

Review

Microplastics in Waste-Derived Fertilisers

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Abstract

Waste-derived fertilising materials, including sewage sludge, compost, digestate, food-waste-derived products and commercial organic or organo-mineral fertilisers, return nutrients to farmland but can also transfer microplastics to agricultural soil. This critical review examines their occurrence across these streams, analytical constraints, fate after application and the EU regulatory framework. Reported abundances span orders of magnitude and cannot be pooled because extraction, polymer identification and reporting are not harmonised, while particle-counting and mass-based methods measure different quantities. Field evidence indicates topsoil retention and accumulation after repeated application, whereas crop transfer and field-scale ecological effects remain poorly quantified. Regulation (EU) 2019/1009 sets no microplastic-specific product limit. For compost qualifying as CMC 3 and digestate other than fresh crop digestate qualifying as CMC 5, it controls plastic impurities above 2 mm by mass, while smaller particles remain outside that criterion. Waste-derived fertilisers can therefore form a recurrent, incompletely regulated pathway for microplastic transfer to soil. Controlled studies demonstrate hazard potential for selected particles and exposure conditions, but the magnitude and likelihood of effects under field conditions remain uncertain. The immediate priority is harmonised monitoring and reporting of the sub-2 mm fraction, including a stated lower size limit, polymer-confirmed particle counts and minimum QA/QC.

Keywords: microplastics; waste-derived fertilisers; biosolids; compost; digestate; polymer identification; agricultural soil; circular economy; EU Fertilising Products Regulation

1. Introduction

Plastic in the environment fragments and is redistributed across compartments rather than being removed. Particles from 1 µm to below five millimetres—microplastics—are now detected across every major environmental compartment, yet terrestrial systems remain comparatively understudied relative to the ocean and freshwater, where most early work was done [1]; soil microplastics are now an established research focus in their own right, reviewed across methods, occurrence, sources and risk [2]. Many conventional microplastic polymers are highly persistent, interacting with the abiotic environment and assisting the transport of other contaminants [1].

Wastewater treatment removes microplastics efficiently from the water line, holding up to 99% of them in the sludge, which is then spread on fields as a fertiliser [3]. A widely cited 2016 model provided an early estimate of the possible scale of this input. Combining sludge-management data with assumptions about sludge application rates and the plastic content of sludge, that analysis put the annual addition at 63,000 to 430,000 tonnes to Eu-

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ropean farmland and 44,000 to 300,000 tonnes to North American farmland, quantities exceeding the microplastic exported to the oceans over the same period [4]. These are scenario-based estimates rather than measured inventories and are best read as order-of-magnitude bounds on the input rather than as current figures. Based on that estimate, agricultural soil behaves as a long-term reservoir rather than a transient sink. Later field measurements support the occurrence and persistence of sludge-derived particles but do not validate the continental tonnage estimates: across a soil time series from 1966 to 2022, microplastic concentrations rose faster in fertilised soils—organic or mineral—marking agricultural soil as a receptor and long-term reservoir [5].

Sewage sludge is the most studied of these inputs but not the only one. In this review, “waste-derived fertilisers” covers waste-derived fertilising products and soil amendments: composts, digestates, biosolids, processed organics and market-ready organic or organo-mineral products. The same waste-to-soil logic governs compost, anaerobic digestate, processed food waste and the commercial organic and organo-mineral fertilisers made from them. These products differ in feedstock and processing, yet share an origin in waste biomass and a destination in food-producing soil. They are grouped here on that shared waste-to-soil logic, not because one legal instrument governs them all: the EU Fertilising Products Regulation applies to CE-marked fertilising products, whereas sewage sludge applied directly to land falls under separate rules (Section 6).

EU policy actively promotes these products and is widening their market. Regulation (EU) 2019/1009 [6], the EU Fertilising Products Regulation, was built to bring recycled and waste-derived fertilisers onto the single market, recover phosphorus and nitrogen from waste, and cut dependence on imported mineral fertilisers. The resource-recovery rationale is well established: phosphate rock is a critical raw material of low EU availability, and phosphorus recovered from sewage sludge could in principle cover a substantial share of European demand [7]. The difficulty is that the routes designed to return nutrients to soil can also carry microplastics into it. Policies that scale nutrient recovery may also scale this contaminant pathway unless quality controls are strengthened.

The tension persists for three reasons. Occurrence is reported widely but in units that do not align because extraction and identification methods are not harmonised, so the numbers cannot be pooled or ranked. The framework governing these products sets no microplastic-specific limit and no method, while the debate over effects is clouded by toxicity studies run far above field concentrations [8]. Existing reviews tend to take one slice—microplastics in sludge, in soil, the route from organic fertiliser into soil [9], or their effects on plants—rather than following the particle from feedstock to field to regulation across the full range of products.

This review takes a broader scope than earlier syntheses. It examines occurrence across the main waste-derived fertiliser streams: sewage sludge and biosolids, compost, digestate and food waste, and processed commercial products (Section 2). It then evaluates their sources and entry points (Section 3), the analytical challenges that make occurrence data non-comparable (Section 4), and particle transfer and fate after application (Section 5). It then considers the EU regulatory framework and its gaps (Section 6), the resulting tension with circular-economy policy (Section 7), and future directions (Section 8). The argument drawn from this evidence is that waste-derived fertilisers function as a systemic vector for microplastics into agricultural soil. A vector is termed systemic here where microplastic entry is intrinsic to the waste-to-soil recycling chain, arising from packaging, textiles or in-process fragmentation, and is not fully removed by current separation and screening technology. The term describes a recurrent route; it does not imply that every waste-derived fertiliser is contaminated, or that this route dominates other agricultural sources. The application of these products to land is deliberate and routine; the microplastic they carry is not intentionally added but arrives as a feature of the feedstock

and its processing that present controls do not eliminate. This distinguishes the route from diffuse sources such as atmospheric fallout or mulch film because it recurs through organised waste collection, treatment and land application (Figure 1).

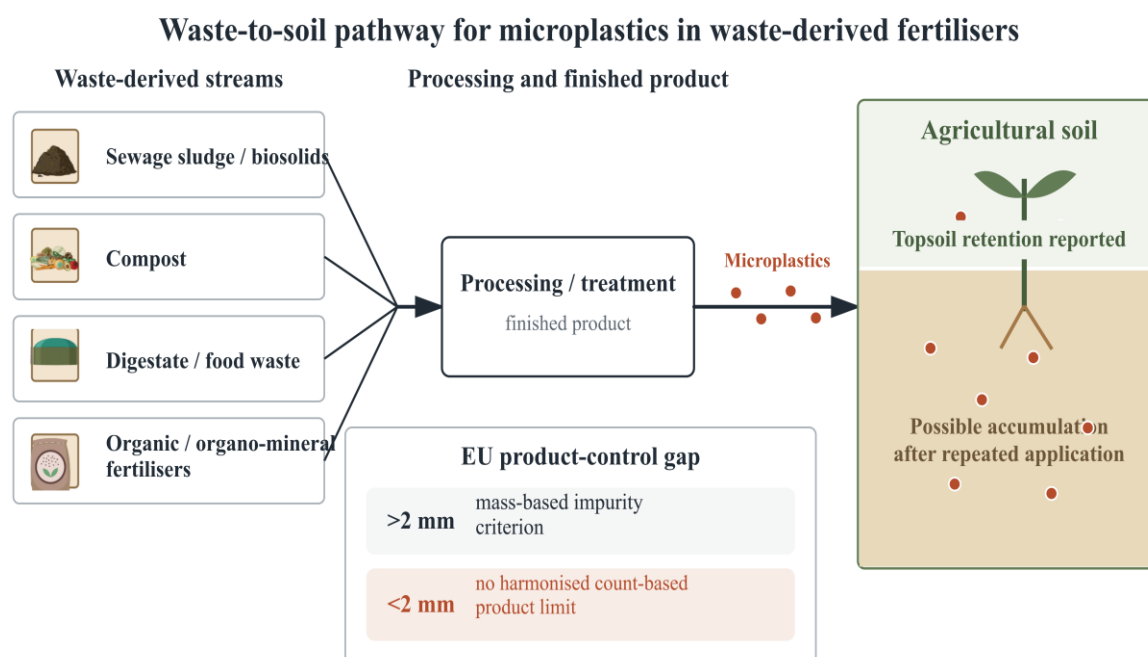


Figure 1. Waste-to-soil pathway by which waste-derived fertilisers can act as a systemic microplastic pathway into agricultural soil. Red dots represent microplastic particles. The figure links feedstock streams, processing and entry points, the 2 mm regulatory threshold, topsoil retention and the regulatory gap for the sub-2 mm fraction. The 2 mm mark denotes the mass-based impurity criterion of Regulation (EU) 2019/1009 applicable to compost qualifying as CMC 3 and digestate other than fresh crop digestate qualifying as CMC 5; it is not a treatment-stage screen size. The criterion is specific to Regulation (EU) 2019/1009 and should not be read as applying universally; requirements vary across jurisdictions, including those from which much of the occurrence evidence in Table 1 originates (Section 6).

The evidence base sets the limits of this review. Unit incomparability prevents a pooled estimate of soil loading, so the review argues from the structure of the evidence rather than a single figure and treats the soil-to-food step, the least evidenced link, with matching caution.

Review Approach

This is a critical review rather than a systematic one. No meta-analysis was attempted because the occurrence units reported in the primary literature are not interconvertible (Section 4.1).

Information sources. The evidence base was assembled through the parallel routes summarised in Figure 2. These comprised the main Scopus Advanced Search; supplementary Scopus AI-assisted candidate identification during revision; backward and forward citation tracing from key studies and reviews; and a separate Boolean Scopus search on microplastic release from plastic recycling (Section 3), a theme the fertiliser-focused query does not retrieve by design. Primary legal and standardisation texts were retrieved from EUR-Lex, the United States Environmental Protection Agency and the ISO catalogue. The ISO catalogue was last consulted on 17 July 2026 for the status and scope of work items under ISO/TC 61/SC 14. Scopus was used as the single bibliographic database because it indexes the environmental-engineering, soil-science and analytical-chemistry journals in

which this literature appears and, unlike Google Scholar, returns a reproducible and filterable record set. The omission of Web of Science is a limitation, noted below.

Search strategy. The search was performed on 17 July 2026 and covered publication years 2015 to 2026. The full string was: TITLE-ABS-KEY((microplastic* OR nanoplastic*) AND (sludge* OR biosolid* OR compost* OR digestat* OR “anaerobic digestion” OR “food waste” OR biowaste OR “bio-waste” OR “organic fertili*” OR organomineral* OR “organo-mineral*” OR “soil amendment*” OR “soil improver*” OR “bio-based fertili*” OR “waste-derived*” OR vermicompost*)) AND PUBYEAR > 2014 AND PUBYEAR < 2027. The asterisk denotes the Scopus truncation wildcard. The search returned 2489 records, of which 2201 were journal articles, reviews or notes; 288 records of other document types were set aside before appraisal. The identification route is summarised in Figure 2.

Use of AI-assisted tools. Scopus AI (Elsevier, Amsterdam, The Netherlands) was used for thematic exploration and candidate-source identification. Three queries were run on 5 June 2026—‘Microplastic contamination in organic fertilisers’, ‘Challenges in microplastics detection in soil’ and ‘EU Fertilising Products Regulation and microplastics’—and one on 17 July 2026, ‘Microplastics in agricultural soils’. The revision route returned 82 records: 24 duplicated the main set and 58 were additional candidates. AI outputs were not used as evidence or to make inclusion or interpretation decisions. The author verified all sources and data and made all inclusion and interpretation decisions.

Eligibility. A source was eligible where its subject was microplastic occurring in, entering or measured in a waste-derived fertilising material; microplastic in soil receiving such materials, where the amendment route was material to the study; analytical methods for these organic-rich matrices; fate after application; or the regulation of plastic content in these products. Studies of aquatic compartments, and studies of soil microplastic attributable only to other sources such as mulch film, tyre wear or atmospheric deposition, fall outside this scope; they are cited where they provide context, but they contribute no occurrence values.

Selection and appraisal. Sources were selected and appraised by the author. The Scopus search documents the breadth and provenance of the evidence base; it was not applied as a per-record systematic screening cascade, and no screening log was maintained, so counts of records screened and excluded at title and abstract or full-text stages are not reported. Reconstructing such counts after the event would misrepresent how the review was conducted. Of the 96 scholarly sources cited here, 52 fall within the main Scopus record set; the remaining 44 were identified through citation tracing and the targeted thematic searches described above, and address contextual topics that a fertiliser-focused query does not retrieve by design (Figure 2).

Data extraction. For each occurrence study included in Table 1, the following were recorded, in the units of the source and without conversion: region; material and feed-stock; reported abundance and reporting unit; dominant polymers; predominant particle shape; extraction and detection method; lower particle-size limit; and QA/QC and blank-correction practice. Source pathways and control points were synthesised separately in Table 2. Count- and mass-based values were not converted into one another (Section 4.1). Where a value could not be extracted from the consulted source it is marked as not reported.

Limitations of the approach. The review draws on a single database, on English-language sources and on a single appraiser. The exact Boolean string used for the supplementary search on microplastic release from plastic recycling was not retained, which limits the reproducibility of that one supplementary route; the main search and the Scopus AI queries are reported in full. The occurrence corpus is geographically uneven and leans on studies from outside the European Union, so statements about products on the EU

market rest on a base that is global rather than European. These constraints are revisited in Section 7.

