Microplastics and Nanoplastics

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Baseline levels of microplastics in agricultural soils obscure the effects of additional microplastics from recycled fertilizers

Collin J. Weber[1*], Dominika Kundel[2], Andreas Fliessbach[2], Else K. Bünemann[2] and Moritz Bigalke[1]

Abstract

Digestate from the recycling of various organic wastes in biogas plants is widely used as organic fertilizer for agricultural soils. Organic fertilizers contribute to microplastic loads, but it is not well constrained how they contribute to the overall accumulation of microplastic in agricultural soils. We investigated a field experiment in Switzerland fertilized since 2018 with liquid or solid digestate from a non-agricultural biogas plant. Microplastic particle concentrations (p) and characteristics were investigated in digestate fertilizers, digestate-treated soils and a control soil that did not receive organic fertilizers. Microplastics were extracted from the soil (two rounds of density separation (1.5 g cm^{-3}) and Fenton treatment), followed by µFTIR chemical imaging analysis with a size detection limit of 20 µm. We found median microplastic concentrations of 16,000 p kg^{-1} (10,600–54,000 p kg^{-1}) in digestate fertilizers, 6,400 p kg^{-1} (800–33,800 p kg^{-1}) in digestate-treated soils and 7,100 p kg^{-1} in the control soil caused by a single outlier value or 5,600 p kg^{-1} when excluding the outlier. Particle sizes and polymer compositions differed between digestate fertilizers and soils. Topsoil (0–20 cm) microplastic stocks varied from 1.8 to 3.8 × 10^6 p m^{-3}. The calculated inputs from the digestate application contributed only 0.9–4.0% to the total microplastic stocks which led to the case that digestate microplastic inputs were not detectable against the variation of the stocks. The study highlights those substantial high concentrations of microplastic might already occur in many soils, due to previous microplastic inputs over several decades from e.g., recycled fertilizer application like sewage sludge or from other diffuse sources. Whilst it was observed from the fluxes that digestate can be a substantial source of microplastics to soils, the comparatively short time of application and the high background at our investigated sites leads to a obscured effect where digestate inputs serve a limited function.

Keywords Biogas, Digestate, Organic fertilizer, Feedstock substrate, Field experiment, µFTIR, Chemical imaging, Particle composition

*Correspondence:
Collin J. Weber
collin.weber@tu-darmstadt.de
[1]Institute of Applied Geosciences, Department of Soil Mineralogy and Soil Chemistry, Schnittspahnstr. 8, 64287 Darmstadt, Germany
[2]FiBL Switzerland, Department of Soil Sciences, Ackerstrasse 113, Frick 5070, Switzerland

Introduction

Microplastics (MP) can affect soil environments by changing soil physical properties [1] and effecting soil (micro-)organisms [2], soil biochemical processes and soil-plant interactions [3, 4]. MP are particulate pollutants of synthetic origin ranging in size from 1 to 5000 µm that can accumulate in soils over time [5]. Arable soils are considered the largest terrestrial reservoir of MP in the environment [6]. The origin of MP within arable soil environments includes non-agricultural and agricultural sources. While non-agricultural sources are often referred to as indirect or diffuse sources like car traffic for tire and road wear particles, littering, flooding or atmospheric deposition [7, 8] which are present but hard to quantify. In contrast, some more direct emissions to soils include agricultural practices, including irrigation water [9], plasticulture (e.g., mulch foil application) [5] with an estimated application of 12.5 million tons yearly [10] and organic fertilizer application [11, 12] are considered as major agricultural MP sources.

Among organic fertilizers, sewage sludge is considered a important carrier of MP to soils, by transferring MP from wastewater, enriched during waste water treatment and carried to soils within sewage sludge and its application [13–15]. Given that sewage sludge contains a range of pollutants such as trace metals or pharmaceuticals, the application of sewage sludge is widely regulated and partly prohibited in several countries [16]. However, before regulation sewage sludge was commonly applied in huge amounts on arable fields and could therefore be considered as a past or even 'historic' MP source [17]. While MP accumulation in soils due to sewage sludge application is now relatively well studied, the contribution of other organic fertilizer, in particular compost and liquid or solid digestate remain elusive due to the small number of quantitative studies [18–20]. Plastic content as a foreign substance in compost is partly regulated, with weight% (wt%) thresholds values of < 0.1 wt% in Germany and < 0.3 wt% in Europe (> 1 mm plastic fragments) referred to the weight of initial processing substances. However, plastic limits for digestate fertilizers are widely missing, except e.g., Switzerland with a threshold value of < 0.1 wt% plastics in digestate products [21]. Considering the missing regulation and use of mixed substrates in biogas plants, high MP loads in solid or liquid digestate products can be expected [22]. Those MP loads can be carried from the original biogas materials through the fermentation process and may end up in the soil when digestates are used as organic fertilizers [23]. Most biogas plants use mixed substrates from energy crops (42%), agricultural residues (24%) or biowaste (16%) for the fermentation process [7, 24]. MP loads in digestate fertilizers may vary strongly depending on the source of input substrates, biogas production process as well as post-processing of fermentation products including e.g., post-composting, drying (solid digestate) or dilution (liquid digestate) [23, 25]. In Europe, already 20,000 biogas plants are operating with a total biogas production of 3 billion m^3 a^{-1} in 2020 and high potential for production increases in future [24, 26]. Taken together, these circumstances pose a high risk of increasing MP inputs from digestate into agricultural soils.

