to determine the role of runoff and infiltration in MP transport from soil under two land use scenarios (bare soil vs cultivated soil); (2) to compare MP mobilization under three different rainfall intensities; and (3) to assess whether the characteristics of transported MPs (size, shape, and polymer type) differ from those retained in the soil. To tackle these objectives, a greenhouse experiment was carried out with experimental units planted with alfalfa and amended with sewage sludge, for which the MP content of different soil layers and the transport by water runoff and infiltration was continuously monitored.

2. Material and methods

2.1. Experimental units

Nine stainless-steel runoff-infiltration systems (RIS) were installed in the greenhouse facility of the IMDEA Water Institute (Alcalá de Henares, Spain). The RIS were modified from the original design proposed by Pinson et al. (2004) for surface runoff studies by including the possibility of collecting infiltration water. These systems (30 × 40 × 40cm) were composed of a frontal collection triangle connected to a stainless-steel tap to sample runoff water and a second stainless-steel tap located at the bottom to collect infiltration water. To prevent water stagnation, the edges of the RIS bottom part are slightly inclined towards the outflow. The systems were placed on a slope of 5° using height adjustable legs in their back part (Fig. S1A). To avoid soil overheating, the sides of the systems were insulated with thermal sheets. To prevent excessive heating of water samples, the collection bottles were covered with aluminium foil (Fig. S1B).

The bottom of each RIS (2 cm) was filled with 4 kg of gravel (ø 3–6 mm, Caolines Lapiedra) to facilitate water drainage once infiltration water reached a depth of 35 cm. Then, 60 ± 0.3 kg of the natural soil were used to fill the rest of the system. Soil was added to the system in 5 cm increment layers, ensuring a homogeneous distribution, and compacting the soil to obtain a bulk density of 1.42 ± 0.04 g/cm^3, a value often measured in Mediterranean agricultural soils (Kosma et al., 2022). The physico-chemical parameters of the natural soil are shown in Table S1.

2.2. Experimental design

The experiment was designed with three different treatments, named: control (bare soil), sludge (bare soil amended with sewage sludge) and alfalfa (soil amended with sewage sludge and planted with alfalfa). The experiment was conducted in triplicate and the RIS were randomly assigned to each treatment to avoid any potential bias (Fig. 1).

The sewage sludge used was provided by a Wastewater Treatment Plant (WWTP) with primary treatment (bar screens, screening sieves and grit chamber), secondary treatment (activated sludge reactor), and tertiary treatment (UV disinfection) and an entry inflow of 35,450 equivalent inhabitants. In Spain sludge application rates vary between different areas and go from 20 to 60 t/ha (Van Den Berg et al., 2020; EU CAP Network, 2021). Hence, an equivalent amount of an application rate of 50 t/ha was applied here, which corresponds to 5 kg of dry sludge per square meter. The sewage sludge was thoroughly mixed with the natural soil in a stainless-steel container using a metal spoon and a shovel and applied as a 5-cm top layer in sludge and alfalfa RIS.

Alfalfa (*Medicago sativa*, Aragon variety) was grown in the cultivated RIS as it is one of the most common forage crops for livestock in Spain (MAPA, 2022). Alfalfa was seeded by the end of March 2023 (one week after sludge application) with an equivalent seeding density of 200 kg/ha (2.4 g of seeds per system). The seeds were spread using quartiles of 15 × 20 cm and applying 0.6 g of seeds per quartile. Alfalfa was harvested once, 26 days after flowering began. According to standard agricultural practices, alfalfa is cut and allowed to regrow for several successive cycles. Irrigation to maintain the plants was provided by mist-sprinklers installed 46 cm above the RIS (Fig. S1A).

The experiment lasted for 5 months, and different rainfall events were simulated (see Table 1). The three monitored rain events had similar water volumes (17.2 ± 0.5 mm) but different intensities: event 1: 137; event 2: 220; event 3: 318 mm/h. These events represent high to extreme rain intensities projected under climate change scenarios in the Mediterranean region, where rising temperatures are expected to decrease the total rainfall while increasing the frequency and severity of heavy rainfall episodes. During the most recent extreme rainfall event in the Spanish Mediterranean region (October 2024), the maximum rainfall intensity registered was 185 mm/h (AEMET, 2024). This indicates that extreme events are already occurring with an intensity between the events 1 and 2 of this study. Before and after the monitored extreme events, other rainfalls, referred to as pre-events and post-events, were simulated under the conditions described in Table 1.

While setting up the experimental systems, three subsamples of the natural soil and three subsamples of the soil/sludge mixture were taken for MP input characterization. During the experiment, runoff and infiltration water from the nine RIS was collected, and samples of the same unit were combined as described in Table S2 for MP characterization. At the end of the experiment, soil from each unit was sampled using a stainless-steel core with a diameter of 2 cm at three sampling points along the flow path (depths: 0–5 cm and 5–15 cm). The stainless-steel core was pre-cleaned with Milli-Q water and ethanol, and the three samples from each soil depth were combined into a single composite sample (one sample per depth and per experimental unit).