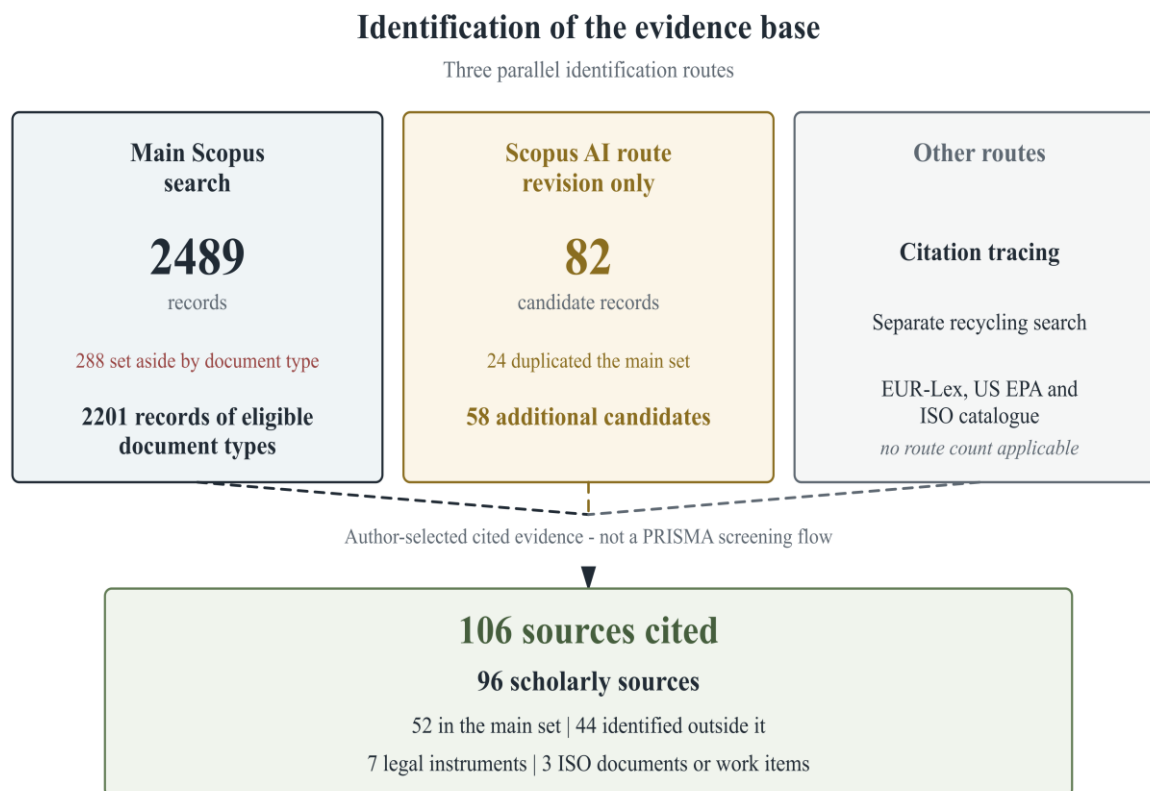


Figure 2. Identification of the evidence base for this review. The main Scopus Advanced Search of 17 July 2026 returned 2489 records, of which 2201 were eligible document types. A supplementary Scopus AI-assisted candidate-identification route used during revision returned 82 records, of which 24 duplicated the main set and 58 were additional candidates. The searches document the breadth and provenance of the evidence base; they were not applied as a per-record systematic screening cascade, and no screening log was maintained, so counts of records screened and excluded are not reported. Of the 96 scholarly sources cited, 52 fall within the main search set and 44 were identified outside it. Seven further sources are EU and US legal instruments; of the three standards documents, one is a published international standard and two are ISO work items under development. Scopus AI was also used for thematic scoping during preparation of the original manuscript (5 June 2026); that use is disclosed in Section Review Approach and is omitted here as a numbered branch, because the candidate records it surfaced were not logged separately. AI-generated summaries and key-findings tables were not used as evidence or as sources of numerical data, and no record was excluded solely on the basis of an AI-generated label. All inclusion, exclusion and interpretation decisions were made by the author. The 44 sources identified outside the main search set address contextual topics—environmental fate, analytical method development, ecotoxicology, human exposure and polymer degradation—that a fertiliser-focused query does not retrieve by design.

2. Waste-Derived Fertilisers as Microplastic Carriers

2.1. Sewage Sludge and Biosolids

Sewage sludge is the most extensively documented carrier of microplastics among waste-derived fertilisers, since it concentrates the particles removed during wastewater treatment; Jiang et al. [10] tracked that transfer from the water line into the sludge filter cake at a Chinese plant. Okoffo et al. [11] estimated that biosolids received around 340 g

of plastic per person in 2021 and projected that the annual global release to agricultural land would continue to rise towards mid-century, framing sludge recycling as a growing input rather than a stabilising one. Direct measurements are available for sludge itself, although concentrations in individual samples cannot validate a continental-scale annual estimate. Schell et al. [12] recorded 5972–7771 MP/kg dw in sewage sludge applied to Spanish farmland, and a compilation by Hooge et al. [3] spanned 1–165 MP/g dw, with 4196–15,385 particles/kg measured across seven treatment plants. In stabilised sludge marketed as fertiliser in Poland, Worek et al. [13] isolated roughly 460 mg of microplastic per 100 g of product, dominated by polyethylene.

Particle morphology and polymer composition recur across these studies. Fragments and fibres prevail; polyethylene and polypropylene dominate the fragments, polyester the fibres [12]. The fibre fraction is plausibly textile-derived. Rimmaudo et al. [14] found that high-density fibres, likely polyester from domestic laundering, made up 55.8–66.4% of the microplastic in Scottish anaerobically digested biosolids, accompanied by more than 20,000 cellulosic microfibrils per gram; biosolids carried the highest load (34–160 particles/g dw) of the amendments examined.

Once applied, sludge-borne particles persist. In a 25-year field experiment, Ramage et al. [15] showed that sludge application raised soil microplastic abundance by 723–1445% and that the elevated level held roughly constant for at least 22 years, with microfibrils and microfilms degrading while other shapes resisted breakdown. Sludge forms a durable deposit rather than a transient one (Section 5). This rests on a single 25-year field site, so it anchors the persistence of the standing stock rather than establishing a general accumulation rate. A separate historical time series points the same way: Cusworth et al. [5] found microplastic concentrations rising in fertiliser-amended soils between 1966 and 2022, consistent with long-term accumulation.

The reported values retain the units of their sources and are not pooled; Section 4.1 explains the resulting limits on comparison, and the global variation catalogued by Harley-Nyang et al. [16] reflects method as much as material. Surveys nevertheless consistently identify sludge as the principal sink for microplastics removed at treatment plants [17–19].

2.2. Compost

Composting is another major route by which microplastics reach soil. During processing, plastic already present in the feedstock can fragment into microplastic particles rather than merely being carried through the system. This redistributes existing plastic into smaller size classes; it does not create new plastic material. Risku et al. [20] traced the breakdown of larger plastic items into microplastics during industrial composting at a biowaste facility, and Peneva et al. [21] followed plastic input and dynamics across an industrial composting line. Mechanical handling, shredding and turning convert packaging residues into smaller fragments that slip through final screening [22].

Early systematic sampling established the pattern: Weithmann et al. [23] found microplastic in every compost and digestate fertiliser sampled from biowaste plants, with loads differing by pretreatment, plant and waste type. Reported abundances span several orders of magnitude. Porterfield et al. [24] compiled green-waste compost values from 12 ± 8 to $82,800 \pm 17,400$ particles/kg dw, with one compost of unknown origin reaching 4.28×10^7 particles/kg dw, and food-waste compost from 20 to 30,000 particles/kg dw; by mass these correspond to 0.00024–1% and 0.001–0.136% *w/w*. Across eleven commercial composts, Bayo et al. [25] measured 137.65 ± 6.01 items/kg dw and up to 631.14 mg/kg dw, with films larger than 1 mm being the dominant shape and fifteen polymer types identified by attenuated total reflectance Fourier-transform infrared spectroscopy (ATR-FTIR); eco-labelled products carried less. Steiner et al. [22] reported that liquid fertiliser sepa-

rated from biowaste digestion held up to 10,000 particles/L (10–1000 µm), while the finished composts likely stayed below the European compost-purity limit (Section 6).

Polymer composition points to packaging as the main source: polyethylene, polypropylene and polylactic acid recur, alongside compostable materials such as Mater-Bi and cellulose-based films [24]. Municipal solid waste compost is a recurring concern, with contamination reported across facilities in Lithuania, Uganda and elsewhere [26–28]. Compost-borne particles also move into crops: Naeem et al. [29] traced microplastics from compost into lettuce, a transfer pathway returned to in Section 5.

The same unit and method constraints apply to these compost data (Section 4.1) [30,31]. The compost-purity thresholds applied in the European Union and Germany remain the only quantitative limits touching these products, and they address visible plastic by mass rather than microplastic counts (Section 6).

2.3. Digestate and Food Waste

Anaerobic digestion and food-waste processing connect household organic waste with farmland and can carry microplastics through the same route. In the studies compiled by Porterfield et al. [24], reported digestate counts were generally lower than compost counts, although both material groups spanned wide ranges. Digestate values ranged from 70 to 1670 particles/kg dw for commercial organic waste and co-digested manure and food waste, with one digestate of unknown origin reaching 3.87×10^7 particles/kg dw, equivalent to 0.01–0.25% *w/w*. Food waste carries plastic before any processing: the same review reported 36 to 1400 particles/kg dw in homogenised food waste, a single grocery-waste survey at 300,000 particles/kg dw, and a mass range of 0.025–5.6% *w/w*, the upper figure from source-separated household biowaste.

When several feedstock streams are processed together, their microplastic signatures overlap. Lu et al. [32] measured 1500–16,000 MP/kg dw (7–760 mg/kg dw) across Australian compost, digestate and dehydrated food waste, with most particles between 25 and 500 µm; polypropylene and polyethylene predominated, and polyester fibres were also present; fragments made up 62–97% of the count. The authors identified compostable bin liners as one source and estimated that 5.2×10^{10} to 6.2×10^{12} particles could reach Australian land each year through these products.

The feedstock of a digester governs its microplastic load. Plants treating mainly sewage sludge route those particles through the biogas process [33], and the anaerobic step complicates detection: Lessa Belone et al. [34] reported that factors in a sludge-fed digester affected Raman identification of the particles, a limitation taken up in Section 4. Outside the EU Fertilising Products Regulation, digestate legislation reviewed in [35] is often framed around bulk quality, with pollutant and ecotoxicity concerns noted but few binding microplastic limits (Section 6).

Differences between digestate and compost cannot be interpreted independently of the unit and method effects described in Section 4.1 (Table 1).

2.4. Commercial and Processed Organic Fertilisers

The streams above often reach farmland through waste-management infrastructure. Where products are CE-marked, commercial organic fertilisers and qualifying compost or digestate products fall directly within the EU fertilising-products framework; directly land-applied wastes follow other legal routes. Processing lowers the load without eliminating it. Xu et al. [36] measured 9210.4 ± 1743.1 items/kg across 23 commercial organic fertilisers, significantly below the $24,344.1 \pm 2697.2$ items/kg of farm composts, with products made from plant material through mechanical shredding and sieving carrying less than manure-based ones; particles were mostly smaller than 3 mm, fibrous and black. Scaling their measurements, the authors estimated a flux on the order of 1014 items per

year to the Chinese environment, comparable to sewage sludge, and 2.1×10^7 to 4.7×10^7 items per hectare each year at recommended doses.

Market surveys in other regions show a similar pattern at different reported concentrations. Rana et al. [37] sampled 18 organic fertilisers from Bangladeshi markets and found 1529.62 ± 420.2 items/kg, ranging from 433.33 to 3466.67 items/kg between products, with fibres dominant, black the commonest colour and particles concentrated at 0.5–1.0 mm; applying polymer-hazard, pollution-load and ecological-risk indices, they returned scores from hazard category III to extreme danger. The polymers identified included nylon, nitrile, ethylene-vinyl acetate, high- and low-density polyethylene and acrylonitrile butadiene styrene. Contamination of commercial amendments has since been recorded across further regions and waste origins [38–40], and long-term application raises the standing microplastic stock of treated soils (Section 5) [41].

These products lie closest to the regulatory boundary. The European framework brings organic fertilisers (Product Function Category, PFC 1(A)) and organo-mineral fertilisers (PFC 1(B)) onto a single market with no microplastic-specific limit, so a product can comply with current fertiliser rules while still containing an unregulated sub-2 mm plastic fraction (Section 6). Xu et al. [36] made the same point from the laboratory side, calling for standards on both raw materials and finished products.

Commercial-product values are retained in the units of their sources and are not pooled (Table 1; Section 4.1).

Because the occurrence values in Table 1 use different matrices and reporting units, Figure 3A plots studies reporting particle counts per unit dry weight, arithmetically rescaled to particles kg^{-1} , while Figure 3B places the reported particle-size range against the EU 2 mm regulatory threshold. Two features of panel A support the argument. The plotted ranges span several orders of magnitude within single streams, but pooling is precluded by incompatible units, size floors and analytical protocols rather than by dispersion alone (Section 4.1). Studies that report no lower size limit of detection cannot be placed on the size axis. The minimum reporting set in Box 1 requires that limit to be reported.

Table 1. Reported microplastic occurrence in waste-derived fertilisers, by feedstock. Concentrations are given in the units reported by each source and are not directly comparable across studies (see Section 4). dw, dry weight; PE, polyethylene; PP, polypropylene; PES, polyester; PLA, polylactic acid; PVC, polyvinyl chloride; PET, polyethylene terephthalate.

Region	Material	Abundance (Units as Reported)	Dominant Polymers or Material Classes	Predominant Shape	Extraction + Detection	Lower Particle-Size limit	QA/QC and Blank Correction	References
Sewage sludge and biosolids								
ES	Sewage sludge	5972–7771 MP/kg dw	PE > PP (fragments); polyester > PP/acrylic (fibres); 15 polymer types	fragments 48–56% (<500 µm) + density separation + fibres 44–52% (>1000 µm)	ATR-FTIR + µ-FTIR	50 µm	Procedural blanks reported; blank correction not applied – contamination deemed negligible	[12]
Global	Sewage sludge/biosolids	1–165 MP/g dw (compiled); 4196–15,385 particles/kg across 7 WWTPs	varies by study	varies by study	FT-IR + Raman	Varies across included studies	Not applicable – review compilation	[3]
PL	Stabilised sewage sludge	461.28/458.92 mg per 100 g; 860/734 particles	PE	fragments + fibres	Oxidative digestion + density separation; Raman microscopy	Not reported	Procedural blanks reported; correction not stated	[13]
UK	Anaerobically digested biosolids	34–160 particles/g dw (highest of amendments); >20,000 cellulosic microfibrils/g	high-density fibres 55.8–66.4% (likely polyester)	fibres	Visual sorting + FTIR	100 µm	Procedural blanks reported; blank correction applied	[14]
Compost								
Global	Green-waste compost	12 ± 8 to 82,800 ± 17,400 particles/kg dw (one unknown-origin compost 4.28 × 10 ⁷); 0.00024–1% w/w	PE, PP, PLA	varies by study	compiled (FTIR/Raman)	Varies across included studies	Not applicable – review compilation	[24]
Global	Food-waste compost	20 to 30,000 particles/kg dw; 0.001–0.136% w/w	PE, PP, PLA, Mater-Bi, cellulose-based	varies by study	compiled	Varies across included studies	Not applicable – review compilation	[24]
ES	Commercial compost (11 products)	137.65 ± 6.01 items/kg dw; up to 631.14 mg/kg dw	15 material classes; PE among polymer matches; chipboard/agglomerate and modified cellulose also reported	film (>1 mm)	ATR-FTIR	Not reported	Procedural blanks reported; blank correction applied	[25]

DE	Compost + liquid fertiliser (biowaste)	liquid fertiliser up to 10,000 particles/L (10–1000 µm); composts likely below source-era EU 0.3% dw (>2 mm) and DE 0.1% dw (>1 mm) limits	n.r.	fragments	Sieving + enzymatic-oxidative digestion; ATR- and µ-FTIR	Liquid fertiliser: 10 µm; compost/solid digestate: 1 mm	Procedural blanks reported; blank correction applied [22]
Digestate and food waste							
Global	Digestate	70 to 1670 particles/kg dw (one unknown-origin 3.87×10^7); 0.01–0.25% w/w	varies by study	varies by study	compiled	Varies across included studies	Not applicable—review compilation [24]
Global	Food waste	36 to 1400 particles/kg dw (US grocery waste: 300,000); 0.025–5.6% w/w	PE, PP, PVC, PET, PLA	varies by study	compiled	Varies across included studies	Not applicable—review compilation [24]
AU	Processed organics: compost, digestate, de-hydrated food waste (>25 µm)	1500–16,000 MP/kg dw (7–760 mg/kg dw)	PP and PE > PES (polyester)	fragments 62–97% > fibres 3–38%	density separation + stereomicroscope + µ-FTIR	>25 µm	Procedural blanks reported; blank correction applied (LOD/LOQ approach) [32]
Commercial/processed organic fertilisers							
CN	Commercial organic fert. (23) + farm compost (2)	9210.4 ± 1743.1 vs 24,344.1 ± 2697.2 items/kg	PP, PE, PVC, PET	fibre; <3 mm; black	Fenton digestion + visual sorting; Raman	Not reported	Procedural blanks reported; correction not stated—no exogenous MPs detected in blanks [36]
BD	Commercial organic fert. (18)	1529.62 ± 420.2 items/kg (433.33–3466.67)	nylon, nitrile, EVA, HDPE, LDPE, ABS	fibre; 0.5–1.0 mm; black	FTIR + SEM-EDAX	Not reported	Procedural blanks reported; correction not stated [37]

n.r. = not reported in the cited source. Rows based on compilations report the range given by the compilation, not a single primary measurement. The two right-hand columns were populated from the Methods sections of the full texts, consulted in July 2026, and distinguish a stated value or procedure from ‘Not reported’, which means the full text was consulted and the item is absent. ‘Varies across included studies’ and ‘Not applicable—review compilation’ mark sources that pool primary studies and apply no single protocol of their own. Where a study applied different limits to different matrices, both are given. Note: Ramage et al. [15] is treated in the text (Sections 2.1 and 5) as a persistence anchor (soil microplastic +723–1445%, stable for approximately 22 years) rather than as a feedstock-abundance row. Steiner et al. [22] compost-purity limits (EU 0.3%/DE 0.1% dw) are carried to Section 6.