Previous studies have reported MP concentrations of up to 146 p kg^{-1} (> 1 mm in size) in solid digestate from household biowaste in Germany [27], 3298 p kg^{-1} (> 50 µm in size) in raw digestate from household biogenic waste in China [25], and 7200 p L^{-1} (> 40 µm in size) in digestate from household biowaste in Finland [23]. However, there is currently no study that examines how MP concentrations and particle characteristics in digestate fertilizers contribute to MP concentrations, stocks and characteristics in soils treated with these fertilizers. To address this knowledge gap, we analysed three different digestate fertilizers and soils fertilized with those digestates from a controlled fertilizer trial in Switzerland to answer the following research questions:

1. Are the concentrations and composition of MP in digestate-treated soils influenced by the type of digestate fertilizer applied, whether liquid, solid, or solid composted after anaerobic digestion?
2. Do MP inputs from digestate fertilizers contribute provable to MP concentrations in agricultural soils fertilized with those digestate?

Materials and methods

Fertilizer trial and sampling

To investigate the MP contribution from different digestate fertilizers, we used a field experiment located in Wallbach (Switzerland, 47°33'44.3"N 7°53'15.7"E). The field trial is part of the Recycle4Bio project [28] and was established in March 2018. The trial consists of a split-plot design (9 × 18 m per plot) with four replicated plots per treatment. Soil is characterised as a Halpic Luvisol with silt-loam texture and a mean total organic carbon content of 15.3 g kg^{-1}. Further details on the experimental trial setup and maintenance are given in Figure S1 and Text S2. We focused on three digestate fertilizer treatments: Liquid digestate from anaerobic digestion (LID); solid digestate from anaerobic digestion (SD) and solid composted digestate (SDC) as well as a control treatment without any organic or nitrogen fertilizer, but an annual phosphorus (P) and potassium (K) fertilization in mineral form, referred to as control (NON). The digestates originated from a single non-agricultural biogas plant (Biopower, Pratteln, Switzerland) which uses plant material from urban green areas and organic wastes from households, supermarkets, food processing industries

and gastronomy as feedstock. These materials then pass a thermophilic anaerobic digestion at 55 °C with a mean residence time of 15 days. To obtain SDC, freshly separated SD material was composted for 8–9 weeks with 5 volume percent addition of mature compost. In the period from 2018 until soil sampling in March 2023, a total of 14.4 tons ha^{-1} dry weight (DW) for LD, 46 tons ha^{-1} DW for SD and 45 tons ha^{-1} DW for SDC were applied to the plots with a mean of 115 g kg^{-1} C_{org}. Liquid digestate was applied on the surface, while solid digestate was superficially incorporated after spreading using a rotary harrow with a working depth of 5–10 cm in April–May (LID, SDC, LID) and September (only LID) of each year. At each field replicate of LID, SD, SDC and NON treatment, 10–12 randomized soil subsamples were extracted with a soil auger (Ø 3 cm) from the top 20 cm of soil, mixed and homogenized in aluminium bowls [29], dried at 40 °C and sieved to 2 mm (*4 plots x 4 treatments = 1 composite sample per plot = total n of 16*). From a total of 2100–2500 g fresh weight per soil sample, 5 g was subsampled for further analysis using quartering method [30] and a riffle splitter. Additionally, three replicate digestate samples of LID, SD and SDC were provided by the Recycle4Bio project as field trial operator (*1 treatments x 3 replicates = 3 composite sample per digestate fertilizer*). Three 2 L^{-1} LID samples were taken upon field delivery in 2022 in stainless-steel bowls and dried at 40 °C before further preparation. Three 1 kg^{-1} samples (wet-weight) of SD and SDC each were sampled after field delivery in 2022 from random positions of the bulk piles, homogenized and stored in glass-jars with metal lids and dried at 40 °C before further preparation. We were provided with dried subsamples ($n = 9$, 100 g dry weight per sample) from LID, SD and SDC fertilizers and produced a 5 g subsample of each sample for further analysis using quartering method [30] Additional details on the sampling procedure, sample pre-processing and soil properties are given in Text S2 and Table S3.