2.3. MP analysis

MPs were extracted from soil and water by oxidizing organic matter with H_2O_2, followed by density separation using a $ZnCl_2$ solution ($\rho >$ 1.6 g/cm^3). Samples were filtered through nitrate cellulose filters (47 mm, 0.45 μm pore size) and examined under a stereomicroscope

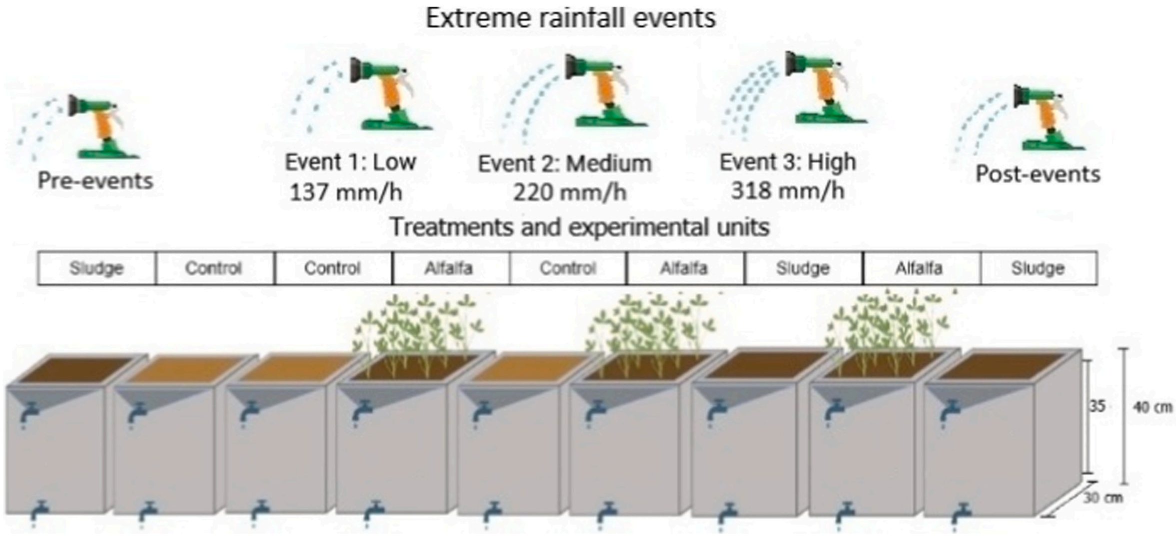

Fig. 1. Overview of the experimental design: rainfall events and experimental units with the different treatments. Figure created with BioRender.com.

Table 1
Runoff and infiltration water volume (mean ± standard deviation) collected in the different treatments before the extreme rainfall events (pre-events), during extreme rainfall events (events 1–3), and after the extreme rainfall events (post-events). The input water is the volume added in the simulated rainfall (or the sum of the rainfall events) and time indicates the duration of the event (or the sum of the duration of the rainfall events). The mean (±SD) intensity of the different pre-events and post-events is indicated, together with the intensity of events 1–3. Further details about the time distribution of the rainfall simulation events, and the amounts of irrigation and evapotranspiration of alfalfa during its growth stages are shown in Fig. S2.

Period	Number of rainfall events	Input water (mm)	Time (min)	Intensity (mm/h)	Runoff (mm)			Infiltration (mm)		
					Control	Sludge	Alfalfa	Control	Sludge	Alfalfa
Pre-events	5	113	115.52	149 ± 140	5.76 ± 1.65	5.45 ± 1.04	0.50 ± 0.36	68.1 ± 7.27	75.54 ± 2.82	9.32 ± 0.54
Event 1	1	17.4	7.63	137	3.66 ± 0.77	1.01 ± 0.46	–	4.07 ± 2.28	11.56 ± 0.35	–
Event 2	1	16.7	4.54	220	7.27 ± 0.71	2.94 ± 1.38	0.05 ± 0.04	3.76 ± 1.17	8.42 ± 1.20	–
Event 3	1	17.6	3.33	318	8.79 ± 1.16	5.38 ± 1.75	–	2.23 ± 1.70	6.70 ± 2.21	–
Post-events	3	58.3	14.3	265 ± 92	27.1 ± 3.47	14.1 ± 2.30	0.07 ± 0.05	7.69 ± 4.04	22.3 ± 2.01	–
Total or mean values$	11	223	145	201 ± 118$	52.5 ± 7.3	28.9 ± 5.4	0.62 ± 0.41	85.9 ± 13.0	125 ± 6.9	9.32 ± 0.54

-: no runoff or infiltration occurred.

(Olympus SZX10). Particles visually identified as plastic were analysed by Fourier-Transform InfraRed (FTIR) spectroscopy. Detailed protocols and FTIR spectra of the most abundant polymers found are provided in the Supporting Information. To minimize contamination, lab coats made of 100 % cotton were routinely worn and all equipment and instrumental material in contact with samples were made of glass and/or metal. During sample extractions, samples were uncovered under a laminar flow fume hood and one blank was added in each batch of samples. Then, the number of MPs found in blanks was subtracted to those obtained in the samples taking into account the polymers encountered. Recovery tests were performed as described in Martínez-Pérez et al. (2025), using a mixture of different polymers and shapes with recoveries percentages ranging between 88 % and 101 %. The extraction method was only slightly adapted from the method followed in the recovery tests when an additional step to speed up H_2O_2 evaporation was added.

