

PAPER • OPEN ACCESS

Characterizing the heterogeneity of microplastics in products from the anaerobic digestion of food waste

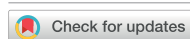
To cite this article: Kristina M Chomiak *et al* 2026 *Environ. Res.: Food Syst.* **3** 035026

View the [article online](#) for updates and enhancements.

You may also like

- [Participatory modelling research to support the validation and co-design of sustainable farming systems](#)
Federico Cainzos Garcia, Natalie Doran-Browne, Karen Michelle Christie-Whitehead et al.
- [Enhancing youth resilience to agri-food system shocks: a pathway to climate justice](#)
Wendy Geza, Tinashe Lindel Dirwai, Nosipho Dlamini et al.
- [Who benefits from sustainable seafood? Examining equity across voluntary sustainability standards in small-scale fisheries](#)
Shreya Yadav, Marah Hardt, Lauren Apollaro et al.

ENVIRONMENTAL RESEARCH FOOD SYSTEMS



PAPER

OPEN ACCESS

RECEIVED

30 January 2026

REVISED

31 July 2026

ACCEPTED FOR PUBLICATION

5 August 2026

PUBLISHED

26 August 2026

Original content from this work may be used under the terms of the [Creative Commons Attribution 4.0 licence](#).

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.



Characterizing the heterogeneity of microplastics in products from the anaerobic digestion of food waste

Kristina M Chomiak¹ , Diana Rodriguez-Alberto¹, Sarah Kakadellis⁴, Nathan C Eddingsaas² , Callie W Babbitt¹ , Edward S Spang⁴ and Anna Christina Tyler^{3,*}

¹ Golisano Institute for Sustainability, Rochester Institute of Technology, Rochester, NY, United States of America

² School of Chemistry and Materials Science, Rochester Institute of Technology, Rochester, NY, United States of America

³ Thomas H. Gosnell School of Life Sciences, Rochester Institute of Technology, Rochester, NY, United States of America

⁴ Department of Food Science and Technology, University of California, Davis, Davis, CA, United States of America

* Author to whom any correspondence should be addressed.

E-mail: actsbi@rit.edu

Keywords: agriculture, anaerobic digestion, microplastic, plastic pollution, food waste

Supplementary material for this article is available [online](#)

Abstract

The food industry consumes more than a third of all plastic packaging, much of which is discarded along with excess and wasted food. As the diversion of food waste (FW) from landfills to more sustainable disposal pathways like anaerobic digestion (AD) increases, food-associated plastics may follow, degrading to form microplastics (MPs) along the way. MPs pose a threat to ecosystems when digestate, the liquid residue of AD, is land-applied as fertilizer or sent to a wastewater treatment plant. To improve understanding of the prevalence, sources, and attributes of MPs associated with AD, we quantified and characterized MPs in liquid digestate from three full-scale digesters that vary in feedstock composition and digester operating conditions. MP abundance ranged from 400 to 25 033 particles L⁻¹ across the three digesters with substantial variation in polymer type, color, and size. Polyethylene terephthalate and polyethylene fragments and films were most common. MP abundance and heterogeneity were higher where facilities accept FW from a greater number of sources. However, there was also variability in MP abundance and composition within each site, related to operational changes or disruptions. We estimated that at typical field spreading rates, approximately 2000–13 200 MP particles m⁻² may enter the environment per application. These results point to a need for improved separation of waste streams prior to AD, especially for facilities that accept organic waste from grocery stores and other post-consumer sources.

1. Introduction

Food waste (FW) is a pressing global environmental, economic, and social challenge. Despite the significant resources committed to cultivate, process, and transport food, FW constitutes 24% and 22% of all landfilled and incinerated materials, respectively (US EPA 2021b), accounting for 6% of greenhouse gas emissions in the United States (Harwood 2023). The cost of FW is \$US 218–444 billion per year (US EPA O 2015, Harwood 2023), posing dilemmas for food insecurity when usable food and the embodied monetary and nutritional value is landfilled. The United States Environmental Protection Agency's Wasted Food Scale recommends a tiered approach to diversion of FW from landfills (US EPA 2023). For unavoidable FW (e.g. spoilage, trimmings, consumer plate waste), anaerobic digestion (AD) is recommended as a valorization strategy because it diverts FW from the landfill, generates biogas, and retains nutrients that can go back into agricultural use.

While AD is often touted as a win-win for FW management, it also has the potential to create unintended consequences. For example, AD generates a nutrient-rich, liquid digestate byproduct, which can, in principle, displace synthetic fertilizer in agricultural applications. However, digestate has a high water content and its resultant high mass and volume limits the distance over which it can economically be transported for land application (Armington *et al* 2026). Digestate can only be applied to bare fields

(Pivato *et al* 2016, Lamolinara *et al* 2022), and its application can lead to nutrient runoff and impact to adjacent waterways (Albuquerque *et al* 2012, Nkoa 2014, Owamah *et al* 2014, US EPA O 2014, Pivato *et al* 2016, Horta and Carneiro 2021, Kovačić *et al* 2022, Lamolinara *et al* 2022, Orner *et al* 2022).

There is also a growing concern that using digestate as a fertilizer may lead to the release of harmful pollutants into agricultural soils. A wide array of contaminants from AD systems have been documented, including plastic (Aspray *et al* 2017, Nghiem *et al* 2017, Smith *et al* 2021, US EPA 2021a, Manu *et al* 2023, Mioduska *et al* 2023), heavy metals (Kupper *et al* 2014, Golovko *et al* 2022, Czatowska *et al* 2025, Liu *et al* 2025), and steroids and antibiotics (Widyasari-Mehta *et al* 2016, Nesse *et al* 2022, Yang *et al* 2022a, Liu *et al* 2025, Ahmed *et al* 2026). If these materials persist during the digestion process and are applied to farm fields along with digestate, the associated risks may erode potential sustainability benefits of FW management by AD. However, the magnitude, composition, and potential risks of such contamination in both FW and the byproducts of valorization remain understudied (Mia and Zzaman 2025).

Of these contaminants, plastic is of particular concern, due to its potential impact in every compartment of the environment (Bank and Hansson 2019, Dybas 2020, Loganathan and Kizhakedathil 2022, Veidis *et al* 2022), contributing to a significant but poorly understood planetary boundary crisis (Villarrubia-Gómez *et al* 2024). Despite the potential risks to ecological and human health posed by mismanaged plastic waste (Landrigan *et al* 2023, Thompson *et al* 2024), plastic is a cornerstone of many industries due to the versatile protection, durability, and low cost that it offers. Globally, 35% of all plastic packaging produced is used by the food industry (Rundh 2005, Chakori *et al* 2021), potentially leading to unintended issues for FW management. Plastics are often commingled with food materials, as in the case of produce stickers and tea bags, and therefore inadvertently enter the FW stream (Nosowitz 2018, Mukesh 2020, Shruti *et al* 2020, Groß *et al* 2024); (Ali *et al* 2023, Xing *et al* 2023, Yousefi *et al* 2024). Other disposable plastics, such as cutlery, hair nets, and gloves, are used during food preparation and service have also been found in FW (Dybka-Śtepien *et al* 2021, Lim *et al* 2018, Müller and Süßbauer 2022, Schwinghammer *et al* 2021, US EPA 2021a).

Some AD facilities use depackaging equipment to remove bulk plastic items, but this mechanical process can break apart larger plastics, forming microplastics (MPs; plastic particles <5 mm) (Alessi *et al* 2020, Do Carmo Precci Lopes *et al* 2019, Hansen *et al* 2007, Hu *et al* 2024). While the full risk of MPs to ecological and human health remains uncertain, studies show that these small particles can accumulate in plants (Giorgetti *et al* 2020, Kalčíková 2020, Schwab *et al* 2020, Liu *et al* 2022, Kallon *et al* 2025) and animal and human tissues (Lavers *et al* 2019, Meaza *et al* 2021, Ragusa *et al* 2021, Li *et al* 2023, Leonard *et al* 2024, Nihart *et al* 2025, Nabi *et al* 2026) leading to documented health impacts (Rivers-Auty *et al* 2023, Schwenger *et al* 2024, De Jersey *et al* 2025). Future initiatives that limit contamination and prevent risks require an understanding of sources, composition, and abundance across different valorization technologies (Alimohammadi and Demirer 2024).

Previous studies evaluating plastic content of organic waste across AD and aerobic compost systems (see table S1), have primarily focused on systems processing wastewater sludge and biosolids feedstocks (Schwinghammer *et al* 2021, Harley-Nyang *et al* 2022, 2023, Yang *et al* 2022b, Naderi Beni *et al* 2023) or from municipal solid waste (Gui *et al* 2021, Van Schothorst *et al* 2021, Sholokhova *et al* 2022, Surendran *et al* 2024), and show a wide range of values, which appear to be associated with feedstocks and operating conditions (Braun *et al* 2021, Harley-Nyang *et al* 2022). While MSW contains FW, proportions vary, limiting our ability to link releases back to specific FW sources. However, comparisons of MP concentration in digestate under low and high FW feedstock scenarios show up to 29 times more plastic in high FW scenarios compared to low FW scenarios (O'Brien 2019, Schwinghammer *et al* 2021). However, detailed information about material composition, morphology, or size is not always provided, and results are often from a single point in time (O'Brien 2019, Ruggero *et al* 2021, Schwinghammer *et al* 2021, Sholokhova *et al* 2022, Steiner *et al* 2022). A recent study comprehensively documenting MP contamination in digestate, manure, and a storage lagoon over time from a single co-digester facility, shows that MP contamination in digestate is substantial, derives largely from the FW feedstock, and that abundance and composition are often influenced by the operational settings of the digester (Whitney *et al* 2025). Whitney *et al* (2025) also present a method for more reliable analysis of MPs from organic matrices that are notoriously difficult to process. However, because the methods and units used to quantify plastic contamination vary widely (table S1), comparison across different waste streams and facilities, and straightforward identification of important sources is limited.

Understanding the extent, drivers, and fate of contamination in digestate is further complicated by inherent variation among AD facilities, with differences not only in feedstock choices and ratios, but in pre-processing steps, operating temperatures, number of stages, and end-uses of liquid digestate (Huerta Lwanga *et al* 2017, Crossman *et al* 2020, Kawecki *et al* 2021, Colombini *et al* 2022,

Table 1. Characteristics of anaerobic digesters, including the temperature and number of stages in each system, ratio of manure to food waste, types of food waste feedstock generally accepted (as a ratio of manure: FW), whether the site utilized a depackager to separate organic waste from inorganic waste prior to entering the AD system, and end-uses of the liquid digestate byproduct. WWTP = waste water treatment plant.

Site ID	Digester type	Feedstock ratio	Use of a depackager	Waste sources	End-uses of digestate
Site 1	One-stage mesophilic	30:70	Yes	Manure, pet food, produce, beverages	Field spread
Site 2	One-stage mesophilic	25:75	No	Dairy waste, manure, fats, oils, grease	Field spread
Site 3—Tank 1 and Tank 2	Multi-stage thermophilic (two tanked)	0:100	Yes	Campus dining waste, grocer waste, community FW, waste disposal company	Solids used for animal feed; liquid stripped of ammonia for fertilizer and residual sent to WWTP

Cydzik-Kwiatkowska *et al* 2022, Baldasso *et al* 2023, Öling-Wärnå *et al* 2023). This variation may be further driven by a patchwork of FW diversion policies in some states in the U.S. (Ryen and Babbitt 2022), which will likely increase demand for AD and other treatment facilities and thereby increase the likelihood of downstream MP release. For example, California Senate Bill 1383 aims for a 75% reduction in landfilled organic waste statewide by 2025 (Lara 2016), and New York has begun requiring many businesses and institutions to send FW to an organics recycler within a 25 mile radius (NY State Senate 2019). At the same time, in some locations, contamination threshold policies have been set to improve the quality of organic waste streams. For example, in New York State, compost products may not contain more than 0.5% physical contaminants greater than 4 mm by weight, with no more than 20% plastic film (New York State 2023). Because contaminant load is typically regulated on a percent by weight basis, ranging from 0.1% to 5%, and/or size (Afnor 2006, Standards Australia 2012, Gilbert and Ricci-Jurgensen 2023, Wilson *et al* 2024), lightweight materials like plastic (Nisticò 2020) and MP particles escape these thresholds.