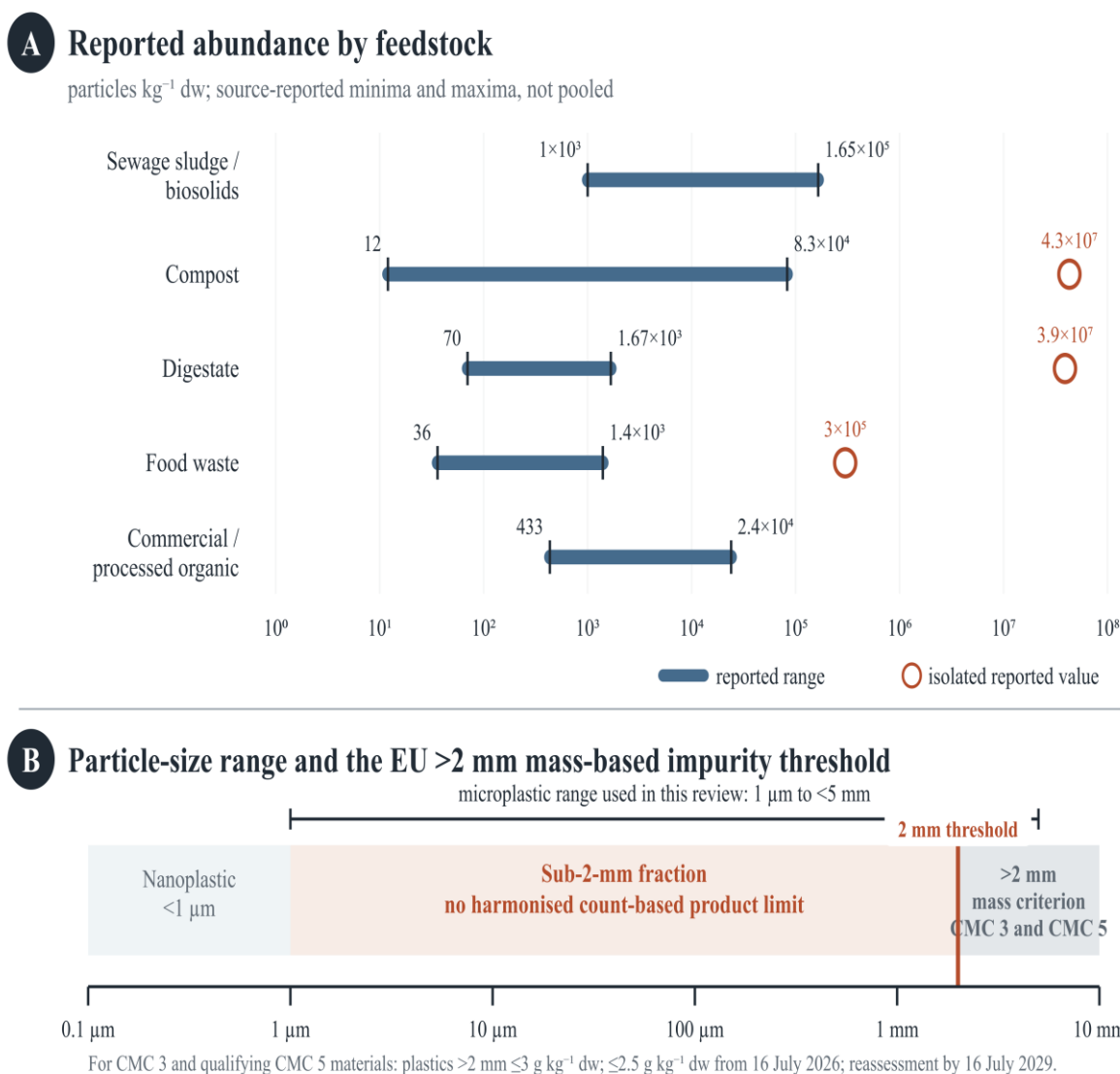


Figure 3. Reported microplastic occurrence ranges and the regulatory size gap. **(A)** Ranges reported as particle counts per unit dry weight across waste-derived fertiliser streams and arithmetically re-scaled to particles kg^{-1} dry weight. Only studies reporting counts per unit dry weight are plotted, because count-based and mass-based values are not interconvertible (Section 4.1); values are source-reported minima and maxima after unit rescaling, compiled from Table 1 and not pooled estimates, and the spread reflects differences in extraction, identification and reporting as much as differences in material. Open circles denote values reported by a single study, for which no range could be compiled. **(B)** Relationship between the reported microplastic size range and the mass-based impurity criterion of the EU Fertilising Products Regulation, which applies to compost qualifying as CMC 3 and digestate other than fresh crop digestate qualifying as CMC 5, and which leaves the sub-2 mm fraction without a harmonised count-based product limit. The 2 mm mark is the EU regulatory threshold; it is not a treatment-stage screen size. The criterion is specific to Regulation (EU) 2019/1009 and should not be read as applying universally; requirements vary across jurisdictions, including those from which much of the evidence in panel A originates (Section 6).

3. Sources and Entry Points

The feedstocks differ, yet the plastic in them enters through a small set of shared routes (Table 2). The first is the incoming material itself: packaging, films and consumer items that arrive with household and municipal waste and survive sorting. Markowicz

and Szymańska-Pulikowska [42] composted biodegradable and oxo-biodegradable bags under industrial conditions and found that several did not fully break down; FTIR and carbonyl-index analysis revealed partially degraded residues, and the breakdown of such materials can itself form microplastic particles. Certification as compostable does not guarantee complete degradation within a working plant. The wastewater feeding treatment is not a uniform input either: microplastic loads track the human activities draining to the sewer [43], and receptor-model source apportionment traces the particles in activated sludge back to identifiable upstream contributions [44].

Processing adds a second route by fragmenting what it cannot remove. Stapleton et al. [45] showed that plastic recycling generates microplastics as an unintended by-product, and the same mechanical principle operates wherever waste plastics are shredded and milled. The scale of that release is documented mainly through water. Effluent from plastic recycling facilities discharged into irrigation canals in Adana, Turkey, raised microplastic concentrations from 16.5 to 2174.5 particles per litre, up to 132-fold downstream of the discharge point, with an estimated flux exceeding 5.3 billion particles per hour; pellets and industrial copolymers occurred only downstream, confirming the recycling origin [46]. In the studied setting, the contaminated canals were used for irrigation, establishing a direct route from recycling-facility effluent to agricultural soil. Two features connect this pathway to fertilising products rather than to water alone. Where recycling and organic-waste treatment share collection or sorting infrastructure, a crossover of residual fines is plausible, although the reviewed literature does not measure that transfer directly; and recyclate degrades during reprocessing and through the life of the products made from it, so increasing recycled content may increase microplastic release across the applications in which that material is used [47]. These separate regulatory regimes do not reach the crossover: recycling is governed as a waste operation and fertilising products as a market category, and particles passing between them are accounted for by neither regulatory regime (Section 6). The quantitative evidence is thin—the flux from recycling into fertiliser feedstock specifically has not been measured—and that absence is itself part of the gap. Within composting and digestion lines, shredding and turning act on packaging residues in the same way (Section 2.2). Sludge stabilisation can also alter measured particle counts and size distributions in biosolids. Across 25 North American facilities, anaerobic digestion was associated with a rise in microplastic counts by about a third and shifted the load towards smaller, more mobile particles, with the 20–150 micrometre fraction rising several-fold and particles above 600 micrometres almost disappearing [48]; Kong et al. [49] likewise characterised microplastics in anaerobic sludge at treatment plants, a matrix that can yield digested sludge and land-applied biosolids.

A third route is external deposition. Atmospheric fallout settles microplastics onto open windrows and feedstock stockpiles: Jia et al. [50] characterised wet atmospheric deposition of microplastics over Shanghai, a flux that reaches any uncovered material. Textile fibres form a fourth, diffuse route. Frost et al. [51] identified the laundering of synthetic fabrics as a major source of microplastic fibres to wastewater, which concentrates them in sewage sludge; the polyester fibres recurring in biosolids (Section 2.1) trace to this origin.

These routes are additive and largely uncontrolled. Source separation and screening reduce the visible fraction but act weakly on particles below a millimetre (Section 2.2), so the entry points stay open even where waste management is otherwise effective. The same fibres and fragments later act as carriers for metals and other contaminants, a role examined in Section 5.

A separate source of uncertainty is contamination introduced during sampling and analysis rather than during fertiliser production. Airborne fibres, plastic laboratory ware and insufficient blanks can inflate particle counts, especially in organic-rich matrices; this

analytical contamination is therefore treated below as a measurement artefact, not as an environmental entry pathway.

Table 2. Main contamination sources and entry points for microplastics in waste-derived fertiliser production. The table distinguishes environmental entry pathways from analytical contamination, which affects measured counts but is not a production-stage source.

Source/Entry Point	Main Affected Streams	Dominant Morphology	Main Control Point	References
Food packaging and films	MSW compost, food-waste compost, processed organics	Fragments, films	Source separation, depackaging, pre-shredding removal, final screening	[22,24,32]
Textile fibres from laundering and human activity	Sewage sludge, biosolids, sludge-derived digestate	Fibres	Upstream textile control, WWTP source control, sludge management	[12,14,43,44,51]
Compostable bags and liners	Food waste, biowaste compost, digestate	Films, fragments	Certified input control, industrial composting conditions, removal of non-certified bags	[24,32,42]
Shredding, turning, milling and screening	Compost, digestate, processed organics	Smaller fragments, films	Removal of plastics before shredding, process optimisation, improved sieving	[20–22,45]
Sludge stabilisation and anaerobic digestion	Biosolids, sludge digestate	Fibres, small fragments	Process optimisation, post-treatment separation, sludge-quality monitoring	[33,34,48,49]
Atmospheric deposition during open processing and storage	Open composting, storage areas, windrows, stockpiles	Fibres, fragments	Covered storage, windrow management, air/dust controls	[50]
Sampling and laboratory contamination	All matrices	Fibres	Procedural blanks, field blanks, cotton lab coats, glass/metal tools, contamination-controlled workflow	[52]

The reported microplastic profile of a waste-derived fertiliser is not inherited from feedstock composition alone; it reflects upstream contamination, process-driven fragmentation, external deposition and measurement artefacts.

4. Analytical Detection Challenges

Occurrence data remain non-comparable for two reasons: count-based and mass-based methods measure different quantities, and organic-rich matrices produce matrix-dependent extraction and identification losses. Table 3 summarises the analytical approaches; the subsections below treat units, matrix effects and quality assurance in turn.

4.1. Reporting Units and the Limits of Comparison

Studies express loads as particle counts, as polymer mass or as area-based fluxes, and no general conversion links count to mass, so the abundances compiled in Table 1 cannot be reduced to a single number. Particle-counting routes report items/kg; thermal mass routes report mg/kg or % *w/w*. The reporting units in Table 1 are not careless variations but the imprint of these distinct measurement principles. The difference is evident within individual datasets, not only across them: in a sludge-amended field, Schell et al. [12] found the soil microplastic count running at about twice the expected value while the matching mass estimate agreed with expectation. Counts and mass describe different quantities of the same material, and material and measurement cannot be separated in the current data [3]. Harmonised soil protocols have been proposed [53], but none is yet in general use.

4.2. Extraction and Identification in Organic-Rich Matrices

Methods diverge first at the extraction step. Organic-rich amendments need digestion before particles can be counted, commonly with Fenton's reagent, hydrogen peroxide, or alkaline and enzymatic treatments [36,54]. Aggressive digestion strips organic matter but can pit or dissolve the more vulnerable polymers, while gentle digestion leaves residue that masks particles; recovery is rarely reported in a way that allows comparison.

Identification follows two incompatible approaches: spectroscopic routes identify polymers particle by particle, while thermal routes quantify polymer mass instead of counting particles. Table 3 and its note set out their principles, size ranges, reported recoveries and limitations, together with the spectroscopic indices used to characterise particle ageing. Comparative appraisals for agricultural matrices recommend pairing techniques rather than relying on one alone [55]; in the comparative study by Peneva et al. [56], Soxhlet extraction with proton nuclear magnetic resonance (NMR) spectroscopy was the only tested protocol that provided reliable mass recovery of the biodegradable polymers examined, whereas staining and spectroscopy produced lower recoveries.

Waste-derived fertilisers intensify each of these problems. The organic load is high, so digestion artefacts are larger; biodegradable polymers such as polylactic acid and starch blends confound spectral libraries built for conventional plastics (Section 2.2); and weathered particles shift their spectra, which the carbonyl index can track but which also complicates automated matching [42].

Biodegradable polymers are a distinct detection problem. Polylactic acid, polybutylene adipate terephthalate (PBAT) and starch blends enter mainly through certified compostable packaging (Table 2), yet methods and spectral libraries developed for conventional plastics can under-detect them, and standard extraction protocols degrade them during sample preparation (Section 5.5). Their systematic under-counting is a blind spot precisely where compostable-packaging policy assumes disappearance.

