Microplastics in Composts, Digestates and Food Wastes: A Review

Katherine K. Porterfield[a,b], Sarah A. Hobson[c], Deborah A. Neher[d,b], Meredith T. Niles[e,b], Eric D. Roy[a,b,c*]

[a] Department of Civil and Environmental Engineering, University of Vermont, 33 Colchester Ave, Burlington, VT, 05405, USA

[b] Gund Institute for Environment, University of Vermont, 210 Colchester Ave, Burlington, VT, 05405, USA

[c] Rubenstein School of Environment and Natural Resources, University of Vermont, 81 Carrigan Drive, Burlington, VT, 05405, USA

[d] Department of Plant and Soil Science, University of Vermont, 63 Carrigan Drive, Burlington, VT, 05405, USA

[e] Department of Nutrition and Food Sciences & Food Systems Program, University of Vermont, 109 Carrigan Drive, Burlington, VT, 05405, USA

*Corresponding author:
Dr. Eric D. Roy
81 Carrigan Dr.
Burlington, VT 05405 USA
+1 802-656-7359
eroy4@uvm.edu

Abstract

Diverting food waste from landfills to composting or anaerobic digestion can reduce greenhouse gas emissions, enable the recovery of energy in usable forms, and create nutrient-rich soil amendments. However, many food waste streams are mixed with plastic packaging, raising concerns that food waste-derived composts and digestates may inadvertently introduce microplastics into agricultural soils. Research on the occurrence of microplastics in food waste-derived soil amendments is in an early phase and the relative importance of this potential pathway of microplastics to agricultural soils needs further clarification. In this paper, we review what is known and what is not known about the abundance of microplastics in composts, digestates and food wastes and their effects on agricultural soils. Additionally, we highlight future research needs and suggest ways to harmonize microplastic abundance and ecotoxicity studies with the design of related policies.

Key Words: microplastic, food waste, compost, digestate, circular economy

1. Introduction

Food waste constitutes approximately a quarter of all material landfilled in the US (USEPA, 2020), and is readily converted to methane—a potent greenhouse gas—under the anaerobic conditions found in landfills (Buzby et al., 2014). Diverting food waste from landfills to anaerobic digestion and composting could reduce methane emissions and enable the recovery of nutrients and energy in usable forms (USEPA, 2021a, 2021b). Both processes produce soil amendments—digestate and compost, respectively—that can be applied to agricultural lands to support soil health and fertility (Cheong et al., 2020; Kelley et al., 2020; Roy, 2017). Anaerobic digestion provides the additional benefit of recovering useable energy from food waste in the form of biogas (Xu et al., 2018). Growing recognition of these co-benefits has prompted recent legislation regarding the diversion of food waste from landfills (Golwala et al., 2021). In the US, this includes the state of Vermont's *Universal Recycling Law* (2012), which mandated the diversion of all food residuals (including those from households) from landfills in 2020, and California's *Short-Lived Climate Pollutant Reduction Law* (2016), which requires a 75% reduction in organic material sent to landfills by 2025.

Contamination from plastic packaging is an emerging challenge for food waste diversion initiatives (O'Connor et al., 2022; USEPA, 2021a). The ubiquitous use of plastics in food packaging means that many pre- and post-consumer food waste streams are mixed with plastic packaging (USEPA, 2021a). Substantial fractions of wasted food from industrial and commercial settings can remain packaged for a variety of reasons (e.g., expiration, off-specification, contamination). For example, a study conducted for the US state of Vermont reported that an estimated 38% of food waste in the state was packaged

(DSM Environmental Services Inc, 2018). Recovering food waste in these cases requires some form of depackaging, using either mechanical depackagers or human labor, both of which are likely to achieve variable and imperfect separation efficiency (do Carmo Precci Lopes et al., 2019; Edwards et al., 2018). Source-separated post-consumer food waste can also be mixed with mis-sorted plastic packaging, with varying levels of contamination that may be influenced by factors such as population density (Friege and Eger, 2021) or food waste diversion program design (Dai et al., 2016).

Despite efforts to separate packaging from food waste streams, early evidence suggests that microplastics (plastic particles <5 mm) may be present in many food waste-derived composts and digestates (**Figure 1**), and could be transferred to agricultural soils when these amendments are land-applied (Kawecki et al., 2020; Weithmann et al., 2018). Microplastics were first reported to be accumulating in the oceans in 2004 (Thompson et al., 2004). In the two decades since, research on microplastics has focused on marine and other aquatic environments, and it was not until 2012 that their presence in terrestrial environments began to receive attention (Rillig, 2012). Since then, the number of studies focusing on terrestrial environments has steadily increased, but still represent a small fraction of all microplastic publications (5% as of 2019) (R. Qi et al., 2020). Previous reviews focused on the abundance and sources of microplastics in soils as well as the challenges of detecting and characterizing microplastics in complex organic matrices (e.g., J. Li et al., 2020; Ruggero et al., 2020; Sun et al., 2019, 2022; J. Wang et al., 2019; Xu et al. 2020; Y. Zhou et al., 2020; Zhu et al., 2019). Few studies to date have measured the abundance of microplastics in food waste (Golwala et al., 2021), though a recent review includes microplastics among emerging contaminants in food waste-derived composts and digestates (O'Connor et al., 2022). The body of peer-reviewed research on soil-microplastic interaction is still in its infancy as well, but several recent reviews summarize documented effects on soil physical properties, biota and crops (e.g., Iqbal et al., 2020; Ng et al., 2018; R. Qi et al., 2020; J. Wang et al., 2019; Xu et al. 2020; Y. Zhou et al. 2020; Zhu et al. 2019). In addition to the potential risks posed to soil-plant systems, plastic contamination can impede circular economy efforts by making composts and digestates less attractive to farmers and consumers (Friege & Eger, 2021; Roy et al., 2021).

Despite the lack of scientific consensus on the risks posed by microplastics in soils and the relative input from organic amendments, a growing number of entities have imposed regulatory thresholds for microplastics in composts and digestates (USEPA, 2021a). Given the lack of data on the extent, impact, and relative magnitude of microplastic pollution from composts and digestates and absence of standardized methods for measuring microplastics in complex organic materials (USEPA, 2021a), the environmental benefits of existing regulations are uncertain. In this paper, we review the current state of understanding of microplastic contamination in food wastes, composts, digestates, and soils (**Figure 2**). This review complements previous reviews by focusing on food waste-derived composts and digestates as a possible source of microplastics to agricultural soils, and discussing the limitations of existing regulatory approaches to microplastic contamination in composts and digestates. For a full description of the systematic review methods, see the **Supplementary Materials**. We begin with an overview of the different methods that have been used to measure microplastics in complex organic matrices, followed by a review of microplastic abundance in food wastes, composts and digestates. Next, we discuss the various inputs of microplastics to agricultural soils and their prevalence therein, followed by an overview of the impacts of microplastics on soil-plant systems. Finally, we provide a roadmap for future research and highlight ways to harmonize efforts to quantify microplastics in food waste-derived materials, understand the effects of microplastics in agricultural soils, and establish related policy.

2. Microplastic Measurement

Methods for measuring microplastics in solid organic matrices typically involve a sequence of steps aimed at isolating, identifying and characterizing the microplastics in each sample. Isolation methods include flotation, elutriation, centrifugation, digestion (with e.g., H_2O_2, Fenton's reagent), and sieving (Junhao et al., 2021; Ruggero et al., 2020). Identification methods include fluorescence microscopy, thermal degradation (e.g., TED-GC-MS, PY-GC-MS), spectroscopy (e.g., Fourier Transform Infrared Spectroscopy (FTIR), Raman) and visual analysis (with or without light microscopy) (Junhao et al., 2021; Ruggero et al., 2020). It is common for multiple isolation and identification methodologies to be combined in series (Ruggero et al., 2020). Studies of microplastic abundance in food wastes, composts and digestates largely report values on a count per weight basis (**Table 1**), with a smaller number of studies reporting values on a weight per weight (*w/w*) basis (**Table 2**). Only 25% of studies reviewed report values in both units (Braun et al., 2021; O'Brien, 2019; Schwinghammer et al., 2020; Sholokhova et al., 2021). For agricultural soils, all studies reviewed reported microplastic abundance on a count per weight basis (**Table 3**). Microplastics are typically characterized by size fraction, shape and polymer type, with some studies further differentiating by color or other properties. Below, we briefly summarize the most common methods used to quantify microplastics in food waste, compost, digestate, and agricultural soil, as well as some of the challenges that arise due to the lack of standardized methods. For a more detailed review of methodologies for microplastic measurement in heterogeneous solid matrices, see Ruggero et al. (2020).

A limited number of studies have measured microplastic abundance in food waste alone (**Tables 1** and **2**). In these studies, microplastic isolation was achieved by organic matter oxidation with 30–35% H_2O_2 (Ruggero et al., 2021; Schwinghammer et al., 2020), density separation with a saturated salt solution (Golwala et al., 2021; Ruggero et al., 2021), and/or wet sieving (do Carmo Precci Lopes et al., 2019; Kawecki et al., 2020; Schwinghammer et al., 2020). Microplastics were identified using fluorescence microscopy (Ruggero et al., 2021), visual analysis (do Carmo Precci Lopes et al., 2019; Golwala et al., 2021; Kawecki et al., 2020; Schwinghammer et al., 2020), and/or FTIR (Golwala et al., 2021; Ruggero et al., 2021; Schwinghammer et al., 2020).

More studies (albeit still a relatively small number) have examined microplastics in food waste-derived composts or digestates than in food waste itself (**Tables 1** and **2**). Among studies reporting microplastic abundance on a count per weight basis, isolation strategies included sieving (Edo et al., 2021; O'Brien, 2019; Schwinghammer et al., 2020; Weithmann et al., 2018), organic matter oxidation with 30% H_2O_2 (Edo et al., 2021; Gui et al., 2021; Meixner et al., 2020; Schwinghammer et al., 2020) or Fenton's reagent (Sholokhova et al., 2021), density separation with a saturated salt solution (Braun et al., 2021; Edo et al., 2021; Gui et al., 2021; Meixner et al., 2020; Sholokhova et al., 2021), and centrifugation (van Schothorst et al., 2021). Light microscopy was used in most cases to identify and count putative microplastics based on morphology, color, and response to heat, resulting in values on a count per weight basis. Subsequently, FTIR was used to confirm and identify the polymer type of some or all of the putative microplastics (Edo et al., 2021; Gui et al., 2021; Schwinghammer et al., 2020; Sholokhova et al., 2021; van Schothorst et al., 2021; Weithmann et al., 2018). Studies reporting microplastic abundance in composts and digestates on a *w/w* basis employed more variable methods, including quantification of a single polymer type using alkaline extraction followed by liquid chromatography with UV detection (Müller et al., 2020), direct weighing of larger size fractions (Bläsing and Amelung, 2018; Braun et al., 2021; Kawecki et al., 2020; O'Brien, 2019; Schwinghammer et al., 2020), and estimation based on polymer densities for smaller size fractions (Braun et al., 2021).

Similar methods were used to measure microplastics abundance in agricultural soils. The most common recovery methods included density separation (e.g., Chen et al., 2020; Corradini et al., 2021; Hu et al., 2021) and organic matter oxidation (e.g., Piehl et al., 2018). Most studies reviewed used both a digestion and density separation step (e.g., Feng et al., 2021; Huang et al., 2021, 2020; Isari et al., 2021; Q. Li et al., 2021; Liu et al., 2018; Rafique et al., 2020; Kumar and Sheela, 2021; J. Wang et al., 2021; J. Yang et al., 2021; L. Yu et al., 2021; B. Zhou et al., 2020). The most common identification methods included visual inspection under a light microscope (e.g., Chen et al., 2020; Corradini et al., 2021; Feng et al., 2021; Isari et al., 2021; J. Wang et al., 2021; B. Zhou et al., 2020) and photographing for photo software visual analysis (e.g., Feng et al., 2021; van Schothorst et al., 2021; L. Yu et al., 2021), often followed by FTIR (e.g., Corradini et al., 2021; Liu et al., 2018; J. Wang et al., 2021), Raman spectroscopy (Chen et al., 2020) or test of response to heat (Beriot et al., 2021; Huerta Lwanga et al., 2017; Meng et al., 2020; van Schothorst et al., 2021) to confirm a portion of or all putative microplastics. The most common soil depth considered was 30 cm (e.g., Harms et al., 2021; Huang et al., 2021; Isari et al., 2021; Kumar and Sheela, 2021; Meng et al., 2020; van Schothorst et al., 2021) and the deepest was 80 cm (Hu et al., 2021).