Enhanced understanding of the coupled nature of plastic and FW, including the potential sources and mechanisms driving microplastic abundance and composition within FW valorization technologies will be key in developing sustainable solutions that minimize contamination to liquid digestate. This work addresses these gaps in the literature by conducting an analysis of MP contamination in digestate from three digester facilities that all accept FW, but vary across other key characteristics, including the nature of FW feedstocks, operational attributes, and regional location. Assessing samples from this range of sources using a single method (Whitney *et al* 2025) allows for a better understanding of the realistic variability of plastic contamination in AD. In sum, this work provides a more detailed and nuanced picture of the complex relationship between FW and plastic pollution, serving to document the most pervasive types, sizes, and morphologies of plastic within the FW stream that persist through the AD process and may pose the greatest downstream risks to ecosystem and public health.

2. Methods

2.1. Site descriptions

We obtained samples in triplicate at three to four sampling times from three digester facilities between April 2023 and February 2025. Two sites (Sites 1 and 2) were one-stage mesophilic (35 °C–39 °C) dairy manure and FW co-digesters that varied in the ratio of manure to FW used as feedstock. The third facility) was a multi-stage thermophilic (50 °C–60 °C) digester exclusively processing FW. During the transfer between Tank 1 and Tank 2 at Site 3, solids are removed using a screw press and all residual liquid continues to Tank 2. Details about each site are in table 1. To maintain privacy, names and identifying information for each of the partnering facilities are withheld. Site 3 was processing a suite of FW feedstock during sample collection in May 2023 and January 2024. Following a disruption to the microbial system in 2024, feedstock was limited to primarily fats, oils, and greases (FOGs) while the system recovered. Impacts of this shift in feedstock inputs and sources on MP abundances are captured in results presented here as July 2024 and February 2025 sampling dates coincided with system recovery.

2.2. Quality assurance & quality control

All reagents and rinse water were prepared with deionized water that had been vacuum filtered through 47 mm diameter 8.0 µm mixed cellulose ester (MCE) filters to remove potential contaminants from

the water system (referred to hereafter as MP-free water). All field and laboratory equipment was glass or metal to minimize contamination from plastic particles shedding during use and was triple-rinsed with MP-free water prior to each use and in between samples. All equipment and samples were capped or covered tightly with aluminum foil when not in active use to prevent contamination from the surrounding air. To minimize textile contamination from clothing, pink cotton lab coats and distinct purple nitrile gloves were worn during all steps of analysis. The known materials and distinct coloration make any nitrile or cotton particles in samples easily identifiable and therefore excluded from reported numbers. Clothing worn in the laboratory under lab coats and in the field was noted on data sheets. Field blanks followed concurrent and identical extraction, identification, and validation procedures with their corresponding digestate samples to capture procedural contamination across the full field and laboratory pipeline.

2.3. Sample collection & preparation

At each site, an 11 l metal bucket was placed under the outlet of the digester and filled approximately three-quarters with digestate. A metal ladle was used to homogenize the sample and transfer roughly 750 ml into three clean 1 l glass Mason jars, which were then secured with airtight lids. Whole digestate was collected; we did not separate liquid and solid fractions prior to analysis. We acknowledge that these samples are not true time-point replicates, given the single original source, but instead give an idea of intra-sample variability. To account for potential atmospheric contamination or particles in the jars, each set of three samples was accompanied by a blank to account for procedural contamination across the entire sample collection and processing pipeline. A fourth Mason jar that served as a blank was uncapped and placed in close proximity to the collection location at the start of sampling, then re-capped after all samples were fully collected and sealed. Blanks were collected for each sampling time point at Sites 2 and 3. When possible, samples were driven directly to the lab following sampling. For more remote sites, samples were shipped overnight using ice packs. All samples were stored at 4 °C in the lab until extraction procedures.

2.4. Microplastic extraction & validation

Microplastic particles were extracted from the digestate samples and the accompanying field blanks using a series of oxidation, and filtration steps as described in Whitney *et al* (2025). This method has a 96% recovery rate with negligible impact to a suite of plastics, as demonstrated by spike and recovery testing (Whitney *et al* 2025). Samples were homogenized using a clean glass rod and three 30 ml subsamples were extracted and added to a 1 L Erlenmeyer flask. Organic matter was oxidized by addition of 30% hydrogen peroxide. The flask was initially placed in an ice bath to prevent bubbling over, and then moved to a 40 °C water bath. Aliquots of hydrogen peroxide were added daily until all bubbling ceased upon addition and the sample was clear. The sample was then filtered through a 25 μm stainless steel sieve, triple rinsing the flask into the sieve with MP-free water. The sample was rinsed from the sieve back into the flask and residual solids, determined to be calcium stearate (Whitney *et al* 2025), were removed by addition of 150 ml of 0.1 M EDTA (Sigma Aldrich, ACS reagent grade)/Triton X-100 (Sigma Aldrich, reagent grade); adjusted to a pH of 9 using sodium hydroxide solution, and placed back in the 40 °C water bath overnight. Once fully clear, contents of the beaker were vacuum filtered onto a 47 mm 8.0 μm MCE filter with 3 mm black gridlines and fastened to a glass petri dish with double-sided tape for optical analysis.

The entirety of the gridded filter was visually inspected for potential MPs under an AmScope stereo microscope with ZM-4T optics and a 20 MP CMOS back illuminated camera (MU2003-BI) following a serpentine pattern. Inspection was first done under white light, and then using a 365 nm black light to uncover particles difficult to detect under white light, but fluoresced under black light. Suspected MPs were counted and classified by color, morphology, and size fraction (50–125 μm , 125–300 μm , 300–1000 μm , and 1000 + μm). Basic morphological categories included fibers, spheres, and fragments, with subsetting of fragments into hard fragments (here as ‘fragments’), films, and foams as defined in (Lusher *et al* 2020). Subsetting standards were aligned with the literature (Munno *et al* 2023, Rathore *et al* 2023) by setting specific requirements and cutoffs for particle verification. For particles of the same morphology and color with abundance less than 10, all particles were selected for FTIR validation. For particle types with abundance greater than 10, we validated ~15%–20% of suspected MP.

MPs selected for validation were carefully picked from the filter using clean needle-point metal tweezers and transferred to a glass microscope slide covered in a metal foil tape. To ensure the particles adhere to the slide, a thin layer of a translucent polymer-free liquid adhesive (Torbot Liquid Skin-Tac Liquid Adhesive; Torbot Group; Cranston, RI, USA) was applied. Fourier-transform infrared spectroscopy (FTIR; Shimadzu AIM 9000 with MCT detector equipped with micro-attenuated total internal

reflection (ATR) attachment) was used to confirm polymer identity (Brandt *et al* 2021) by comparing obtained particle spectra to spectral libraries of known materials supplied by the instrument manufacturer alongside a custom MP database established by our lab (Primpke *et al* 2018, Whitney *et al* 2025). Both reflectance and micro-ATR were utilized, depending on which method provided the clearest spectra. The software used provides a match score from 0 to 1000; values below 700 are typically regarded as unreliable matches, and were not considered. Given that match scores alone are not a perfect form of identification given variability in spectra within the same polymer types (Clough *et al* 2024, Parham *et al* 2026), especially when using reflectance IR spectroscopy, we further validated spectra with match scores >700 by overlaying the library match spectra with the sample spectra of the particle and visually confirming agreement with key spectral features. Typically a lower score was due to additional features, often in the O–H stretch region due to aging or contamination. Following validation, a polymer-validation correction factor was developed for each polymer/morphology type for each sample, serving as a confirmation rate to exclude false positives in data analysis. The confirmation rate ranged between 81% and 100% for individual samples, with an overall average confirmation rate of 96% across all samples. Particles observed in samples and blanks that were attributed to known contamination sources (e.g. pink cotton fibers from lab coats) were not included as potential MPs when seen in digestate samples and are not factored into the confirmation rate. The number of confirmed plastic particles in our blanks was very low (0–7 particles; table S2) relative to the number in each individual 30 ml sample (42–791 particles). For example, in the May 2023 sample from Site 3, there were 297 ± 57 blue PE fragments in the 30 ml digestate samples. The associated blank contained three blue PE fragments—the highest number of any one particle type found in any blank—which is approximately 1% of the total. Because the number of particles in each blank was consistently lower than the standard deviation of replicate samples at each time point, we did not do a blank correction.

2.5. Data processing & analysis

All data were analyzed in JMP Pro 18 and RStudio (Posit Software 2025). Within RStudio, the *vegan* (Oksanen *et al* 2025), *ggplot2* (Wickham 2016), and *tidyverse* (Wickham *et al* 2019) packages were used. After log-transforming MP abundance data to meet the assumptions required for analysis of variance (ANOVA), we analyzed the differences among sites using a one-way ANOVA across all dates; a two-way analysis was not done because of the differences in timing of sampling at individual sites. We treated the two sampling locations at Site 3 (Tank 1 and 2) as unique in this comparison because they represent different types of digestate products and, at two time points, were sampled separately. Within each site, we acknowledge that all three samples originated from a single source and point in time. As a result, reported variation at each sampling time point represents within-time point variation to assess measurement error, but is not included as a true biological replicate. For ANOVA, the three replicates from each site and time point were averaged so that *n* is equal to the number of time points. To examine the association between site and MP characteristics (morphology, color, size, polymer type), a Chi-square test of independence was performed on each variable separately. A contingency table was created and the Pearson Chi-square statistic was calculated. The significance level was set at $\alpha = 0.05$. Nonmetric multidimensional scaling (NMDS) analyses were performed in R (*vegan*, Oksanen *et al* 2025) to further evaluate variation in the morphology and polymer compositions across the different sites. These plots were based on Bray–Curtis dissimilarities, resulting in two-dimensional ordination plots. The ‘stat_ellipse’ function was used, and set at a level of 0.95, to generate 95% confidence interval ellipses in the visual output. All individual replicates were retained for Chi-square and NMDS analyses.

3. Results

3.1. MP abundance across digesters

All digestate samples contained MPs, with notable variation in abundance among and within sites across different sampling periods (figure 1; figure 2). MP abundance across all sites ranged from 400 to 25 033 particles L^{-1} . While the high variability in abundance of MP in digestate from Tank 1 at Site 3 (range 2667–25 033 particles L^{-1}) led to no significant differences among sites, this location consistently contained 2–4-fold higher MP abundance than the other sites (mean MP abundance of $12\,194 \pm 2782$ particles L^{-1} [mean $\pm$ standard error]; $F = 2.2$; $df = 3$; $p = 0.15$). Tank 2 at Site 3 was significantly lower than that of Tank 1 (3857 ± 941 ; range 900–6633 particles L^{-1}), as were digestates from Sites 1 and 2 with mean values of 3662 ± 527 particles L^{-1} (range: 1900–5067 particles L^{-1}) and 3265 ± 493 particles L^{-1} (mean $\pm$ standard error; range: 1000–5213 particles L^{-1}), respectively.