4.3. Quality Assurance and Minimum Reporting

Variable quality assurance and quality control (QA/QC) adds further uncertainty, and the occurrence studies compiled here illustrate it directly. Table 1 draws on eight primary studies, all of which were consulted in full text. Four state a lower particle-size limit and four do not. The stated limits span two orders of magnitude, from 10 µm to 1 mm, and one study applies different limits to different matrices within the same dataset, counting from 10 µm in liquid fertiliser but only above 1 mm in compost and solid digestate. The four studies that state no counting limit cannot be placed on a size axis at all, so their abundances are not comparable with the rest. Blank practice is more consistent but still varies: four studies report procedural blanks and apply a correction, one reports blanks and states that no correction was needed because contamination was negligible, and three report blanks without stating whether the reported values were corrected. The size-limit spread matters more than it appears: a study counting from 10 µm and a study counting from 1 mm are not measuring the same particle population, and no conversion reconciles them, just as no conversion links count to mass (Section 4.1).

A minimum reporting set would make the basis for comparison transparent. The set is summarised in Box 1. Reporting these five items would not harmonise methods by itself, but it would let readers judge which figures can be compared and which cannot.

Box 1. Minimum reporting set for occurrence studies, synthesised from data-quality and QA/QC guidance [52].

Reporting Item	What to Report
Matrix and dry mass	Matrix type and the dry mass extracted and analysed
Lower size-detection limit	Smallest particle size counted (e.g., >10 µm versus >500 µm); studies with different floors are not comparable
Blanks and recovery	Procedural and field blanks, and the spike-recovery rate
Reporting unit	Particle count or polymer mass; state which (count and mass are not interconvertible)
Polymer identification	Method used (FTIR, Raman or pyrolysis-GC/MS); staining reported separately as screening only

Table 3. Analytical approaches for microplastics in waste-derived fertilisers. Method characteristics are synthesised from Hooge et al. [3], Sheriff et al. [54], Adelugba and Emenike [55] and Soliz et al. [57]; soil spike-recovery values are from Peneva et al. [56].

Method	What It Measures	Particle Size	Strength and Reported Recovery (Soil Spike Tests)	Key Limitation in Organic-Rich Fertilisers	References
FTIR-ATR/ μ -FTIR	polymer identification + count (items/kg)	coarser fraction; small particles difficult	fast, non-destructive, versatile; ATR-FTIR recovered $80 \pm 3\%$ of large particles (68–90% across soils), FPA- μ -FTIR 29–57% of small conventional particles and less of biodegradable ones reaches smaller particles; recovered 60	polymer mixtures and weathered particles hard to match even with a library	[56,57]
Raman	polymer identification + count (items/kg)	finer fraction than FTIR	$\pm 17\%$ of large particles (lower in heavier-textured soils) and 34–39% of small particles; sensitive to organic-matter residues	fluorescence interference; identification affected by factors in sludge digesters	[34,56,57]
Pyrolysis-GC/MS, TGA-GC/MS	polymer mass (mg/kg, % w/w)	bulk; no size/count	quantitative mass per polymer; recovered $34 \pm 5\%$ of small LDPE and $49 \pm 21\%$ of PBAT (up to 94% in sandy soil), with no reliable PLA signal; recovery fell as clay content rose	destructive; no count, size or shape; not comparable with particle methods	[56,57]
Fluorescence staining (e.g., Nile Red)	rapid screening/count	n/a	cheap, fast; the highest large-particle recovery ($88 \pm 4\%$) and best for small conventional LDPE ($62 \pm 22\%$), but missed 56–93% of small biodegradable particles	uneven dye uptake; false positives from natural organics; inadequate for polymer identification alone	[56,57]
SEM	morphology, surface	approximately $1 \mu\text{m}$ –1 mm	surface and size detail; no recovery metric (morphology only) the only tested route in Peneva et al. [56] giving reliable mass recovery of the biodegradable polymers examined ($92 \pm 0\%$ for PBAT, $98 \pm 2\%$ for PLA) where staining and spectroscopy under-recover	no polymer chemistry alone; low throughput	[57]
Soxhlet extraction + ^1H NMR	polymer mass of targeted (esp. biodegradable) polymers	bulk; no count		targeted to named polymers; low throughput; no count, size or shape; not yet standard for fertiliser matrices	[56]

Reported recoveries were determined in soil spike-recovery tests across three soils [56] and cannot be transferred to organic-rich fertiliser matrices without matrix-specific validation. n/a = not applicable. Ageing and degradation indices are polymer- and protocol-specific. The carbonyl index tracks oxidation of the polymer backbone and is the most widely used ageing marker; the hydroxyl and oxidation indices track complementary oxidation products; the crystallinity index tracks changes in polymer order during weathering. Each quantifies change in selected absorption bands relative to polymer-specific reference peaks, so values are comparable only where the bands, reference peaks and calculation procedure are reported. The indices characterise the condition of a particle rather than its identity, and are reported inconsistently across the occurrence literature.

5. Soil Transfer and Fate

5.1. Retention, Accumulation and Vertical Transport

Available field studies indicate that a substantial fraction of fertiliser-borne microplastics can remain in soil, particularly in topsoil. Schell et al. [12] tracked sludge-borne particles for a year and found very little infiltration into deeper layers and negligible export by surface runoff, which mobilised only 0.2–0.4% of the soil load; the particles stayed in the topsoil where they were applied. The 25-year record of Ramage et al. [15] extends this in time, with the abundance added by sludge holding roughly constant for at least 22 years (Section 2.1). The same pattern of surface accumulation is reported across terrestrial systems [58]. An independent field series makes the dose–response explicit: across 31 fields, soils with one to five sludge applications held a rising median of 1.1 to 3.5 micro-

plastic particles per gram, almost all fibres, and counts increased in step with the number of applications [59]. Repeated sludge applications can build a standing stock of particles, with each application adding to the existing burden rather than replacing it.

The accumulated particles do not remain in place. Over years to decades, they move slowly down the profile, as tillage, rainfall and the burrowing of soil fauna redistribute particles to depth; a recent critical review identifies these processes as the main controls on vertical movement [60]; the literature reviewed by Fu et al. [61] includes reports of microplastics at depths approaching 90 cm and persisting long after application ceased. The movement is size-selective: particles above roughly ten micrometres are largely held by the soil matrix, smaller fragments travel furthest, and weathering makes larger particles more mobile as they break down over time [62]. At elevated local contents the particles also act on the soil rather than sitting inertly in it, inducing water repellency and impeding the capillary flow that governs their own transport [63]. Onward transfer to groundwater is plausible along these pathways but remains poorly evidenced. Field mass budgets are themselves inconsistent: where Schell et al. [12] found export limited to a few tenths of a percent, a biosolids study by Crossman et al. [64] reported that more than 99% of the applied microplastic remained unaccounted for after one year, which the authors attributed to export by water and air. That attribution is one reading among several: unrecovered particles may equally reflect differences in sampling design, uneven lateral distribution across the field, movement below the sampled depth, fragmentation into sizes below the detection limit, or dilution by tillage. The divergence between the two budgets constrains method as much as it constrains fate. The accumulated load is not necessarily inert: it may be slowly redistributed within the soil profile and may act as a soil-altering reservoir, which is part of why the absence of any count or cap on the entering fraction (Section 6) matters below the surface as much as at it. The balance among these processes is strongly soil- and climate-dependent, so rates measured in temperate arable systems should not be generalised across soil types.

5.2. Transfer to Crops and the Food Chain

Retention in the topsoil places the particles where roots and soil organisms meet them. Naeem et al. [29] reported microplastics moving from compost into lettuce tissue, evidence that transfer to crops can occur; reviews now map the uptake routes—crack-entry at lateral-root junctions, apoplastic transport and stomatal entry—while noting that the field evidence remains uneven [8,65]. Uptake and translocation findings remain contested and sensitive to particle size and exposure design, so this is treated here as plausible rather than established.

Plant uptake also raises a food-chain question that the regulation of these products leaves unaddressed. Submicrometre plastics can enter crop roots through cracks at the sites where lateral roots emerge and then move into stems and leaves; wheat and lettuce have been shown to take up and translocate such particles, so a route from soil into the edible parts of plants exists in principle [65,66]. Much of this uptake evidence concerns submicrometre and nanoscale plastics rather than the larger, field-realistic microplastics carried by fertilisers, so reading it across to fertiliser-borne particles describes the smaller tail of the size range, not a measured transfer. Humans ingest microplastics through diet as well, though the published intake estimates carry large uncertainty, are acknowledged as likely underestimates, and rest on a narrow set of foods and drinking water rather than soil-grown produce [67]. What is missing is the quantitative middle of the chain: how much of the burden applied with waste-derived fertilisers reaches harvestable tissue, and what share of dietary microplastic that represents, are not established [8]. The pathway from sludge, compost or commercial organic fertiliser to crop to consumer is plausible but poorly constrained, not a demonstrated exposure of known size. Regulation (EU)

2019/1009 engages none of it—no limit on the fine fraction in the product, no requirement to test transfer into crops, no food-safety trigger tied to fertiliser-borne particles (Section 6)—so a plausible route by which these products might contribute to dietary exposure remains uncharacterised by the current framework. The food-safety implication is not a demonstrated dietary burden but an unquantified exposure pathway that the current fertiliser framework does not require producers to assess.

5.3. Effects on Soil Organisms and Soil Function

Under controlled spiking conditions, microplastics can alter soil physical and biological properties; whether the accumulated field load produces comparable effects remains unresolved. In spiking experiments, microplastics altered the bulk density, water-holding capacity and microbial activity of a loamy sand and changed the link between microbial function and soil aggregation [68]; a companion study on spring onion found shifts in plant biomass, tissue elemental composition, root traits and the soil microbial community [69]. Two features prevent this evidence from translating directly into an assessment of field risk. The effects depend strongly on particle shape: fibres and beads drive the largest changes, while fragments resembling natural soil particles have the least effect. Fibres are prominent in biosolids (Section 2.1), but fragments and films dominate many composts and digestates (Table 1), so the shapes that produce the strongest experimental responses are not those that dominate every stream. And the doses are high: the responses were measured at contents up to about 2% *w/w*, the upper end of reported soil contamination and far above the sub-0.1% *w/w* typical of amended fields [8]. A review of the soil-fauna literature makes the same point structurally, finding that around 58% of studies used concentrations or units of little environmental meaning and that fibres, the dominant field morphology, are under-represented relative to the polystyrene microspheres common in experiments [70]. Across the reviewed experiments, active uptake by soil fauna and effects on motility, growth, reproduction and survival recur most consistently at high concentrations and for small particles, but what the evidence does not yet establish is whether the burden now building in amended soils reaches the concentrations at which these effects appear. That gap, between hazard potential demonstrated under controlled exposure at concentrations above those reported for amended fields and uncertain effects at field-realistic ones, is why the available evidence supports hazard potential but does not yet permit field-scale risk characterisation, and it mirrors the dose-and-method incoherence that already blocks comparison of occurrence data (Section 4). These were spiking experiments at concentrations above field levels (Section 7), so they demonstrate a mechanism rather than a field-scale effect.

Effects on the soil community have been studied more systematically than occurrence. A synthesis of 182 studies found that microplastic exposure reduces bacterial alpha diversity in soil and destabilises microbial co-occurrence networks, with biodegradable and conventional polymers producing distinct responses [71]. Fauna and plants respond as well: a one-year incubation with polybutylene adipate terephthalate substantially reduced *Brassica chinensis* biomass under the tested exposure conditions, mediated by shifts in the rhizosphere bacterial community [72], while polylactic acid altered soil pH, organic matter content, enzyme activities and microbial community structure in a particle-size and concentration-dependent way [73], with comparable responses reported for maize [74]. Dose qualifies most of this work, as it qualifies the spiking studies above. One mesocosm experiment addresses that limitation directly: at loads of 0 to 0.8% *w/w*, a range the authors describe as environmentally realistic and whose lower part overlaps the concentrations reported from amended fields (Section 7), starch-polybutylene adipate terephthalate particles altered bacterial and fungal alpha diversity and raised soil respiration in a system containing microorganisms, earthworms, springtails and plants [75]. This study

reports biological responses across a test range whose lower concentrations overlap values reported for amended fields; such studies remain few, and none isolates the response attributable specifically to fertiliser-derived particles under field conditions.

5.4. Interactions with Co-Contaminants and Potential Carrier Function

Microplastics can sorb co-contaminants and modify their mobility, persistence or biological availability, although their field-scale contribution relative to natural soil phases remains unresolved. Frost et al. [51] reviewed microplastic fibres as a vector for metal(loid)s, tracing transport from laundry water through treatment plants to soil. Sorption of metal ions such as cadmium and mercury onto PET fibres is measurable and expected during sewage treatment [76]. For methylmercury, the predicted loading on PET fibres sits about four orders of magnitude below concentrations in natural particulates, so the fibres are not expected to raise exposure for organisms that ingest them [77]. The mechanism is plausible without being established as a major exposure route. The carrier role is not limited to metals. Biosolids and manures are themselves reservoirs of antibiotic resistance, and the plastic surfaces arriving with them offer a niche where biofilms form and resistance genes pass between bacteria; microplastics can raise the frequency of this horizontal transfer, so the amended-soil plastic load is a plausible vehicle for antibiotic resistance as well [78,79]. Sorption of co-contaminants onto these surfaces is governed by hydrophobic interaction, complexation and electrostatic forces, and has been reviewed across both per- and polyfluoroalkyl substances and heavy metals [80]. The direction of the effect is not uniform. Polyamide particles adsorb per- and polyfluoroalkyl substances 72 to 122 times more strongly than soil alone, and adding them to soil raises the sorption capacity of the mixture. Their own capacity is nevertheless suppressed once their surfaces are coated by soil constituents and biofilm, so sorption measured on clean particles overstates what they do in an amended soil [81]. In contrast, high-density polyethylene reduced lead adsorption and increased lead desorption in a field soil, so mobility rose rather than fell [82]. For pesticides, a review of more than ninety studies found that microplastics generally lower bioavailability through adsorption while extending persistence, with biodegradable and aged particles behaving differently as they break down [83]. The carrier role extends to polycyclic aromatic hydrocarbons (PAHs). Microplastics derived from polyethylene mulch films sorbed both pesticides and PAHs at environmentally realistic concentrations, with sorption up to 90% higher than on pure polyethylene microspheres and increasing with the octanol-water partition coefficient: among the PAHs tested, pyrene sorption reached 75.7% and 86.4% at 5 and 200 µg/L, against 22.0% and 48.0% for naphthalene [84]. That evidence comes from agricultural mulch film rather than from particles delivered with waste-derived fertilisers, and it does not establish transport through the route reviewed here. Co-exposure of soil to a sulfonamide antibiotic and microplastics shifted microbial communities, and the combination of degradable particles with the antibiotic raised expression of the resistance genes *sul1* and *int1* [85]. Biodegradable particles again behave distinctly: in soils co-contaminated with albendazole and pyraclostrobin, polybutylene adipate terephthalate and starch-based particles affected survival and reproduction of *Folsomia candida*, whereas low-density polyethylene did not [86]. These studies demonstrate condition-dependent interaction mechanisms, but their contribution to contaminant transport at fertiliser-derived field loads has not been quantified.