There are several challenges associated with current approaches to quantifying microplastics. First, some of the most common methods used to isolate plastics from complex organic matrices may not be appropriate for all polymer types. High-density plastics (e.g., PVC, PET) may not be recovered with density separation and flotation methods (Liu et al., 2018), and organic matter oxidation with 30% H_2O_2 has been shown to cause visual changes to PA, PP, PC, PET and linear LDPE (Nuelle et al., 2014). Another major challenge is the lack of standard units for measuring microplastic abundance. There is no consistent way to convert between microplastic count per weight and *w/w* values without knowing or assuming shape, size and polymer type (Braun et al., 2021; Leusch and Ziajahromi, 2021). This is problematic not only because it prevents comparison between studies, but also because microplastic ecotoxicity thresholds and regulatory limits are typically determined on a *w/w* basis (Leusch and Ziajahromi, 2021; USEPA, 2021a). This disconnect makes it difficult to design studies that evaluate microplastic ecotoxicity risk at real world concentrations, or in ways that can contribute directly to existing policy.

Variation in microplastic size fractions complicate comparison between studies too. While it is widely accepted that microplastics are defined as particles <5 mm in size, there is far less consensus on other size-based delineations (Gigault et al., 2018). Macroplastics are sometimes defined as plastic particles >5 mm (Zhang et al., 2018), although other studies further divide into meso- (5–25 mm) and macro- (>25 mm) plastics (Braun et al., 2021; Golwala et al., 2021; Gui et al., 2021). The term “nanoplastic” remains under debate as well and has been used to refer to plastic particles less than 0.1, 1, or even 1000 µm throughout the literature (Gigault et al., 2018; R. Qi et al., 2020). Most of the studies reviewed here focused on microplastics >1 mm (**Tables 1** and **2**). However, some studies have used lower bounds as small as 30 µm (van Schothorst et al., 2021), while others report no lower limit of detection at all (**Tables 1** and **2**). On the other end of the spectrum, some studies include or even exclusively measure macroplastics (e.g., Kawecki et al., 2020). These methodological differences likely exert a strong influence on total counts of microplastic abundance, and underscore the need to develop standard methods for measuring microplastics in complex organic matrices. This should include standard sampling, isolation and identification protocols as well as known lower thresholds and efficiencies.

3. Microplastic Abundance in Food Wastes, Composts and Digestates

We used a systematic literature search to identify scientific articles providing primary data on microplastic abundance in food wastes, composts, and/or digestates (**Table S1**). We intentionally excluded studies focusing on biosolids-derived organic amendments unless there was co-digestion with food waste because microplastic occurrence in wastewater has been reviewed elsewhere (Sun et al. 2019). We included studies of green waste-derived composts (e.g., yard and landscape trimmings) for comparison with food waste-derived composts. The studies that report microplastic abundance in terms of particles per weight (standardized to particles kg^{-1} dry material where possible) are summarized in **Table 1** and the studies that report microplastic abundance in terms of *w/w* (standardized to *w/w* dry material where possible) are summarized in **Table 2**. For composts, digestates and food wastes, we report plastic abundance values that include all size fractions measured for a given study. In some instances, this includes or is solely comprised of macroplastics. All the studies we reviewed reported finding plastics in composts, digestates and/or food wastes, even in cases where the compost was derived exclusively from green waste. The most frequently identified polymers included polyethylene (PE), polypropylene (PP) and polystyrene (PS) (**Tables 1** and **2**), which are also some of the most common plastics used in food packaging (Ncube et al., 2020). "Biodegradable" or "compostable" bioplastics, including polylactic acid (PLA), Mater-Bi®, and cellulose-based polymers were identified as well (**Tables 1** and **2**).

Plastic abundance in food waste alone spanned five orders of magnitude on a count per weight basis (**Table 1**), and three orders of magnitude on a *w/w* basis (**Table 2**). Values for homogenized food waste ranged from ~40 (Schwinghammer et al., 2020) to 1,400 ± 150 particles kg^{-1} dry material (Ruggero et al., 2021); however, the former study only considered larger particles (1–5 mm) and the latter only considered smaller particles (0.1–2 mm). A study of grocery waste in the US found 300,000 particles kg^{-1} dry material (Golwala et al., 2021). On a mass basis, plastic abundance ranged from ~0.025% *w/w* in homogenized food waste (Schwinghammer et al., 2020) to 5.6% *w/w* in source-separated household biowaste (do Carmo Precci Lopes et al., 2019).

Reported values also varied widely both within and between studies measuring plastic abundance in composts—spanning seven orders of magnitude on a count per mass basis (**Table 1**), and four orders of magnitude on a *w/w* basis (**Table 2**.). Plastic abundance ranged from 12 ± 8 (Braun et al., 2021) to 82,800 ± 17,400 (Huerta-Lwanga et al., 2021) particles dry kg^{-1} green waste-derived composts and from 20 (Weithmann et al., 2018) to

30,000 (Edo et al., 2021) particles dry kg^{-1} of composts made with food waste, with one study reporting 4.28×10^7 particles dry kg^{-1} of a compost of unknown origin (Meixner et al., 2020). On a mass basis, plastic abundance ranged from 0.00024% *w/w* in a green waste-derived compost (Bläsing and Amelung, 2018) to $0.1358 \pm 0.0596\%$ *w/w* in a compost made from household biowaste (Braun et al., 2021).

Plastic levels in digestates were comparable to those found in composts in both magnitude and variability—also spanning seven orders of magnitude on a count per mass basis (**Table 1**), and just two orders of magnitude on a *w/w* basis (**Table 2**), albeit with fewer studies. Plastic counts typically ranged between 70 and 1670 particles dry kg^{-1} in digestates derived from commercial organic waste and co-digested manure and food waste, respectively (O'Brien, 2019; Weithmann et al., 2018), with one study reporting up to 38.7×10^7 particles dry kg^{-1} of a digestate of unknown origin (Meixner et al., 2020). On a *w/w* basis, plastic estimates ranged from 0.01% *w/w* in digestate derived from the organic fraction of municipal waste (Schwinghammer et al., 2020), to 0.25% *w/w* in digestate derived from co-digested dairy manure and food waste (O'Brien, 2019).

With such a limited number of studies reporting microplastic abundance in composts, digestates and food wastes, caution should be taken when drawing any conclusions. Nonetheless, we observed the following patterns: 1) Microplastic abundance varies widely both within and between studies of food wastes, composts, and digestates, 2) The overlapping ranges of microplastic abundance in food-waste derived composts and digestates indicates that neither practice necessarily produces contaminant-free soil amendments, and 3) The presence of microplastics in green-waste derived composts indicates that packaging from food waste is not the only possible source of plastics in organic soil amendments.

4. Microplastic Inputs to Agricultural Soils

Land application of contaminated organic amendments is just one of multiple potential pathways by which microplastics may enter agricultural soils. Primary microplastics—those that are intentionally engineered to be small (Golwala et al., 2021)—are directly applied to agricultural soils in the form of plastic-coated controlled-release fertilizers, treated seeds, and capsule suspension plant protection products (ECHA, 2020; Stubenrauch and Ekardt, 2020). Secondary microplastics—which form from the breakdown of macroplastics—can be unintentionally added to soils in the form of contaminated soil amendments (e.g., biosolids, composts, digestates) or through the breakdown of plastic mulching (Bläsing and Amelung, 2018; Corradini et al., 2021; Zhu et al., 2019). Plastic mulching made with LDPE or biodegradable polymers is often used in agriculture to boost crop yields, suppress weeds, retain water and fumigants and reduce fertilizer and herbicide requirements (Brodhagen et al., 2017; Serrano-Ruiz et al., 2021). However, it can also fragment over time and release microplastics into agricultural soils, and in some cases is even tilled into soils intentionally at the end of the season (Brodhagen et al., 2017; Feng et al., 2021; Serrano-Ruiz et al., 2021; B. Zhou et al., 2020). Other sources of secondary microplastics include irrigation water (B. Zhou et al., 2020), roads (Chen et al., 2020; Sommer et al., 2018), litter (de Souza Machado et al., 2018a), and atmospheric deposition (Bianco and Passananti, 2020; Scheurer and Bigalke, 2018; J. Zhang et al., 2020).

However, these other sources will not all influence microplastic abundance at a specific site (Corradini et al., 2021; Yu et al., 2021) and are beyond the scope of this review.

5. Microplastic Abundance in Agricultural Soils

Understanding existing levels of microplastic pollution in agricultural soils is required to assess potential future impacts of microplastics in food waste-derived compost and digestates. We conducted a systematic literature search to identify studies providing primary data on microplastic abundance in agricultural soils (**Table S1**). Because plastic mulching contributes microplastics to agricultural soils (Feng et al., 2021; B. Zhou et al., 2020), we collated soil microplastic abundance values by plastic mulch use history. Microplastic (<5 mm) abundance values are reported in **Table S2** for soils where plastic mulching was used, in **Table S3** for soils where plastic mulching was not used, in **Table S4** where plastic mulching was used on some but not all sites and in **Table S5** where plastic mulch use was not specified. Results from these studies are synthesized in **Table 3**.

Microplastic abundance in agricultural soils typically ranged in the 10s to 1000s of particles dry kg^{-1} in soils where plastic mulching was used as well as soils where it was not used (**Table 3**). These ranges overlap with the range of reported plastic content for food waste-derived composts and digestates (**Table 1**). More research is needed to understand the importance of different pathways of microplastics introduction to agricultural soils, including the use of soil amendments derived from food waste. This will require knowledge of the magnitudes of existing microplastic inputs from all possible sources and the use of reference soils (i.e., experimental controls) to help delineate microplastic inputs from various sources (e.g., distinguish between microplastics introduced by soil amendments versus atmospheric deposition) (Harms et al., 2021; Kumar and Sheela, 2021).

6. Impact of Microplastics in Agricultural Soils

Recent peer-reviewed literature documents several negative effects of microplastics in agricultural soils, but these effects are still not well understood. Microplastic impacts in soil vary depending on several factors, including polymer type, size and shape, soil characteristics, and microplastic dose and exposure time (de Souza Machado et al., 2018b; Lozano et al., 2021; Zhao et al., 2021). Degradation times for plastic in soil are long (Roy et al., 2011), resulting in accumulation through time, especially in surface soils (Yu and Flury, 2021). Plastic degradation in soil can result in fragmentation of macroplastics into micro- or nano-plastics and the release of toxic compounds through time (Rillig et al., 2021). Here we provide a brief overview of available information on microplastic impacts on soil physical properties, crops and biota.

6.1. Physical Effects

Microplastics have variable effects on soil physical properties. They are shown to increase soil water repellence (Y. Qi et al., 2020) and porosity (Y. Qi et al., 2020; Zhang et al., 2019). Soil bulk density (de Souza Machado et al., 2019, 2018b; Mbachu et al., 2021; Y. Qi et al., 2020) and aggregate size (Kim et al., 2021; Lozano et al., 2021) tend to decrease with addition of microplastics. Microplastics have variable effects on water holding capacity (de Souza Machado et al., 2019, 2018b; Y. Qi et al., 2020). In most cases, the observed physical effects vary depending on microplastic size, shape and polymer type and soil conditions. Polymer type can, for example, determine the effects of microplastics on soil bulk density, which in turn can influence water infiltration, surface runoff, and erosion (de Souza Machado et al., 2018b; Jiang et al., 2017; Kim et al., 2021; Mbachu et al., 2021; Y. Qi et al., 2020; Zhang et al., 2019). Plastic particle size may also mediate effects on soil physical properties. For example, the saturated hydraulic conductivity of a sandy soil increased with the addition of LDPE and starch-based macroplastics, but decreased with the addition of the same polymers as microplastics (Y. Qi et al., 2020). Other studies have found no significant effects on soil physical properties with the addition of microplastics (Huerta-Lwanga et al., 2021).

6.2. Ecotoxicity

Ecotoxicity in soils may result from either introduction of microplastics themselves or associated contaminants. Plastics contain additives such as plasticizers, pigments, and thermal stabilizers which are not chemically bound to the polymers and can therefore be lost more easily to the environment (Blackburn and Green, 2021; Billings et al., 2021; Hahladakis et al., 2018). Plastics can also adsorb other chemical contaminants (e.g., per- and polyfluoroalkyl substances) which may confound impacts on soil biota (Hahladakis et al., 2018; Sobhani et al., 2021; J. Yang et al., 2021). While the release rates and bioavailability of chemical contaminants associated with microplastics are not yet well understood, there is evidence that microplastic effects on contaminant mobility are likely negligible (Castan et al., 2021; Gouin et al., 2011, 2019).