2.4. MPs fate assessment

The number of MP particles in soil, runoff, and infiltration water was assessed. Particle size was recorded along the three axes (X, Y, Z), and volume was approximated based on shape: fibres were considered as cylinders, and fragments as ellipsoids. Particle mass was estimated using the calculated volume and polymer densities from Table S3. Before data analysis, plastic particles with x-axis lengths below 50 μm or above 5000 μm, and those with a mass exceeding 4 μg, were excluded. MPs found in blanks were subtracted from their corresponding samples (see Table S4 for blank results). To calculate the percentage of MPs mobilized, the number of MPs and MP mass per RIS at the start of the experiment were calculated by extrapolating from the initial soil samples. When assessing MP characteristics per matrix, blank corrections were applied to shape and polymer percentages, but not to size bin percentages as sometimes there is no coincidence between the size of MPs in the blanks and size of MPs in the samples. The influence of blanks was provided in Table S5.

2.5. Data analyses

Normality and homogeneity of variances of the MP concentration data in the different matrices were first assessed using the Shapiro-Wilk test and Levene's test, respectively, to determine the appropriate statistical analyses. A one-way ANOVA followed by Tukey's HSD post-hoc test (for homogeneous variances) or Games-Howell post-hoc test (for heterogeneous variances) were performed to compare MPs (in number or in mass) and MP concentrations (MPs/L or μg/L) in water samples across the three treatments (control, sludge and alfalfa). The same statistical tests were used to compare soil MP concentrations (MPs/g and μg/g) by layer (0–5 cm, and 5–15 cm) between the start and end of the experiment, and between sludge and alfalfa treatments. When assumption of normality was not met, Kruskal-Wallis test was used as the nonparametric alternative, followed by Dwass-Steel-Critchlow-Fligner post-hoc test for pairwise comparisons.

The effect of different rainfall intensities (i.e., low, medium and high) on MP infiltration and MP runoff of sludge systems was assessed using a one-way ANOVA followed by a Tukey's HSD post-hoc test. The influence of rainfall intensity on alfalfa treatment was not evaluated due to the low degree of mobilization of MPs in these systems, which impeded proper statistical evaluations.

All statistical analyses were performed using Jamovi software version 2.3 (Jamovi, 2022), which is based on the R programming language (R Core Team, 2021), employing "car" package (Fox & Weisberg, 2020). Statistical significance was determined when the calculated p-value was <0.05.

3. Results and discussion

3.1. Hydraulic conditions

The experimental data about RIS hydraulic conditions indicate that water runoff was more pronounced in the controls (52.5 mm) than in the sewage sludge treatment (28.9 mm), whereas water infiltration showed the opposite trend, with 85.9 mm in controls and 125 mm in the sewage sludge treatment (Table 1). As pointed out by Zoghlami et al. (2020), the incorporation of organic matter through sludge application improves soil structure, thereby likely favouring water infiltration (Bruggeman & Mostaghimi, 1993). A completely different behaviour was observed for the RIS with alfalfa, where runoff or infiltration rarely occurred. This behaviour is likely linked to plants′ ability to stabilize the soil, reduce erosion and enhance water retention (Haruna et al., 2020). However, other studies focusing on alfalfa have highlighted that foliage and root system reduce runoff and rise infiltration by increasing hydraulic roughness and soil structure (Wu et al., 2011; Yao et al., 2023).

During the experiment, greenhouse conditions, particularly the high temperatures (20.8–45.8 °C), increased alfalfa evapotranspiration, preventing the drainage of water at 35 cm depth. Indeed, potential evapotranspiration was not always met, boosting alfalfa roots to dig deeply into the soil, with taproots reaching approximately 30 cm and nearly contacting the bottom of the test units (Fig. S2). Therefore, although alfalfa enhances water infiltration, measured infiltration water outflow was minimal and occurred only when the plants were still at an incipient growth stage and evapotranspiration rates were relatively low (Table 1 and Fig. S3).

3.2. MP assessment

3.2.1. MP mobilization in water

Of the initial 401,769 ± 137,390 MPs (mean ± SD) in sludge-amended systems, only 0.32 ± 0.15 % were transported via runoff. This rate was two orders of magnitude lower (0.004 ± 0.003 %) in the alfalfa systems. Similarly, a very small proportion of the initial MP mass (59,763 ± 23,406 μg; mean ± SD) was mobilized: 0.35 ± 0.15 % by runoff and 0.014 ± 0.007 % by infiltration in sludge systems, and 0.008 ± 0.007 % and 0.003 ± 0.002 % in alfalfa systems, respectively (Table 2). Therefore, the overall MP mobilization was minimal in both treatments.

Table 2
Mean (± SD) percentage of MPs mobilized by runoff and infiltration based on number of MPs (#) and MP mass (μg). Runoff and infiltration percentages were calculated based on the initial number of MPs per RIS in the whole soil column (0–35 cm). The percentages for controls were omitted due to the low initial amounts of MPs. The detailed data for each individual RIS is provided in Table S6.

Treatment	Measurement	Runoff (% mobilized)	Infiltration (% mobilized)
Sludge	MPs (#)	0.316 ± 0.145	0.008 ± 0.004
	Mass (μg)	0.354 ± 0.153	0.014 ± 0.007
Alfalfa	MPs (#)	0.004 ± 0.003	0.002 ± 0.001
	Mass (μg)	0.008 ± 0.007	0.003 ± 0.002

Despite the large volumes of water infiltrating through the soil (Fig. 2A and B), the number of MP particles and mass in infiltration water was much lower than in the runoff water (Fig. 2C, D, 2G and 2H). A notable order-of-magnitude difference exists between the number and mass of MPs mobilized via runoff and infiltration, as reflected in the differing scales used in the corresponding plots. For instance, in sludge systems, runoff water transported an average of 1268 ± 584 MP particles, while infiltration water carried an average of 34 ± 15 MPs, which means 1.6 orders of magnitude difference or almost 40 times less (Fig. 2C and D). The greater transport capacity of runoff water compared to infiltration water can be attributed to the resistance of MPs to pass through the soil profile due to retention within soil pores and aggregates, the entanglement of fibres, and other physical processes that govern particle infiltration (Luo et al., 2024).