5.5. Biodegradable and Compostable Polymers as a Distinct Case

Replacing conventional plastics with certified compostable polymers does not by itself eliminate the microplastic concern. Their degradation requires specific processes, including anaerobic pathways for aromatic and aliphatic biodegradable plastics [87], thermophilic methane fermentation for polylactic acid [88], and dedicated enzymatic routes, including bacterial breakdown of polyethylene terephthalate by *Ideonella sakaiensis* [89,90]. Under optimised large-scale industrial composting, certified compostable packaging can mineralise almost completely—close to 98% for polylactic acid and 93% for PBAT, with residual fragments continuing to degrade once in soil [91]. The persistence problem is conditional: field soils and many treatment lines rarely sustain those conditions, so fragments described as compostable can persist much as conventional polymers do (Section 3).

Reliable quantitative data linking the volume of compostable packaging entering bio-waste systems to the amount of residual microplastic in the resulting fertilisers were not identified. The scale of this input therefore cannot be estimated from the available evidence.

Outside optimised industrial composting conditions, degradation can fall short of certified expectations. Two years after burial in Nordic field soils, polybutylene adipate terephthalate blended with starch or polylactic acid had fragmented into microplastic while 52–93% of the original mass remained recoverable [92]. In an industrial biowaste composting facility, plastics fragmented rather than degraded, leaving 944 ± 586 particles per gram dry weight in mature compost [20]. Household-waste compost buried for more than thirty years still held microplastic concentrated near the surface, at 2.9 g/kg at 0–5 cm against 0.9 g/kg at 30–35 cm, and only partially degraded [93]. Measurement compounds the problem in both directions. Techniques based primarily on visible surface disintegration can overestimate mineralisation [94]; the standard carbon dioxide evolution test overestimated polylactic acid mineralisation by up to 3.3-fold in acidic soils [95]; and standard extraction protocols, among them density separation, Fenton oxidation and enzymatic digestion, degrade polylactic acid and polyhydroxybutyrate films during sample preparation, so occurrence studies under-count the very polymers whose disappearance policy assumes [96]. The regulatory consequence follows. Compostable packaging is admitted into biowaste streams on the premise that it disappears. Under optimised industrial conditions it largely does, as the near-complete mineralisation figures above show; under the conditions actually prevailing in many treatment lines and in field soil it fragments and persists, and selected extraction and identification methods can under-recover the polymers involved. Occurrence data carry a blind spot precisely where policy places its confidence, and the biodegradability criteria of Regulation (EU) 2019/1009 (Section 6) reach polymers added on purpose, not these incidental residues.

The fate evidence closes the loop opened in Section 2. The particles documented across feedstocks can enter soil; retention and accumulation are documented most directly for sludge-amended soils. For the smaller fraction, crop uptake and contaminant-carrier functions remain plausible but incompletely quantified, and their exposure relevance remains uncertain. This is why the absence of a microplastic-specific limit in the fertiliser framework (Section 6) matters beyond the point of application.

6. Regulatory Framework and Gaps

Where they are placed on the EU market as CE-marked fertilising products, waste-derived fertilisers fall under Regulation (EU) 2019/1009, the EU Fertilising Products Regulation, whose stated aim is to bring recycled and bio-based products into circulation and reduce dependence on imported mineral fertilisers. Composts enter as Component Material Category (CMC) 3 and digestates as CMC 4 and 5, and the finished products fall

mainly under PFC 1(A) organic fertilisers, PFC 1(B) organo-mineral fertilisers, PFC 3(A) organic soil improvers and PFC 4 growing media. The framework that channels recovered phosphorus and nitrogen back to soil is the same one that governs what those products may legally contain. This distinction matters because Regulation (EU) 2019/1009 applies to CE-marked EU fertilising products, whereas sewage sludge or other waste-derived materials applied directly to land may remain subject to other instruments, including Directive 86/278/EEC; the regulatory gap discussed here concerns the absence of a harmonised microplastic-specific criterion across the product, waste and sludge-to-land interfaces, rather than a claim that all waste-derived soil inputs are governed by the same legal route.

For contaminants, the limits are specific. An organic fertiliser may not exceed set values for cadmium (1.5 mg/kg dw), hexavalent chromium (2), mercury (1), nickel (50), lead (120) and inorganic arsenic (40), must be free of biuret, and is capped for copper (300) and zinc (800), with pathogen limits for *Salmonella* and *E. coli* (Regulation (EU) 2019/1009). The regulation names plastic as well: its recitals state that polymer impurities in bio-waste-derived products, with metal and glass, should be prevented or limited to the extent technically feasible through detection in separately collected bio-waste before processing, because such contaminants accumulate in the environment and enter the food chain.

The regulation expresses this recognition through a single operational limit. For compost qualifying as CMC 3 and digestate other than fresh crop digestate qualifying as CMC 5, the material may contain no more than 3 g/kg dw of macroscopic impurities above 2 mm in the form of glass, metal or plastics, and no more than 5 g/kg dw of those impurities combined. From 16 July 2026, the plastics-above-2 mm fraction is tightened to 2.5 g/kg dw, a value the Commission is to reassess by 16 July 2029 (Regulation (EU) 2019/1009). For CMC 3 and CMC 5, these are the only explicit plastic-impurity limits identified in Regulation (EU) 2019/1009, and three features of it leave microplastics outside.

The threshold operates as a lower size cut-off. The limit acts only on particles above 2 mm, while the microplastic range used in this review extends from 1 µm to below 5 mm and occurrence studies include a sub-2 mm fraction reported as particle counts rather than mass (Sections 2 and 4; Figure 3B). The limit is a mass, in grams per kilogram, whereas particle-counting methods report items per kilogram (Section 4); a product can hold large numbers of small particles and still sit far below a gram-per-kilogram cap. The Regulation contains no microplastic-specific provision and sets no count-based threshold, monitoring requirement or detection method for the sub-2 mm fraction. A mass-based limit on particles above 2 mm does not provide count-based control of particles below it. Particle number alone does not determine environmental significance, which also depends on the size distribution, the polymers present and their toxicity (Section 5.3); a count-based metric is a necessary instrument, not a sufficient measure of harm.

The polymer rules address a different object. CMC 8 covers nutrient polymers, and CMC 9 covers polymers other than nutrient polymers, permitted only where they control nutrient release or water retention (Regulation (EU) 2019/1009). The biodegradability criteria for CMC 9 were left to be set by delegated act, and have since been laid down for coating agents and water-retention polymers by Commission Delegated Regulation (EU) 2024/2770; point 1 of Annex II to that Regulation applies from 17 October 2028 [97]. They require decomposition in natural conditions, so that polymer use does not lead to plastic accumulation. These rules govern polymers added on purpose, such as controlled-release coatings; they do not reach the microplastic that arrives unintentionally with the feedstock.

The product regulation forms part of a wider EU framework that treats microplastics unevenly. The 2023 REACH restriction (Commission Regulation (EU) 2023/2055, Annex XVII entry 78) [98] restricts the placing on the market of synthetic polymer microparticles

intentionally present to confer a sought-after characteristic, subject to a 0.01% *w/w* concentration threshold and derogations—but it reaches only intentionally added particles and exempts those formed or released unintentionally, which is the fraction that arrives with waste feedstock. Microplastic of incidental origin is left to a patchwork of instruments not designed for it, among them the Urban Wastewater Treatment Directive and the Sewage Sludge Directive, none of which sets a count-based limit or method for the particles entering soil through waste-derived fertilisers. The gap is not a single silence but a division of labour in which the unintentional fraction falls between mandates. Read as a whole, Table 4 spans distinct regulatory levels—product regulation under Regulation (EU) 2019/1009, chemical restriction under REACH, and background waste, wastewater and sludge-to-land policy—rather than a single tier of control.

Two further instruments affect the upstream load. The recast Urban Wastewater Treatment Directive (Directive (EU) 2024/3019) [99] strengthens treatment and sludge-management requirements that determine how many particles reach biosolids, and it goes further than the fertilising-products framework in one respect: for agglomerations above 10,000 population equivalent, Member States are to monitor microplastics in sludge when relevant and, in particular, when the sludge is reused in agriculture. The obligation is a monitoring duty attached to the sludge, not a limit attached to the product placed on the market, and no threshold accompanies it. No harmonised method is specified either; the Commission is required to adopt implementing acts establishing a methodology for measuring microplastics in urban wastewater and in sludge by 2 July 2027. The Packaging and Packaging Waste Regulation (Regulation (EU) 2025/40) [100] governs the compostable packaging that enters food-waste and compost streams. Neither instrument sets a microplastic limit for fertilising products, but both act on the feedstocks, so a count-based provision in the Fertilising Products Regulation would sit within, not duplicate, this wider framework.

National and sectoral limits leave the same fraction uncontrolled. At the time of [22], the EU criterion was 0.3% dw for plastics above 2 mm, while the German threshold was 0.1% dw above 1 mm; the current EU value is given in Section 6. Digestate legislation outside the EU Fertilising Products Regulation is often framed around bulk quality rather than fine particles [35]. Each instrument limits the plastic it can see and weigh, leaving the sub-millimetre fraction uncontrolled.

The same gap is present in the United States, where biosolids-to-land programmes regulate pathogens and heavy metals but set no count-based microplastic limit. In the United States, for example, the EPA biosolids rule (40 CFR Part 503) [101] sets numerical limits for heavy metals together with pathogen and vector-attraction standards for land-applied sewage sludge, but contains no microplastic provision.

The current regulatory framework promotes the return of organic matter to soil while leaving the finer plastic fraction without a count-based limit [102]. A defensible microplastic threshold would need a count-based metric, a size range reaching below 2 mm and a harmonised method to support it—none of which exists while occurrence data stay non-comparable (Section 4). For now, circularity policy and microplastic control operate separately.

Table 4. Microplastic-relevant regulatory controls and gaps across EU fertilising-product, chemical, waste and sludge-to-land frameworks.

Regulatory Level	Provision	Object	Basis	Size Range	Microplastic Gap	References
Product conformity	Contaminant limits, PFC 1(A)/1(B)	heavy metals (Cd, Cr VI, Hg, Ni, Pb, As), Cu, Zn, biuret, pathogens	concentration (mg/kg dw)	n/a	no microplastic-specific parameter in contaminant limits; plastics are addressed separately only as macroscopic impurities for selected CMCs	[6]
Component material / product conformity	Macroscopic impurities, CMC 3 (compost) and CMC 5 (digestate other than fresh crop digestate)	glass, metal, plastics > 2 mm	mass (≤3 g/kg dw; sum ≤5 g/kg dw)	>2 mm only	excludes < 2 mm, the bulk of the MP range; mass not count; plastics > 2 mm ≤ 2.5 g/kg dw from 16 Jul 2026, review by 16 Jul 2029	[6]
Component material requirements	CMC 8 nutrient polymers; CMC 9 other functional polymers	intentionally added functional polymers (nutrient polymers, controlled-release coatings)	compositional + biodegradability tests	n/a	CMC 9 biodegradability criteria address specified coating agents and water-retention polymers; neither CMC route addresses incidental fragments arriving with waste feedstocks	[6,97]
Voluntary or sectoral quality scheme	Compost/digestate quality schemes	visible plastic in compost; digestate bulk quality	mass (% dw)	>1–2 mm	same size floor and mass basis	[22,35]
Chemical restriction	REACH restriction, Annex XVII entry 78 (Reg (EU) 2023/2055)	Intentionally added synthetic polymer microparticles in products, fertilisers included	Concentration, 0.01% w/w or more	<5 mm	Covers only intentionally added particles; unintentional feedstock contamination excluded	[98]
Waste, wastewater and sludge-to-land policy	Urban Wastewater Treatment Directive; Sewage Sludge Directive (86/278/EEC)	Waste handling, wastewater treatment, sludge applied to land	Qualitative; heavy-metal limits for sludge	Not specified	UWWTD requires monitoring of microplastics in sludge (>10,000 p.e.) when relevant and, in particular, where the sludge is reused in agriculture, but sets no threshold; measurement methods are to be adopted by implementing act by 2 July 2027. No count-based microplastic limit exists for EU fertilising products	[99,103]
Missing instrument	Microplastic limit as such	n/a	n/a	<2 mm, count-based	no current EU fertilising-product instrument sets a count-based limit for particles below 2 mm; see Section 8	Author's synthesis; see Section 8

n/a = not applicable.

7. Discussion and Conclusions

Three findings recur across the preceding sections, and together they define the problem. Microplastics occur across the main waste streams that feed waste-derived fertilisers—sewage sludge, compost, digestate, food waste and processed commercial products (Section 2). The numbers attached to that occurrence cannot be compared across studies, because extraction, identification, and reporting are not harmonised and two method families measure different quantities (Section 4). For CMC 3 compost and qualifying CMC 5 digestate, the Regulation controls plastic impurities above 2 mm by mass; separate provisions govern specified intentionally added functional polymers, but no harmonised count-based limit or method applies to incidental sub-2 mm particles (Section 6).

Together, these findings support more than the observation that “fertilisers can contain plastic”. The route from waste to farmland is structurally embedded in waste-to-soil nutrient recycling. Circular-economy policy is designed to move recovered organic matter and nutrients from waste streams onto agricultural soil, and microplastics can follow the same engineered pathway when they are retained, fragmented or insufficiently removed during treatment (Sections 2 and 3). Waste-derived fertilisers act as a structural entry point—a systemic vector—for microplastics into soil. Land application is deliberate and routine, whereas the associated transfer of microplastics is unintentional. This distinguishes the route operationally from diffuse sources such as atmospheric fallout or mulch-film residues.

The strength of the evidence varies across these claims. Delivery, retention and accumulation are supported, most directly for sludge-amended soils: particles enter with the amendment, remain in the topsoil and build up under repeated application (Sections 2 and 5). What is not established is the magnitude of downstream harm under field conditions. Field concentrations sit well below the doses used in most toxicity work, and this gap limits direct extrapolation of laboratory effects to amended fields and leaves the cumulative, long-term concern poorly resolved [8]. The contaminant-carrier role carries the same caution: fibres sorb metals, but the environmental significance of that sorption is contested (Section 5). Effects on soil organisms and soil function have been demonstrated under controlled exposure, confirming hazard potential for the polymers, particle properties and exposures tested; what remains unresolved is whether the burden accumulating in amended soils reaches the concentrations at which those effects appear. On current evidence, waste-derived fertilisers can deliver particles for which hazard potential has been demonstrated under controlled conditions, while their field-scale significance remains unquantified and current controls do not provide harmonised, count-based control of incidental sub-2 mm particles.