Effects of microplastics on soil biota are documented in recent literature (Guo et al., 2020; W. Wang et al., 2020). For example, microplastics affect species dominance, diversity, and richness at microplastic doses in soils of 0.2–5% *w/w* (Fei et al., 2020; Ren et al., 2020; J. Wang et al., 2020; Y. Wang et al., 2021; Yi et al., 2021) and overall microbial biomass at 1% *w/w* (Blöcker et al., 2020). In some cases, observed effects are clearly deleterious (J. Wang et al., 2020; Y. Wang et al., 2021). However, shifts in the soil microbial community do not necessarily equate to changes in function. There is considerable debate about the ability of microbial community composition and structure to predict ecosystem function (Hicks et al., 2021). Soil macrofauna are also affected by microplastics. For example, microplastics cause oxidative stress and abnormal gene expression at a dosing level of 0.25% *w/w* for earthworms (*Eisenia fetida*) (Cheng et al., 2020; B. Li et al., 2021). Microplastic exposure perturbs the gut microbiota of some soil collembolans (*Folsomia candida*) (Zhu et al., 2018, Ju et al., 2019) and inhibits the movement of others (*Lobella sokamensis*) (Kim and An, 2019). Microplastics consumed by soil organisms can enter food chains and bioaccumulate, as was observed for earthworms and chickens (*Gallus domesticus*) (Huerta-Lwanga et al., 2017). Microplastics introduced into agricultural soils or in food waste can also be ingested by livestock and have been found in the manure of sheep (*Ovis aries*) (Beriot et al. 2021) and pigs (*Sus scrofa domesticus*) (J. Yang et al., 2021).

Recent research efforts also aim to assess the effect of microplastics on plant growth in agroecosystems. Delayed or reduced germination rates have been observed for rye grass (*Lolium perenne*) (Boots et al., 2019) and garden cress (*Lepidium sativum*) (Bosker et al., 2019; Pflugmacher et al., 2020) in the presence of microplastics. Microplastics also reduced root, shoot and/or total biomass growth at dosing rates of 1–2% *w/w* for wheat (*Triticum aestivum*) (Pflugmacher et al., 2021; Qi et al., 2018), 0.1–10% *w/w* for garden cress (Pflugmacher et al., 2020), 1–2% *w/w* for Chinese cabbage (*Brassica chinesis*) (M. Yang et al., 2021), 0.1–1% *w/w* for corn (*Zea mays*) (F. Wang et al., 2020), 0.2–0.6% *w/w* for rice (*Oryza sativa*) (Liu et al., 2021), 2% *w/w* for spring onion (*Allium fistolsum*) (de Souza Machado et al., 2019), and 1% *w/w* for lime trees (*Citrus aurantium*) (Enyoh et al., 2020). However, in some instances, biomass reductions were only observed for some polymer types but not others (de Souza Machado et al., 2019; Qi et al., 2018; F. Wang et al., 2020; M. Yang et al., 2021), at certain sizes but not others (Z. Li et al., 2020; M. Yang et al., 2021), or under certain soil pH conditions (Liu et al., 2021). Mechanisms by which microplastics affect plant growth are being explored and could be linked to oxidative damage (Dong et al., 2021; Jiang et al., 2019; Pignattelli et al., 2021). Recent studies report finding nanoplastics in tissues of cultivated crops (Azeem et al., 2021), including wheat (L. Li et al., 2020; Lian et al., 2020), radish (*Raphanus sativus*) (Tympa et al., 2021), lettuce (*Latuca sativa*) (Li et al., 2019; L. Li et al., 2020), corn (Sun et al., 2021), and cucumber (*cucumis sativus*) (Z. Li et al., 2021). Transpirational pull is credited as the main driving force for uptake of nanoplastics from plant roots into above-ground biomass in wheat (L. Li et al., 2020) and lettuce (Li et al., 2019). Nanoplastics have also been shown to translocate from plant leaves to roots via vascular bundles in maize (Sun et al., 2021). Further research is needed to better understand the effects of plastic size, shape, and charge on plastic uptake by plants (Sun et al., 2020).

While several studies report potential negative effects of microplastics in soil-plant systems, the existing data are not sufficient to fully evaluate the risks of microplastics in agricultural soils (Gouin et al., 2019, USEPA, 2021a). For instance, the lack of common units between microplastic ecotoxicity and abundance studies precludes evaluation of the environmental relevance of the microplastic doses at which negative effects are observed

(Leusch and Ziajahromi, 2021). Connors et al. (2017) suggest nine areas of improvement to advance the quality of environmental microplastic research, which we suggest should be applied in the context of food waste-derived soil amendments and agricultural soils: "1) Environmental relevance of test concentrations, 2) Provision of sufficient detail for converting particle concentrations, 3) Thorough characterization and/or description of test particles, 4) Detailed reporting of particle preparation techniques and [stability], 5) Analytical verification of test concentrations, 6) Consideration of the environmental relevance of particle size, 7) Inclusion of appropriate controls, 8) Consideration of endpoint applicability to environmental risk assessment framework, and 9) Reporting findings accurately, without conjecture beyond experimental limits."

7. Harmonizing Science and Policy

Prevailing scientific uncertainty creates a challenging context for policy design related to microplastics and food waste diversion efforts. Scientists continue to debate the risk posed by microplastics generally and the best course of action for risk management, with differing viewpoints (Backhaus and Wagner, 2020; Burton, 2017; Coffin et al., 2021; Gouin et al., 2019; Hale, 2018; Kramm et al., 2018). Most scientists continue to frame microplastic risks as uncertain, which stands in contrast to the prevailing media narrative that microplastics are emphatically harmful to humans and the environment (Völker et al., 2020). Multiple entities currently regulate microplastics in composts and/or digestates, despite the lack of scientific consensus on the risks posed by microplastics in soils more broadly and the relative contribution of contaminated organic amendments specifically. Thirteen states in the US (California, Iowa, Maryland, Minnesota, Montana, New

Hampshire, New York, North Carolina, Ohio, Rhode Island, South Carolina, Washington, and Wisconsin) have enacted regulatory limits on physical contaminants in compost, and the state of California regulates physical contaminants in both composts and digestates (USEPA, 2021a). Total physical contaminant limits (a category encompassing glass, metal, and other human-made inert materials in addition to plastics) range from 0.5 to 6% *w/w* with most falling in the 1–2% *w/w* range (USEPA, 2021a). Four of the thirteen states—California, Maryland, Ohio, Washington—have additional limits specifically for plastics or film plastics ranging from 0.1 to 2% *w/w* (USEPA, 2021a). Only five states specify a lower size threshold for consideration—4 mm in all cases—though testing requirements and detection limitations may implicitly determine the size fractions measured (USEPA, 2021a). Compost and digestate regulations tend to be more stringent outside the US, with limits largely falling between 0.25 and 0.5% *w/w* for total physical contaminants and between 0.05 and 0.5% *w/w* for plastics or film plastics (USEPA, 2021a). Most countries set the lower size threshold for consideration at 2 mm except for Germany, which regulates particles >1 mm (USEPA, 2021a).

There are multiple limitations to the existing regulatory approach to microplastic contamination in composts and digestates. First, regulatory standards are in units of *w/w,* while 50% of the studies we reviewed reported microplastic abundance in composts and/or digestates exclusively on a count per weight basis (**Table 1**). This results in a mismatch between science and policy whereby many existing studies cannot accurately inform regulatory limits. Second, due to an incomplete understanding of the risks posed by microplastics in soils under different conditions (e.g., dosing rates, edaphic factors, polymer types, size distributions etc.), allowable contamination levels and lower particles size thresholds may instead be determined by aesthetic concerns and detection limits rather than known risk (USEPA, 2021a). Third, regulating microplastics content in finished products, without considering the fertilizer value of the material or application rate, does not limit the ultimate flow of microplastics to soils via organic amendments. For example, under the current regulatory structure, it may be permissible to land apply a large amount of microplastics in a dilute form, but not a smaller amount of microplastics in a more concentrated form. Finally, regulating contamination levels in organic amendments alone may be insufficient to fully mitigate the flow of microplastics into agricultural soils given the existence of other entry points. There are other examples of narrowly focused microplastics policy that similarly do not address multiple pathways of introduction to the environment. For example, current or proposed policies in the US, EU, China and South Korea restrict the use of primary microplastics in cosmetic products, but exclude other sources of microplastics (e.g., plastic mulching, plastic packaging, tires) (Mitrano and Wohlleben, 2020).

There are, however, existing regulations that could be applicable to microplastics and should be considered in current discussions. Certain heavy metals in biosolids, for example, underwent rigorous toxicity assessments to determine allowable contamination thresholds grounded in scientific evidence (Lu et al., 2012). Currently, the same is not true for microplastics in composts and digestates; thus, current regulatory thresholds lack a scientific basis, and the benefits of those thresholds are largely unknown. Given the persistence of microplastics, uncertainties regarding toxicity, and the upward trend in both plastic production and environmental detection, some have argued for a more precautionary approach than the traditional regulatory paradigms for threshold contaminants (Coffin et al., 2021). This type of approach would create tradeoffs in the context of present-day food waste diversion efforts. For example, how should the more certain costs of methane emissions from landfilled food waste be weighed against the uncertain impacts of terrestrial microplastic pollution in cases where it is not possible to have 100% microplastic-free food waste? It is critical to consider counterfactual scenarios given the options available to clarify the consequences of microplastic regulations.

We propose the following path forward to better align efforts to quantify microplastics in organic amendments, understand their effects in soils, and establish related policy. First, standard methods for measuring microplastics in food wastes, composts, digestates and soils must be developed (**Figure 3A**). Second, using these standard methods, future studies should characterize both the extent of microplastic contamination in food wastes, composts, digestates, and soils as well as the sources, impacts, and most effective strategies to mitigate this contamination (**Figure 3B**). Third, if toxicity is well established, evidence- and risk-based regulatory measures can be implemented to reduce microplastic contamination from all sources (**Figure 3C**).

8. Conclusions

Microplastic abundance varies widely within and among studies of food wastes, composts, digestates, and agricultural soils. There is some evidence that microplastics may adversely affect soils and plants; however, lack of common units between microplastic ecotoxicity and abundance studies precludes rigorous assessment. Existing regulations establish weight-based limits in finished composts and digestates, which is incongruent with many scientific studies that use count-based estimates of microplastic abundance.

Further work is necessary to elucidate tradeoffs associated with diverting food waste to agricultural soils and to design policies that maximize the benefits of recovering food waste while minimizing risk of microplastic pollution in soils.

Acknowledgements

This work was supported by the Gund Institute for Environment at the University of Vermont (Gund Barrett PhD Fellowship for K.P.) and Casella Waste Systems, Inc. (Sustainable Materials Management Graduate Fellowship for S.H.). The funders had no role in the literature collection and interpretation, decision to publish, or preparation of the manuscript.