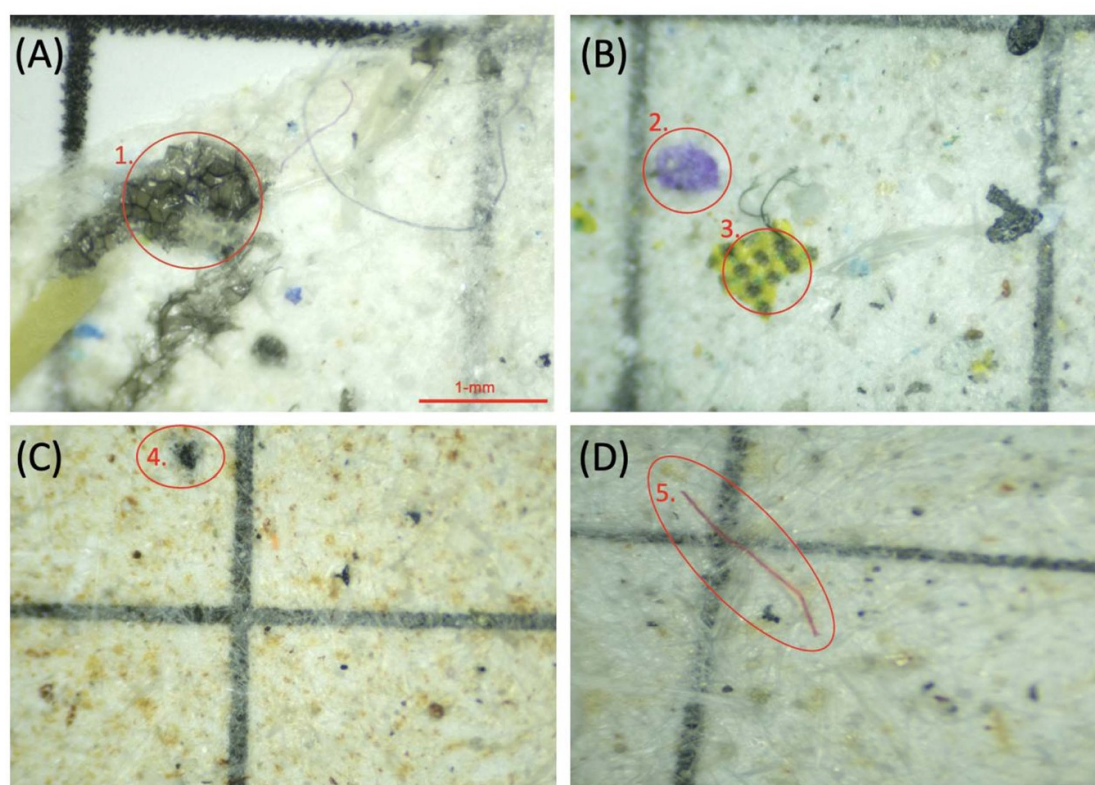


Figure 1. Optical images of MPs found in samples from Site 3 (images (A) and (B)), and Site 2 (images (C) and (D)). 1. Black EPS foam, 2. Purple PHA film, 3. Multicolored PET film, 4. Black PE fragment, 5. Red PET fiber. A 1 mm scale bar is featured in the bottom right of panel A as a reference for actual particle size.

Within sites, MP abundance fluctuated between sampling periods in both Tank 1 and Tank 2 at Site 3, and Site 2, but was more consistent at Site 1. The decrease in MP abundance at Site 3 between July 2024 and February 2025 coincided with a shift in feedstock. Site 2 also demonstrated variations in MP abundance across the study period, with samples collected in April 2023 similar to all other time points, while MP abundance in December 2024 samples was lower than both May and September 2024.

3.2. MP composition

While the morphology and polymer composition of microplastic particles varied among and within sites, fragments were the most common morphology, comprising more than 50% of MPs. Films and fibers were also frequently found, though in lower quantities. There were site-specific patterns as well (figure 3(A); table S3; figure S1, $X^2 = 559.2$, $df = 4$, $N = 5771$, $p = <0.0001$), with more fibers at Site 2 ($>20\%$ of total MP), and substantially more foams at Site 3 than other sites. The differences among morphological profiles is demonstrated clearly in the NMDS plot (figure 4(A)), with very tight clustering at Site 3, and a much broader distribution at the other sites. The stress value of 0.113 supports an acceptable fit of the ordination plot. The 50–125 μm size fraction was more than 60% of the total MPs at every digester, with the greatest amount of larger particles at Site 3 Tank 1 (figure 3(C); table S4; figure S2, $X^2 = 35.2$, $df = 3$, $N = 6158$, $p = <0.0001$). There was a shift in particle distribution between Tank 1 and Tank 2 at Site 3, with smaller particles in Tank 2.

Despite general similarities in size and morphology among sites, there were site-specific MP color patterns. Most MPs were either black or blue, but at Site 2, 77% of MPs were black, respectively, while blue particles made up 46% and 64% of MPs found in Tank 1 and Tank 2 of the Site 3 digester, respectively (table S5; figure S3, $X^2 = 1542$, $df = 12$, $N = 6259$, $p = <0.0001$). We also saw a wider array of colors at Sites 1 and 3 compared to Site 2 (figure 1); finding more clear, multicolored and purple particles that made up to 6% of the particles found at these sites, while these colors represented less than 1% at Site 2.

Polyethylene terephthalate (PET) and both high-density and low-density forms of polyethylene (PE) were the most abundant polymers across all samples (figure S4; table S6, $X^2 = 2324$, $df = 14$, $N = 5669$, $p = <0.0001$), followed by bioplastics in the form of polybutylene adipate terephthalate (PBAT) polyhydroxyalkanoates (PHA), and other petroleum based polymers including polystyrene (PS)

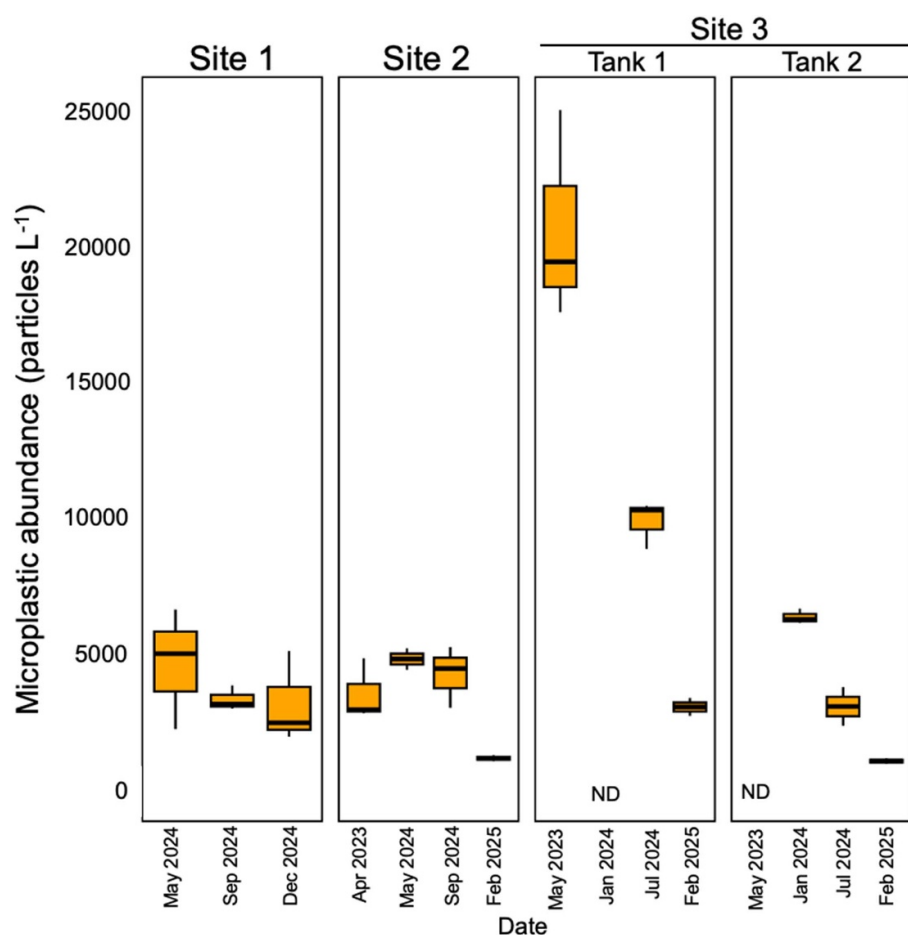


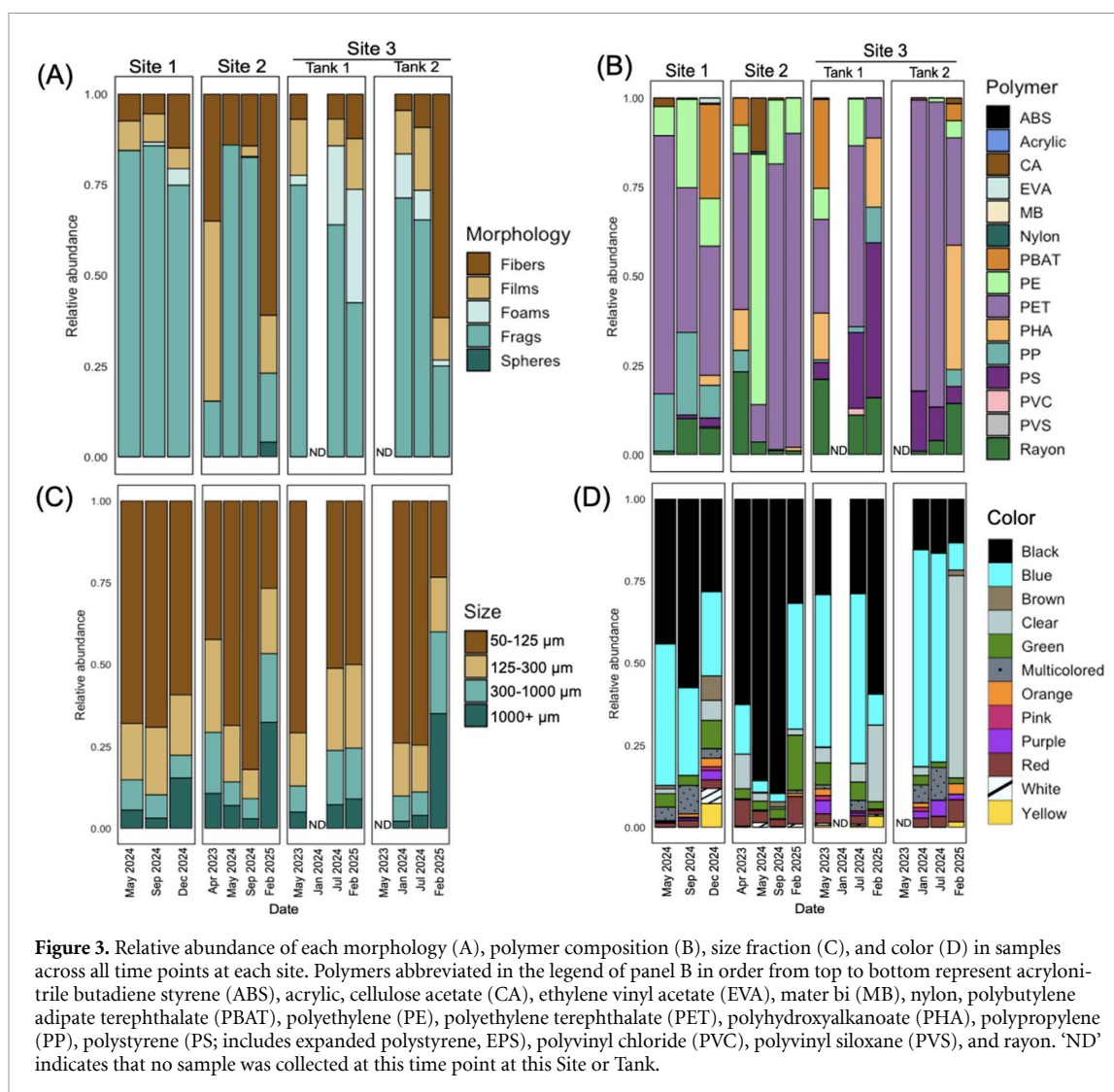
Figure 2. Microplastic abundance in particles L^{-1} at each site across all time points assessed. Values reflect mean $\pm$ SE, $n = 3$ per time point. Time points with 'ND' reflect 'no data' when samples could not be collected at the denoted location at the respective time point.

and polypropylene (PP). Notable amounts of rayon, a semi-synthetic polymer, were also found in all samples evaluated. The dominance of PET and PE is further showcased in the NMDS, where the overlap of ellipses show polymeric similarity across samples (figure 4(B); stress value = 0.176). Sites 1 and 3 featured the largest range of polymer types, including materials like polyvinyl-chloride (PVC), acrylonitrile butadiene styrene (ABS), and ethylene-vinyl acetate (EVA) that were not observed in other samples.