Microplastics extraction from soil and digestate samples

MP extraction from air-dried soil samples followed the protocol developed by Foetisch et al. (2024) and applied by Klaus et al. (2024) with a reported recovery rate of 85% (tested with artificial tire wear particles and polyethylene particles, >20 µm) [31, 32]. The mineral soil fraction was separated by density separation with sodium bromide solution (NaBr, ρ 1.5 g cm^{-3}). Soil sample aliquots (5 g) were mixed with 30 ml NaBr solution in corning tubes and ultrasonicated (10 min), shaken (30 min, 100 rpm) and centrifuged (30 min, 2500 xg). Afterwards, the supernatant was filtered (stainless-steel filter, Ø47 mm, 10 µm) and the retained sample material was resuspended in NaUT solution containing 6% urea, 8% thiouea and 8% NaOH. Afterwards, the solution was stored at -16 °C for 60 min to predigest the sample for the oxidation, before the NaUT was washed out with MilliQ on stainless-steel filters. The remaining particulate organic matter was oxidised via a Fenton reaction using hydrogen peroxide (H_2O_2, 30%) and iron(II)sulfate (Fe_2SO_4) as a catalyst. The remaining sample material was filtered again, washed and a second density separation was applied (NaBr, ρ 1.5 g cm^{-3}). The final supernatant was transferred to an Anodisc filter (Ø13 mm, 0.02 µm pore size, Whatman, Maidstone, UK) and treated with 2M H_2SO_4 to dissolve residual iron oxides on the filter [31].

For digestate samples, an aligned extraction method was applied, to handle the high organic matter content. Here, we applied the binary-solvent extraction following the protocol of Fadare et al. (2023) and a reported recovery rate of 89–93% (tested with 0.1 g MP mixture added to 0.5 g particulate organic matter). This protocol enables to overcome the hydrophobicity of organic matter as the solvent-water mixture acts as an anti-hydrophobic agent and a proper separation of MP [33]. A 98% EtOH – MilliQ mixture (8:2) was added to 5 g digestate aliquots dried at 40 °C, shaken (15 min, 100 rpm) and left to soak for two hours [33]. Afterwards, the supernatant was removed using a glass pipette before 30 mL ultrapure water (MilliQ) was added. The samples were shaken (5 min, 100 rpm) and let settle for 10 min. The supernatant was then transferred with MilliQ to a 10 µm stainless-steel filter and rinsed with at least 50 mL MilliQ. The digestate samples were then subjected to the same purification procedure as the soil samples.

Microplastics analysis

The full filter area of each Anodisc filter was measured with a focal-plane array (FPA, 32 × 32 detector) detector at a µFTIR spectrometer (Lumos II, Bruker Corporation, Billerica, MA). Chemical imaging was performed in transmission mode (1250–4000 cm^{-1}, 4 cm^{-1} resolution, one scan per pixel and binning of 2 × 2 pixels), with a resulting pixel resolution of 11 × 11 µm. Chemical image analysis and particle identification were achieved using the Purency Microplastic Finder software (Version 4.17, former Purency GmbH, Vienna) [34]. For polymer identification, an identification relevance threshold (relevance of classification) of 0.3 and a spectra similarity threshold (similarity of sample spectra and reference spectra) of 0.1 were applied [35]. The low similarity threshold was chosen, as the applied resolution of 1 scan leads to comparatively noisy spectra and missing fits with reference spectra recorded with higher scan time. The classification was manually checked, single pixel identifications were excluded and fragmented particles joined, resulting in a total of 1762 classified particles and mean of 70 particles per sample.

Quality assurance and quality control

To avoid contamination, sampling, sample storage and sample pre-processing were performed without any plastic tools. Within the laboratory, all extraction steps were performed within a laminar flow box and while wearing cotton lab coats. All glassware and equipment used was previously cleaned with MilliQ. NaBr salt solutions and EtOH were filtered (Nuclepore membrane filter, 0.8 µm pore size, Whatman) before usage. Contamination was controlled via blank samples, with two samples each for the soil and the digestate extraction. Based on the blank samples, we calculated the limit of detection (LOD) via Eq. 1 [36].

$$LOD = \underline{M}_{blank} + (3 \times STD_{blank}) \quad (1)$$

with $\underline{M}_{blank}$ the average particle concentration in blank samples and STD_{blank} the standard deviation of particle concentration in blank samples. Based on the chemical imaging analysis, we calculated a size detection limit (LOD_{size}) of 22 µm. For data correction and reported concentrations (MP_{corr}), we subtracted the calculated LOD from the total number of identified particles (MP_{tot}) according to Eq. 2 [36]:

$$MP_{corr} = MP_{tot} - LOD \quad (2)$$

Overall, we found a LOD of 4 MP particles per sample for digestate samples and a LOD of 6 MP particles per sample for soil samples. The average MP count in the blank samples was clearly ($p \leq 0.001$) smaller than the MP count in soil and digestate samples.

MP stocks were calculated for the upper 20 cm of soil, using MP_{corr} concentration and soil bulk densities (Table S3). Total MP input from fertilizers was estimated by multiplying total fertilizer application rates (kg ha^{-1}, 2018–2022) by the median MP concentrations (particles kg^{-1}) assessed in the fertilizer samples ($n = 3$ per fertilizer). The MP proportion in soil originating from fertilizers was then calculated as the percentage of total MP stocks in soil, assuming uniform mixing through tillage. However, this calculation was performed despite the challenges for mass balances occurring from different sample preparation methods. MP particle sizes were reported in µm considering the minor axis of each identified MP particle above the LOD_{size} of 22 µm. MP particle sizes and polymer identification were analyzed in digestate samples from LID ($n = 184$), SDC ($n = 254$) and SD ($n = 501$), as well as in soil samples from LID ($n = 147$), SDC ($n = 145$), SD ($n = 252$) and NON ($n = 279$).