References

1. Azeem, I., Adeel, M., Ahmad, M.A., Shakoor, N., Jiangcuo, G.D., Azeem, K., Ishfaq, M., Shakoor, A., Ayaz, M., Xu, M., Rui, Y., 2021. Uptake and accumulation of nano/microplastics in plants: a critical review. Nanomaterials 11, 2935. https://doi.org/10.3390/nano11112935
2. Backhaus, T., Wagner, M., 2020. Microplastics in the environment: much ado about nothing? a debate. Glob. Chall. 4, 1900022. https://doi.org/10.1002/gch2.201900022
3. Beriot, N., Peek, J., Zornoza, R., Geissen, V., Huerta Lwanga, E., 2021. Low density-microplastics detected in sheep faeces and soil: A case study from the intensive vegetable farming in Southeast Spain. Sci. Total Environ. 755, 142653. https://doi.org/10.1016/j.scitotenv.2020.142653
4. Bianco, A., Passananti, M., 2020. Atmospheric Micro and Nanoplastics: An Enormous Microscopic Problem. Sustainability 12, 7327. https://doi.org/10.3390/su12187327
5. Billings, A., Jones, K.C., Pereira, M.G., Spurgeon, D.J., 2021. Plasticisers in the terrestrial environment: sources, occurrence and fate. Environ. Chem. 18, 111–130. https://doi.org/10.1071/EN21033
6. Blackburn, K., Green, D., 2021. The potential effects of microplastics on human health: what is known and what is unknown. Ambio. https://doi.org/10.1007/s13280-021-01589-9

7. Bläsing, M., Amelung, W., 2018. Plastics in soil: analytical methods and possible sources. Sci. Total Environ. 612, 422–435. https://doi.org/10.1016/j.scitotenv.2017.08.086

8. Blöcker, L., Watson, C., Wichern, F., 2020. Living in the plastic age - different short-term microbial response to microplastics addition to arable soils with contrasting soil organic matter content and farm management legacy. Environ. Pollut. 267, 115468. https://doi.org/10.1016/j.envpol.2020.115468

9. Boots, B., Russell, C.W., Green, D.S., 2019. Effects of microplastics in soil ecosystems: above and below ground. Environ. Sci. Technol. 53, 11496–11506. https://doi.org/10.1021/acs.est.9b03304

10. Bosker, T., Bouwman, L.J., Brun, N.R., Behrens, P., Vijver, M.G., 2019. Microplastics accumulate on pores in seed capsule and delay germination and root growth of the terrestrial vascular plant *Lepidium sativum*. Chemosphere 226, 774–781. https://doi.org/10.1016/j.chemosphere.2019.03.163

11. Braun, M., Mail, M., Heyse, R., Amelung, W., 2021. Plastic in compost: prevalence and potential input into agricultural and horticultural soils. Sci. Total Environ. 760, 143335. https://doi.org/10.1016/j.scitotenv.2020.143335

12. Brodhagen, M., Goldberger, J.R., Hayes, D.G., Inglis, D.A., Marsh, T.L., Miles, C., 2017. Policy considerations for limiting unintended residual plastic in agricultural soils. Environ. Sci. Pol. 69, 81–84. https://doi.org/10.1016/j.envsci.2016.12.014

13. Burton, G.A., 2017. Stressor exposures determine risk: so, why do fellow scientists continue to focus on superficial microplastics risk? Environ. Sci. Technol. 51, 13515–13516. https://doi.org/10.1021/acs.est.7b05463

14. Buzby, J.C., Farah-Wells, H., Hyman, J. The Estimated Amount, Value, and Calories of Postharvest Food Losses at the Retail and Consumer Levels in the United States. EIB-121, US Department of Agriculture, Economic Research Service, February 2014. https://doi.org/10.2139/ssrn.2501659

15. Castan, S., Henkel, C., Hueffer, T., Hofmann, T., 2021. Microplastics and nanoplastics barely enhance contaminant mobility in agricultural soils. Commun. Earth Environ. 2, 193. https://doi.org/10.1038/s43247-021-00267-8

16. Chen, Y., Leng, Y., Liu, X., Wang, J., 2020. Microplastic pollution in vegetable farmlands of suburb Wuhan, central China. Environ. Pollut. 257, 113449. https://doi.org/10.1016/j.envpol.2019.113449

17. Cheng, Y., Zhu, L., Song, W., Jiang, C., Li, B., Du, Z., Wang, Jinhua, Wang, Jun, Li, D., Zhang, K., 2020. Combined effects of mulch film-derived microplastics and atrazine on oxidative stress and gene expression in earthworm (*Eisenia fetida*). Sci. Total Environ. 746, 141280. https://doi.org/10.1016/j.scitotenv.2020.141280

18. Cheong, J.C., Lee, J.T.E., Lim, J.W., Song, S., Tan, J.K.N., Chiam, Z.Y., Yap, K.Y., Lim, E.Y., Zhang, J., Tan, H.T.W., Tong, Y.W., 2020. Closing the food waste loop: food waste anaerobic digestate as fertilizer for the cultivation of the leafy vegetable, xiao bai cai (*Brassica rapa*). Sci. Total Environ. 715, 136789. https://doi.org/10.1016/j.scitotenv.2020.136789

19. Coffin, S., Wyer, H., Leapman, J.C., 2021. Addressing the environmental and health impacts of microplastics requires open collaboration between diverse sectors. PLOS Biology 19, e3000932. https://doi.org/10.1371/journal.pbio.3000932

20. Connors, K.A., Dyer, S.D., Belanger, S.E., 2017. Advancing the quality of environmental microplastic research. Environ. Toxicol. Chem. 36, 1697–1703. https://doi.org/10.1002/etc.3829

21. Corradini, F., Casado, F., Leiva, V., Huerta-Lwanga, E., Geissen, V., 2021. Microplastics occurrence and frequency in soils under different land uses on a regional scale. Sci. Total Environ. 752, 141917. https://doi.org/10.1016/j.scitotenv.2020.141917

22. Dai, Y.C., Lin, Z.Y., Li, C.J., Xu, D.Y., Huang, W.F., Harder, M.K., 2016. Information strategy failure: personal interaction success, in urban residential food waste segregation. J. Clean. Prod. 134, 298–309. https://doi.org/10.1016/j.jclepro.2015.12.104

23. de Souza Machado, A.A., Kloas, W., Zarfl, C., Hempel, S., Rillig, M.C., 2018a. Microplastics as an emerging threat to terrestrial ecosystems. Global Change Biol. 24, 1405–1416. https://doi.org/10.1111/gcb.14020

24. de Souza Machado, A.A., Lau, C.W., Kloas, W., Bergmann, J., Bachelier, J.B., Faltin, E., Becker, R., Görlich, A.S., Rillig, M.C., 2019. Microplastics can change soil properties and affect plant performance. Environ. Sci. Technol. 53, 6044–6052. https://doi.org/10.1021/acs.est.9b01339

25. de Souza Machado, A.A., Lau, C.W., Till, J., Kloas, W., Lehmann, A., Becker, R., Rillig, M.C., 2018b. Impacts of microplastics on the soil biophysical

environment. Environ. Sci. Technol. 52, 9656–9665. https://doi.org/10.1021/acs.est.8b02212

26. do Carmo Precci Lopes, A., Robra, S., Müller, W., Meirer, M., Thumser, F., Alessi, A., Bockreis, A., 2019. Comparison of two mechanical pre-treatment systems for impurities reduction of source-separated biowaste. Waste Manag. 100, 66–74. https://doi.org/10.1016/j.wasman.2019.09.003

27. Dong, Y., Song, Z., Liu, Y., Gao, M., 2021. Polystyrene particles combined with di-butyl phthalate cause significant decrease in photosynthesis and red lettuce quality. Environ. Pollut. 278, 116871. https://doi.org/10.1016/j.envpol.2021.116871

28. DSM Environmental Services Inc, 2018. 2018 Vermont Waste Characterization.

29. ECHA, 2020. Background Document to the Opinion on the Annex XV report proposing restrictions on intentionally added microplastics, ECHA/RAC/RES-O-0000006790-71-01/F.

30. Edo, C., Fernández-Piñas, F., Rosal, R., 2021. Microplastics identification and quantification in the composted organic fraction of municipal solid waste. Sci. Total Environ. 151902. https://doi.org/10.1016/j.scitotenv.2021.151902

31. Edwards, J., Othman, M., Crossin, E., Burn, S., 2018. Life cycle assessment to compare the environmental impact of seven contemporary food waste management systems. Bioresour. Technol. 248, 156–173. https://doi.org/10.1016/j.biortech.2017.06.070

32. Enyoh, C.E., Verla, A.W., Verla, E.N., Enyoh, E.C., 2020. Effect of macro- and micro-plastics in soil on quantitative phytochemicals in different part of

juvenile lime tree (*Citrus aurantium*). Int. J. Environ. Res. 14, 705–726. https://doi.org/10.1007/s41742-020-00292-z

33. Fei, Y., Huang, S., Wang, J., Luo, Y., Zhang, H., 2020. Microplastics contamination in the protected agricultural soils and its effects on bacterial community diversity. Chin. Sci. Bull. 66, 1592–1601. https://doi.org/10.1360/TB-2020-0685

34. Feng, S., Lu, H., Liu, Y., 2021. The occurrence of microplastics in farmland and grassland soils in the Qinghai-Tibet plateau: different land use and mulching time in facility agriculture. Environ. Pollut. 279, 116939. https://doi.org/10.1016/j.envpol.2021.116939

35. Friege, H., Eger, Y., 2021. Best practice for bio-waste collection as a prerequisite for high-quality compost. Waste Manag. Res. 0734242X211033714. https://doi.org/10.1177/0734242X211033714

36. Gigault, J., ter Halle, A., Baudrimont, M., Pascal, P.Y., Gauffre, F., Phi, T.L., El Hadri, H., Grassl, B., Reynaud, S., 2018. Current opinion: what is a nanoplastic? Environ. Pollut. 235, 1030–1034. https://doi.org/10.1016/j.envpol.2018.01.024

37. Golwala, H., Zhang, X., Iskander, S.M., Smith, A.L., 2021. Solid waste: an overlooked source of microplastics to the environment. Sci. Total Environ. 769, 144581. https://doi.org/10.1016/j.scitotenv.2020.144581

38. Gouin, T., Becker, R.A., Collot, A.G., Davis, J.W., Howard, B., Inawaka, K., Lampi, M., Ramon, B.S., Shi, J., Hopp, P.W., 2019. Toward the development and application of an environmental risk assessment framework for

microplastic. Environ. Toxicol. Chem. 38, 2087–2100. https://doi.org/10.1002/etc.4529

39. Gouin, T., Roche, N., Lohmann, R., Hodges, G., 2011. A thermodynamic approach for assessing the environmental exposure of chemicals absorbed to microplastic. Environ. Sci. Technol. 45, 1466–1472. https://doi.org/10.1021/es1032025

40. Gui, J., Sun, Y., Wang, J., Chen, X., Zhang, S., Wu, D., 2021. Microplastics in composting of rural domestic waste: abundance, characteristics, and release from the surface of macroplastics. Environ. Pollut. 274, 116553. https://doi.org/10.1016/j.envpol.2021.116553

41. Guo, J.J., Huang, X.P., Xiang, L., Wang, Y.Z., Li, Y.W., Li, H., Cai, Q.Y., Mo, C.H., Wong, M.H., 2020. Source, migration and toxicology of microplastics in soil. Environ. Int. 137, 105263. https://doi.org/10.1016/j.envint.2019.105263

42. Hahladakis, J.N., Velis, C.A., Weber, R., Iacovidou, E., Purnell, P., 2018. An overview of chemical additives present in plastics: migration, release, fate and environmental impact during their use, disposal and recycling. J. Hazard. Mater. 344, 179–199. https://doi.org/10.1016/j.jhazmat.2017.10.014

43. Hale, R.C., 2018. Are the risks from microplastics truly trivial? Environ. Sci. Technol. 52, 931–931. https://doi.org/10.1021/acs.est.7b06615

44. Harms, I.K., Diekötter, T., Troegel, S., Lenz, M., 2021. Amount, distribution and composition of large microplastics in typical agricultural soils in northern Germany. Sci. Total Environ. 758, 143615. https://doi.org/10.1016/j.scitotenv.2020.143615

45. Hicks, L.C., Frey, B., Kjøller, R., Lukac, M., Moora, M., Weedon, J.T., Rousk, J., 2021. Toward a function- first framework to make soil microbial ecology predictive. Ecology. https://doi.org/10.1002/ecy.3594

46. Hu, C., Lu, B., Guo, W., Tang, X., Wang, X., Xue, Y., Wang, L., He, X., 2021. Distribution of microplastics in mulched soil in Xinjiang, China. Int. J. Agr. Biol. Eng. 14, 196–204. https://doi.org/10.25165/ijabe.v14i2.6165

47. Huang, B., Sun, L., Liu, M., Huang, H., He, H., Han, F., Wang, X., Xu, Z., Li, B., Pan, X., 2021. Abundance and distribution characteristics of microplastic in plateau cultivated land of Yunnan Province, China. Environ. Sci. Pollut. Res. 28, 1675–1688. https://doi.org/10.1007/s11356-020-10527-3

48. Huang, Y., Liu, Q., Jia, W., Yan, C., Wang, J., 2020. Agricultural plastic mulching as a source of microplastics in the terrestrial environment. Environ. Pollut. 260, 114096. https://doi.org/10.1016/j.envpol.2020.114096

49. Huerta Lwanga, E., Mendoza Vega, J., Ku Quej, V., Chi, J. de los A., Sanchez del Cid, L., Chi, C., Escalona Segura, G., Gertsen, H., Salánki, T., van der Ploeg, M., Koelmans, A.A., Geissen, V., 2017. Field evidence for transfer of plastic debris along a terrestrial food chain. Sci. Rep. 7, 14071. https://doi.org/10.1038/s41598-017-14588-2