The evidence supports a staged response centred on measurement, source control and proportionate regulation. A recurrent pathway with plausible mechanisms and identifiable control points warrants measurement and governance rather than alarm. The agronomic and resource-recovery benefits are quantitatively documented: sewage sludge alone amounts to roughly 19 kg of dry matter per inhabitant each year across the EU, carrying recoverable nitrogen and on the order of 0.23 million tonnes of phosphorus annually, and phosphorus recovered from it could in principle cover up to about 15% of EU phosphate-fertiliser demand—a material contribution while phosphate rock remains classified as a critical raw material [7]. The aim is to close the contaminant gap within nutrient recycling rather than to halt it. Circularity and contaminant control can be pursued together within one system.

The microplastic concern must be weighed against the scale of nutrient recovery. Field-reported soil concentrations are typically below 0.1% *w/w*, according to Boctor et al. [8], whereas controlled toxicity studies have used nominal loadings up to about 2% *w/w* and, on a different basis, up to 50% by volume. This mismatch limits direct extrapolation of laboratory effects to amended fields and leaves the cumulative risk poorly resolved. Modest concentrations still move large numbers of particles at the tonnages involved: the flux estimates already cited, on the order of 10^{10} to 10^{12} particles per year to land from processed organics in one country [32] and around 10^{14} items per year from commercial organic fertilisers in another [36], together with $5.9\text{--}7.5 \times 10^{12}$ particles—some 5.0×10^4 to 1.1×10^5 kg—added to Spanish farmland each year through sewage sludge [12], describe a recurrent, spatially distributed input.

The current market framework gives producers little regulatory incentive to reduce this load. With no microplastic-specific limit, no count-based metric and no standard method (Sections 4 and 6), a manufacturer has no harmonised basis for demonstrating a

lower-microplastic product, and buyers have no standardised criterion for comparing products on this axis. Substitution with certified compostable polymers does not by itself remove the concern, because degradation depends on treatment and field conditions (Section 5.5). Control has to move upstream, to separation and screening of feedstock (Section 3) and to process steps acting on the sub-millimetre fraction, because the finished-product stage measures only what it can see and weigh.

Several limitations constrain these conclusions. The occurrence literature is geographically uneven, weighted towards a few countries, so the global picture is partial. All methodological fields reported in Table 1 were checked against the full texts; some contextual claims elsewhere in the review were verified at abstract level where the full text was unavailable, and those sources were not used to populate Table 1. Unit incomparability prevents any pooled estimate of soil loading, which is why the argument here is built from consistent patterns across studies rather than from a meta-analytic number. The soil-to-food step, the one most relevant to human exposure, remains the least well-evidenced link in the chain. These constraints are themselves part of the finding: the field cannot yet say how much microplastic reaches soil through fertilisers, and that uncertainty is a direct product of the methodological and regulatory gaps the review documents.

This review claims neither a quantified soil burden nor harm demonstrated at field scale: the data support neither, and toxicological evidence at field-relevant concentrations remains scarce. It claims that a real entry route exists, that its scale cannot yet be measured, and that no current fertilising-product instrument sets a count-based limit or cap for the sub-2 mm fraction. Each part of the problem is addressable. At the field concentrations reported to date, typically below 0.1% *w/w* [8], the appropriate response is measurement and proportionate governance rather than alarm. Quantifying the pathway depends on harmonised measurement and on a metric that counts the sub-2 mm fraction, the subject of Section 8.

8. Future Directions

The gaps documented here define a sequence of research priorities, each following from a specific finding.

Methodological harmonisation comes first. Until extraction, identification and reporting follow agreed protocols, occurrence figures will stay non-comparable and no pooled estimate of soil loading will be possible (Section 4); every quantitative step that follows, including any threshold, depends on it. Such harmonisation should include interlaboratory validation and well-characterised reference materials for compost, digestate and biosolid matrices, because recovery values derived from mineral soils cannot be assumed to transfer directly to organic-rich fertiliser products.

A fit-for-purpose metric must follow harmonisation. A microplastic-specific limit for fertilising products would need four elements absent from the current mass-based criterion. First, the measure should be count-based and expressed as items per kilogram of dry matter. Second, the size range should reach well below 2 mm and state the lower limit of detection, since a count without a floor is not comparable between laboratories. Third, a designated analytical route is needed because particle-counting and mass-based methods measure different quantities (Section 4.1). Fourth, mandatory quality assurance should include, at minimum, procedural blanks, recovery checks and reporting of the size floor (Box 1). Spectroscopic identification is what allows a particle count to be expressed as items per kilogram of a confirmed polymer; counting without spectroscopic confirmation, as in fluorescence screening, yields a particle count but does not provide polymer identification (Table 3). A count-based limit would rest on the confirmatory routes, with thermal mass methods retained for cross-checking rather than for compliance. Such a metric

would also need to separate feedstock-derived incidental microplastics from intentionally added functional polymers (CMC 8 and CMC 9, Section 6), which are governed by different control logics. The existing mass-based limit on particles above 2 mm does not provide count-based control of the sub-2 mm fraction reported in occurrence studies.

A standardisation basis is emerging, but it does not yet reach the metric proposed here. EN ISO 24187:2023 sets principles for the analysis of microplastics in environmental matrices, covering particle-size classification and minimum requirements for sampling, sample preparation and the determination of representative sample quantities [104]. It is a framework standard rather than a method, and it does not specify monitoring requirements or a matrix-specific method for waste-derived fertilisers. Two further projects under ISO/TC 61/SC 14 come closer to the matrices at issue, and their scope limits are instructive. ISO/DIS 24899 specifies extraction of microplastics from industrial and home compost, and allows downstream analysis by either number-based or mass-based techniques; it applies only to particles up to 1 mm and to polymers with densities below 1.4 g/cm³, it does not specify detection methods, and it is not validated for matrices other than compost [105]. ISO/WD 25654 specifies the production of reference materials for validating detection methods, but only as irregular thermoplastic powders between 10 and 1000 micrometres, and it expressly excludes fibres [106]. The consequences for a count-based sub-2 mm metric are direct. The emerging extraction standard does not cover the full sub-2 mm range and excludes the densest polymers; the reference-material work excludes the morphology that dominates biosolids (Section 2.1); and neither reaches digestate, biosolids or finished organic fertilisers. The regulatory challenge lies in converting general analytical principles into a validated, matrix-specific compliance method.

A scheduled legislative review provides an opportunity to act, although the legal route is not the one it first appears to be. Regulation (EU) 2019/1009 requires the Commission to re-assess the limit on plastics above 2 mm by 16 July 2029. That mandate is expressly confined to the existing mass-based limit above 2 mm; it is not an instruction to consider a count-based metric for smaller particles. A possible legal route lies elsewhere: contaminant limit values for organic and organo-mineral fertilisers sit in Annex I, and Article 42 empowers the Commission to amend Annex I by delegated act to adapt it to technical progress, with cadmium limit values and the definitions and scope of the product function categories expressly excluded from that power. The same article requires the Commission, when introducing new contaminant limit values in Annex I, to take account of the scientific opinions of the European Food Safety Authority, the European Chemicals Agency or the Joint Research Centre [6]. Article 42 may therefore provide a delegated-act route for amending Annex I, but whether a new count-based microplastic parameter falls within that power requires legal assessment.

These legal and analytical prerequisites make a binding count-based threshold by 2029 unlikely. A scientific opinion able to support a limit value would need a validated method for these matrices, interlaboratory comparison and reference materials, none of which is available today (Section 4). A more realistic sequence places a mandatory monitoring and reporting duty first: reporting a count together with a stated size floor for CMC 3 and CMC 5 materials requires a designated method but no agreed threshold, and it would generate the comparable dataset on which a later limit could rest. The 2029 reassessment could provide an occasion to consider such a duty, since the Commission will already be examining the plastics limit, with a threshold following only once the data support one. Extending the reassessment to the sub-2 mm fraction would itself require a separate evaluation of legal basis, analytical readiness and regulatory impact.

The burden of such a duty falls unevenly and has not been quantified. Routine count-based analysis would probably require specialist laboratories and spectroscopic instrumentation, creating a compliance cost that would depend on sampling frequency and an-

alytical scope. Mineral fertilisers are not subject to an equivalent microplastic-specific monitoring requirement, so a duty applied to waste-derived EU fertilising products alone would place a compliance cost on the products the policy is designed to promote. That asymmetry argues for phasing and proportionate sampling, not against the duty. No published estimate of that cost for these product categories was identified here, and producing one is a prerequisite for any impact assessment.

Field-realistic effects research is equally needed. Long-term studies at concentrations aligned with those reported for amended fields would establish whether the accumulating soil burden carries ecological consequences, and on what timescale. Boctor et al. [8] set out the same priorities, listing improved detection, long-term field studies, environmentally relevant toxicity testing and policy intervention.

The soil-to-food link requires dedicated study. Transfer of field-relevant microplastic from amended soil into edible tissue is the least evidenced step in the chain and the one most relevant to human exposure (Sections 5 and 7); it warrants treatment as a research priority in its own right, distinct from work on nanoscale particles.

These priorities form a single sequence: harmonised measurement first, then a fit-for-purpose metric, then a regulatory rule, with effects and exposure research running alongside. These priorities are compatible with continued nutrient recycling and would support contaminant control without compromising the resource-recovery function of nutrient recycling.

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References

1. Baho, D.L.; Bundschuh, M.; Futter, M.N. Microplastics in terrestrial ecosystems: Moving beyond the state of the art to minimize the risk of ecological surprise. *Glob. Change Biol.* **2021**, *27*, 3969–3986. <https://doi.org/10.1111/gcb.15724>.
2. Yang, L.; Zhang, Y.; Kang, S.; Wang, Z.; Wu, C. Microplastics in soil: A review on methods, occurrence, sources, and potential risk. *Sci. Total Environ.* **2021**, *780*, 146546. <https://doi.org/10.1016/j.scitotenv.2021.146546>.
3. Hooge, A.; Hauggaard-Nielsen, H.; Heinze, W.M.; Lyngsie, G.; Ramos, T.M.; Sandgaard, M.H.; Vollertsen, J.; Syberg, K. Fate of microplastics in sewage sludge and in agricultural soils. *TrAC Trends Anal. Chem.* **2023**, *166*, 117184. <https://doi.org/10.1016/j.trac.2023.117184>.
4. Nizzetto, L.; Futter, M.; Langaas, S. Are agricultural soils dumps for microplastics of urban origin? *Environ. Sci. Technol.* **2016**, *50*, 10777–10779. <https://doi.org/10.1021/acs.est.6b04140>.

5. Cusworth, S.J.; Davies, W.J.; McAinsh, M.R.; Gregory, A.S.; Storkey, J.; Stevens, C.J. Agricultural fertilisers contribute substantially to microplastic concentrations in UK soils. *Commun. Earth Environ.* **2024**, *5*, 7. <https://doi.org/10.1038/s43247-023-01172-y>.
6. EU. Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products. *Off. J. Eur. Union* **2019**, *L 170*, 1–114.
7. Battista, F.; Frison, N.; Pavan, P.; Cavinato, C.; Gottardo, M.; Fatone, F.; Eusebi, A.L.; Majone, M.; Zeppilli, M.; Valentino, F.; et al. Food wastes and sewage sludge as feedstock for an urban biorefinery producing biofuels and added-value bioproducts. *J. Chem. Technol. Biotechnol.* **2020**, *95*, 328–338. <https://doi.org/10.1002/jctb.6096>.
8. Boctor, J.; Hoyle, F.C.; Farag, M.A.; Ebaid, M.; Walsh, T.; Whiteley, A.S.; Murphy, D.V. Microplastics and nanoplastics: Fate, transport, and governance from agricultural soil to food webs and humans. *Environ. Sci. Eur.* **2025**, *37*, 68. <https://doi.org/10.1186/s12302-025-01104-x>.
9. Zhang, S.; Li, Y.; Jiang, L.; Chen, X.; Zhao, Y.; Shi, W.; Xing, Z. From organic fertilizer to the soils: What happens to the microplastics? A critical review. *Sci. Total Environ.* **2024**, *919*, 170217. <https://doi.org/10.1016/j.scitotenv.2024.170217>.
10. Jiang, J.; Wang, X.; Ren, H.; Cao, G.; Xie, G.; Xing, D.; Liu, B. Investigation and fate of microplastics in wastewater and sludge filter cake from a wastewater treatment plant in China. *Sci. Total Environ.* **2020**, *746*, 141378. <https://doi.org/10.1016/j.scitotenv.2020.141378>.
11. Okoffo, E.D.; Tschärke, B.J.; Thomas, K.V. Predicted growth in plastics entering biosolids and agricultural lands exceeds efforts to control source emissions. *ACS ES&T Water* **2023**, *3*, 2238–2246. <https://doi.org/10.1021/acsestwater.3c00037>.
12. Schell, T.; Hurley, R.; Buenaventura, N.T.; Mauri, P.V.; Nizzetto, L.; Rico, A.; Vighi, M. Fate of microplastics in agricultural soils amended with sewage sludge: Is surface water runoff a relevant environmental pathway? *Environ. Pollut.* **2022**, *293*, 118520. <https://doi.org/10.1016/j.envpol.2021.118520>.
13. Worek, J.; Kawoń, K.; Chwiej, J.; Styszko, K. Stabilized sewage sludge as fertilizer: Risks related to the presence of microplastics. *Appl. Sci.* **2025**, *15*, 7420. <https://doi.org/10.3390/app15137420>.
14. Rimmaudo, A.; Cundill, A.; Singleton, I.; Morrison, D.; Bland, A. Quantification and characterisation of microplastics in organic waste-derived soil amendments. *Water Air Soil Pollut.* **2026**, *237*, 450. <https://doi.org/10.1007/s11270-026-09145-5>.
15. Ramage, S.J.F.F.; Coull, M.; Cooper, P.; Campbell, C.D.; Prabhu, R.; Yates, K.; Dawson, L.A.; Devalla, S.; Pagaling, E. Microplastics in agricultural soils following sewage sludge applications: Evidence from a 25-year study. *Chemosphere* **2025**, *376*, 144277. <https://doi.org/10.1016/j.chemosphere.2025.144277>.
16. Harley-Nyang, D.; Memon, F.A.; Osorio Baquero, A.; Galloway, T. Variation in microplastic concentration, characteristics and distribution in sewage sludge & biosolids around the world. *Sci. Total Environ.* **2023**, *891*, 164068. <https://doi.org/10.1016/j.scitotenv.2023.164068>.
17. Gao, D.; Li, X.-Y.; Liu, H.-T. Source, occurrence, migration and potential environmental risk of microplastics in sewage sludge and during sludge amendment to soil. *Sci. Total Environ.* **2020**, *742*, 140355. <https://doi.org/10.1016/j.scitotenv.2020.140355>.
18. Kong, W.; Jalalah, M.; Alsareii, S.A.; Harraz, F.A.; Almadiy, A.A.; Zheng, Y.; Thakur, N.; Salama, E.-S. Microplastics (MPs) in wastewater treatment plants sludges: Substrates, digestive properties, microbial communities, mechanisms, and treatments. *J. Environ. Chem. Eng.* **2023**, *11*, 111408. <https://doi.org/10.1016/j.jece.2023.111408>.
19. Liu, S.; Oshita, K.; Guo, W.; Takaoka, M. Behavior and flow of microplastics during sludge treatment in Japan. *Sci. Total Environ.* **2024**, *957*, 177553. <https://doi.org/10.1016/j.scitotenv.2024.177553>.
20. Risku, N.; Dahl, O.; Vanhanen, H.; Pulkkinen, K.; Litmanen, J.J.; Rigaud, C.; Taipale, S.J. Breakdown of plastic waste into microplastics during an industrial composting: A case study from a biowaste facility. *Waste Manag.* **2025**, *203*, 114889. <https://doi.org/10.1016/j.wasman.2025.114889>.
21. Peneva, S.; Phan Le, Q.N.; Munhoz, D.R.; Wrigley, O.; Macan, G.P.F.; Doose, H.; Amelung, W.; Braun, M. Plastic input and dynamics in industrial composting. *Waste Manag.* **2025**, *193*, 283–292. <https://doi.org/10.1016/j.wasman.2024.11.043>.
22. Steiner, T.; Möller, J.N.; Löder, M.G.J.; Hilbrig, F.; Laforsch, C.; Freitag, R. Microplastic contamination of composts and liquid fertilizers from municipal biowaste treatment plants: Effects of the operating conditions. *Waste Biomass Valorization* **2023**, *14*, 873–887. <https://doi.org/10.1007/s12649-022-01870-2>.
23. Weithmann, N.; Möller, J.N.; Löder, M.G.J.; Piehl, S.; Laforsch, C.; Freitag, R. Organic fertilizer as a vehicle for the entry of microplastic into the environment. *Sci. Adv.* **2018**, *4*, eaap8060. <https://doi.org/10.1126/sciadv.aap8060>.
24. Porterfield, K.K.; Hobson, S.A.; Neher, D.A.; Niles, M.T.; Roy, E.D. Microplastics in composts, digestates, and food wastes: A review. *J. Environ. Qual.* **2023**, *52*, 225–240. <https://doi.org/10.1002/jeq2.20450>.