Data handling and statistical analysis

Data was analysed in R (Version 4.2.2) via RStudio Version (2022.02.3) [37] using the standard R-packages and "ggplot2" [38] for the data visualization. To assess differences in MP concentration and MP size in the fertilizers and differently digestate-treated soils, we used analysis of variance (ANOVA). Effects from fertilizer treatments on MP concentration in digestate-treated soils were investigated by linear mixed-effects models in the R package "afex" [39]. To estimate the 95% confidence intervals (CIs) for the estimated MP stocks, we employed the bootstrapping technique as a non-parametric resampling method [40]. This approach was chosen to provide robust confidence intervals that are less sensitive to assumptions about the underlying distribution of the data, particularly given the small sample size ($n = 4$) in each group. Outlier identification was performed via cook distances plots. Model assumptions were confirmed numerically (Shapiro-Wilk test, Kruskal-Wallis rank sum test) and graphically. Pairwise mean comparisons were conducted using the Tukey test.

Results

Within the studied field experiment, we found median MP concentrations of 16,000 p kg^{-1} (10,600–54,000 p kg^{-1}) in the investigated digestate fertilizers and 6,400 p kg^{-1} (800–33,800 p kg^{-1}) in the digestate-treated soils samples (Fig. 1a). In digestate samples highest median MP concentrations were found in SD (22,600 p kg^{-1}) driven by a single outlier (54,000 p kg^{-1}) and a reduced median of 21,900 p kg^{-1} when excluding the outlier value. Other digestates showed lower medians of 16,000 p kg^{-1} (SDC) and 11,600 p kg^{-1} (LID) (Fig. 1a, Table S4). Variance analysis by ANOVA for MP concentrations demonstrated that there was no clear difference in MP loads between the digestates ($p = 0.13$). Soils receiving these different fertilizers showed a comparable pattern with highest median MP concentrations found in soils treated with SD (12,100 p kg^{-1}), followed by soils fertilized with SDC (5,200 p kg^{-1}) and LID (2,200 p kg^{-1}). Soils from the control plots contained unexpectedly high concentrations of MPs (7,100 p kg^{-1} including and 5,600 p kg^{-1} excluding a single outlier), exceeding MP concentrations in soil treated with SDC and LID. Figure 1a shows that the MP concentrations seem to increase from LID to SDC to SD when excluding the outlier. However, statistically this trend was only moderate ($p = 0.09$) (Fig. 1a). Variance analysis by ANOVA revealed that there was no clear trend between MP concentrations in digestate-treated soils and the control soils ($p = 0.64$), even if the control outlier is removed.

Particle size distribution of MP in digestate samples was similar for LID (mean 89 ± 100 µm) and SDC (mean 106 ± 135 µm) (Fig. 1b). In contrast, MPs in SD digestates were on average smaller (39 ± 61 µm) compared to MPs in LID and SDC digestates ($p < 0.01$), and approximately 50% of the SD digestate MPs were below 100 µm (Fig. 1b,