50. Huerta-Lwanga, E., Mendoza-Vega, J., Ribeiro, O., Gertsen, H., Peters, P., Geissen, V., 2021. Is the polylactic acid fiber in green compost a risk for *Lumbricus terrestris* and *Triticum aestivum*? Polymers 13, 703. https://doi.org/10.3390/polym13050703

51. Iqbal, S., Xu, J., Allen, S.D., Khan, S., Nadir, S., Arif, M.S., Yasmeen, T., 2020. Unraveling consequences of soil micro- and nano-plastic pollution on soil-plant system: implications for nitrogen (N) cycling and soil microbial activity. Chemosphere 260, 127578. https://doi.org/10.1016/j.chemosphere.2020.127578

52. Isari, E.A., Papaioannou, D., Kalavrouziotis, I.K., Karapanagioti, H.K., 2021. Microplastics in agricultural soils: a case study in cultivation of watermelons and canning tomatoes. Water 13, 2168. https://doi.org/10.3390/w13162168

53. Jiang, X.J., Liu, W., Wang, E., Zhou, T., Xin, P., 2017. Residual plastic mulch fragments effects on soil physical properties and water flow behavior in the Minqin Oasis, northwestern China. Soil and Tillage Research 166, 100–107. https://doi.org/10.1016/j.still.2016.10.011

54. Jiang, X., Chen, H., Liao, Y., Ye, Z., Li, M., Klobučar, G., 2019. Ecotoxicity and genotoxicity of polystyrene microplastics on higher plant *Vicia faba*. Environ. Pollut. 250, 831–838. https://doi.org/10.1016/j.envpol.2019.04.055

55. Ju, H., Zhu, D., Qiao, M., 2019. Effects of polyethylene microplastics on the gut microbial community, reproduction and avoidance behaviors of the soil springtail, *Folsomia candida*. Environ. Pollut. 247, 890–897. https://doi.org/10.1016/j.envpol.2019.01.097

56. Junhao, C., Xining, Z., Xiaodong, G., Li, Z., Qi, H., Siddique, K.H.M., 2021. Extraction and identification methods of microplastics and nanoplastics in

agricultural soil: A review. J. Environ. Manag. 294, 112997. https://doi.org/10.1016/j.jenvman.2021.112997

57. Kawecki, D., Goldberg, L., Nowack, B., 2020. Material flow analysis of plastic in organic waste in Switzerland. Soil Use Manag. 00, 1–12. https://doi.org/10.1111/sum.12634

58. Kelley, A., Wilkie, A.C., Maltais-Landry, G., 2020. Food-based composts provide more soil fertility benefits than cow manure-based composts in sandy soils. Agriculture 10, 69. https://doi.org/10.3390/agriculture10030069

59. Kim, S.W., Liang, Y., Zhao, T., 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. https://doi.org/10.3389/fenvs.2021.681934

60. Kim, S.W. and An, Y.J. 2019. Soil microplastics inhibit the movement of springtail species. Environ. Int. 126: 699-706. https://doi.org/10.1016/j.envint.2019.02.067

61. Kramm, J., Völker, C., Wagner, M., 2018. Superficial or substantial: why care about microplastics in the Anthropocene? Environ. Sci. Technol. 52, 3336–3337. https://doi.org/10.1021/acs.est.8b00790

62. Kumar, V.M. and Sheela, M.A., 2021. Effect of plastic film mulching on the distribution of plastic residues in agricultural fields. Chemosphere 273, 128590. https://doi.org/10.1016/j.chemosphere.2020.128590

63. Leusch, F.D.L., Ziajahromi, S., 2021. Converting mg/L to particles/L: reconciling the occurrence and toxicity literature on microplastics. Environ. Sci. Technol. 55, 11470–11472. https://doi.org/10.1021/acs.est.1c04093

64. Li, B., Song, W., Cheng, Y., Zhang, K., Tian, H., Du, Z., Wang, Jinhua, Wang, Jun, Zhang, W., Zhu, L., 2021. Ecotoxicological effects of different size ranges of industrial-grade polyethylene and polypropylene microplastics on earthworms *Eisenia fetida*. Sci. Total Environ. 783, 147007. https://doi.org/10.1016/j.scitotenv.2021.147007

65. Li, J., Song, Y., Cai, Y., 2020. Focus topics on microplastics in soil: analytical methods, occurrence, transport, and ecological risks. Environ. Pollut. 257, 113570. https://doi.org/10.1016/j.envpol.2019.113570

66. Li, L., Luo, Y., Li, R., Zhou, Q., Peijnenburg, W.J.G.M., Yin, N., Yang, J., Tu, C., Zhang, Y., 2020. Effective uptake of submicrometre plastics by crop plants via a crack-entry mode. Nat. Sustain. 3, 929–937. https://doi.org/10.1038/s41893-020-0567-9

67. Li, L., Zhou, Q., Yin, N., Tu, C., Luo, Y., 2019. Uptake and accumulation of microplastics in an edible plant. Chin. Sci. Bull. 64, 928–934. https://doi.org/10.1360/N972018-00845

68. Li, Q., Zeng, A., Jiang, X., Gu, X., 2021. Are microplastics correlated to phthalates in facility agriculture soil? J. Hazard. Mater. 412, 125164. https://doi.org/10.1016/j.jhazmat.2021.125164

69. Li, Z., Li, Q., Li, R., Zhou, J., Wang, G., 2021. The distribution and impact of polystyrene nanoplastics on cucumber plants. Environ. Sci. Pollut. Res. 28, 16042–16053. https://doi.org/10.1007/s11356-020-11702-2

70. Li, Z., Li, R., Li, Q., Zhou, J., Wang, G., 2020. Physiological response of cucumber (*Cucumis sativus* L.) leaves to polystyrene nanoplastics pollution. Chemosphere 255, 127041. https://doi.org/10.1016/j.chemosphere.2020.127041

71. Lian, J., Wu, J., Xiong, H., Zeb, A., Yang, T., Su, X., Su, L., Liu, W., 2020a. Impact of polystyrene nanoplastics (PSNPs) on seed germination and seedling growth of wheat (*Triticum aestivum* L.). J. Hazard. Mater. 385, 121620. https://doi.org/10.1016/j.jhazmat.2019.121620

72. Liu, M., Lu, S., Song, Y., Lei, L., Hu, J., Lv, W., Zhou, W., Cao, C., Shi, H., Yang, X., He, D., 2018. Microplastic and mesoplastic pollution in farmland soils in suburbs of Shanghai, China. Environ. Pollut. 242, 855–862. https://doi.org/10.1016/j.envpol.2018.07.051

73. Liu, Y., Huang, Q., Hu, W., Qin, J., Zheng, Y., Wang, J., Wang, Q., Xu, Y., Guo, G., Hu, S., Xu, L., 2021. Effects of plastic mulch film residues on soil-microbe-plant systems under different soil pH conditions. Chemosphere 267, 128901. https://doi.org/10.1016/j.chemosphere.2020.128901

74. Lozano, Y.M., Lehnert, T., Linck, L.T., Lehmann, A., Rillig, M.C., 2021. Microplastic shape, polymer type, and concentration affect soil properties and plant biomass. Front. Plant. Sci. 12, 616645. https://doi.org/10.3389/fpls.2021.616645

75. Lu, Q., He, Z.L., Stoffella, P.J., 2012. Land application of biosolids in the USA: a review. Appl. Environ. Soil Sci. 2012, e201462. https://doi.org/10.1155/2012/201462

76. Mbachu, O., Jenkins, G., Kaparaju, P., Pratt, C., 2021. The rise of artificial soil carbon inputs: reviewing microplastic pollution effects in the soil environment. Sci. Total Environ. 780, 146569. https://doi.org/10.1016/j.scitotenv.2021.146569

77. Meixner, K., Kubiczek, M., Fritz, I., 2020. Microplastic in soil–current status in Europe with special focus on method tests with Austrian samples. AIMS Environ. Sci. 7(2), 174–191. https://doi.org/10.3934/environsci.2020011

78. Meng, F., Fan, T., Yang, X., Riksen, M., Xu, M., Geissen, V., 2020. Effects of plastic mulching on the accumulation and distribution of macro and micro plastics in soils of two farming systems in northwest China. PeerJ 8, e10375. https://doi.org/10.7717/peerj.10375

79. Mitrano, D.M., Wohlleben, W., 2020. Microplastic regulation should be more precise to incentivize both innovation and environmental safety. Nat Commun. 11, 5324. https://doi.org/10.1038/s41467-020-19069-1

80. Müller, A., Goedecke, C., Eisentraut, P., Piechotta, C., 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. https://doi.org/10.1186/s12302-020-00358-x

81. Ncube, L.K., Ude, A.U., Ogunmuyiwa, E.N., Zulkifli, R., Beas, I.N., 2020. Environmental impact of food packaging materials: a review of contemporary development from conventional plastics to polylactic acid based materials. Materials 13, 4994. https://doi.org/10.3390/ma13214994

82. Ng, E.L., Huerta Lwanga, E., Eldridge, S.M., Johnston, P., Hu, H.W., Geissen, V., Chen, D., 2018. An overview of microplastic and nanoplastic pollution in agroecosystems. Sci. Total Environ. 627, 1377–1388. https://doi.org/10.1016/j.scitotenv.2018.01.341

83. Nuelle, M.T., Dekiff, J.H., Remy, D., Fries, E., 2014. A new analytical approach for monitoring microplastics in marine sediments. Environmental Pollution 184, 161–169. https://doi.org/10.1016/j.envpol.2013.07.027

84. 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 (Master's thesis, University of Vermont, USA). Retrieved from https://scholarworks.uvm.edu/graddis/1015

85. O'Connor, J., Mickan, B., Siddique, K.H.M., Rinklebe, J., Kirkham, M.B., Bolan, N.S., 2022. Physical, chemical, and microbial contaminants in food waste management for soil application: A review. Environ. Pollut. 118860. https://doi.org/10.1016/j.envpol.2022.118860

86. Pflugmacher, S., Sulek, A., Mader, H., Heo, J., Noh, J.H., Penttinen, O.P., Kim, Y., Kim, S., Esterhuizen, M., 2020. The influence of new and artificial aged microplastic and leachates on the germination of *Lepidium sativum* L. Plants 9, 339. https://doi.org/10.3390/plants9030339

87. Pflugmacher, S., Tallinen, S., Mitrovic, S.M., Penttinen, O.P., Kim, Y.J., Kim, S., Esterhuizen, M., 2021. Case study comparing effects of microplastic derived from bottle caps collected in two cities on *Triticum aestivum* (wheat). Environments 8, 64. https://doi.org/10.3390/environments8070064

88. Piehl, S., Leibner, A., Löder, M.G.J., Dris, R., Bogner, C., Laforsch, C., 2018. Identification and quantification of macro- and microplastics on an agricultural farmland. Sci. Rep. 8, 17950. https://doi.org/10.1038/s41598-018-36172-y

89. Pignattelli, S., Broccoli, A., Piccardo, M., Felline, S., Terlizzi, A., Renzi, M., 2021. Short-term physiological and biometrical responses of *Lepidium sativum* seedlings exposed to PET-made microplastics and acid rain. Ecotoxicol. Environ. Saf. 208, 111718. https://doi.org/10.1016/j.ecoenv.2020.111718

90. Qi, R., Jones, D.L., Li, Z., Liu, Q., Yan, C., 2020. Behavior of microplastics and plastic film residues in the soil environment: a critical review. Sci. Total Environ. 703, 134722. https://doi.org/10.1016/j.scitotenv.2019.134722

91. Qi, Y., Beriot, N., Gort, G., Lwanga, E.H., Gooren, H., Yang, X., Geissen, V., 2020. Impact of plastic mulch film debris on soil physicochemical and hydrological properties. Environ. Pollut. 266, 115097. https://doi.org/10.1016/j.envpol.2020.115097

92. Qi, Y., Yang, X., Pelaez, A.M., Huerta Lwanga, E., Beriot, N., Gertsen, H., Garbeva, P., Geissen, V., 2018. Macro- and micro- plastics in soil-plant system: effects of plastic mulch film residues on wheat (*Triticum aestivum*) growth. Sci. Total Environ. 645, 1048–1056. https://doi.org/10.1016/j.scitotenv.2018.07.229

93. Rafique, A., Irfan, M., Mumtaz, M., Qadir, A., 2020. Spatial distribution of microplastics in soil with context to human activities: a case study from the urban center. Environ. Monit. Assess 192, 671. https://doi.org/10.1007/s10661-020-08641-3

94. Ren, X., Tang, J., Liu, X., Liu, Q., 2020. Effects of microplastics on greenhouse gas emissions and the microbial community in fertilized soil. Environ. Pollut. 256, 113347. https://doi.org/10.1016/j.envpol.2019.113347

95. Rillig, M.C., 2012. Microplastic in terrestrial ecosystems and the soil? Environ. Sci. Technol. 46, 6453–6454. https://doi.org/10.1021/es302011r

96. Rillig, M.C., Kim, S.W., Kim, T.Y., Waldman, W.R., 2021. The global plastic toxicity debt. Environ. Sci. Technol. 55, 2717–2719. https://doi.org/10.1021/acs.est.0c07781

97. Roy, E.D., 2017. Phosphorus recovery and recycling with ecological engineering: a review. Ecol. Eng. 98, 213–227. https://doi.org/10.1016/j.ecoleng.2016.10.076

98. Roy, E.D., Esham, M., Jayathilake, N., Otoo, M., Koliba, C., Wijethunga, I.B., Fein-Cole, M.J., 2021. Compost quality and markets are pivotal for sustainability in circular food-nutrient systems: a case study of Sri Lanka. Front. Sustain. Food Syst. 5, 748391.