25. Bayo, J.; López-Castellanos, J.; Doval-Miñarro, M.; Olmos, S. Eco-labeled composts reduce microplastic contamination and mitigate heavy metal bioavailability in agricultural ecosystems. *Sci. Rep.* **2025**, *15*, 32793. <https://doi.org/10.1038/s41598-025-17034-w>.
26. Sholokhova, A.; Čeponkus, J.; Šablinskas, V.; Denafas, G. Abundance and characteristics of microplastics in treated organic wastes of Kaunas and Alytus regional waste management centres, Lithuania. *Environ. Sci. Pollut. Res.* **2022**, *29*, 20665–20674. <https://doi.org/10.1007/s11356-021-17378-6>.
27. Okori, F.; Schwarzböck, T.; Neuburg, S.; Komakech, A.J.; Lederer, J.; Fellner, J. Macro- and microplastics in composts from municipal solid waste industrial composting plants in Uganda. *Waste Manag.* **2025**, *204*, 114942. <https://doi.org/10.1016/j.wasman.2025.114942>.
28. Panahi Fard, M.; Mahvi, A.H.; Jorfi, S.; Takdastan, A.; Schönberger, H.; Azari, A.; Jaafarzadeh, N. Microplastics in MSW-derived compost: Release rate, characteristics, ecological risks, and mitigation strategies for sustainable agriculture. *Environ. Pollut. Bioavailab.* **2025**, *37*, 2529998. <https://doi.org/10.1080/26395940.2025.2529998>.
29. Naeem, A.; Farooq, M.A.; Shafiq, M.; Arshad, M.; Din, A.A.; Alazba, A.A. Quantification and polymeric characterization of microplastics in composts and their accumulation in lettuce. *Chemosphere* **2024**, *361*, 142520. <https://doi.org/10.1016/j.chemosphere.2024.142520>.
30. El Hayany, B.; Rumpel, C.; Hafidi, M.; El Fels, L. Occurrence, analysis of microplastics in sewage sludge and their fate during composting: A literature review. *J. Environ. Manag.* **2022**, *317*, 115364. <https://doi.org/10.1016/j.jenvman.2022.115364>.
31. Hussain, M.; Sarfraz, W.; Chen, C.; Shabir, R.; Abbas, G.; Rezaei Rashti, M. From waste to resource: Unveiling the nexus between compost, microplastics, and agroecosystem. *J. Hazard. Mater. Adv.* **2026**, *21*, 101033. <https://doi.org/10.1016/j.hazadv.2026.101033>.
32. Lu, H.-C.; Cao, W.; Jones, S.; Leusch, F.D.L.; Slynkova, N.; Trevorah, R.; Warwick, B.; Ziajahromi, S. Microplastic in Australian processed organics: Abundance, characteristics and potential transport to soil ecosystem. *J. Environ. Manag.* **2025**, *375*, 124359. <https://doi.org/10.1016/j.jenvman.2025.124359>.
33. Yli-Rantala, E.; Sarlin, E.; Kokko, M. Fate of microplastics in a centralized biogas plant treating mainly sewage sludge. *J. Environ. Manag.* **2025**, *395*, 127892. <https://doi.org/10.1016/j.jenvman.2025.127892>.
34. Lessa Belone, M.C.; Yli-Rantala, E.; Sarlin, E.; Kokko, M. Microplastics in an anaerobic digester treating sewage sludge: Occurrence and factors affecting their identification with Raman spectroscopy. *J. Hazard. Mater.* **2025**, *491*, 138015. <https://doi.org/10.1016/j.jhazmat.2025.138015>.
35. Diéguez-Santana, K.; Chicaiza-Ortiz, C.; Zhang, J.; Logroño, W. Anaerobic digestate: Pollutants, ecotoxicology, and legislation. In *Anaerobic Digestate Management*; Tyagi, V.K., Aboudi, K., Eskicioglu, C., Eds.; IWA Publishing: London, UK, 2022; pp. 359–384. https://doi.org/10.2166/9781789062755_0359.
36. Xu, J.; Yang, A.; Yan, Y.; Xu, Y.; Tang, M.; Li, P.; Zhao, L.; Zhang, X.; Ren, Z. Quantification and identification of microplastics in organic fertilizers: The implication for the manufacture and safe application. *Water Air Soil Pollut.* **2024**, *235*, 169. <https://doi.org/10.1007/s11270-024-06977-x>.
37. Rana, M.M.; Haque, M.R.; Tasnim, S.S.; Rahman, M.M. The potential contribution of microplastic pollution by organic fertilizers in agricultural soils of Bangladesh: Quantification, characterization, and risk appraisals. *Front. Environ. Sci.* **2023**, *11*, 1205603. <https://doi.org/10.3389/fenvs.2023.1205603>.
38. Imasha, H.U.E.; Babel, S. Unveiling the abundance and potential impacts of microplastic contamination in commercial organic fertilizers/compost produced from different solid waste. *Environ. Sci. Pollut. Res.* **2024**, *31*, 50767–50781. <https://doi.org/10.1007/s11356-024-34554-6>.
39. Fosu-Mensah, B.Y.; Laryea, N.N.-O.; Darko, D.; Mensah, M. Assessing microplastics contamination and characteristics in organic soil amendments in the Greater Accra Metropolitan Area of Ghana. *Heliyon* **2024**, *10*, e40882. <https://doi.org/10.1016/j.heliyon.2024.e40882>.
40. Thomas, D.; Dorau, K.; Bloem, E. Investigating plastic in organic fertilizers: A 2-year comparative study. *Chemosphere* **2026**, *394*, 144765. <https://doi.org/10.1016/j.chemosphere.2025.144765>.
41. Guo, S.; Xiao, G.; Chen, Y.; Zhang, J.; Zhang, B.; Ru, S.; Zhao, M. Unraveling the characteristics of microplastics in agricultural soils upon long-term organic fertilizer application: A comprehensive study using diversity indices. *Chemosphere* **2024**, *364*, 143235. <https://doi.org/10.1016/j.chemosphere.2024.143235>.
42. Markowicz, F.; Szymańska-Pulikowska, A. Assessment of the decomposition of oxo- and biodegradable packaging using FTIR spectroscopy. *Materials* **2021**, *14*, 6449. <https://doi.org/10.3390/ma14216449>.

43. Yang, F.; Li, D.; Zhang, Z.; Wen, L.; Liu, S.; Hu, E.; Li, M.; Gao, L. Characteristics and the potential impact factors of microplastics in wastewater originated from different human activity. *Process Saf. Environ. Prot.* **2022**, *166*, 78–85. <https://doi.org/10.1016/j.psep.2022.07.048>.
44. Mi, J.; Lu, J.; Liu, T.; Li, Z.; Shi, X.; Lv, C.; Jia, Y.; Wu, Z. Activated sludge in municipal wastewater treatment plant serves as a potentially source of microplastics: Source apportionment based on APCS-MLR and PMF receptor models. *J. Hazard. Mater.* **2026**, *503*, 141072. <https://doi.org/10.1016/j.jhazmat.2026.141072>.
45. Stapleton, M.J.; Ansari, A.J.; Ahmed, A.; Hai, F.I. Evaluating the generation of microplastics from an unlikely source: The unintentional consequence of the current plastic recycling process. *Sci. Total Environ.* **2023**, *902*, 166090. <https://doi.org/10.1016/j.scitotenv.2023.166090>.
46. Gündoğdu, S.; Avcıoğlu, S. Illicit discharges, global waste trade, and microplastic contamination in irrigation canals: Evidence from Adana, Turkey. *Environ. Monit. Assess.* **2026**, *198*, 379. <https://doi.org/10.1007/s10661-026-15263-8>.
47. Kahlert, S.; Bening, C.R. Look before you leap: Are increased recycling efforts accelerating microplastic pollution? *J. Ind. Ecol.* **2024**, *28*, 1926–1939. <https://doi.org/10.1111/jiec.13578>.
48. Hamza, M.; Bakhshae, A.; Tufail, S.A.; Bell, K.; Oza, S.; da Silva, A.K.; Norton, J.; Jazaei, F. Variation in microplastic characteristics during biosolid stabilization across wastewater resource recovery facilities in the United States and Canada. *J. Environ. Manag.* **2026**, *397*, 128374. <https://doi.org/10.1016/j.jenvman.2025.128374>.
49. Kong, W.; Jalalah, M.; Alsareii, S.A.; Harraz, F.A.; Almadiy, A.A.; Thakur, N.; Salama, E.-S. Occurrence, characteristics, and microbial community of microplastics in anaerobic sludge of wastewater treatment plants. *Environ. Pollut.* **2024**, *344*, 123370. <https://doi.org/10.1016/j.envpol.2024.123370>.
50. Jia, Q.; Duan, Y.; Han, X.; Sun, X.; Munyaneza, J.; Ma, J.; Xiu, G. Atmospheric deposition of microplastics in the megalopolis (Shanghai) during rainy season: Characteristics, influence factors, and source. *Sci. Total Environ.* **2022**, *847*, 157609. <https://doi.org/10.1016/j.scitotenv.2022.157609>.
51. Frost, H.; Bond, T.; Sizmur, T.; Felipe-Sotelo, M. A review of microplastic fibres: Generation, transport, and vectors for metal(loid)s in terrestrial environments. *Environ. Sci. Process. Impacts* **2022**, *24*, 504–524. <https://doi.org/10.1039/d1em00541c>.
52. Ziajahromi, S.; Leusch, F.D.L. Systematic assessment of data quality and quality assurance/quality control (QA/QC) of current research on microplastics in biosolids and agricultural soils. *Environ. Pollut.* **2022**, *294*, 118629. <https://doi.org/10.1016/j.envpol.2021.118629>.
53. Withana, P.A.; Senadheera, S.S.; He, D.; Bank, M.S.; Gu, C.; Hwang, S.Y.; Ok, Y.S. Soil microplastic analysis: A harmonized methodology. *Crit. Rev. Environ. Sci. Technol.* **2024**, *54*, 1138–1163. <https://doi.org/10.1080/10643389.2023.2301052>.
54. Sheriff, I.; Awang, N.A.; Halim, H.B.; Ikechukwu, O.S.; Jusoh, A.F. Extraction and analytical methods of microplastics in wastewater treatment plants: Isolation patterns, quantification, and size characterization techniques. *Desalin. Water Treat.* **2024**, *318*, 100399. <https://doi.org/10.1016/j.dwt.2024.100399>.
55. Adelugba, A.; Emenike, C. Comparative review of instrumental techniques and methods for the analysis of microplastics in agricultural matrices. *Microplastics* **2024**, *3*, 1–21. <https://doi.org/10.3390/microplastics3010001>.
56. Peneva, S.; Phan Le, Q.N.; Munhoz, D.R.; Wrigley, O.; Wille, F.; Doose, H.; Halsall, C.; Harkes, P.; Sander, M.; Braun, M.; et al. Microplastic analysis in soils: A comparative assessment. *Ecotoxicol. Environ. Saf.* **2025**, *289*, 117428. <https://doi.org/10.1016/j.ecoenv.2024.117428>.
57. Soliz, D.L.; Paniagua González, G.; Muñoz-Arnanz, J.; Bravo-Yagüe, J.C.; Fernández Hernando, P.; Garcinuño Martínez, R.M. Identification and morphological characterization of different types of plastic microparticles. *Heliyon* **2024**, *10*, e30749. <https://doi.org/10.1016/j.heliyon.2024.e30749>.
58. Nigina; Sajith, V.; Nair, B.G. Microplastics and nanoplastics in terrestrial systems. In *Toxic Effects of Micro- and Nanoplastics: Environment, Food and Human Health*; Inamuddin, Altalhi, T., Fernandes, V.C., Eds.; Wiley: Hoboken, NJ, USA, 2024; pp. 163–213. <https://doi.org/10.1002/9781394238163.ch9>.
59. Corradini, F.; Meza, P.; Eguiluz, R.; Casado, F.; Huerta-Lwanga, E.; Geissen, V. Evidence of microplastic accumulation in agricultural soils from sewage sludge disposal. *Sci. Total Environ.* **2019**, *671*, 411–420. <https://doi.org/10.1016/j.scitotenv.2019.03.368>.
60. Li, Q.; Bogush, A.; Van De Wiel, M.; Wu, P.; Holtzman, R. Microplastics transport in soils: A critical review. *Earth-Sci. Rev.* **2025**, *264*, 105108. <https://doi.org/10.1016/j.earscirev.2025.105108>.
61. Fu, B.; Zhou, W.; Chen, Y.; Wu, Y.; Gan, W.; She, N.; Ma, Y. A bibliometric perspective on the occurrence and migration of microplastics in soils amended with sewage sludge. *Water Environ. Res.* **2024**, *96*, e11054. <https://doi.org/10.1002/wer.11054>.
62. Yu, Y.; Flury, M. Current understanding of subsurface transport of micro- and nanoplastics in soil. *Vadose Zone J.* **2021**, *20*, e20108. <https://doi.org/10.1002/vzj2.20108>.