4. Discussion

While variable across sites and time, we found microplastic in all digestate samples analyzed. The lack of standardization across reporting units makes it difficult to directly compare MP abundance among studies (Leusch and Ziajahromi 2021). However, our range (400–25 033 particles L^{-1}) overlaps with Whitney *et al* (2025) who reported 261–1536 particles L^{-1} in a single co-digester, but extends higher at Site 3, likely due to diverse feedstocks. Our results also align with studies evaluating MPs in composts (Gui *et al* 2021, Porterfield *et al* 2023a), organic wastes (Weithmann *et al* 2018, Edo *et al* 2022, Sholokhova *et al* 2022, Tan *et al* 2022, Porterfield *et al* 2023a), and other digestates (Nghiem *et al* 2017, Yang *et al* 2022b, Porterfield *et al* 2023a, Whitney *et al* 2025, Lessa Belone *et al* 2025). The somewhat higher MP concentration with increasing amount of FW in the feedstock also agrees with prior studies (O'Brien 2019, Braun *et al* 2021, O'Connor *et al* 2022, Surendran *et al* 2024, Xu *et al* 2024, Whitney *et al* 2025, Lessa Belone *et al* 2025), demonstrating MP contamination as a significant barrier to FW valorization. We further observed differences in the characteristics of MPs found in the different digestates that suggest contamination is likely site-specific and dependent on waste sources and digester management that may change over time.

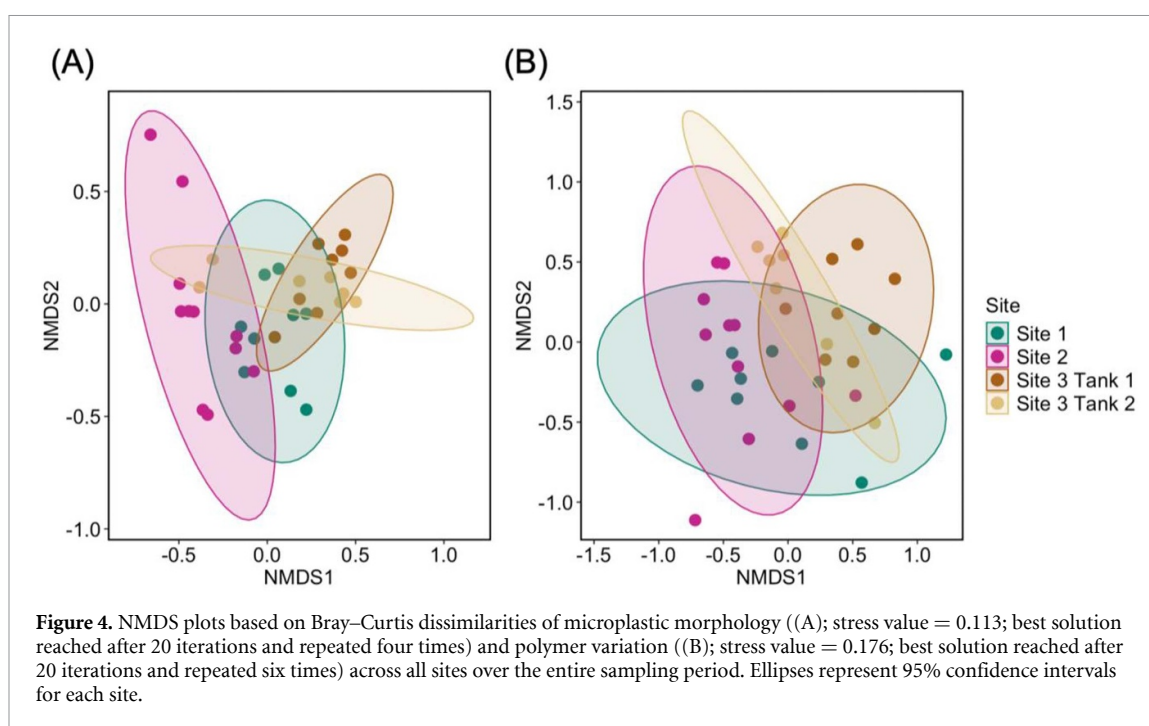
Because MPs are a diverse suite of potential contaminants derived from a multitude of sources (Rochman *et al* 2019), understanding the characteristics of MPs is important for mitigation of upstream



sources and for prediction of downstream risk. While the polymeric profile of Site 2 remained generally consistent, the morphological profile fluctuated the most out of the three sites (figure 3(A)), featuring the most fibers relative to the total MPs at any site. While we did not trace sources of the fibers observed in our samples, microfibers are of great concern as the most prevalent form of MP found in the natural environment (Mishra and Das 2023). The small cylindrical shape makes them easily released via wastewater effluent (Mason *et al* 2016, Sun *et al* 2019, Ramasamy *et al* 2022) and laundry (Napper and Thompson 2016), and may be transported across great distances in the environment (Xiao *et al* 2023). Microfibers, specifically, have shown extensive negative impacts to wildlife (Yadav *et al* 2024), water quality (Huang *et al* 2021, Silva *et al* 2022, Chomiak *et al* 2023, 2024), and human health (Schirizzi *et al* 2017, Periyasamy 2023), and the presence in digestate identifies another potential source of microfiber release to the environment. Despite featuring a wide range of polymer types, the morphological profile at the Site 1 remained consistent over time (figure 3(A)), dominated by fragments and films. These observations are also corroborated by the NMDS where the widespread clustering of points for Site 2 in the morphology NMDS (figure 4(A)) and the wider clustering of points for the Site 1 site in the polymer NMDS (figure 4(B)). These patterns are useful clues to the potential sources and impacts of MPs in digestate.

4.1. Potential sources of MPs

Sources of the MPs found here are most likely a combination of MPs directly traveling with FW, on-farm/facility sources (Sintim *et al* 2020, Khalid *et al* 2022, Briassoulis 2023), airborne sources (Peñalver *et al* 2021, Chen *et al* 2024), secondary MPs produced as feedstock goes through the depackagers (Yang *et al* 2022b, Hu *et al* 2024, Porterfield *et al* 2023b, Beigmohammadi *et al* 2025) and as larger pieces are transformed in the digester (Luo *et al* 2020, Whitney 2024). It is also possible that indirect sources of



MPs are entering digesters with FW by how feedstock is delivered to facilities. Films and other packaging materials used to stabilize FW feedstocks as it is transported may be a source of contamination, though comprehensively disentangling these direct and indirect sources is challenging.

PET and PE were the most observed materials across all samples, and may be derived from a variety of sources due to their wide array of uses and long-term status as two of the most commonly produced plastic materials globally (Plastics Europe 2022, Hardin 2021) are among the most common plastics used as food packaging (Welle 2011, Nisticò 2020, Soong *et al* 2022) and found in post-consumer organic waste (Park *et al* 2026). The widest variety of PET and PE items in terms of color, size, and morphology were observed at Site 3, which processes the most diverse FW stream, including community, grocery, and campus dining waste, and is the only site that includes post-consumer waste. The array of colors and morphologies may derive from a variety of consumer packaging. For example, some MPs at this site had visible printing on them (see figure 1(B)), suggesting brightly colored wrappers or labels. Here, Tank 1 had more plastic than the Tank 2 at each sampling point, suggesting that a notable portion of the microplastic gets removed with the organic solids before continuing digestion in Tank 2. There is also a minor shift in MP composition at this site, with an increase in the relative proportions of PS and smaller particles between Tank 1 and Tank 2.

The presence of measurable quantities of bioplastic particles, including PBAT and PHA, suggests that these plastics do not fully degrade during AD. This is consistent with experimental studies that report both low degradability and insignificant impacts on methane production when bioplastics are incubated under typical digester conditions (Battista *et al* 2021, Álvarez-Méndez *et al* 2023). Our methods were insufficient to assess whether these materials were changed from their original form and had degraded more than conventional plastics, but this result confirms other studies that suggest that bioplastics are not biodegradable under AD conditions.

Aside from PET and PE, we observed notable quantities of PS and EPS films and foams across samples. While PS can be seen on farms, it appears more often as high impact PS for nursery containers (Malarkey and Babbitt 2025), whereas we observed softer foams and thin films (figure 1(A)) more suggestive of food packaging sources. These black EPS foams (figure 1(A)) and PS films were observed in the largest quantities at the Sites 1 and 3, and may originate from food packing trays, shrink wrap, or other wrappers (Kedzierski *et al* 2020, Sobhani *et al* 2020, Jadhav *et al* 2021, Wang *et al* 2023). While many states have enacted bans on the use of EPS for food packaging, waivers may exist for certain products, including raw meat and seafood (see, for example, (NYS Senate 2022)) and these materials are still part of the waste stream in some cases both for food-contact packaging and also in other forms associated with transport. Many of the EPS foams identified were in the larger size fractions (300–1000 +

μm), corroborating that they likely originate from larger items that may be more resistant to degradation (Ghoshal *et al* 2023, Beigmohammadi *et al* 2025) in both the thermophilic and mesophilic digester conditions evaluated.

4.2. Role of feedstock sourcing, co-digestion ratios, and depackagers as sources of variation

While the first tank at Site 3 site had higher concentrations of MPs than all other sites, these three digesters utilizing FW as feedstock at different ratios did not significantly differ from one another. MP concentrations in manure are typically less than in digestate (Whitney *et al* 2025), where the manure added to feedstocks in co-digesters may have a diluting effect on MP concentrations. Waste sources vary across all the sites, and may even vary within sites at times, depending on what is in the processing queue. While Sites 1 and 2 process FW at similar ratios, the sources from which they are obtained differ. Abundance and characteristics at Site 2, where primarily industrial FOGs are accepted, remained fairly consistent over the duration of the study, while there was a greater variety of MPs at Site 1, which processes a mix of dairy, pet food, and pre-consumer items like produce and beverages. Similarly, the depackager used at some sites may be further contributing to the high total of MPs found (Porterfield *et al* 2023b, Hu *et al* 2024, Beigmohammadi *et al* 2025). There is thus a need for a more comprehensive approach to unavoidable FW that takes into account end-of-life and prevention of plastic contamination of organic waste streams (Urugo *et al* 2024).