99. Roy, P.K., Hakkarainen, M., Varma, I.K., Albertsson, A.C., 2011. Degradable polyethylene: fantasy or reality. Environ. Sci. Technol. 45, 4217–4227. https://doi.org/10.1021/es104042f

100. Ruggero, F., Gori, R., Lubello, C., 2020. Methodologies for microplastics recovery and identification in heterogeneous solid matrices: a review. J. Polym. Environ. 28, 739–748. https://doi.org/10.1007/s10924-019-01644-3

101. Ruggero, F., Porter, A.E., Voulvoulis, N., Carretti, E., Lotti, T., Lubello, C., Gori, R., 2021. A highly efficient multi-step methodology for the quantification of micro-(bio)plastics in sludge. Waste Manag. Res. 39, 956–965. https://doi.org/10.1177/0734242X20974094

102. Scheurer, M., Bigalke, M., 2018. Microplastics in Swiss floodplain soils. Environ. Sci. Technol. 52, 3591–3598. https://doi.org/10.1021/acs.est.7b06003

103. Schwinghammer, L., Krause, S., Schaum, C., 2020. Determination of large microplastics: wet-sieving of dewatered digested sludge, co-substrates, and compost. Water Sci. Tech. 84, 384–392. https://doi.org/10.2166/wst.2020.582

104. Serrano-Ruiz, H., Martin-Closas, L., Pelacho, A.M., 2021. Biodegradable plastic mulches: impact on the agricultural biotic environment. Sci. Total Environ. 750, 141228. https://doi.org/10.1016/j.scitotenv.2020.141228

105. Sholokhova, A., Ceponkus, J., Sablinskas, V., Denafas, G., 2021. Abundance and characteristics of microplastics in treated organic wastes of Kaunas and Alytus regional waste management centres, Lithuania. Environ. Sci. Pollut. Res. https://doi.org/10.1007/s11356-021-17378-6

106. Short-lived climate pollutants: methane emissions: dairy and livestock: organic waste: landfills, SB 1383. 2016.

107. Sobhani, Z., Fang, C., Naidu, R., Megharaj, M., 2021. Microplastics as a vector of toxic chemicals in soil: Enhanced uptake of perfluorooctane sulfonate and

perfluorooctanoic acid by earthworms through sorption and reproductive toxicity. Environ. Technol. Innov. 22, 101476. https://doi.org/10.1016/j.eti.2021.101476

108. Sommer, F., Dietze, V., Baum, A., Sauer, J., Gilge, S., Maschowski, C., Gieré, R., 2018. Tire abrasion as a major source of microplastics in the environment. Aerosol Air Qual. Res. 18, 2014–2028. https://doi.org/10.4209/aaqr.2018.03.0099

109. Stubenrauch, J., Ekardt, F., 2020. Plastic pollution in soils: governance approaches to foster soil health and closed nutrient cycles. Environments 7, 38. https://doi.org/10.3390/environments7050038

110. Sun, H., Lei, C., Xu, J., Li, R., 2021. Foliar uptake and leaf-to-root translocation of nanoplastics with different coating charge in maize plants. J. Hazard. Mater. 416, 125854. https://doi.org/10.1016/j.jhazmat.2021.125854

111. Sun, J., Dai, X., Wang, Q., van Loosdrecht, M.C.M., Ni, B.J., 2019. Microplastics in wastewater treatment plants: detection, occurrence and removal. Water Research 152, 21–37. https://doi.org/10.1016/j.watres.2018.12.050

112. Sun, Q., Li, J., Wang, C., Chen, A., You, Y., Yang, S., Liu, H., Jiang, G., Wu, Y., Li, Y., 2022. Research progress on distribution, sources, identification, toxicity, and biodegradation of microplastics in the ocean, freshwater, and soil environment. Front. Environ. Sci. Eng. 16, 1. https://doi.org/10.1007/s11783-021-1429-z

113. Sun, X.D., Yuan, X.Z., Jia, Y., Feng, L.J., Zhu, F.P., Dong, S.S., Liu, J., Kong, X., Tian, H., Duan, J.L., Ding, Z., Wang, S.G., Xing, B., 2020. Differentially

charged nanoplastics demonstrate distinct accumulation in *Arabidopsis thaliana*. Nat. Nanotechnol. 15, 755–760. https://doi.org/10.1038/s41565-020-0707-4

114. Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W.G., McGonigle, D., Russell, A.E., 2004. Lost at sea: where is all the plastic? Science 304, 838–838. https://doi.org/10.1126/science.1094559

115. Tympa, L.E., Katsara, K., Moschou, P.N., Kenanakis, G., Papadakis, V.M., 2021. Do microplastics enter our food chain via root vegetables? a Raman based spectroscopic study on *Raphanus sativus*. Materials 14, 2329. https://doi.org/10.3390/ma14092329

116. Universal recycling of solid waste. Sec. 6. 10 V.S.A. § 6605k. 2012.

117. USEPA, 2021a. Emerging Issues in Food Waste Management: Plastic Contamination (No. EPA/600/R-21/116).

118. USEPA, 2021b. Inventory of US Greenhouse Gas Emissions and Sinks 1990-2019 (No. EPA430- R-21– 005).

119. USEPA, 2020. Advancing Sustainable Materials Management: 2018 Fact Sheet.

120. van Schothorst, B., Beriot, N., Huerta Lwanga, E., Geissen, V., 2021. Sources of light density microplastic related to two agricultural practices: the use of compost and plastic mulch. Environments 8, 36. https://doi.org/10.3390/environments8040036

121. Völker, C., Kramm, J., Wagner, M., 2020. On the creation of risk: framing of microplastics risks in science and media. Glob. Chall. 4, 1900010. https://doi.org/10.1002/gch2.201900010

122. Wang, F., Zhang, X., Zhang, Shuqi, Zhang, Shuwu, Adams, C.A., Sun, Y., 2020. Effects of co-contamination of microplastics and Cd on plant growth and Cd accumulation. Toxics 8, 36. https://doi.org/10.3390/toxics8020036

123. Wang, J., Li, J., Liu, S., Li, H., Chen, X., Peng, C., Zhang, P., Liu, X., 2021. Distinct microplastic distributions in soils of different land-use types: a case study of Chinese farmlands. Environ. Pollut. 269, 116199. https://doi.org/10.1016/j.envpol.2020.116199

124. Wang, J., Liu, X., Dai, Y., Ren, J., Li, Y., Wang, X., Zhang, P., Peng, C., 2020. Effects of co-loading of polyethylene microplastics and ciprofloxacin on the antibiotic degradation efficiency and microbial community structure in soil. Sci. Total Environ. 741, 140463. https://doi.org/10.1016/j.scitotenv.2020.140463

125. Wang, J., Liu, X., Li, Y., Powell, T., Wang, X., Wang, G., Zhang, P., 2019. Microplastics as contaminants in the soil environment: a mini-review. Sci. Total Environ. 691, 848–857. https://doi.org/10.1016/j.scitotenv.2019.07.209

126. Wang, W., Ge, J., Yu, X., Li, H., 2020. Environmental fate and impacts of microplastics in soil ecosystems: progress and perspective. Sci. Total Environ. 708, 134841. https://doi.org/10.1016/j.scitotenv.2019.134841

127. Wang, Y., Wang, X., Li, Y., Liu, Y., Sun, Y., Xia, S., Zhao, J., 2021. Effects of coexistence of tetracycline, copper and microplastics on the fate of antibiotic resistance genes in manured soil. Sci. Total Environ. 790, 148087. https://doi.org/10.1016/j.scitotenv.2021.148087

128. Weithmann, N., Möller, J.N., Löder, M.G.J., Piehl, S., Laforsch, C., Freitag, R., 2018. Organic fertilizer as a vehicle for the entry of microplastic into the environment. Sci. Adv. 4, eaap8060. https://doi.org/10.1126/sciadv.aap8060

129. Xu, B., Liu, F., Cryder, Z., Huang, D., Lu, Zhijiang, He, Y., Wang, H., Lu, Zhenmei, Brookes, P.C., Tang, C., Gan, J., Xu, J., 2020. Microplastics in the soil environment: occurrence, risks, interactions and fate – a review. Crit. Rev. Environ. Sci. Technol. 50, 2175–2222. https://doi.org/10.1080/10643389.2019.1694822

130. Xu, F., Li, Yangyang, Ge, X., Yang, L., Li, Yebo, 2018. Anaerobic digestion of food waste – challenges and opportunities. Bioresour. Technol. 247, 1047–1058. https://doi.org/10.1016/j.biortech.2017.09.020

131. Yan, Y., Chen, Z., Zhu, F., Zhu, C., Wang, C., Gu, C., 2021. Effect of polyvinyl chloride microplastics on bacterial community and nutrient status in two agricultural soils. Bull. Environ. Contam. Toxicol. 107, 602–609. https://doi.org/10.1007/s00128-020-02963-1

132. Yang, J., Li, R., Zhou, Q., Li, L., Li, Y., Tu, C., Zhao, X., Xiong, K., Christie, P., Luo, Y., 2021. Abundance and morphology of microplastics in an agricultural soil following long-term repeated application of pig manure. Environ. Pollut. 272, 116028. https://doi.org/10.1016/j.envpol.2020.116028

133. Yang, M., Huang, D.Y., Tian, Y.B., Zhu, Q.H., Zhang, Q., Zhu, H.H., Xu, C., 2021. Influences of different source microplastics with different particle sizes and application rates on soil properties and growth of Chinese cabbage (*Brassica*

chinensis L.). Ecotoxicol. Environ. Saf. 222, 112480. https://doi.org/10.1016/j.ecoenv.2021.112480

134. Yi, M., Zhou, S., Zhang, L., Ding, S., 2021. The effects of three different microplastics on enzyme activities and microbial communities in soil. Water Environ. Res. 93, 24–32. https://doi.org/10.1002/wer.1327

135. Yu, L., Zhang, J., Liu, Y., Chen, L., Tao, S., Liu, W., 2021. Distribution characteristics of microplastics in agricultural soils from the largest vegetable production base in China. Sci. Total Environ. 756, 143860. https://doi.org/10.1016/j.scitotenv.2020.143860

136. Yu, Y., Flury, M., 2021. Current understanding of subsurface transport of micro- and nanoplastics in soil. Vadose Zone J. 20, e20108. https://doi.org/10.1002/vzj2.20108

137. Zhang, G.S., Liu, Y.F., 2018. The distribution of microplastics in soil aggregate fractions in southwestern China. Sci. Total Environ. 642, 12–20. https://doi.org/10.1016/j.scitotenv.2018.06.004

138. Zhang, G.S., Zhang, F.X., Li, X.T., 2019. Effects of polyester microfibers on soil physical properties: perception from a field and a pot experiment. Sci. Total Environ. 670, 1–7. https://doi.org/10.1016/j.scitotenv.2019.03.149

139. Zhang, J., Dong, P., Zhang, Y., Tian, Y., Liu, C., Sun, H., Wang, L., 2020. Quantitative evaluation of non-active land input of microplastics: a case of PET polymer. Chin. Sci. Bull. 66, 1563–1570. https://doi.org/10.1360/TB-2020-0694

140. Zhao, T., Lozano, Y.M., Rillig, M.C., 2021. Microplastics increase soil pH and decrease microbial activities as a function of polymer type and exposure time. Front. Environ. Sci. 9, 675803. https://doi.org/10.3389/fenvs.2021.675803

141. Zhou, B., Wang, J., Zhang, H., Shi, H., Fei, Y., Huang, S., Tong, Y., Wen, D., Luo, Y., Barceló, D., 2020. Microplastics in agricultural soils on the coastal plain of Hangzhou Bay, east China: multiple sources other than plastic mulching film. J. Hazard. Mater. 388, 121814. https://doi.org/10.1016/j.jhazmat.2019.121814

142. Zhou, Y., Wang, J., Zou, M., Jia, Z., Zhou, S., Li, Y., 2020. Microplastics in soils: a review of methods, occurrence, fate, transport, ecological and environmental risks. Sci. Total Environ. 748, 141368. https://doi.org/10.1016/j.scitotenv.2020.141368

143. Zhu, D., Chen, Q.L., An, X.L., Yang, X.R., Christie, P., Ke, X., Wu, L.H., Zhu, Y.G., 2018. Exposure of soil collembolans to microplastics perturbs their gut microbiota and alters their isotopic composition. Soil Biol. Biochem. 116, 302–310. https://doi.org/10.1016/j.soilbio.2017.10.027

144. Zhu, F., Zhu, C., Wang, C., Gu, C., 2019. Occurrence and ecological impacts of microplastics in soil systems: a review. Bull. Environ. Contam. Toxicol. 102, 741–749. https://doi.org/10.1007/s00128-019-02623-z

Table 1. Plastic abundance in composts, digestates and food wastes on a count basis.