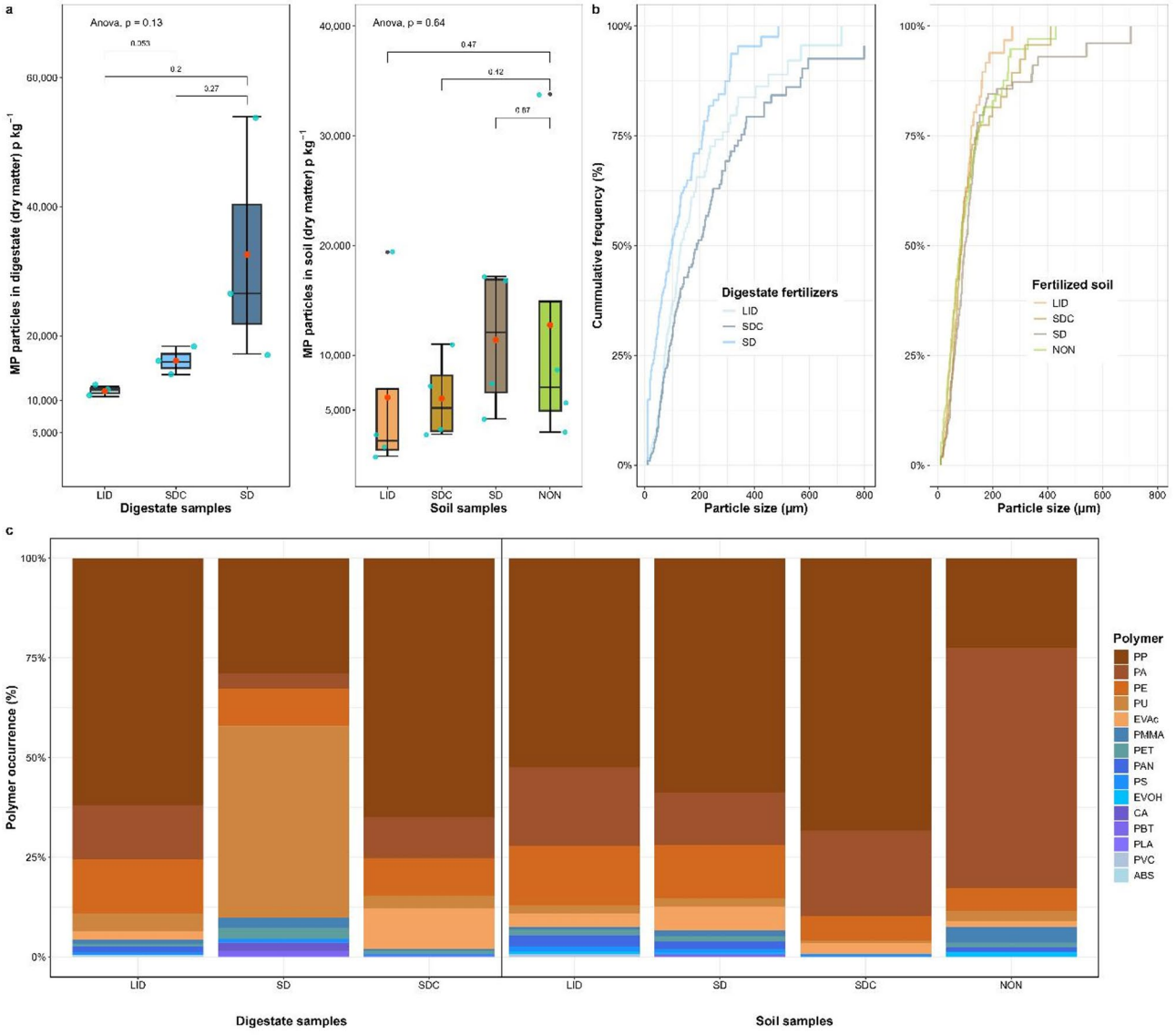

Fig. 1 Microplastics concentration and particle properties in digestate and soil samples. **(a)** Microplastics particle count (p kg^{-1}) in digestate fertilizer samples ($n = 3$) and soil samples ($n = 4$) from the four fertilizer treatments, with LID: Liquid digestate; SDC: Composted solid digestate; SD: Solid digestate; NON: control. Full dataset without outlier exclusion displayed. Absolute p-values from the ANOVA tests and pairwise comparisons of t-test provided. Boxplot boxes show 1st and 3rd quartile, centre line the median and red dot the mean value, while whisker indicate min/max (without outliers) and data points indicates by blue dots. **(b)** Microplastics particle size distribution (µm) given as cumulative frequency (%) in digestate fertilizer samples and soil samples. **(c)** Plastic polymer composition (%) in digestate fertilizer samples and soil samples (absolute values given in Table S5)

Table S4). However, the reduced particle size in SD digestate was driven by the single outlier sample which had a mean particle size of only 27 µm (from 133 single particles out of a total 489 particles from SD samples) and could therefore also contribute to the outlier within the SD MP concentration. Across all soil samples MP particle size distribution ranged between 52 µm and 71 µm and was similar irrespective of treatment (Fig. 1b). Overall, mean MP sizes in digestate samples (67 µm ± 99 µm) and soils that received digestates (61 µm ± 62 µm) were comparable ($p = 0.13$), albeit more variable in the digestates (Fig. 1b).

The polymeric composition revealed a dominance of polypropylene (PP), polyamide (PA) and polyethylene (PE) within digestate fertilizer samples, with PP representing 62–64% of all polymers in LID and SDC digestates. In contrast, MPs in SD digestate samples were dominated by polyurethane (PU) (48%), followed by PP (29%) and PE (9%) (Fig. 1c, Table S5). The outlier sample with highest MP concentration in SD fertilizer did not cause the higher PU share in polymer composition. Within digestate-treated soils samples, PP (52–68%), PA (13–21%) and PE (6–15%) accounted for the dominant