4.3. Digestate as a vector for release of MPs to the environment

AD with beneficial use of digestate is considered a more environmentally beneficial FW solution than landfilling (US EPA 2023), and many AD facilities, including two represented here, use digestate as a soil amendment. If digestate containing a mean MP abundance of 3444 particles L^{-1} (± 1582 particles L^{-1} ; global mean $\pm$ SD of Sites 1 and 2, where land-application is the current use; range = 1000–6600 particles L^{-1}) were to be land applied at a standard application rate of 20 $\text{m}^3 \text{ha}^{-1}$ (Korba *et al* 2024), the resulting emission of MPs to land may exceed 68 million particles ha^{-1} (or approximately 1 particle per cm^2), although there is great variability across sites and times (min = 20 million particles ha^{-1} ; max = 132 million particles ha^{-1}). Thus, the environmental benefits of landfill diversion may be offset if land application of digestate leads to release of MPs to the environment and downstream ecological impacts (Crossman *et al* 2020, Braun *et al* 2021, Golwala *et al* 2021, Colombini *et al* 2022, Liu *et al* 2023, Öling-Wärnå *et al* 2023, Rana *et al* 2023). While the fate and impact of particles released from the land application of digestate is not fully understood, literature suggests long-term accumulation in agricultural soils (De Souza Machado *et al* 2018, Kim *et al* 2021, Schöpfer *et al* 2022, Cydzik-Kwiatkowska *et al* 2022, Heinze *et al* 2024) and that plastics may be taken up by crops with implications for food safety and consumption by higher trophic levels (Huerta Lwanga *et al* 2017, Lozano *et al* 2021, Du *et al* 2025, Kallon *et al* 2025, Srećkov *et al* 2025). Plastics hitchhiking with land-applied digestate may also continue their travels with stormwater runoff (Naderi Beni *et al* 2023, Armitage and Rohais 2025, Severe *et al* 2025), depositing in nearby waterways and impacting water quality (Nava and Leoni 2021, Chomiak *et al* 2023, 2024, Marchant *et al* 2023). Liquid digestates that are not land applied are often treated by wastewater treatment plants (WWTP), as in the case of Site 3. Wastewater effluent is a known conduit of MPs to waterways (Mason *et al* 2016, Dyachenko *et al* 2017, Cavazzoli *et al* 2025, Shi *et al* 2025), highlighting that this disposal scenario is also problematic. Additional detailed investigations into transport of MPs to the environment via digestate is warranted to better understand the full impact of plastic across the life cycle of FW and to develop sustainable solutions to minimize potential environmental harm.

4.4. Limitations and challenges

MPs are notoriously difficult to measure because of their small size, diverse composition, and lack of standardized methods (e.g. (Méndez Rodríguez *et al* 2023)). The significant variation in methods among studies that have evaluated MPs in AD and other organic matrices substantially limits the ability to compare among studies (table S1; Leusch and Ziajahromi 2021, Munno *et al* 2023, Porterfield *et al* 2023a). One persistent obstacle is that while MP count per weight is commonly used (Weithmann *et al* 2018, Schwinghammer *et al* 2021, Ruggero *et al* 2021), some studies use weight per weight (Müller *et al* 2020, Braun *et al* 2021) or mass per volume (Xu *et al* 2023, Zuri *et al* 2025). In our case, we report results in MP count per volume because volumetric assessments are typically used when making decisions about digestate management and field spreading.

Further, recent work suggests the potential risks associated with much smaller particles (Cunningham *et al* 2023), which may exist in quantities that are orders of magnitude greater than those measured here (Egoshi *et al* 2026, Segur *et al* 2026). Our methods limit the ability to measure and report MPs $< 50 \mu\text{m}$. As such, our values are likely a significant underestimate of the total plastic particle load when the very

smallest particles are considered. Further, we did not do a mass-based MP quantification, which may be needed in the future for complete assessment of potential risk (Mei *et al* 2026). Given these uncertainties, and the potential harm associated with nano-scale plastic particles, policies that limit plastic contamination based on mass may not be appropriate.

A further widespread limitation to microplastic research is ensuring that the materials of a representative number of particles have been validated. As confirming every potential polymer is a laborious and time intensive process, studies have utilized subsampling methods, including analysis of 10%–20% of the final filter post-digestion, or randomly selecting particles for validation. However, recent literature points out that many of these subsampling methods may skew results, leading to an incomplete picture of MP presence. MPs may not be equally distributed across filters, and random selection may underrepresent some materials while overrepresenting others (Mintenig *et al* 2017, Leusch and Ziajahromi 2021, Munno *et al* 2023, Rathore *et al* 2023). The implementation here of a strategic subsetting plan driven by the characteristics of suspected MPs, as suggested by the literature (Munno *et al* 2023), allowed for comprehensive material validation while minimizing time and resources spent. However, as with all MP research, we acknowledge the margin of error and challenges for intercomparisons.

Limited insight into detailed operational information at private facilities like those studied here inhibit the ability to trace MPs back to their definitive sources, however, the collaboration with multiple facilities better unravels pervasive sources of MPs found broadly across the FW stream. Greater insight into how MPs move and transform during AD may aid in fully understanding the extent of contamination in these systems. We collected samples solely from the bottom outlet of each digester, and while we found a mix of positively buoyant (e.g. PE, PP) and negatively buoyant (e.g. PET, PVC) materials, sampling one outlet may only represent MPs near that outlet at the time of sampling. The consistent agitation and mixing of material in AD systems may continuously resuspend plastic and ensure a homogenized sample, however, concurrent samples from the top and bottom of digesters can more accurately confirm the distribution of MPs within the system. Additionally, a longer-term study spanning multiple years with additional tracking of specific feedstocks may allow for enhanced understanding of residence time and degradation of particles in AD systems.

5. Conclusions

The work presented here contributes to the growing body of knowledge of plastic pollution in the FW stream. Results of this study demonstrate MP contamination as a significant barrier to sustainable FW management, finding MPs in all digestate samples analyzed up to 25 000 particles per liter. This work also demonstrates that MP contamination to digestate is largely driven by waste sources, with the largest amounts of MPs found at the digester processing the most diverse FW sources, including post-consumer waste. Changes in MP abundance were seen when waste sources changed to maintain digester stability over the course of the study, though these stochastic events warrant longer-term study to elucidate how specific management strategies impact MP abundance. The difference between Tank 1 and Tank 2 at the same facility demonstrates that removal of solids may decrease the MP load in the liquid fraction of the digestate.

When land-applied as a soil amendment, digestate may release a significant amount of MPs to the environment. Further research into the fate, degradation, and impacts of these released particles is needed to fully understand the ecological risks posed by plastics travelling alongside FW. As the diversion of FW from landfills increases globally, addressing contamination as a barrier to diversion efforts is more necessary than ever. Without upstream interventions (e.g. source separation, alternative packaging, improved depackaging), AD of FW may inadvertently become a major pathway for MPs to agricultural soils. There is room for improvement all along the FW stream, starting at the source, with strategic interventions needed especially for streams that include grocery store and post-consumer waste. Reducing FW in the first place is the most effective minimization strategy; however, there are a number of actions that may be effective over both short- and long-term time frames. Interventions that may be rapidly implemented include improved source separation and depackager maintenance through operator training. Interventions that may require long-term infrastructure change, but will yield more substantial MP reduction include implementing plastic alternatives in food packaging design, prohibiting the use of plastic in packaging and food service items, requiring that all food-contact packaging accepted at AD facilities be certified biodegradable under anaerobic conditions, and improved depackager efficiencies. Together, these shifts will reduce potential hazards posed by plastic hitchhiking in FW.

Acknowledgments

This material is based upon work supported by the National Science Foundation under Award 2115405. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. The authors gratefully acknowledge and thank the operators at our partnering facilities, Abbey Whitney, and RIT's Collaborative for Plastic and the Environment and the RECIPES Valorization Cluster for feedback on experimental design and interpretation of results.

Data availability statement

The data that support the findings of this study will be openly available after acceptance (but before publication) at the following URL/DOI: <https://figshare.com/s/f9cc3c907edaac35469c>.

Supplementary data 1 available at: <https://doi.org/10.1088/2976-601X/ae9555/data1>.

Conflict of interest

There are no conflicts of interest for any of the authors.

Author contributions

Kristina M Chomiak  0009-0002-8928-7134

Conceptualization (equal), Data curation (equal), Formal analysis (equal), Investigation (lead), Methodology (lead), Visualization (lead), Writing – original draft (lead), Writing – review & editing (equal)

Diana Rodriguez-Alberto

Conceptualization (supporting), Investigation (supporting), Methodology (supporting), Writing – review & editing (supporting)

Sarah Kakadellis

Conceptualization (supporting), Investigation (supporting), Methodology (supporting), Writing – review & editing (supporting)

Nathan C Eddingsaas  0000-0003-1539-5415

Conceptualization (equal), Investigation (equal), Methodology (equal), Writing – review & editing (supporting)

Callie W Babbitt  0000-0001-5093-2314

Conceptualization (equal), Funding acquisition (lead), Methodology (supporting), Project administration (equal), Writing – review & editing (equal)

Edward S Spang  0000-0001-9883-078X

Conceptualization (equal), Investigation (supporting), Resources (supporting), Writing – review & editing (supporting)

Anna Christina Tyler  0000-0002-7845-995X

Conceptualization (equal), Data curation (supporting), Formal analysis (supporting), Investigation (supporting), Methodology (supporting), Project administration (lead), Resources (supporting), Supervision (lead), Writing – review & editing (lead)

References

- Afnor B 2006 NF U44-051: organic soil improvers—designations, specifications and marking (available at: www.simer86.fr/files/wysiwyg/dechets/analyse_compost.pdf)
- Ahmed I, Zhang D, Farooq M U, Sheikh Z and Dai X 2026 Microplastics exacerbate antibiotic resistance by regulating microbial and functional gene dynamics in sludge and food waste composting *Water Res.* **291** 125161
- Albuquerque J A, De La Fuente C and Bernal M P 2012 Chemical properties of anaerobic digestates affecting C and N dynamics in amended soils *Agric. Ecosyst. Environ.* **160** 15–22