Feedstock [d]	Abundance (particles kg^{-1} dry)	Sizes (mm)	Polymer Types [d]	Location	Reference
Compost					
Green waste	5733 ± 850 to 6433 ± 751	0.05–5	Mostly PP, also PE, nitrile rubber, PES	Lithuania	Sholokhova et al., 2021
Green waste	12 ± 8 to 46 ± 8	>0.0003	n/a	Germany	Braun et al., 2021
Green waste	1253 ± 561	0.03–2	PE, PP	Netherlands	van Schothorst et al., 2021
Green waste	82800 ± 17400	>1	PLA	Netherlands	Huerta-Lwanga et al., 2021
Household & green waste	20–24	>1	Mostly styrene-based polymers (PS etc.) & PE, also PES, PP, PET, PVC	Germany	Weithmann et al., 2018
Food waste	3783 ± 351 to 4066 ± 658	0.05–5	Mostly PE & PS, also PET, PP	Lithuania	Sholokhova et al., 2021
Household biowaste	32 ± 20	>0.0003	n/a	Germany	Braun et al., 2021
Rural domestic waste	2400 ± 358	0.05–5	Mostly PP, PE, also PES, PVC, PS, PE:PP, PU	China	Gui et al., 2021
OFMW digestate	39–102	1–5	Mostly PE & PVC, also PET, PS, PES, PUR, Other	Germany	Schwinghammer et al., 2020
OFMW	2800 ± 616	0.03–2	PE, PP	Netherlands	van Schothorst et al., 2021
OFMW	10000–30000	<0.025	Mostly PE, also PS, PP, PES, PVC, ACR	Spain	Edo et al., 2021
Unknown	5.2–42.8 (15.4) Mil [a]	<1	n/a	Austria	Meixner et al., 2020
Digestate					
OFMW	75–326 [c]	1–5	Mostly PES & PVC, also PP, PE, PET, PS, PA, EVA	Germany	Schwinghammer et al., 2020
Commercial biowaste	895	>1	n/a	Germany	Weithmann et al., 2018
Household biowaste	70–146	>1	Mostly styrene-based polymers (PS etc.), also PES, PE, PP, PET, PVC, PVDC, PA, PUR, latex- & cellulose-based polymers	Germany	Weithmann et al., 2018
Food Waste & Dairy Manure	1670	>1	n/a	USA	O'Brien, 2019
Unknown	0.6–38.7 (7.1) Mil [a]	<1	n/a	Austria	Meixner et al., 2020
Food Waste					
Grocery store	300000 [a]	n/a	n/a	USA	Golwala et al., 2021
Pulped food waste	1400 ± 150 [a]	0.1–2	Mostly Mater-Bi®, also PP, PE, PS, CE	Italy	Ruggero et al., 2021

Homogenized food waste	40 [c]	1–5	Mostly PE, also PP, PS	Germany	Schwinghammer et al., 2020

[a] dry/as-is not reconciled; [b] as-is; [c] estimated from graph; [d] Abbreviations: OFMW: organic fraction municipal waste; ACR: acrylic polymers; CE: cellophane; PA: polyamide; EVA: ethylene vinyl acetate; PE: polyethylene; PES: polyester; PET: polyethylene terephthalate; PLA: Polylactic acid; PP: polypropylene; PS: polystyrene; PU/PUR: polyurethane; PVC: polyvinyl chloride; PVDC: polyvinylidene chloride

Table 2. Plastic abundance in composts, digestates and food wastes on a *w/w* basis.

Feedstock [d]	Abundance (% *w/w* dry)	Sizes (mm)	Polymer Types [d]	Location	Reference
Compost					
Green waste	0.00024–0.0065	>0.5	n/a	Germany	Bläsing and Amelung, 2018
Green waste	0.0048 ± 0.0089 to 0.053 ± 0.05 [c]	>0.0003	n/a	Germany	Braun et al., 2021
Green waste	0.0237	1–5	Mostly PP, also PE, nitrile rubber, PES	Lithuania	Sholokhova et al., 2021
Food waste	0.0845	1–5	Mostly PE & PS, also PET, PP	Lithuania	Sholokhova et al., 2021
Biowaste	0.018	>0.5	n/a	Germany	Bläsing and Amelung, 2018
Household biowaste	0.1358 ± 0.0596	>0.0003	n/a	Germany	Braun et al., 2021
Urban organic waste	0.001–0.0102 [a]	All	PET	Germany	Müller et al., 2020
OFMW digestate	0.005–0.05 [c]	1–5	Mostly PE & PVC, also PET, PS, PES, PUR	Germany	Schwinghammer et al., 2020
Digestate					
Kitchen & green waste	0.12 ± 0.12 [b]	>6	n/a	Switzerland	Kawecki et al., 2020
Organic waste	0.0209–0.0776 [a]	All	PET	Germany	Müller et al., 2020
Food Waste + Dairy Manure	0.25	>1	n/a	USA	O'Brien, 2019
OFMW	0.01–0.0350 [c]	1–5	Mostly PES & PVC, also PP, PE, PET, PS, PA, EVA	Germany	Schwinghammer et al., 2020
Food Waste					
Kitchen & green waste	0.5 ± 0.46 [b]	>6	n/a	Switzerland	Kawecki et al., 2020
Homogenized food waste	0.025 [c]	1–5	Mostly PE, also PP and PS	Germany	Schwinghammer et al., 2020
Household biowaste	3.0–5.6 [d]	>2	n/a	Austria	do Carmo Precci Lopes et al., 2019
Household biowaste (mechanically sorted)	0.04–2.9	>2	n/a	Austria	do Carmo Precci Lopes et al., 2019

[a] dry/as-is not reconciled; [b] as-is; [c] estimated from graph; [d] calculated by mass balance; [e] Abbreviations: OFMW: organic fraction municipal waste; PA: polyamide; EVA: ethylene vinyl acetate; PE: polyethylene; PES: polyester; PET: polyethylene terephthalate; PP: polypropylene; PS: polystyrene; PUR: polyurethane; PVC: polyvinyl chloride

Table 3. Summary of microplastic abundance in agricultural soils by mulching practice.

Plastic Mulch Practice	**Agriculture Type**	**Mean Range (particles kg^{-1} dry)**	**Typical Order of Magnitude (particles kg^{-1} dry)**	**Sizes (mm)**	**Common Plastic Types Identified [a]**	**Soil Depth (cm)**	**Locations**	**References**
Mulched	Mixed vegetable, Tomatoes, Beans, Cotton, Watermelon, Rice, Corn, Sorghum	63–18760	10's–1000's	0.02–5, 0.05–5, 1–5, 0.0011–5, 0.00045–5, 0.007–5, 0.02–5, 0.02–2, 0.03–2	PE, PP, PA, PS, PES, PVC, ACR	0–6, 0–10, 0–30, 0–40, 0–80	China, Spain, India, Greece	Beriot et al., 2021; Hu et al., 2021; Huang et al., 2020, 2021; Isari et al., 2021; Liu et al., 2018; Meng et al., 2020; van Schothorst et al., 2021; Kumar and Sheela, 2021; J. Wang et al., 2021; Zhang and Liu, 2018; B. Zhou et al., 2020
Non-mulched	Mixed crop, Pasture, Grasslands, Peanut, Wheat, Paddy, Woodland, Orchard, Unspecified	0.34–5490	10's–1000's	0.0004–2, 0.02–1, 1–5, 0.03–2, 0.02–5	PE, PP, PES, PA, ACR, PVC, EVA, rayon	0–5, 0–10, 0–20, 0–30	China, Germany, Netherlands, Chile	Corradini et al., 2021; Q. Li et al., 2021; Piehl et al., 2018; van Schothorst et al., 2021; J. Wang et al., 2021; J. Yang et al., 2021; B. Zhou et al., 2020
Some mulched	Mixed crop, Farm / Grassland	4–1444	10's–1000's	0.00045–2, 1–5, 0.02–5	PE, PP, PA, PS	0–6, 0–25, 0–30	China, Germany	Feng et al., 2021; Harms et al., 2021; Yu et al., 2021
Not Specified	Mixed vegetable, Mixed crop, Unspecified	870–3712	100's–1000's	0.02–5, 0.01–2, 0.05–5	PA, PP, PS, PE, PVC	0–5, 0–20, n/a	China, Mexico, Pakistan	Chen et al., 2020; Huerta Lwanga et al., 2017; Rafique et al., 2020

[a] Abbreviations: ACR: acrylic polymers; EVA: ethylene vinyl acetate; PA: polyamide; PE: polyethylene; PES: polyester; PP: polypropylene; PS: polystyrene; PVC: polyvinyl chloride

Figure 1. Visible plastic contamination in (A) organic municipal solid waste compost windrows prior to screening (credit: E.D. Roy, S. Asia), (B) screw-press separated solid digestate from co-digestion of dairy manure and food waste (credit: E.D. Roy, United States), and (C–F) Putative microplastics found in food waste digestate (credit: K.K. Porterfield, United States).

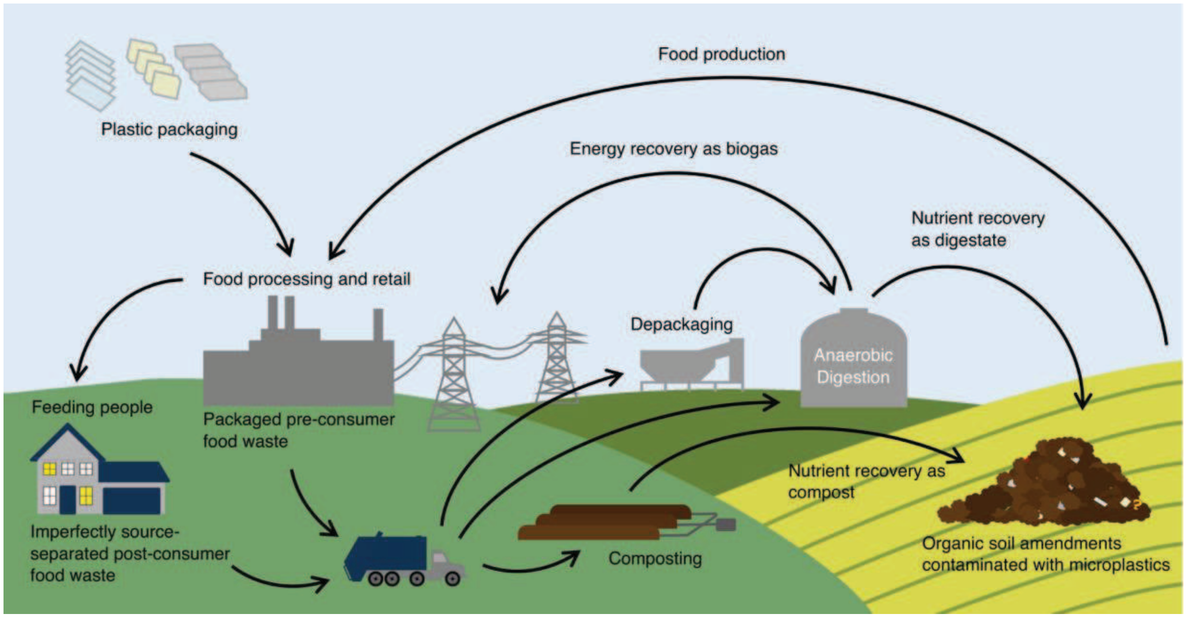

Figure 2. Conceptual diagram showing flows of food waste and microplastics to composting and anaerobic digestion and on to agricultural soils.