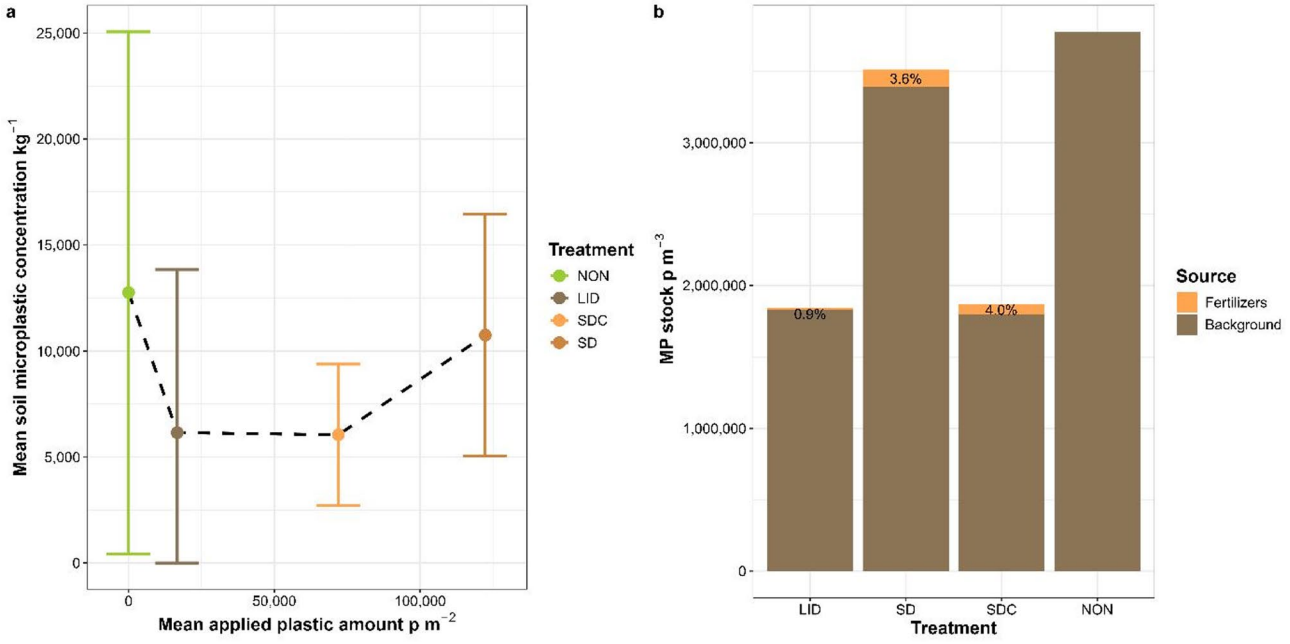

Fig. 2 Comparison of microplastics concentrations in soils and estimated microplastics amount applied through fertilization. **(a)** Mean microplastics concentration in soils (p kg^{-1}) with standard error lines and mean estimated microplastics amount (p m^{-2}) applied through total fertilizer amounts for LID: Liquid digestate; SD: Solid digestate; SDC: Composted solid digestate. **(b)** Total estimated microplastics stocks in topsoils (p m^{-3}) and proportion of microplastics contributed by digestate fertilization

polymers. In contrast, the control soil was clearly dominated by PA (60%) (Fig. 1c, Table S5).

We estimated the total expected input of MPs over the five-year period (2018–2022) for each of the soils considering the MPs detected in the digestate samples taken in 2022 (Fig. 2a). Accordingly, we expected MP concentrations of 16,700 ± 950 p m^{-2} in soils treated with LID, 122,000 ± 71,000 p m^{-2} for SD and 72,000 ± 8,000 p m^{-2} for SDC treated soils. However, no linear trend ($p = 0.95$) was found between the amount of applied fertilizers and the mean soil microplastics concentrations, irrespective of inclusion or not of the SD outlier sample (Fig. 2a). In contrast to the estimated MP input, microplastics stocks in topsoil (0–20 cm) extrapolated from measured MP concentrations resulted in 3.8×10^6 p m^{-3} for the control, 3.4×10^6 p m^{-3} for SD, 1.8×10^6 p m^{-3} for LID and 1.8×10^6 p m^{-3} for SDC. Despite the insecurity occurring from the data resolution, the higher MP stock in the control (NON) compared to SD treated soil, results from the higher mean of MP concentrations in the control, caused by the single outlier value. MP stocks occurred with a high variance with an overall standard deviation of 2.6×10^6 particles p m^{-3} ($n = 12$) resulting in 95% confidence intervals of 0.3–4.4 × 10^6 (LID), 1.8–5.0 × 10^6 (SD) and 0.9–2.7 × 10^6 (SDC) and 1.3–7.9 × 10^6 (NON). Direct MP inputs from digestate fertilizers applied between 2018 and 2022 accounted for 0.9% under LID treatment, 3.6% under SD and 4.0% under SDC treatment compared to the total soil MP stocks (Fig. 2b).

Discussion

Microplastics in digestate fertilizer and digestate-treated soils

The investigated fertilizers had MP concentrations (10,600–54,000 p kg^{-1}) within the upper range of reported MP concentrations of digestate fertilizers [20]. Previous studies found a broad range of MP concentrations within digestate or biowaste products, influenced mainly by the initial substrate used for the digestion process [20]. For instance, concentrations ranged from 14 to 146 p kg^{-1} (> 1 mm particles only) within digestate from a biogas plant [27]. In other studies, MP concentration reached 6,000–12,000 p L^{-1} (> 10 µm particles) [21] or 2290–7200 p L^{-1} (> 40 µm particles) [23] and up to 10,000–30,000 p kg^{-1} (> 25 µm particles) in municipal solid wastes [41]. Direct comparisons of those values or data ranges are complicated by the different sampling, sample preparation and analytical methods used as well as size detection limits reported [42]. In general, highly diverse substrates used for biogas production represent the initial source of MP in digestate fertilizers. Substrate mixtures including household waste, green waste or energy crops, can lead to heterogeneous MP loads and properties in digestate products. When considering the differences in waste regulations and digestate treatments [20], a highly diverse MP occurrence in soils can be expected, if digestate fertilizers are subsequent applicated to arable fields. When comparing the different digestate fertilizers investigated, we only found a weak