- Alessi A, Lopes A Do C P, Müller W, Gerke F, Robra S and Bockreis A 2020 Mechanical separation of impurities in biowaste: comparison of four different pretreatment systems *Waste Manag.* **106** 12–20
- Ali T, Habib A, Muskan F, Mumtaz S and Shams R 2023 Health risks posed by microplastics in tea bags: microplastic pollution—a truly global problem *Int. J. Surg.* **109** 515–6
- Alimohammadi M and Demirel G N 2024 Microplastics in anaerobic digestion: occurrence, impact, and mitigation strategies *J. Environ. Health Sci. Eng.* **22** 397–411
- Álvarez-méndez S, Ramos-suárez J, Ritter A, Mata J and Pérez Á 2023 Anaerobic digestion of commercial PLA and PBAT biodegradable plastic bags: potential biogas production and ¹H NMR and ATR-FTIR assessed biodegradation *Heliyon* **9** e16691
- Armington W R, Shrestha S, Tomaszewski B, Babbitt C W and Tyler A C 2026 Integrating regional transportation and ecological factors into anaerobic digestion siting decisions *npj Sustain. Agric.* **4** 31
- Armitage J J and Rohais S 2025 A numerical model of microplastic erosion, transport, and deposition for fluvial systems *Earth Surf. Dyn.* **13** 771–89
- Aspray T, Dimambro M and Steiner H 2017 *Investigation into Plastic in Food Waste Derived Digestate and Soil* (Scottish Environmental Protection Agency)
- Baldasso V, Bonet-garcia N, Sayen S, Guillon E, Frunzo L, Gomes C A R, Alves M J, Castro R, Mucha A P and Almeida C M R 2023 Trace metal fate in soil after application of digestate originating from the anaerobic digestion of non-source-separated organic fraction of municipal solid waste *Front. Environ. Sci.* **10** 1007390
- Bank M S and Hansson S V 2019 The plastic cycle: a novel and holistic paradigm for the anthropocene *Environ. Sci. Technol.* **53** 7177–9
- Battista F, Frison N and Bolzonella D 2021 Can bioplastics be treated in conventional anaerobic digesters for food waste treatment? *Environ. Technol. Innov.* **22** 101393
- Beigmohammadi F, Early M, Updegraff K, Pham T, Curtzwiler G, Edlund I and Vorst K 2025 Microplastic residue in recycled food co-products from mechanical depacking systems: a simulation study for animal food *Waste Manag.* **208** 115166
- Brandt J, Fischer F, Kanaki E, Enders K, Labrenz M and Fischer D 2021 Assessment of subsampling strategies in microspectroscopy of environmental microplastic samples *Front. Environ. Sci.* **8** 579676
- Braun M, Mail M, Heyse R and Amelung W 2021 Plastic in compost: prevalence and potential input into agricultural and horticultural soils *Sci. Total Environ.* **760** 143335
- Briassoulis D 2023 Agricultural plastics as a potential threat to food security, health, and environment through soil pollution by microplastics: problem definition *Sci. Total Environ.* **892** 164533
- Cavazzoli S, Murari F, Donegà M, Tirlor W and Andreottola G 2025 Microplastic removal and environmental emissions from municipal wastewater treatment plants *J. Clean. Prod.* **521** 146267
- Chakori S, Aziz A A, Smith C and Dargusch P 2021 Untangling the underlying drivers of the use of single-use food packaging *Ecol. Econ.* **185** 107063
- Chen N-T, Yeh C-L and Jung C-C 2024 Influence of agricultural activity in corn farming on airborne microplastic in surrounding elementary school *Sci. Total Environ.* **948** 174807
- Chomiak K M, Eddingsaas N C and Tyler A C 2023 Direct and indirect impacts of disposable face masks and gloves on freshwater benthic fauna and sediment biogeochemistry *ACS EST Water* **3** 51–59
- Chomiak K M, Owens-rios W A, Bangkong C M, Day S W, Eddingsaas N C, Hoffman M J, Hudson A O and Tyler A C 2024 Impact of microplastic on freshwater sediment biogeochemistry and microbial communities is polymer specific *Water* **16** 348
- Clough M E, Ochoa Rivera E, Parham R L, Ault A P, Zimmerman P M, McNeil A J and Tewari A 2024 Enhancing confidence in microplastic spectral identification via conformal prediction *Environ. Sci. Technol.* **58** 21740–9
- Colombini G, Rumpel C, Houot S, Biron P and Dignac M-F 2022 A long-term field experiment confirms the necessity of improving biowaste sorting to decrease coarse microplastic inputs in compost amended soils *Environ. Pollut.* **315** 120369
- Crossman J, Hurley R R, Futter M and Nizzetto L 2020 Transfer and transport of microplastics from biosolids to agricultural soils and the wider environment *Sci. Total Environ.* **724** 138334
- Cunningham B E, Sharpe E E, Brander S M, Landis W G and Harper S L 2023 Critical gaps in nanoplastics research and their connection to risk assessment *Front. Toxicol.* **5** 1154538
- Cydzik-kwiatkowska A, Milojevic N and Jachimowicz P 2022 The fate of microplastic in sludge management systems *Sci. Total Environ.* **848** 157466
- Czatkowska M, Rolbiecki D, Korzeniewska E and Harnisz M 2025 Heavy metal and antimicrobial residue levels in various types of digestate from biogas plants—a review *Sustainability* **17** 416
- De Jersey A M, Lavers J L, Bond A L, Wilson R, Zosky G R and Rivers-Auty J 2025 Seabirds in crisis: plastic ingestion induces proteomic signatures of multiorgan failure and neurodegeneration *Sci. Adv.* **11** eads0834
- De Souza Machado A A, Lau C W, Till J, Kloas W, Lehmann A, Becker R and Rillig M C 2018 Impacts of microplastics on the soil biophysical environment *Environ. Sci. Technol.* **52** 9656–65
- Do Carmo Precci Lopes A, Robra S, Müller W, Meirer M, Thumser F, Alessi A and Bockreis A 2019 Comparison of two mechanical pre-treatment systems for impurities reduction of source-separated biowaste *Waste Manag.* **100** 66–74
- Du H, Peng C, Li Y, Shi X, Liu C, Liu W and Wang L 2025 Absorption of microplastics by terrestrial plants and their ecological risk *NEW* **1**
- Dyachenko A, Mitchell J and Arsem N 2017 Extraction and identification of microplastic particles from secondary wastewater treatment plant (WWTP) effluent *Anal. Methods* **9** 1412–8
- Dybas C L 2020 Silent scourge: microplastics in water, food, and air *BioScience* **70** 1048–55
- Dybka-stepień K, Antolak H, Kmiotek M, Piechota D and Koziróg A 2021 Disposable food packaging and serving materials—trends and biodegradability *Polymers* **13** 3606
- Edo C, Fernández-piñas F and Rosal R 2022 Microplastics identification and quantification in the composted organic fraction of municipal solid waste *Sci. Total Environ.* **813** 151902
- Egoshi K, Tanaka M and Nihei Y 2026 Power-law size spectra of microplastic number and mass concentration in river water *Environ. Pollut.* **398** 128058
- Ghoshal T, Parmar P R, Bhuyan T and Bandyopadhyay D 2023 Polystyrene foams: materials, technology, and applications *ACS Symposium Series* R K Gupta ed (American Chemical Society) vol 1439 pp 121–41
- Gilbert J and Ricci-Jurgensen M 2023 *A Practicioners Guide to Preventing and Managing Contaminants in Organic Waste Recycling* (International Solid Waste Association) (available at: www.iswa.org/wp-content/uploads/2023/11/14803_ISWA-Contaminants-Report-2023_60pp_v8-DIGITAL.pdf)

- Giorgetti L, Spanò C, Muccifora S, Bottega S, Barbieri F, Bellani L and Ruffini Castiglione M 2020 Exploring the interaction between polystyrene nanoplastics and *Allium cepa* during germination: internalization in root cells, induction of toxicity and oxidative stress *Plant Physiol. Biochem.* **149** 170–7
- Golovko O, Ahrens L, Schelin J, Söregård M, Bergstrand K-J, Asp H, Hultberg M and Wiberg K 2022 Organic micropollutants, heavy metals and pathogens in anaerobic digestate based on food waste *J. Environ. Manag.* **313** 114997
- Golwala H, Zhang X, Iskander S M and Smith A L 2021 Solid waste: an overlooked source of microplastics to the environment *Sci. Total Environ.* **769** 144581
- Groß M, Mail M, Wrigley O, Debastiani R, Scherer T, Amelung W and Braun M 2024 Plastic fruit stickers in industrial composting—surface and structural alterations revealed by electron microscopy and computed tomography *Environ. Sci. Technol.* **58** 7124–32
- Gui J, Sun Y, Wang J, Chen X, Zhang S and Wu D 2021 Microplastics in composting of rural domestic waste: abundance, characteristics, and release from the surface of macroplastics *Environ. Pollut.* **274** 116553
- Hansen T L, Jansen J L C, Davidsson Å and Christensen T H 2007 Effects of pre-treatment technologies on quantity and quality of source-sorted municipal organic waste for biogas recovery *Waste Manag.* **27** 398–405
- Hardin T 2021 7 Types of plastic that are most common (Plastic Oceans International (available at: <https://plasticoceans.org/7-types-of-plastic/>))
- Harley-Nyang D, Memon F A, Jones N and Galloway T 2022 Investigation and analysis of microplastics in sewage sludge and biosolids: a case study from one wastewater treatment works in the UK *Sci. Total Environ.* **823** 153735
- Harley-nyang D, Memon F A, Osorio Baquero A and Galloway T 2023 Variation in microplastic concentration, characteristics and distribution in sewage sludge & biosolids around the world *Sci. Total Environ.* **891** 164068
- Harwood A 2023 ReFED's new estimates on food waste in the United States: 2020–2021, trends, and COVID-19 impact (available at: <https://refed.org/articles/refed-s-new-estimates-on-food-waste-in-the-united-states-2020-2021-trends-and-covid-19-impact/>)
- Heinze W M, Steinmetz Z, Rathje Klemmensen N D, Vollertsen J and Cornelis G 2024 Vertical distribution of microplastics in an agricultural soil after long-term treatment with sewage sludge and mineral fertiliser *Environ. Pollut.* **356** 124343
- Horta C and Carneiro J P 2021 Phosphorus losses to surface runoff waters after application of digestate to a soil over fertilised with phosphorus *Water Air. Soil Pollut.* **232** 439
- Hu T, Lü F, Yang Z, Shi Z, Yang Y, Zhang H and He P 2024 Pretreatment as a microplastics generator during household biogenic waste treatment *Engineering* **32** 116–26
- Huang Y et al 2021 Effect of microplastics on ecosystem functioning: microbial nitrogen removal mediated by benthic invertebrates *Sci. Total Environ.* **754** 142133
- Huerta Lwanga E et al 2017 Field evidence for transfer of plastic debris along a terrestrial food chain *Sci. Rep.* **7** 14071
- Jadhav E B, Sankhla M S, Bhat R A and Bhagat D S 2021 Microplastics from food packaging: an overview of human consumption, health threats, and alternative solutions *Environ. Nanotechnol. Monit. Manag.* **16** 100608
- Kalčíková G 2020 Aquatic vascular plants—a forgotten piece of nature in microplastic research *Environ. Pollut.* **262** 114354
- Kallon Y E, Sinha R K, Gupta I, Dutta N, Bhattacharya S, Biswas J K and Sharma P 2025 Uptake and bioaccumulation of microplastics by plants: exploring impacts and remediation potential in terrestrial and aquatic environment *Chemosphere* **393** 144764
- Kawecki D, Goldberg L and Nowack B 2021 Material flow analysis of plastic in organic waste in Switzerland *Soil Use Manag.* **37** 277–88
- Kedzierski M, Lechat B, Sire O, Le Maguer G, Le Tilly V and Bruzard S 2020 Microplastic contamination of packaged meat: occurrence and associated risks *Food Packag. Shelf Life* **24** 100489
- Khalid N, Aqeel M, Noman A and Fatima Rizvi Z 2022 Impact of plastic mulching as a major source of microplastics in agroecosystems *J. Hazard. Mater.* **445** 130455
- Kim S W, Liang Y, Zhao T and Rillig M C 2021 Indirect effects of microplastic-contaminated soils on adjacent soil layers: vertical changes in soil physical structure and water flow *Front. Environ. Sci.* **9** 681934
- Korba J, Šařec P, Novák V, Brož P, Dolan A and Dědina M 2024 Digestate application methods and rates with regard to greenhouse gas emissions and crop conditions *Agronomy* **14** 336
- Kovačić Đ, Lončarić Z, Jović J, Samac D, Popović B and Tišma M 2022 Digestate management and processing practices: a review *Appl. Sci.* **12** 9216
- Kupper T, Bürge D, Bachmann H J, Güsewell S and Mayer J 2014 Heavy metals in source-separated compost and digestates *Waste Manag.* **34** 867–74
- Lamolinara B, Pérez-martínez A, Guardado-yordi E, Guillén Fiallos C, Diéguez-santana K and Ruiz-mercado G J 2022 Anaerobic digestate management, environmental impacts, and techno-economic challenges *Waste Manag.* **140** 14–30
- Landrigan P J et al 2023 The minderoo-monaco commission on plastics and human health *Ann. Glob. Health* **89** 23
- Lara R 2016 *Short-lived Climate Pollutant Reduction Strategy* (available at: <https://calrecycle.ca.gov/organics/slcpl/>)
- Lavers J L, Hutton I and Bond A L 2019 Clinical pathology of plastic ingestion in marine birds and relationships with blood chemistry *Environ. Sci. Technol.* **53** 9224–31
- Leonard S V L, Liddle C R, Atherall C A, Chapman E, Watkins M, Calaminus D J S and Rotchell J M 2024 Microplastics in human blood: polymer types, concentrations and characterisation using µFTIR *Environ. Int.* **188** 108751
- Lessa Belone M C, Yli-rantala E, Sarlin E and Kokko M 2025 Microplastics in an anaerobic digester treating sewage sludge: occurrence and factors affecting their identification with Raman spectroscopy *J. Hazard. Mater.* **491** 138015
- Leusch F D L and Ziajahromi S 2021 Converting mg/L to Particles/L: reconciling the occurrence and toxicity literature on microplastics *Environ. Sci. Technol.* **55** 11470–2
- Li Y, Tao L, Wang Q, Wang F, Li G and Song M 2023 Potential health impact of microplastics: a review of environmental distribution, human exposure, and toxic effects *Environ. Health* **1** 249–57
- Lim J W, Ting D W Q, Loh K-C, Ge T and Tong Y W 2018 Effects of disposable plastics and wooden chopsticks on the anaerobic digestion of food waste *Waste Manag.* **79** 607–14
- Liu H, Yuan X, Yao Y, Yao L, Zhang J and Maurer C 2025 Microplastics, antibiotics, and heavy metals in anaerobic digestion systems: a critical review of sources, impacts, and mitigation strategies *Recycling* **10** 116
- Liu X, Lin H, Xu S, Yan Y, Yu R and Hu G 2023 Occurrence, distribution, and characteristics of microplastics in agricultural soil around a solid waste treatment center in southeast China *J. Soils Sediments* **23** 936–46
- Liu Y, Guo R, Zhang S, Sun Y and Wang F 2022 Uptake and translocation of nano/microplastics by rice seedlings: evidence from a hydroponic experiment *J. Hazard. Mater.* **421** 126700
- Loganathan Y and Kizhakedathil M P J 2022 A review on microplastics—an indelible ubiquitous pollutant *Biointerface Res. Appl. Chem.* **13** 126