The presence of alfalfa significantly reduced the number and mass of MPs mobilized by water, especially in runoff, compared to unplanted sludge systems. Runoff water from alfalfa systems contained only 15 ± 13 MPs (5 ± 4 μg), representing a drastic reduction compared with the 1268 ± 584 MPs (212 ± 91 μg) measured in runoff from sludge systems, corresponding to an almost two order-of-magnitude reduction (factor of 1.9) (Fig. 2C and G). The sludge runoff also contained significantly more MPs than the control (p-value: 0.04), confirming sludge as a major source of MP pollution.

A more limited reduction was observed in infiltration water from alfalfa systems (8 ± 4.5 MPs and 1.8 ± 1.3 μg) compared with sludge systems (34 ± 15 MPs and 8.3 ± 4.1 μg). This reduced transport is likely the combined result of enhanced MP retention by roots and reduced water movement, as reported in previous studies (Han et al., 2022) and supported by the hydraulic data presented earlier.

The concentration of MPs (both by number and mass) per litre of water did not differ significantly between treatments (Fig. 2E, F, 2I, 2J). However, unplanted sludge systems tended to yield more concentrated runoff (Fig. 2E and I), while alfalfa systems produced more concentrated infiltration water (Fig. 2F and J).

3.2.2. MP concentrations in soil

The concentration of MPs in soil of sludge and alfalfa treatments at the start of the experiment (after the sludge amendment) was 33.38 ± 9.82 MP/g, whereas the MP concentration in the initial soil of the controls was 1.90 ± 2.16 MP/g (Fig. 3A). In terms of mass, the soil/sludge mixture contained 4.00 ± 1.71 μg/g, while the soil in the controls had 0.46 ± 0.61 μg/g (Fig. 3B). After five months, the MP concentration in the topsoil layer (0–5 cm) was reduced to 16.30 ± 7.15 MP/g (4.31 ± 3.26 μg/g) in sludge systems and to 10.61 ± 4.67 MP/g (1.66 ± 1.68 μg/g) in alfalfa systems. A significant reduction from the initial MP concentration (in terms of MPs/g) occurred only in the alfalfa treatment (p = 0.023). The reduction in the sludge treatment was marginally significant (p = 0.071), and the difference between the two treatments was not significant (p = 0.644). The overall lack of strong statistical effects is likely due to the limited capacity of water to mobilize MPs. Furthermore, control soil MP concentrations remained unchanged, indicating minimal experimental contamination.

No statistical differences were found in the MP content (by number or mass) in the 5–15 cm soil layer between the start and end of the experiment, or between the sludge and alfalfa treatments. Consequently, MP concentrations in this deeper horizon remained relatively stable. This finding aligns with other studies confirming minimal vertical MP transport and most MPs retained in the topsoil (Kim et al., 2021; Schefer et al., 2025).

While long-term field studies often report stable MP concentrations in topsoil (Ramage et al., 2025; Weber et al., 2022), our study observed a significant reduction in alfalfa systems that was not attributable to