tendency that MP concentrations were lower in the LID fertilizer. Different digestates have different dry matter contents resulting in different total amounts of digestates applied to reach desired levels for nitrogen fertilization. In that sense, much smaller amounts of LID were applied in terms of dry weights compared to SD and SDC. Thus, the solid digestates contribute more to MP pollution of soils based on their higher application rate.

Compared to the global dataset provided by Koutnik et al. (2021), MP concentrations of our field study are in the upper range of reported MP concentrations for agricultural soils, independent of the fertilizer applied [43]. Digestate-treated soils samples demonstrated higher MP concentrations compared to the average of 2900 p kg^{-1} reported for European soils, but are within the 3rd quartile to maximum values of reported concentrations [18]. Given the high MP concentrations and loads in digestate fertilizers, we identify them as primary carriers of MPs to soils [23], with the sources linked to littering and waste mismanagement upstream in the production chain. Although MP concentrations were high in the digestates themselves, their relatively low application rates as well as the dilution during the incorporation into the soil matrix [44] limited their overall impact on MP stocks in the soil. Although our data supports this argument, direct comparisons in particles per kilogram (p kg^{-1}) are limited due to the process and the inherent heterogeneity of MPs in soils. The soils fertilized with different digestates applied at different total dry weights (DW) and also the control in our study revealed that MP concentrations ranging within previously reported values. However, methodological differences in sampling, sample preparation and sample analysis across different studies make it challenging to directly compare absolute concentrations.

In our study, MP size distributions both in the digestate fertilizers and in soil samples were similar to those reported earlier, showing a trend of increasing particle counts as particle size decreased until the methodological size detection limit is reached [18, 20]. There were no detectable trends between the three digestate types that would allow us to conclude whether digestate processing influences the size of MPs in final fertilizer products. The higher variance of detected MP sizes within digestate fertilizers compared to soil samples could be explained with the overall heterogeneity of MP in digestate substrate source [20]. Slight trends of smaller particle sizes within soil samples compared to digestate fertilizers could be attributed in general to particle break-down during soil cultivation or initial physio-chemical MP ageing processes within the soil environment [45]. However, the different sample preparation methods applied for soil and digestate samples could influence the particle size distribution as smaller MP particles are more easily bound to organic matrices [33] and are therefore more difficult to separate. In the digestate-treated soils studied, smaller MP sizes could be a consequence of ongoing ageing processes for older MPs introduced by non-recent digestate fertiliser sources like sewage sludge fertilizers [46] or others [47].

The dominant polymers PP, PE and PA identified in digestate fertilizers and digestate-treated soil as well as control soil match the polymeric composition reported earlier, despite the general limitation in method comparability [42]. Nevertheless, our investigated digestate fertilizers had a higher share of PU and PA compared to previous fertilizer studies. Those studies highlighted the overall dominance of PE, PP and PS in biogas digestates [20, 21, 41], but also the presence of polyethylene terephthalate (PET) fragments [21] or styrene-based polymers [27]. In the case of household biogenic waste as the main substrate for anaerobic digestion, dominance of just PE and PET was observed [25]. Reasons for those different polymer shares could be found in the different input substrates used in biogas production, but also within the different methods used for sample extraction within this study as well as polymer identification between studies [25], especially when focusing on the polymer reference databases [34].

In summary, we demonstrated an obvious variability in MP loads, MP sizes, and polymeric composition across different digestate fertilisers originating from the same biogas plant. We propose that the digestate production process contributing already to a wide range of MP types and sizes within the original feedstocks based on urban green waste [48] or household organic waste [49]. In the digestate-treated soils, the variability may derive from the general small-scale heterogenic MP distribution in soils [8] or as a consequence of the high variety of feedstock substrate materials used in the biogas plant. In addition, MP often occur in highly heterogeneous distributions within soils, whether in the same sample [42], the same field [50], or under comparable soil management practices [5], which hampers representative sampling and makes comparisons difficult.