- Lozano Y M, Lehnert T, Linck L T, Lehmann A and Rillig M C 2021 Microplastic shape, polymer type, and concentration affect soil properties and plant biomass *Front. Plant Sci.* **12**
- Luo H, Li Y, Zhao Y, Xiang Y, He D and Pan X 2020 Effects of accelerated aging on characteristics, leaching, and toxicity of commercial lead chromate pigmented microplastics *Environ. Pollut.* **257** 113475
- Lusher A L, Bråte I L N, Munno K, Hurley R R and Welden N A 2020 Is it or is not it: the importance of visual classification in microplastic characterization *Appl. Spectrosc.* **74** 1139–53
- Malarkey K A and Babbitt C W 2025 The plastic footprint of U.S. agriculture *Resour. Conserv. Recycl.* **223** 108515
- Manu M K, Luo L, Kumar R, Johnravindar D, Li D, Varjani S, Zhao J and Wong J 2023 A review on mechanistic understanding of microplastic pollution on the performance of anaerobic digestion *Environ. Pollut.* **325** 121426
- Marchant D J, Martínez Rodríguez A, Francelle P, Jones J I and Kratina P 2023 Contrasting the effects of microplastic types, concentrations and nutrient enrichment on freshwater communities and ecosystem functioning *Ecotoxicol. Environ. Saf.* **255** 114834
- Mason S A, Garneau D, Sutton R, Chu Y, Ehmann K, Barnes J, Fink P, Papazissimos D and Rogers D L 2016 Microplastic pollution is widely detected in US municipal wastewater treatment plant effluent *Environ. Pollut.* **218** 1045–54
- Meaza I, Toyoda J H and Wise Sr J P 2021 Microplastics in sea turtles, marine mammals and humans: a one environmental health perspective *Front. Environ. Sci.* **8** 575614
- Mei W, Li J, Ding X, Liu S, Qin S, Wang X and Luo C 2026 Comparative analysis of microplastics in aquatic environments: matching thresholds, abundance versus mass concentration, and risk assessment *Environ. Pollut.* **392** 127655
- Méndez Rodríguez K B, Jiménez Avalos J A, Fernández Macías J C and González Palomo A K 2023 Microplastics: challenges of assessment in biological samples and their implication for *in vitro* and *in vivo* effects *Environ. Sci. Pollut. Res.* **30** 119733–49
- Mia M S and Zzaman W 2025 Food waste–derived organic fertilizers: critical insights, agronomic impacts, and pathways for sustainable adoption ed S Roy *Int. J. Food Sci.* **2025** 1551054
- Minténig S M, Int-veen I, Löder M G J, Primpke S and Gerdt G 2017 Identification of microplastic in effluents of waste water treatment plants using focal plane array-based micro-Fourier-transform infrared imaging *Water Res.* **108** 365–72
- Mioduska J, Grabowiec A and Hupka J 2023 Digestate quality originating from kitchen waste *Appl. Sci.* **13** 10353
- Mishra S and Das A P 2023 *Microbial Remediation of Synthetic Microfiber Contaminated Wastewater Microbial Technologies in Industrial Wastewater Treatment* M P Shah ed pp 337–50 (Springer)
- Mukesh K 2020 *Alternative Solutions for Fruit and Vegetable Price Look-Up Stickers Generating Waste in the Environment* (Sustainable Energy Development) (available at: <https://ucalgary.scholaris.ca/handle/1880/112616>)
- Müller A, Goedecke C, Eisentraut P, Piechotta C and Braun U 2020 Microplastic analysis using chemical extraction followed by LC-UV analysis: a straightforward approach to determine PET content in environmental samples *Environ. Sci. Eur.* **32** 85
- Müller A and Süßbauer E 2022 Disposable but indispensable: the role of packaging in everyday food consumption *Eur. J. Cult. Polit. Sociol.* **9** 299–325
- Munno K et al 2023 Patterns of microparticles in blank samples: a study to inform best practices for microplastic analysis *Chemosphere* **333** 138883
- Nabi G, Aziz T and Lin L 2026 The bioaccumulation and carcinogenic potential of micro- and nanoplastics in humans *Toxicol. Res.* **42** 273–87
- Naderi Beni N, Karimifard S, Gilley J, Messer T, Schmidt A and Bartelt-hunt S 2023 Higher concentrations of microplastics in runoff from biosolid-amended croplands than manure-amended croplands *Commun. Earth Environ.* **4** 42
- Napper I E and Thompson R C 2016 Release of synthetic microplastic plastic fibres from domestic washing machines: effects of fabric type and washing conditions *Mar. Pollut. Bull.* **112** 39–45
- Nava V and Leoni B 2021 A critical review of interactions between microplastics, microalgae and aquatic ecosystem function *Water Res.* **188** 116476
- Nesse A S, Aanrud S G, Lyche J L, Sogn T and Kallenborn R 2022 Confirming the presence of selected antibiotics and steroids in Norwegian biogas digestate *Environ. Sci. Pollut. Res.* **29** 86595–605
- New York State 2023 *Regulations For Organic Recycling Facilities—NYSDEC* (available at: <https://dec.ny.gov/environmental-protection/recycling-composting/organic-materials-management/facilities-regulations/regulations>)
- Nghiem L D, Koch K, Bolzonella D and Drewes J E 2017 Full scale co-digestion of wastewater sludge and food waste: bottlenecks and possibilities *Renew. Sustain. Energy Rev.* **72** 354–62
- Nihart A J et al 2025 Bioaccumulation of microplastics in decedent human brains *Nat. Med.* **31** 1114–9
- Nisticò R 2020 Polyethylene terephthalate (PET) in the packaging industry *Polym. Test.* **90** 106707
- Nkoa R 2014 Agricultural benefits and environmental risks of soil fertilization with anaerobic digestates: a review *Agron. Sustain. Dev.* **34** 473–92
- Nosowitz D 2018 Those little produce stickers? They are a big waste problem Modern Farmer (available at: <https://modernfarmer.com/2018/03/little-produce-stickers-are-big-waste-problem/>)
- NY State Senate 2019 *Food Donation and Food Scraps Recycling* (available at: www.nysenate.gov/legislation/laws/ENV/A27T22)
- NYS Senate 2022 *ECL Article 27 Title 30: Expanded Polystyrene Foam Containers and Polystyrene Loose Fill Packaging Ban* (available at: www.nysenate.gov/legislation/laws/ENV/A27T30)
- O'brien B J 2019 *Physicochemical Properties of Residuals from Anaerobic Digestion of Dairy Manure and Food Waste: Nutrient Cycling Implications and Opportunities for Edible Mushroom Cultivation* M.S (The University of Vermont and State Agricultural College) (available at: www.proquest.com/docview/2159015362/abstract/9E125E362F604B9DPQ/1)
- O'connor J, Mickan B, Siddique K H, Rinklebe J, Kirkham M and Bolan N S 2022 Physical, chemical, and microbial contaminants in food waste management for soil application: a review *Environ. Pollut.* **300** 118860
- Oksanen J et al 2025 vegan: community ecology package (available at: <https://CRAN.R-project.org/package=vegan>)
- Öling-wärnå V, Åkerback N and Engblom S 2023 Digestate from biowaste and sewage sludge as carriers of microplastic into the environment: case study of a thermophilic biogas plant in ostrobothnia, Finland *Water Air. Soil Pollut.* **234** 432
- Orner K D, Smith S, Nordahl S, Chakrabarti A, Breunig H, Scown C D, Leverenz H, Nelson K L and Horvath A 2022 Environmental and economic impacts of managing nutrients in digestate derived from sewage sludge and high-strength organic waste *Environ. Sci. Technol.* **56** 17256–65
- Owamah H I, Dahunsi S O, Oranusi U S and Alfa M I 2014 Fertilizer and sanitary quality of digestate biofertilizer from the co-digestion of food waste and human excreta *Waste Manag.* **34** 747–52