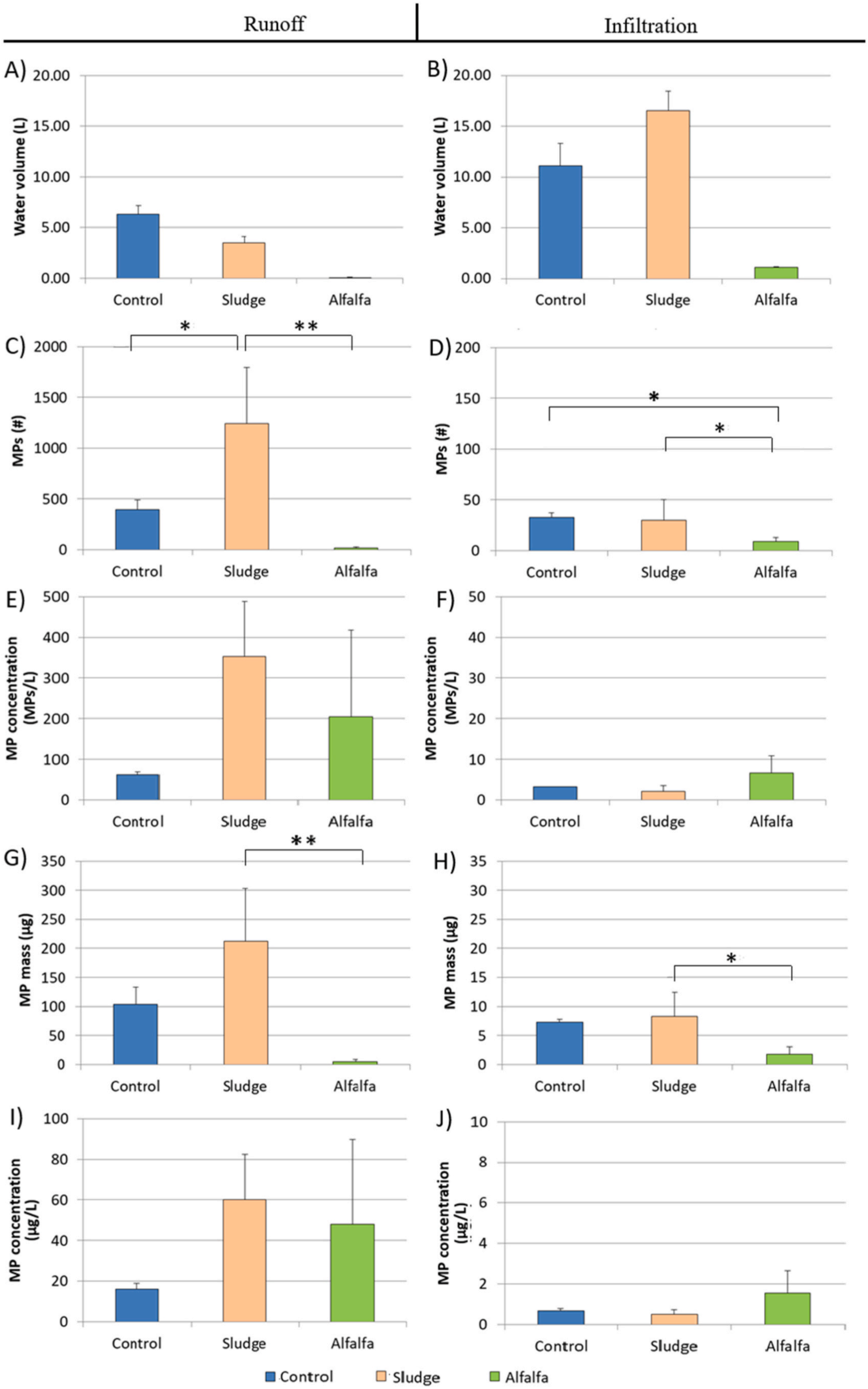

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Fig. 2. Collected runoff and infiltration water volumes the abundance of MPs (in number of MPs and MP mass), and MP concentration in water (in number of MPs and MP mass) across the different treatments Total runoff water volume (A), total infiltration water volume (B), total number of MPs in runoff samples (C), total number of MPs in infiltration samples (D), runoff MP concentration (i.e. total number of MPs in total runoff volume) (E), MP concentration in infiltration water (i.e. total number of MPs total infiltration volume) (F), total mass of MPs in runoff samples (G), total mass of MPs in infiltration samples (H), runoff MP concentration (i.e. total mass of MPs in total runoff volume) (I), and MP concentration in infiltration water (i.e. total mass of MPs in total infiltration volume) (J). The asterisks mean $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***) according to the Turkey Test (when variances were homogeneous) or to Games-Howell Test (when the variances were not homogeneous). Note that there is an order of magnitude difference in the scale between runoff and infiltration plots except for water volume: (A) and (B).

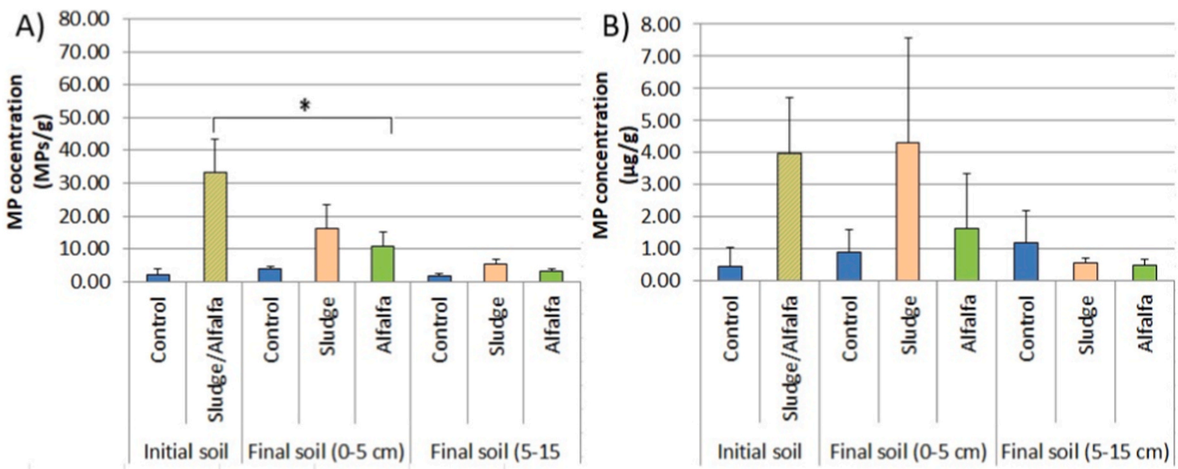

Fig. 3. MP concentration in number of MPs (MPs/g) (A) and in MP mass (μg/g) (B) in the initial soil/sludge mixture applied to the sludge and alfalfa treatments, in the control soil at the start of the experiment, and soils at two depths (0–5 cm and 5–15 cm) at the end of the experiment for each treatment. The asterisk (*) indicates significant differences between the two contents according to Tukey post hoc-test (p-value <0.05).

increased hydrological transport. This discrepancy may be explained by plant-mediated capture. Tumwet et al. (2024) demonstrated that wheat (*Triticum aestivum*), grown in soil amended with 0.24 % (w/w) polyester fibres—the dominant polymer (82 %) and shape in our study—retained these fibres adhered along its entire root length (~50 cm). Although alfalfa develops a taproot system (~30 cm, Fig. S2), in contrast to the fibrous roots of wheat, a similar capture mechanism is plausible. We hypothesize that water preferentially infiltrated along the taproots, facilitating the entrapment and adhesion of MPs. This would account for the concurrent lack of increased MP concentration in the 5–15 cm soil layer and the infiltrating water, despite the overall reduction of MPs in topsoil.