Microplastics stocks and sources

Our case study shows that MPs originating from digestate fertilizers only account for a minor fraction of the actual measured MP stocks in fertilized agricultural soils during the experimental period (2018–2023, 5 applications for SD and SDC, 10 applications for LID). This contradicts the findings of previous studies reporting a clear increase of MP concentrations in soils treated with recycling fertilizers. This is the case for source-independent studies [11], as well as source-dependent studies focusing on recycling fertilizers like compost or sewage sludge but also on other sources like plastic mulch film application [15, 19, 51, 52]. Considering recycling fertilizers,

Colombini et al. (2024) reported a clear increase of MP concentrations in soils treated with urban waste compost, in line with the findings of Braun et al. (2023) for compost and Corradini et al. (2019) for sewage sludge treatment. Focusing on long-term MP accumulation Cusworth et al. (2024) reported increasing MP concentration over time in soils treated with non-recycling fertilizers like farmyard manure or inorganic [53]. However, it is important to note that Cusworth et al. (2024) found that MP concentrations increase in higher amounts under fertilizer treatments, compared to unfertilized control soils. The increase in their control soil is comparable to the high MP loads in the control soil in the present study. Despite this finding, above mentioned studies like e.g., Cusworth et al. (2024) or Corradini et al. (2019) do not report or discuss a possible MP baseline concentration or changes within this baseline, except Braun et al. (2023) who state the role of littering as a dominant undefined or diffuse MP source especially for field margins.

Considering our contrary findings with high MP concentrations in the control, the MP presence and properties within the control have to be examined more closely. The clear differences in polymeric composition with an overall dominance of PA in control soil compared to the soils with fertilizer treatment could indicate a baseline concentration of MPs that is independent of the added digestate fertilizers, likely resulting from past cultivation practices. This is also supported by the small contribution of MP from digestate fertilizer to the estimated total MP stocks in soils. Although our extrapolation of MP stocks is limited by the small sample number causing a high uncertainty within a single timepoint measurement, already the expected range of MP stocks in control soil is higher compared to digestate-treated soils. Furthermore, the application of different sample preparation methods for digestate and soil samples within this case study, could lead to an underestimation of actual MP loads in digestates based on interactions between MP and soil organic matter [31, 33].

Possible earlier sources causing a baseline concentration could be sewage sludge application [14], as a major MP input pathway, but prohibited in Switzerland since 2006 [54]. There are no precise records of previous field management, but the current farmer confirmed that sewage sludge from a municipal, non-industrial waste water treatment plant was applied during the 1970s and 1980s. This specific management history combined with the MP particle size distribution, could suggest the legacy of sewage sludge application and long-lasting effects from MP introduced to soils by past pollution sources. Previous use of plasticulture such as plastic mulching or drip-irrigation as well as previous use of digestates can be ruled out. The observed high MP baseline levels may reflect MP inputs from diffuse sources like littering [48], transfer from nearby field sites by tillage movement of soils [50, 55] or wind transport [56] as well as atmospheric deposition [7, 57]. Those diffuse sources could explain baseline MP concentrations along with 'historic' fertilization and the thereby obscured impact of the additional digestate fertilizers as a MP carrier in more recent times.

Conclusion

In this case study the quantity of MPs present in the applied digestates was small compared to the pre-existing baseline MP loads in the soils. Regarding our research questions, we conclude that the concentration and composition of MP in digestate digestate-treated soils seem to be little influenced by the different digestate fertilizers applied, due to high background of MP and therefore contradicting findings in other studies. Furthermore, we conclude that the input of MP with digestate to uncontaminated soils can be substantial but the contribution of digestate fertilizer derived MP during the 5-year fertilization in our case study soils seems obscured through undefined baseline pollution of MPs in soils from diffuse or 'historic' contributions. However, even if the short-term contribution of recycling fertilizers to MP accumulation in soils is low, proactive regulations, such as limiting foreign substances in biogas feedstocks or improving organic waste processing, could help prevent long-term MP stock build-up in arable soils. Further research should also address the so far underrated MP sources of littering and atmospheric MP deposition. In addition, specific site history, including field management, fertilizer use, and crop rotation over time, should be considered to help identify past or historical sources of MP. A more thorough consideration of the temporal dimension, next to spatial scales and distribution, is essential when evaluating MP inputs to soils. After a history of about 70 years of plastic use a serious background of MPs might have developed at several sites and short-term inputs (even if high) might not be most decisive for total MPs stocks. Considering the role of organic fertilizers as MP carriers, it becomes increasingly important to focus on MP loads throughout the full production chain of organic fertilizers. Track (micro-)plastic in- and outputs in soil systems and its contribution to total MP stocks is required.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s43591-025-00136-7.

Supplementary Material 1

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Author contributions
Collin J. Weber: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization. Dominika Kundel: Conceptualization, Methodology, Investigation, Resources, Data Curation, Writing - Review & Editing, Project administration, Funding acquisition. Andreas Fliessbach: Resources, Writing - Review & Editing, Project administration, Funding acquisition. Else K. Bünemann: Resources, Writing - Review & Editing, Project administration, Funding acquisition. Moritz Bigalke: Conceptualization, Methodology, Resources, Writing - Review & Editing, Project administration, Funding acquisition.

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Data availability
The processed data required to reproduce the above findings are available to download from Weber, C.J. (2024): Microplastics in digestate fertilizers and fertilized soil. Figshare dataset. DOI: 10.6084/m9.figshare.27247125.

Declarations

Competing interests
The authors declare no competing interests.

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