63. Cramer, A.; Benard, P.; Zarebanadkouki, M.; Kaestner, A.; Carminati, A. Microplastic induces soil water repellency and limits capillary flow. *Vadose Zone J.* **2023**, *22*, e20215. <https://doi.org/10.1002/vzj2.20215>.
64. Crossman, J.; Hurley, R.R.; Futter, M.; Nizzetto, L. Transfer and transport of microplastics from biosolids to agricultural soils and the wider environment. *Sci. Total Environ.* **2020**, *724*, 138334. <https://doi.org/10.1016/j.scitotenv.2020.138334>.
65. Yu, Z.; Xu, X.; Guo, L.; Jin, R.; Lu, Y. Uptake and transport of micro/nanoplastics in terrestrial plants: Detection, mechanisms, and influencing factors. *Sci. Total Environ.* **2024**, *907*, 168155. <https://doi.org/10.1016/j.scitotenv.2023.168155>.
66. Li, L.; Luo, Y.; Li, R.; Zhou, Q.; Peijnenburg, W.J.G.M.; Yin, N.; Yang, J.; Tu, C.; Zhang, Y. Effective uptake of submicrometre plastics by crop plants via a crack-entry mode. *Nat. Sustain.* **2020**, *3*, 929–937. <https://doi.org/10.1038/s41893-020-0567-9>.
67. Cox, K.D.; Covernton, G.A.; Davies, H.L.; Dower, J.F.; Juanes, F.; Dudas, S.E. Human consumption of microplastics. *Environ. Sci. Technol.* **2019**, *53*, 7068–7074. <https://doi.org/10.1021/acs.est.9b01517>.
68. de Souza Machado, A.A.; Lau, C.W.; Till, J.; Kloas, W.; Lehmann, A.; Becker, R.; Rillig, M.C. Impacts of microplastics on the soil biophysical environment. *Environ. Sci. Technol.* **2018**, *52*, 9656–9665. <https://doi.org/10.1021/acs.est.8b02212>.
69. 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. Microplastics can change soil properties and affect plant performance. *Environ. Sci. Technol.* **2019**, *53*, 6044–6052. <https://doi.org/10.1021/acs.est.9b01339>.
70. Büks, F.; van Schaik, L.; Kaupenjohann, M. What do we know about how the terrestrial multicellular soil fauna reacts to microplastic? *Soil* **2020**, *6*, 245–267. <https://doi.org/10.5194/soil-6-245-2020>.
71. Huang, S.; Huang, C.; Xiao, Y. Microplastics reduce soil bacterial alpha diversity and network stability. *Soil Biol. Biochem.* **2026**, *215*, 110085. <https://doi.org/10.1016/j.soilbio.2026.110085>.
72. Liu, J.; Han, S.; Wang, P.; Zhang, X.; Zhang, J.; Hou, L.; Zhang, Y.; Wang, Y.; Li, L.; Lin, Y. Soil microorganisms play an important role in the detrimental impact of biodegradable microplastics on plants. *Sci. Total Environ.* **2024**, *933*, 172933. <https://doi.org/10.1016/j.scitotenv.2024.172933>.
73. Liu, S.; Chen, B.; Wang, K.; Wang, J.; Suo, Y.; Yang, X.; Zhu, Y.; Zhang, J.; Lu, M.; Liu, Y. Unveiling the impact of biodegradable polylactic acid microplastics on meadow soil health. *Environ. Geochem. Health* **2025**, *47*, 45. <https://doi.org/10.1007/s10653-025-02358-3>.
74. Liu, R.; Liang, J.; Yang, Y.; Jiang, H.; Tian, X. Effect of polylactic acid microplastics on soil properties, soil microbes and plant growth. *Chemosphere* **2023**, *329*, 138504. <https://doi.org/10.1016/j.chemosphere.2023.138504>.
75. Kim, S.W.; Šmídová, K.; van Loon, S.; van Gestel, C.A.; Rillig, M.C.; Fritze, H.; Velmala, S. Effects of biodegradable microplastics on soil microbial communities and activities: Insight from an ecological mesocosm experiment. *Sci. Total Environ.* **2025**, *975*, 179288. <https://doi.org/10.1016/j.scitotenv.2025.179288>.
76. Frost, H.; Bond, T.; Sizmur, T.; Felipe-Sotelo, M. Sorption of metal ions onto PET-derived microplastic fibres. *Environ. Sci. Process. Impacts* **2024**, *26*, 2309–2319. <https://doi.org/10.1039/d4em00373j>.
77. Sizmur, T.; Frost, H.; Felipe-Sotelo, M.; Bond, T.; Mallory, M.L.; O'Driscoll, N.J. Methylmercury sorption to polyethylene terephthalate (PET) fibers and relevance to environmental exposure. *Environ. Toxicol. Chem.* **2025**, *44*, 335–343. <https://doi.org/10.1093/etjnl/vgae067>.
78. Yu, X.; Zhou, Z.-C.; Shuai, X.-Y.; Lin, Z.-J.; Liu, Z.; Zhou, J.-Y.; Lin, Y.-H.; Zeng, G.-S.; Ge, Z.-Y.; Chen, H. Microplastics exacerbate co-occurrence and horizontal transfer of antibiotic resistance genes. *J. Hazard. Mater.* **2023**, *451*, 131130. <https://doi.org/10.1016/j.jhazmat.2023.131130>.
79. Tuvo, B.; Scarpaci, M.; Bracaloni, S.; Esposito, E.; Costa, A.L.; Ioppolo, M.; Casini, B. Microplastics and antibiotic resistance: The magnitude of the problem and the emerging role of hospital wastewater. *Int. J. Environ. Res. Public Health* **2023**, *20*, 5868. <https://doi.org/10.3390/ijerph20105868>.
80. Shaji, S.; Allabakshi, S.M.; Satyaji Rao, Y.; Sundaram, B. Unravelling the co-occurrence and interactions of microplastics with PFAS and heavy metals in soil: A review. *Groundw. Sustain. Dev.* **2026**, *34*, 101635. <https://doi.org/10.1016/j.gsd.2026.101635>.
81. Sun, J.; Xiang, H.; Jiang, X.; Wang, X.; Luo, X.; Fu, J.; Fan, J. Effects of polyamide microplastics on the adsorption of perfluoroalkyl substances in soil. *J. Hazard. Mater. Adv.* **2024**, *13*, 100391. <https://doi.org/10.1016/j.hazadv.2023.100391>.
82. Shirkhorshidi, B.; Ghanatghesani, M.D.; Moeinpour, F.; Parvaresh, H. Exploring the interaction between microplastics and heavy metals: Unveiling the impact of microplastics on lead sorption and desorption in soil. *Environ. Monit. Assess.* **2023**, *195*, 1017. <https://doi.org/10.1007/s10661-023-11640-9>.
83. Tang, K.H.D. Effects of Microplastics on Bioavailability, Persistence and Toxicity of Plant Pesticides: An Agricultural Perspective. *Agriculture* **2025**, *15*, 356. <https://doi.org/10.3390/agriculture15040356>.

84. Sahai, H.; García Valverde, M.; Murcia Morales, M.; Hernando, M.D.; Aguilera del Real, A.M.; Fernández-Alba, A.R. Exploring sorption of pesticides and PAHs in microplastics derived from plastic mulch films used in modern agriculture. *Chemosphere* **2023**, *333*, 138959. <https://doi.org/10.1016/j.chemosphere.2023.138959>.
85. Shen, W.; Wu, Y.; Li, F.; Zhang, S.; Jin, H.; Gao, B. The impact of microplastic and sulfanilamide co-exposure on soil microbiota. *Ecotoxicol. Environ. Saf.* **2025**, *292*, 117968. <https://doi.org/10.1016/j.ecoenv.2025.117968>.
86. Saldi, E.; Forestieri, B.; Nuzzi, C.; Toledo, M.; Lwanga, E.H.; Karpouzas, D.G.; Negri, I. Role of Biodegradable and Non-Biodegradable Microplastic in Modulating the toxicological Effects of Organic Pollutants in the Soil Organism *Folsomia candida*. *Water Air Soil Pollut.* **2025**, *236*, 710. <https://doi.org/10.1007/s11270-025-08351-x>.
87. Zhang, Y.; Wang, Z.; Wang, F.; Zhou, H.; Zhang, L.; Xie, B. Anaerobic degradation of aromatic and aliphatic biodegradable plastics: Potential mechanisms and pathways. *Environ. Sci. Technol.* **2024**, *58*, 19462–19474. <https://doi.org/10.1021/acs.est.4c07554>.
88. Tseng, H.-C.; Fujimoto, N.; Ohnishi, A. Biodegradability and methane fermentability of polylactic acid by thermophilic methane fermentation. *Bioresour. Technol. Rep.* **2019**, *8*, 100327. <https://doi.org/10.1016/j.biteb.2019.100327>.
89. Walter, A.; Sopracolle, L.; Mutschlechner, M.; Spruck, M.; Griesbeck, C. Biodegradation of different PET variants from food containers by *Ideonella sakaiensis*. *Arch. Microbiol.* **2022**, *204*, 711. <https://doi.org/10.1007/s00203-022-03306-w>.
90. Suresh, V.; Shams, R.; Dash, K.K.; Shaikh, A.M.; Kovács, B. Comprehensive review on enzymatic polymer degradation: A sustainable solution for plastics. *J. Agric. Food Res.* **2025**, *20*, 101788. <https://doi.org/10.1016/j.jafr.2025.101788>.
91. Coulibaly, C.A.; Domenek, S.; Greuet, P.; George, M.; Fabre, P.; Auras, R.; Gastaldi, E. Residual biodegradable microplastics derived from compostable packaging under large-scale industrial composting fully degrade in soil. *Bioresour. Technol.* **2026**, *451*, 134496. <https://doi.org/10.1016/j.biortech.2026.134496>.
92. Coutiris, C.; Rivier, P.A.; Torp, T.; Klaus, J.; Joner, E.J. In situ degradation of biodegradable plastic mulch in Nordic agricultural soils. *Chemosphere* **2025**, *384*, 144516. <https://doi.org/10.1016/j.chemosphere.2025.144516>.
93. Wahl, A.; Davranche, M.; Rabiller-Baudry, M.; Pédrot, M.; Khatib, I.; Labonne, F.; Canté, M.; Cuisinier, C.; Gigault, J. Condition of composted microplastics after they have been buried for 30 years: Vertical distribution in the soil and degree of degradation. *J. Hazard. Mater.* **2024**, *462*, 132686. <https://doi.org/10.1016/j.jhazmat.2023.132686>.
94. Alcaraz-Dólera, M.; Ros, M.; Penalver, R.; Pascual, J.A. Bioplastics in agricultural soils: Biodegradability, analytical techniques, and soil microbial impact. *J. Hazard. Mater.* **2026**, *507*, 141783. <https://doi.org/10.1016/j.jhazmat.2026.141783>.
95. Yu, Y.; Lin, S.; Sarkar, B.; Wang, J.; Liu, X.; Wang, D.; Ge, T.; Li, Y.; Zhu, B.; Yao, H. Mineralization and microbial utilization of poly(lactic acid) microplastic in soil. *J. Hazard. Mater.* **2024**, *476*, 135080. <https://doi.org/10.1016/j.jhazmat.2024.135080>.
96. Davies, G.; Kernchen, S.; Löder, M.G.J.; Brenninkmeijer, L.; Laforsch, C.; Krause, S.; Lynch, I. Determining the impact of common microplastic extraction methods from soil matrices on the biodegradable polymers polylactic acid and polyhydroxybutyrate. *Microplastics Nanoplastics* **2026**, *6*, 18. <https://doi.org/10.1186/s43591-025-00167-0>.
97. Commission Delegated Regulation (EU) 2024/2770 of 15 July 2024 amending Regulation (EU) 2019/1009 of the European Parliament and of the Council as Regards Biodegradability Criteria for Coating Agents and Water Retention Polymers. Official Journal of the European Union, L, 2024/2770, 28.10.2024. Available online: https://eur-lex.europa.eu/eli/reg_del/2024/2770/oj (accessed on 21 July 2026).
98. Commission Regulation (EU) 2023/2055 of 25 September 2023 Amending Annex XVII to Regulation (EC) No 1907/2006 (REACH) as Regards Synthetic Polymer Microparticles. Official Journal of the European Union, L 238, 27.9.2023. Available online: <https://eur-lex.europa.eu/eli/reg/2023/2055/oj> (accessed on 21 July 2026).
99. Directive (EU) 2024/3019 of the European Parliament and of the Council of 27 November 2024 Concerning Urban Wastewater Treatment (Recast). Official Journal of the European Union, L, 2024/3019. Available online: <https://eur-lex.europa.eu/eli/dir/2024/3019/oj> (accessed on 21 July 2026).
100. Regulation (EU) 2025/40 of the European Parliament and of the Council of 19 December 2024 on Packaging and Packaging Waste. Official Journal of the European Union, L, 2025/40. Available online: <https://eur-lex.europa.eu/eli/reg/2025/40/oj> (accessed on 21 July 2026).
101. US EPA. *Standards for the Use or Disposal of Sewage Sludge. 40 CFR Part 503*; United States Environmental Protection Agency: Washington, DC, USA, 1993. Available online: <https://www.ecfr.gov/current/title-40/chapter-I/subchapter-O/part-503> (accessed on 21 July 2026).
102. Bünnemann, E.K.; Reimer, M.; Smolders, E.; Smith, S.R.; Bigalke, M.; Palmqvist, A.; Brandt, K.K.; Möller, K.; Harder, R.; Hermann, L.; et al. Do contaminants compromise the use of recycled nutrients in organic agriculture? A review and synthesis of current

- knowledge on contaminant concentrations, fate in the environment and risk assessment. *Sci. Total Environ.* **2024**, *912*, 168901. <https://doi.org/10.1016/j.scitotenv.2023.168901>.
103. Council Directive 86/278/EEC of 12 June 1986 on the Protection of the Environment, and in Particular of the Soil, When Sewage Sludge is Used in Agriculture. Official Journal of the European Communities, L 181, 4.7.1986. Available online: <https://eur-lex.europa.eu/eli/dir/1986/278/oj> (accessed on 21 July 2026).
 104. *ISO 24187:2023*; Principles for the Analysis of Microplastics Present in the Environment. International Organization for Standardization: Geneva, Switzerland, 2023. Available online: <https://www.iso.org/standard/78033.html> (accessed on 21 July 2026).
 105. *ISO/DIS 24899*; Plastics—A Method for Extraction of Microplastics from Compost Samples. International Organization for Standardization: Geneva, Switzerland, 2026. Available online: <https://www.iso.org/standard/88369.html> (accessed on 21 July 2026).
 106. *ISO/WD 25654*; Plastics—Reference Materials for the Validation of Microplastic Detection Methods. International Organization for Standardization: Geneva, Switzerland, 2025. Available online: <https://www.iso.org/standard/91028.html> (accessed on 21 July 2026).

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