3.3. Impact of rainfall intensity

The impact of rainfall intensity on MP mobilization was analysed taking into account exclusively data from the sludge treatment since the mobilization in alfalfa systems was very low. Fig. 4 shows the relationship between the three different rainfall intensities (event 1–3) and both the water volume and the MP mobilization by runoff and infiltration water. A notable difference exists between the number or mass of MPs mobilized via runoff versus infiltration, as evidenced by the one-order–magnitude different in the scales used in the corresponding plots (Fig. 4C–J).

As expected, the different rainfall intensities significantly affected runoff and infiltration water volumes, with runoff being highest at the greatest intensity and infiltration being highest at the lowest intensity (Fig. 4A and B). The changes generated in water volumes did not translate into a clear effect on MP mobilization, either through runoff or infiltration (no significant differences). Regarding the average MP mobilization by runoff, the number of MPs increased during the medium intensity rainfall events as compared to the lowest intensity (58 ± 47 MPs in low intensity and 252 ± 233 MPs in medium intensity) (Fig. 4C). When the rainfall intensity reached the highest level, MP mobilization did not substantially increase, and the number of MPs mobilized remained almost unchanged (235 ± 106 MPs). An increasing trend in MP mass mobilized with rising rainfall intensity was observed; although the statistical test did not indicate significant differences (Fig. 4G). Regarding MPs and MP mass mobilized by infiltration no significant differences were detected among the three rainfall intensities, and the amounts mobilized were very low. MP concentrations in number or mass per litre of runoff or infiltration water (Fig. 4E, F, 4I, 4J), neither showed significant differences or a trend under the three rainfall intensities. Such behaviour suggests that MP mobilization in high to extreme rainfall events remains similar.

Other studies investigating the effect of rainfall on MP transport found a correlation in the number of MPs transported by runoff and infiltration with the increase in rainfall intensity (Ling et al., 2023; Soltani Tehrani et al., 2025; Zhang et al., 2022a,b). However, these studies were conducted at rainfall intensities that were lower than the high to extreme values used in our study. Moreover, we observed a high variability among samples, both in the amount of water collected and in the number of MPs in the samples, which prevented us to find clear differences between the evaluated rainfall events.

Based on existing literature and our results, we hypothesize that a rainfall intensity threshold exists, beyond which MP mobilization exhibits no further increase. This plateau may be mechanistically linked to the established non-linear relationship between rainfall intensity and soil erosion. For instance, soil loss from raindrop detachment has been shown to increase non-linearly with intensity (Sharma et al., 1993). This aligns with our hypothesis, as the extreme intensities simulated in our study (137–318 mm/h) exceed the linear domain described for lower intensities (Mohamadi & Kavian, 2015) and may instead correspond to the non-linear erosion regime directly associated with MP runoff by Rehm et al. (2021).