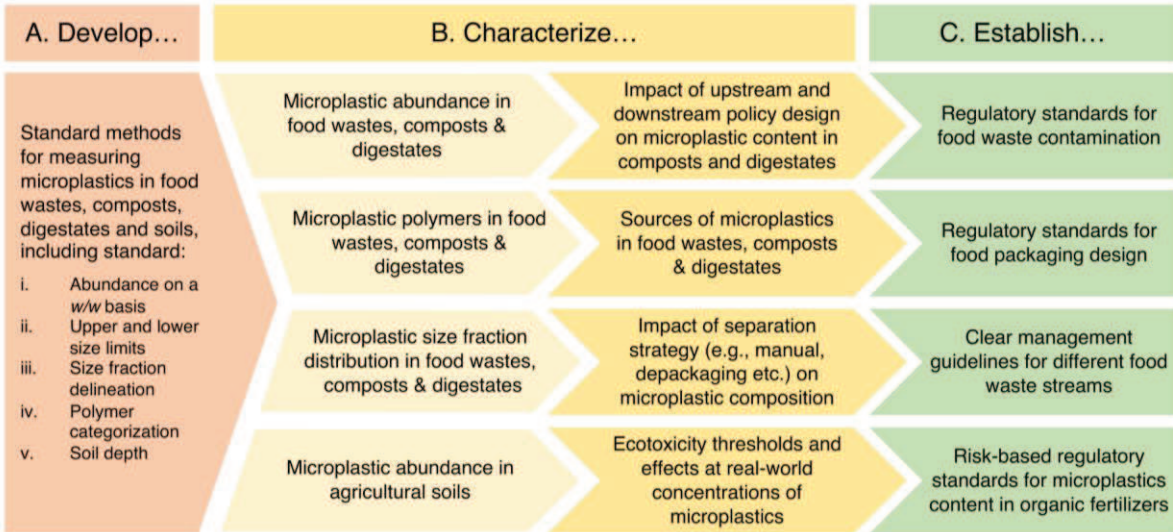

Figure 3. Schematic illustrating a design process to harmonize food waste microplastics science and policy.

Microplastics in Composts, Digestates and Food Wastes: A Review

Katherine K. Porterfield, Sarah A. Hobson, Deborah A. Neher, Meredith T. Niles,

Eric D. Roy

Supplementary Material

We conducted a systematic review using the Web of Science core collection to identify studies providing primary data on microplastics abundance in composts and digestates, food wastes and agricultural soils. One search focusing on composts and digestates was conducted on July 22nd, 2021 and another focusing on agricultural soils was conducted on September 8th, 2021 (**Table S1**). The two searches resulted in 172 and 159 articles, respectively. If the article abstract included quantification or discussion of microplastics in an organic waste stream, organic amendment, fertilizer derived from an organic waste stream, or an agricultural soil, the article was selected for further review, if not, it was excluded. Of the original articles, 32 and 94, respectively, were found to be relevant and 11 and 21, respectively, were found to contain primary data on microplastic abundance in composts and/or digestates and agricultural soils. Articles that focused on microplastic abundance in marine or aquatic environments were excluded, as were papers that focused on sewage sludge and biosolids. Additional studies beyond the ones identified by the systematic literature search were included if they were found to meet the established criteria.

Table S1. Web of Science search terms

	Compost & Digestate Search
Topic	"organic waste*" OR "organic residual*" OR "solid waste*" OR "compost*" OR "digestate*" OR "organic amendment*" OR "organic fertilizer*"
Topic	AND microplastic* OR nanoplastic*
	Agriculture Search
Topic	"agricultur*" OR "farm*" OR "horticultur*" OR "cultivat*" OR "agro"
Topic	AND microplastic* OR nanoplastic*
Topic	NOT "biosolid*" OR "wastewater*"OR "marine*" OR "aquatic" OR "wetland*"

Table S2. Microplastic abundance in plastic mulched agricultural soils.

Cropland Type	Abundance (particles kg^{-1} dry)	Sizes (mm)	Plastic Type [a]	Soil Depth (cm)	Location	Reference
Mixed vegetable	78 ± 13	0.02–5	Mostly PE & PP, also PES	0–3	China	Liu et al., 2018
Mixed vegetable	63 ± 13	0.02–5	Mostly PE & PP, also PES	3–6	China	Liu et al., 2018
Rice, corn, sorghum	571	0.05–5	Mostly PE & PE:PP, also PE:PP:Polydiene, PP:Vistalon, PP, nylon, PES, rayon, ACR, PA	0–10	China	B. Zhou et al., 2020
Mixed vegetable	2116 ± 1024	n/a	n/a	0–10	Spain	Beriot et al., 2021
Tomatoes, Beans	8–30	1–5	n/a	0–30	India	Kumar & Sheela, 2021
Cotton	1615 ± 52	0.0011–5	PE	0–30	China	Hu et al., 2021
Cotton	112 ± 11	0.0011–5	PE	40–80	China	Hu et al., 2021
Mixed vegetable	9000–40800 (9800)	0.00045–5	n/a	0–30	China	Huang et al., 2021
Mixed	80 ± 49 to 1076 ± 347	0.007–5	PE	0–40	China	Huang et al., 2020
Watermelon	301 ± 140	0.02–5	PE	0–30	Greece	Isari et al., 2021
Canning tomatoes	69 ± 38	0.02–5	PE	0–30	Greece	Isari et al., 2021
Mixed	0–2200	0.02–2	n/a	0–30	China	Meng et al., 2020
Mixed vegetable	2242 ± 984	0.03–2	PE	0–30	Spain	van Schothorst et al., 2021
Mixed vegetable	7100–42960 (18760)	0.05–10 [b]	n/a	0–10	China	Zhang and Liu, 2018
Mixed vegetable	5386 ± 835	0.02–5	Mostly PE & PA, also PVC, PP, PS, PES, ACR, other	n/a	China	J. Wang et al., 2021
Mixed vegetable (greenhouse)	5124 ± 632	0.02–5	Mostly PE & PA, also PVC, PP, PS, PES ACR, other	n/a	China	J. Wang et al., 2021

[a] Abbreviations: ACR: acrylic polymers; PA: polyamide; EVA: ethylene vinyl acetate; PE: polyethylene; PES: polyester; PP: polypropylene; PS: polystyrene; PVC: polyvinyl chloride, [b] macroplastics included

Table S3. Microplastic abundance in agricultural soils where no plastic mulching was used.

Cropland Type	Abundance (particles kg^{-1} dry)	Sizes (mm)	Polymer Types [a]	Soil Depth (cm)	Location	Reference
Mixed croplands	306 ± 360	0.0004–2	Mostly ACR, PUR, varnish, PE & EVA, also PP, Nitrile rubber, PS, Polyethylene chlorinated, PES, PA, PLA	0–20	Chile	Corradini al., 2021
Pasture	184 ± 266	0.0004–2	ACR, PUR, varnish, PE, EVA, PP, Nitrile rubber, Polyethylene chlorinated, PES	0–20	Chile	Corradini et al., 2021
Grass/ rangelands	none observed	0.0004–2	n/a	0–20	Chile	Corradini et al., 2021
Wheat	380–1093	0.02–1	Mostly PP, PE, PA & PET, also PS, PTFE, PVC, EVA	0–10	China	Li et al., 2021
Mixed vegetable farmlands; greenhouse	1000–3786	0.02–1	Mostly PP, PE, PA & PET, also PS, PTFE, PVC, EVA	0–10	China	Li et al., 2021
Unspecified Agricultural soils	0–1(0.34 ± 0.36)	1–5	Mostly PE, also PP, PS, PVC, PMMA, PET	0–5	Germany	Piehl et al., 2018
Mixed croplands	888 ± 500	0.03–2	PE, PP	0–30	The Netherlands	van Schothorst et al., 2021
Unspecified agricultural soils	16 ± 3	0.02–5	PES, PP, PE, rayon, PET	0–20	China	Yang et al., 2021
Peanut (pig manure mulched)	44 ± 16	0.02–5	PES, PP, PE, rayon, PET	0–20	China	Yang et al., 2021
Mixed croplands	263	0.05–5	Mostly PE & PE:PP, also PE:PP:Polydiene, PP:Vistalon, PP, nylon, PES, rayon, ACR, PA	0–10	China	B. Zhou et al., 2020
Wheat	3910 ± 1031	0.02–5	Mostly PE & PA, also PVC, PP, PS, PES, ACR	n/a	China	J. Wang et al., 2021
Paddy	5490 ± 573	0.02–5	Mostly PE & PA, also PVC, PP, PS, PES, ACR	n/a	China	J. Wang et al., 2021
Woodland	3683 ± 362	0.02–5	Mostly PE & PA, also PVC, PP, PS, PES, ACR	n/a	China	J. Wang et al., 2021
Orchard	3386 ± 593	0.02–5	Mostly PE & PA, also PVC, PP, PS, PES, ACR	n/a	China	J. Wang et al., 2021

[a] Abbreviations: ACR: acrylic polymers; PA: polyamide; EVA: ethylene vinyl acetate; PE: polyethylene; PES: polyester; PET: polyethylene terephthalate; PLA: Polylactic acid; PP: polypropylene; PS: polystyrene; PUR: polyurethane; PVC: polyvinyl chloride

Table S4. Microplastics abundance in agricultural soils where plastic mulching was used on some but not all sites.

Cropland Type	**Abundance (particles kg^{-1} dry)**	**Sizes (mm)**	**Polymer Types** [a]	**Soil Depth (cm)**	**Location**	**Reference**
Farm/grassland	53 ± 30	0.00045–2	Mostly PE, PP, PS & PA, also PET, PC, PVC	0–3	China	Feng et al., 2021
Farm/grassland	44 ± 22	0.00045–2	Mostly PE, PP, PS & PA, also PET, PC, PVC	3–6	China	Feng et al., 2021
Mixed croplands	0–218 (4 ± 12)	1–5	Mostly PE, also PP, nylon, PA, PVDF, PDAP, PMMA, PET, PVF, poly(1.4-Butylene Adipate), PVA, PVS	0–30	Germany	Harms et al., 2021
Mixed croplands	310–5698 (1444 ± 986)	0.02–5	PP, ethylene-propylene copolymer, PE	0–25	China	Yu et al., 2021

[a] Abbreviations: ACR: acrylic polymers; PA: polyamide; EVA: ethylene vinyl acetate; PC: polycarbonate; PDAP: polydiallylpthalate; PE: polyethylene; PES: polyester; PET: polyethylene terephthalate; PLA: Polylactic acid; PMMA: polymethyl methacrylate; PP: polypropylene; PS: polystyrene; PUR: polyurethane; PVA: polyvinyl acetate; PVC: polyvinyl chloride; PVDF: polyvinylidene fluoride; PVF: polyvinyl formal; PVS: polyvinyl stearate

Table S5. Microplastic abundance in agricultural soils where plastic mulch use was unspecified.

Cropland Type	Abundance (particles kg^{-1} dry)	Sizes (mm)	Polymer Types [a]	Soil Depth (cm)	Location	Citation
Mixed vegetable croplands	320–12560 (2020)	0.02–5	Mostly PP & PA, also PS, PE, PVC	0–5	China	Chen et al., 2020
Mixed crop gardens	870 ± 1900	0.01–2	n/a	0–20	Mexico	Huerta Lwanga et al., 2017
Unspecified agricultural soils	2200–6875 (3712 ± 2156)	0.05–5	n/a	n/a	Pakistan	Rafique et al., 2020

[a] Abbreviations: PA: polyamide; PE: polyethylene; PP: polypropylene; PS: polystyrene; PVC: polyvinyl chloride