- Parham R L, Ochoa Rivera E, Ayala A M, Clough M E, Patel Y, McNeil A J, Tewari A and Ault A P 2026 Improved microplastic identification from simultaneously collected photothermal infrared and raman spectra using multiview conformal prediction *ACS Meas. Sci. Au* **6** 690–702
- Park J, Babbitt C W, Eddingsaas N C, Tyler A C and Trabold T A 2026 Characterization of plastic contamination entering food waste management and implications for food system impacts *Environ. Res.: Food Syst.* **3** 035010
- Peñalver R, Costa-gómez I, Arroyo-manzanares N, Moreno J M, López-garcía I, Moreno-grau S and Córdoba M H 2021 Assessing the level of airborne polystyrene microplastics using thermogravimetry-mass spectrometry: results for an agricultural area *Sci. Total Environ.* **787** 147656
- Periyasamy A 2023 Microfiber emissions from functionalized textiles: potential threat for human health and environmental risks *Toxics* **11** 406
- Pivato A, Vanin S, Raga R, Lavagnolo M C, Barausse A, Rieple A, Laurent A and Cossu R 2016 Use of digestate from a decentralized on-farm biogas plant as fertilizer in soils: an ecotoxicological study for future indicators in risk and life cycle assessment *Waste Manag.* **49** 378–89
- Plastics Europe 2022 Plastics—the facts 2022 • Plastics Europe *Plast. Eur.* (available at: <https://plasticseurope.org/knowledge-hub/plastics-the-facts-2022/>)
- Porterfield K K, Hobson S A, Neher D A, Niles M T and Roy E D 2023a Microplastics in composts, digestates, and food wastes: a review *J. Environ. Qual.* **52** 225–40
- Porterfield K K, Scarborough M J and Roy E D 2023b Organics recycling tradeoffs: biogas potential and microplastic content of mechanically depackaged food waste *ACS Sustain. Chem. Eng.* **11** 10422–9
- Posit team 2025 RStudio: Integrated Development Environment for R. Posit Software, PBC, Boston, MA (available at: <http://www.posit.co/>)
- Primpke S, Wirth M, Lorenz C and Gerdt G 2018 Reference database design for the automated analysis of microplastic samples based on Fourier transform infrared (FTIR) spectroscopy *Anal. Bioanal. Chem.* **410** 5131–41
- Ragusa A et al 2021 Plasticenta: first evidence of microplastics in human placenta *Environ. Int.* **146** 106274
- Ramasamy R, Aragaw T A and Balasaraswathi Subramanian R 2022 Wastewater treatment plant effluent and microfiber pollution: focus on industry-specific wastewater *Environ. Sci. Pollut. Res.* **29** 51211–33
- Rana M M, Haque M R, Tasnim S S and Rahman M M 2023 The potential contribution of microplastic pollution by organic fertilizers in agricultural soils of Bangladesh: quantification, characterization, and risk appraisals *Front. Environ. Sci.* **11** 1205603
- Rathore C, Saha M, Gupta P, Kumar M, Naik A and De Boer J 2023 Standardization of micro-FTIR methods and applicability for the detection and identification of microplastics in environmental matrices *Sci. Total Environ.* **888** 164157
- Rivers-Auty J, Bond A L, Grant M L and Lavers J L 2023 The one-two punch of plastic exposure: macro- and micro-plastics induce multi-organ damage in seabirds *J. Hazard. Mater.* **442** 130117
- Rochman C M et al 2019 Rethinking microplastics as a diverse contaminant suite *Environ. Toxicol. Chem.* **38** 703–11
- Ruggero F, Porter A E, Voulvoulis N, Carretti E, Lotti T, Lubello C and Gori R 2021 A highly efficient multi-step methodology for the quantification of micro-(bio)plastics in sludge *Waste Manag. Res. J. Sustain. Circ. Econ.* **39** 956–65
- Rundh B 2005 The multi-faceted dimension of packaging: marketing logistic or marketing tool? *Br. Food J.* **107** 670–84
- Ryen E G and Babbitt C W 2022 The role of U.S. policy in advancing circular economy solutions for wasted food *J. Clean. Prod.* **369** 133200
- Schirinzì G F, Pérez-pomeda I, Sanchís J, Rossini C, Farré M and Barceló D 2017 Cytotoxic effects of commonly used nanomaterials and microplastics on cerebral and epithelial human cells *Environ. Res.* **159** 579–87
- Schöpfer L et al 2022 Microplastics persist in an arable soil but do not affect soil microbial biomass, enzyme activities, and crop yield *J. Plant Nutr. Soil Sci.* **185** 836–49
- Schwab F, Rothen-rutishauser B and Petri-fink A 2020 When plants and plastic interact *Nat. Nanotechnol.* **15** 729–30
- Schwenger K J P et al Okrainec A and Allard JP 2024 Links between fecal microplastics and parameters related to metabolic dysfunction-associated steatotic liver disease (MASLD) in humans: an exploratory study *Sci. Total Environ.* **953** 176153
- Schwinghammer L, Krause S and Schaum C 2021 Determination of large microplastics: wet-sieving of dewatered digested sludge, co-substrates, and compost *Water Sci. Technol.* **84** 384–92
- Segur T, Hough I, Dobiasova N, Voisin D, Richon C, Angot H, Thomas J L and Sonke J E 2026 Using the power law size distribution to extrapolate and compare microplastic number and mass concentrations in environmental media *Microplastics Nanoplastics* **6** 45
- Severe E, Surridge B W J, Fiener P, Coogan M P, Platel R H, James M R and Quinton J 2025 The transport of microplastics from soil in response to surface runoff and splash erosion *Environ. Sci. Technol.* **59** 14063–74
- Shi X, Ma Y, Ma Y, Lin W, Zhu L, Li D, Tong Y and Lin Y 2025 A comprehensive modeling of microplastic emission from wastewater treatment plants to the sea via rivers in China *Environ. Sci. Technol.* **59** 3679–90
- Sholokhova A, Ceponkus J, Sablinskas V and Denafas G 2022 Abundance and characteristics of microplastics in treated organic wastes of Kaunas and Alytus regional waste management centres, Lithuania *Environ. Sci. Pollut. Res.* **29** 20665–74
- Shruti V C, Pérez-guevara F, Elizalde-martínez I and Kutralam-muniasamy G 2020 First study of its kind on the microplastic contamination of soft drinks, cold tea and energy drinks—Future research and environmental considerations *Sci. Total Environ.* **726** 138580
- Silva C J M, Machado A L, Campos D, Rodrigues A C M, Patrício Silva A L, AMVM S and Pestana J L T 2022 Microplastics in freshwater sediments: effects on benthic invertebrate communities and ecosystem functioning assessed in artificial streams *Sci. Total Environ.* **804** 150118
- Sintim H Y et al 2020 *In situ* degradation of biodegradable plastic mulch films in compost and agricultural soils *Sci. Total Environ.* **727** 138668
- Smith S J, Satchwell A J, Kirchstetter T W and Scown C D 2021 The implications of facility design and enabling policies on the economics of dry anaerobic digestion *Waste Manag.* **128** 122–31
- Sobhani Z, Lei Y, Tang Y, Wu L, Zhang X, Naidu R, Megharaj M and Fang C 2020 Microplastics generated when opening plastic packaging *Sci. Rep.* **10** 4841
- Soong Y-H V, Sobkowicz M J and Xie D 2022 Recent advances in biological recycling of polyethylene terephthalate (PET) plastic wastes *Bioengineering* **9** 98
- Srećkov Z, Mrkonjić Z, Bojović M, Nikolić O, Radić D and Vasić V 2025 Microplastic uptake in vegetables: sources, mechanisms, transport and food safety *Toxics* **13** 609
- Standards Australia 2012 Australian Standard: composts, soil conditioners and mulches (available at: <https://soilwealth.com.au/wp-content/uploads/2023/08/AS4454-2012A1.pdf>)

- Steiner T, Möller J N, Löder M G J, Hilbrig F, Laforsch C and Freitag R 2022 Microplastic contamination of composts and liquid fertilizers from municipal biowaste treatment plants: effects of the operating conditions *Waste Biomass Valorization* **14** 873–87
- Sun J, Dai X, Wang Q, Van Loosdrecht M C M and Ni B-J 2019 Microplastics in wastewater treatment plants: detection, occurrence and removal *Water Res.* **152** 21–37
- Surendran D, Varghese G K and Zafiu C 2024 Characterization and source apportionment of microplastics in Indian composts *Environ. Monit. Assess.* **196** 5
- Tan M, Sun Y, Gui J, Wang J, Chen X, Song W and Wu D 2022 Distribution characteristics of microplastics in typical organic solid wastes and their biologically treated products *Sci. Total Environ.* **852** 158440
- Thompson R C, Courtene-jones W, Boucher J, Pahl S, Raubenheimer K and Koelmans A A 2024 Twenty years of microplastic pollution research—what have we learned? *Science* **386** eadl2746
- Urugo M M, Teka T A, Gemedie H F, Mersha S, Tessema A, Woldemariam H W and Admassu H 2024 A comprehensive review of current approaches on food waste reduction strategies *Compr. Rev. Food Sci. Food Saf.* **23** e70011
- US EPA O 2014 Guidelines and permitting for livestock anaerobic digesters (available at: www.epa.gov/agstar/guidelines-and-permitting-livestock-anaerobic-digesters)
- US EPA O 2015 International efforts on wasted food recovery (available at: www.epa.gov/international-cooperation/international-efforts-wasted-food-recovery)
- US EPA 2021a *Emerging Issues in Food Waste Management Plastic Contamination*
- US EPA 2021b *From Farm to Kitchen: the Environmental Impacts of U.S. Food Waste*
- US EPA 2023 Wasted food scale (available at: www.epa.gov/sustainable-management-food/wasted-food-scale)
- Van Schothorst B, Beriot N, Huerta Lwanga E and Geissen V 2021 Sources of light density microplastic related to two agricultural practices: the use of compost and plastic mulch *Environments* **8** 36
- Veidis E M, LaBeaud A D, Phillips A A and Barry M 2022 Tackling the ubiquity of plastic waste for human and planetary health *Am. J. Trop. Med. Hyg.* **106** 12–14
- Villarrubia-gómez P, Almroth B C, Eriksen M, Ryberg M and Cornell S E 2024 Plastics pollution exacerbates the impacts of all planetary boundaries *One Earth* **7** 2119–38
- Wang J, Lee J, Kwon E E and Jeong S 2023 Quantitative analysis of polystyrene microplastic and styrene monomer released from plastic food containers *Heliyon* **9** e15787
- Weithmann N, Möller J N, Löder M G J, Piehl S, Laforsch C and Freitag R 2018 Organic fertilizer as a vehicle for the entry of microplastic into the environment *Sci. Adv.* **4** eaap8060
- Welle F 2011 Twenty years of PET bottle to bottle recycling—an overview *Resour. Conserv. Recycl.* **55** 865–75
- Whitney A L, Chomiak K M, Babbitt C W, Eddingsaas N C and Tyler A C 2025 Microplastic abundance and characterization in the anaerobic co-digestion of food waste and dairy manure *Front. Sustain. Food Syst.* **9** 1666814
- Whitney A 2024 Plastic abundance and degradation in the anaerobic digestion of food waste *MS Thesis* Rochester Institute of Technology (available at: <https://repository.rit.edu/theses/11909>)
- Wickham H 2016 *Ggplot2: Elegant Graphics for Data Analysis* (Springer)
- Wickham H et al 2019 Welcome to the tidyverse *J. Open Source Softw.* **4** 1686
- Widyasari-mehta A, Hartung S and Kreuzig R 2016 From the application of antibiotics to antibiotic residues in liquid manures and digestates: a screening study in one European center of conventional pig husbandry *J. Environ. Manag.* **177** 129–37
- Wilson D, Anderson C, Ormsby T, Lewis A, Stoner R and Whetu A 2024 *Contaminants Present in Organic Waste: phase 3 Management Framework and Thresholds Report* (Ministry for the Environment (available at: <https://environment.govt.nz/assets/publications/Waste/Phase-3-Framework-and-Threshold-Report.pdf>)
- Xiao S, Cui Y, Brahney J, Mahowald N M and Li Q 2023 Long-distance atmospheric transport of microplastic fibres influenced by their shapes *Nat. Geosci.* **16** 863–70
- Xing D, Hu Y, Sun B, Song F, Pan Y, Liu S and Zheng P 2023 Behavior, characteristics and sources of microplastics in tea *Horticulturae* **9** 174
- Xu J, Yang A, Yan Y, Xu Y, Tang M, Li P, Zhao L, Zhang X and Ren Z 2024 Quantification and identification of microplastics in organic fertilizers: the implication for the manufacture and safe application *Water Air. Soil Pollut.* **235** 169
- Xu Y, Ou Q, Wang X, Hou F, Li P, van der Hoek J P and Liu G 2023 Assessing the mass concentration of microplastics and nanoplastics in wastewater treatment plants by pyrolysis gas chromatography–mass spectrometry *Environ. Sci. Technol.* **57** 3114–23
- Yadav M, Negi V and Verma H 2024 *Impact of Synthetic Microfibers and Their Toxicity on the Environment Sustainable Microbial Technology for Synthetic and Cellulosic Microfiber Bioremediation* A P Das, I D Behera and D Bhanja ed (Springer) pp 123–56
- Yang G, Xie S, Yang M, Tang S, Zhou L, Jiang W, Zhou B, Li Y and Si B 2022a A critical review on retaining antibiotics in liquid digestate: potential risk and removal technologies *Sci. Total Environ.* **853** 158550
- Yang Z, Lü F, Hu T, Xu X, Zhang H, Shao L, Ye J and He P 2022b Occurrence of macroplastics and microplastics in biogenic waste digestate: effects of depackaging at source and dewatering process *Waste Manag.* **154** 252–9
- Yousefi A, Attar H M and Yousefi Z 2024 Investigating the release of microplastics from tea bags into tea drinks and human exposure assessment *Environ. Health Eng. Manag.* **11** 337–47
- Zuri G, Bedia C, Spitieri C S, Vassilatou V, Karanasiou A and Lacorte S 2025 Quantification of microplastics in bottled water by Pyr-GC-Orbitrap-MS, human exposure, and in vitro hepatotoxicity assessment *Food Control* **178** 111489