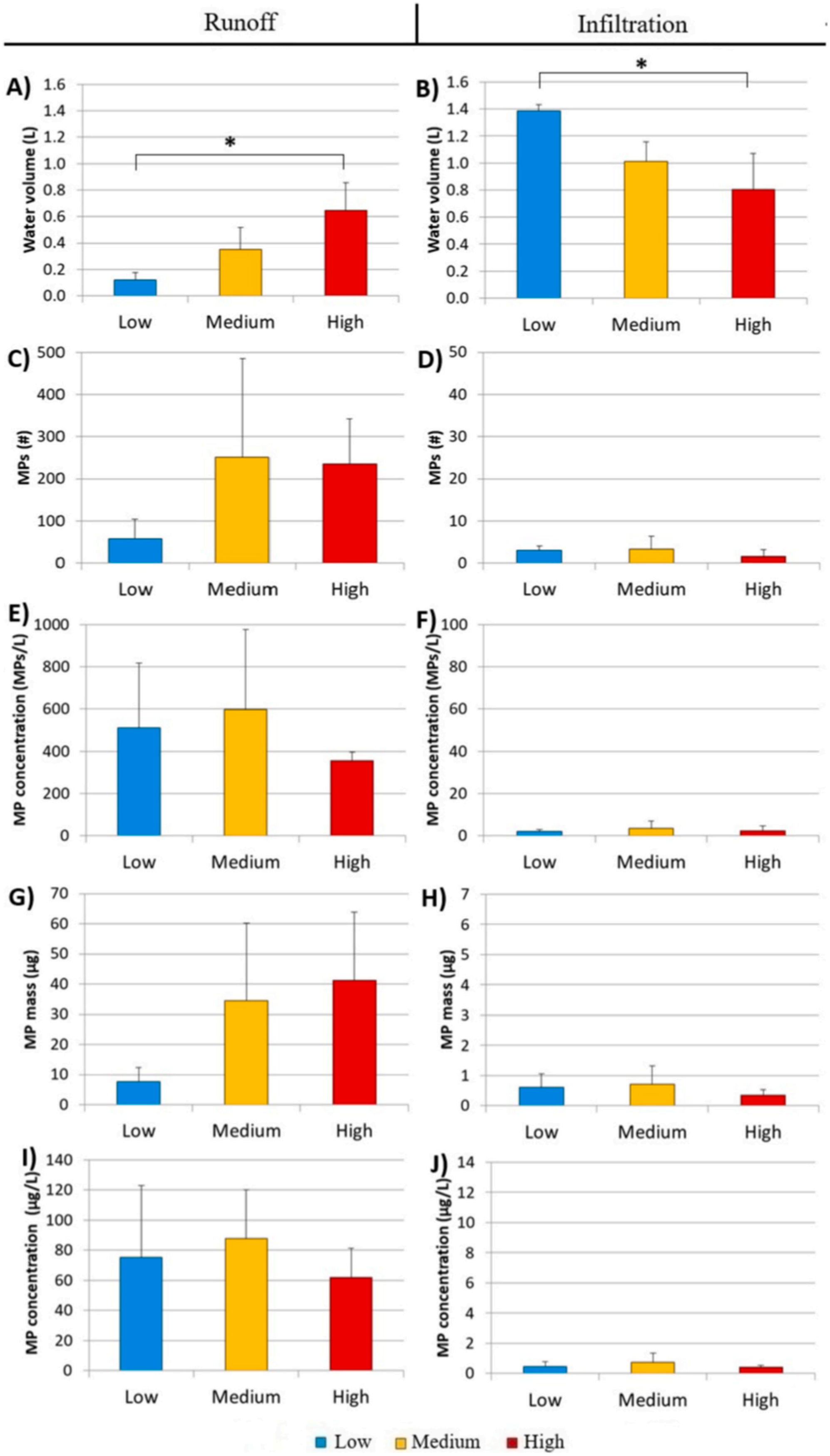

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Fig. 4. Relationship between rainfall intensity, water volume generated, MPs abundance (number of MPs and MP mass), and MP concentration in water (number of MPs and MP mass) in runoff and infiltration samples of the sludge treatment. Runoff water volume (A), infiltration water volume (B), number of MPs in runoff water (C), number of MPs in infiltration water (D), concentration as number of MPs per L of runoff (E), number of MPs per L of infiltration (F), mass of MPs in runoff water (G), mass of MPs in infiltration water (H), mass of MPs per L of runoff water (I), concentration mass of MPs per L of infiltration water (J). Low intensity refers to a rainfall event of 137 mm/h, medium intensity to 220 mm/h, and high intensity to 318 mm/h. The asterisk (*) indicates significant differences between the two contents according to Tukey's post-hoc test (p-value <0.05). Please note that there is an order of magnitude difference between runoff and infiltration plots except in water volume (A) and (B).

3.4. MP characteristics

Infiltration water contained a higher proportion of MP fragments than runoff water. This disparity was most pronounced in the alfalfa systems, where fragments constituted 28 % of MPs in infiltration versus only 2.2 % in runoff (Fig. 5). In soil samples, in the 0–5 cm layer, the proportion of fragments decreased from initial levels in both treatments, suggesting shape-dependent transport. However, differences emerged at the deeper 5–15 cm layer: fragments were absent in sludge systems, whereas their proportion in alfalfa systems was 13 %. Fibres are less mobile due to entanglement within soil pores (Corradini, 2025; De Frond et al., 2021), making smaller, more rigid fragments inherently more likely to infiltrate to depth. The enhanced fragment mobility in alfalfa systems is likely a root-mediated process. Roots may create preferential flow paths that facilitate the translocation of fragments (Li et al., 2021), while simultaneously retaining fibres within their dense network (Tumwet et al., 2024), effectively filtering one shape while enabling the transport of another.

In terms of polymer type distribution, polyethylene (PE) was the only polymer consistently translocated from the topsoil to deeper soil layers or water compartments in both sludge and alfalfa systems, suggesting a relatively higher mobility of this material (Fig. 5). Some authors suggested that low-density polymers might be more easily transported by runoff (Han et al., 2022), while higher density polymers may reach deeper soil layers (O'Connor et al., 2019). PE has a density of 0.94 g/cm^3, which is lower than the density of polyester (1.37 g/cm^3) and similar to that of PP (0.9 g/cm^3). Therefore, density may only partially explain their higher mobility. Other factors such as hydrophobicity or zeta potential, and shape have also been suggested to affect MP transport (Waldschläger and Schüttrumpf, 2020; Gao et al., 2021). Indeed, the fact that most fibres were polyester (82 %) might imply that shape has a greater influence on their mobility than the polymer composition and density (Li et al., 2025).

Interestingly, our study showed that, overall, water samples contained larger MPs than soil samples (Fig. 5). This finding contrasts with previous studies, which suggest that smaller particles have higher mobility than larger ones through runoff due to their settling velocity (Han et al., 2022; Zhang et al., 2022a,b) and through infiltration due to pore size restricting their path (Luo et al., 2024). However, our result is in agreement with Park et al. (2023), who also found greater vertical mobility with greater MP size into sandy soil columns, and attributes this finding to the interfacial tension that might be causing a greater aggregation of smaller particles.

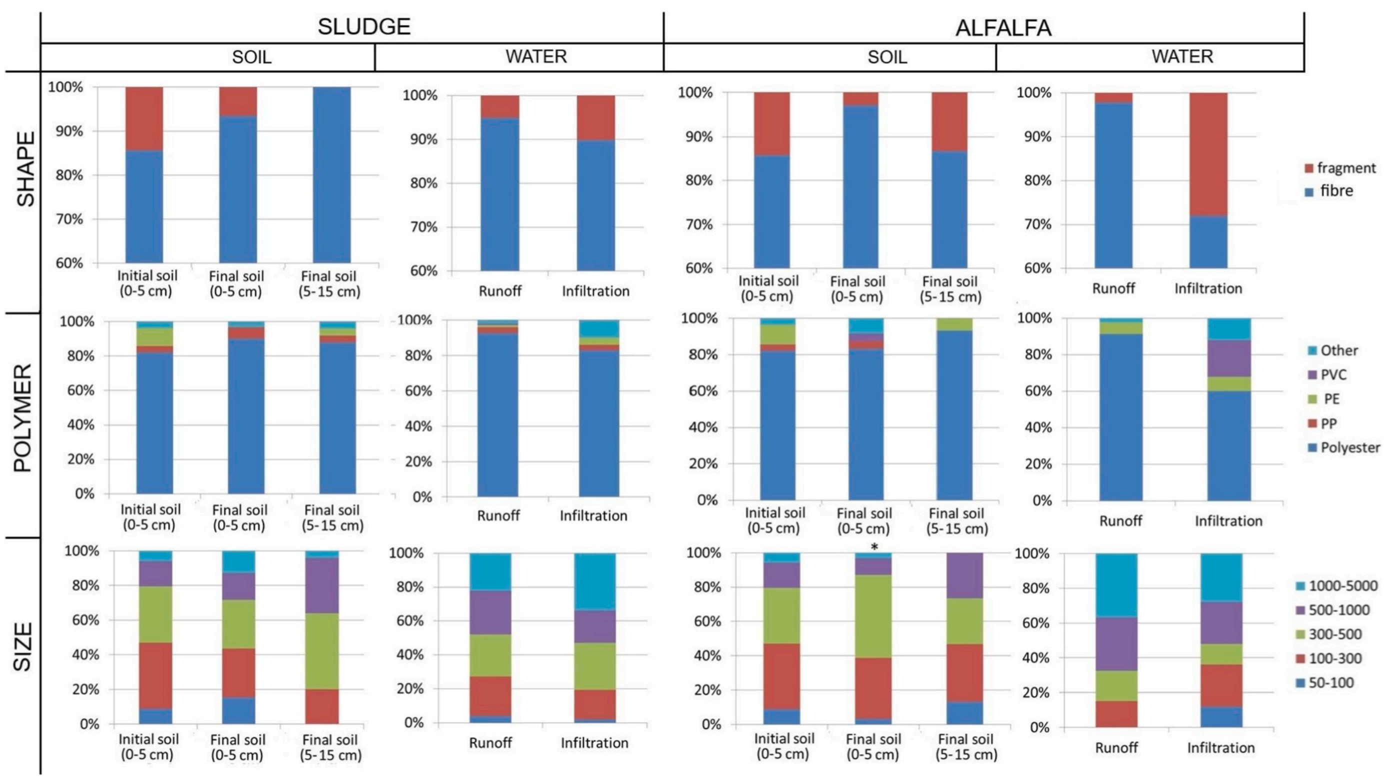

Fig. 5. MP distribution by shape, polymer type and size in soil and water samples from sludge and alfalfa treatments. The asterisk (*) indicates that the blanks in those samples contained more than 10 % of the particles, so that the results should be interpreted with caution.

4. Conclusions

This study provides a comprehensive assessment of the factors influencing MP mobilization in agricultural soils amended with sewage sludge. Results indicate that MP mobilization from bare soil is almost two orders of magnitude greater than from alfalfa-planted soil, attributable to the crop's capacity to modify soil conditions and retain MPs. Furthermore, runoff water transported significantly more MPs than infiltration water in bare soils (1268 ± 584 by runoff and 34 ± 15 MPs by infiltration), whereas this difference was less pronounced in the alfalfa systems (15 ± 13 MPs by runoff and 8 ± 4.5 by infiltration). This suggests sludge-derived MPs in soil ecosystems pose a greater contamination risk to surface waters than groundwater, particularly in uncultivated soils. The study also demonstrates that while increased high to extreme rainfall intensities generate higher runoff volumes; it does not necessarily enhance MP mobilization. Moreover, we confirm the predominance of polyester fibres in soils amended with sewage sludge (82 %) and show that larger fibres exhibit greater mobility than smaller particles via water transport.

Overall, we conclude that soils function as long-term MP sinks, with less than 0.4 % of MPs mobilized by hydrological processes. Multiple sludge applications may therefore lead to substantial MP accumulation in soils, whose potential risks to plants and soil organisms require further evaluation. Finally, this work demonstrates that vegetation can mitigate surface water contamination following heavy rainfall events by reducing soil erosion and MP transport via runoff.

CRediT authorship contribution statement

Sara Martínez-Pérez: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Isabel Fernández Artime:** Methodology, Investigation. **Ana García Arcos:** Methodology, Investigation. **Raffaella Meffe:** Writing – review & editing, Methodology, Conceptualization. **Andreu Rico:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Virtudes Martínez-Hernández:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sara Martinez Perez reports financial support was provided by Spanish Ministry of Science Innovation and Universities. Andreu Rico reports financial support was provided by Generalitat Valenciana. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2025.127608.

Data availability

Data will be made available on request.

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