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# Plastics and other extraneous matter in municipal solid waste compost: A systematic review of sources, occurrence, implications, and fate in amended soils

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A R T I C L E  I N F O

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A B S T R A C T

Municipal solid waste (MSW) composting is rapidly growing globally as a sustainable approach to valorize the organic fraction of municipal solid waste (OFMSW) into compost for agricultural use. However, MSW compost use in agriculture is threatened by physical contaminants, mainly plastics, glass, metals, and stones in the compost, exceeding the legal thresholds in some cases. This study comprehensively reviews the literature on various physical contaminants in MSW compost, focusing on sources, occurrence, environmental implications, and fate in amended soils. The review shows that physical contaminants in MSW compost are highly heterogeneous depending on waste origin, source separation, and sorting and sieving practices before and after composting. Plastics are the most widely occurring and abundant physical contaminant in MSW compost, reaching up to 15,300 mg/kg in compost, capable of inputting up to 536 kg plastics/ha/year in amended soils. Glass, stones, and metals also regularly occur in MSW compost, reaching up to 17.2%, 18.2%, and 1.5% of the compost mass respectively. Repeated application of contaminated compost increases physical contaminant accumulation in amended soils, severely impacting the soil's physical, chemical, and biological performance. Synthetic plastics in compost-amended soils tend to have a long residence time, slowly degrading and releasing small-sized plastic particles and their metabolites. Further, they may be transported from the point of application by biotic or abiotic agents, posing secondary pollution effects. Microplastics (MPs) are the most significant emerging physical contaminant in MSW compost, and present detection challenges and regulatory laxity in compost marketing. The strategies to mitigate physical contaminants in MSW compost include proper biowaste source separation, improved biowaste separation and screening before and after composting, regulatory adherence and monitoring of contaminants in compost, and the adoption of compostable biodegradable plastics in MSW biowaste collection.

## 1. Introduction

With continuous global economic development, urbanization, population growth, and increased demand for consumer goods and services (Jalalipour et al., 2020), there is a concomitant rise in the generation and complexity of MSW. According to the World Bank (2023), at least two billion tonnes of MSW are generated globally annually due to anthropogenic activities, with a substantial fraction of these managed using landfilling, open dumping, and open burning (Hasan et al., 2021; Kumar and Samadder, 2017). These methods are unsustainable for MSW management according to the waste management hierarchy (Sakai et al., 2011; Wang et al., 2020); they pollute the environment through greenhouse gas emissions, soil and water contamination, release of toxic environmental compounds, and generation of offensive odors, severely impacting lives, public health, and the environment (Ayilara et al., 2020; Talang and Sirivithayapakorn, 2021). A substantial fraction of MSW globally is biodegradable organic matter, including food and kitchen waste, garden waste, livestock residues, green cuttings, and

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agricultural residues (Babu et al., 2021; Komakech et al., 2014). These have recoverable potential into high-value nutrient and energy byproducts (Jalalipour et al., 2020; Kumar and Samadder, 2017). There are increasing calls for sustainable MSW management practices that mitigate their negative environmental and public health impacts.

MSW composting is one of the most economical and sustainable approaches for recovering and recycling nutrients through the microbial degradation of the OFMSW under aerobic conditions. Composting of the OFMSW for agricultural use is recommended and accepted in many countries only for source-separated biowaste (Wei et al., 2017). However, the lack of legislation means mixed MSW composting is also practiced in several other countries. MSW composting offers numerous benefits, including reduced waste volumes sent to landfills/dumpsites (Rodrigues et al., 2020); the derived compost is a source of income for municipalities through reduced disposal costs and sales of compost (Lu et al., 2012); reduced greenhouse gas emissions (Rodrigues et al., 2020); and the compost obtained is a source of plant nutrients and can improve soil properties. In developing and low-income countries where inorganic fertilizer use is low and expensive, yet crop yields are low, MSW compost can be an affordable input to replenish soil nutrients and improve vital soil properties (Lederer et al., 2015). Compost is also one of the main inputs in organic agriculture, which is highly reputed for sustainability in agricultural production.

The utilization of MSW compost, however, is under immense threat due to the increasing occurrence of physical contaminants in its content, which arise from improper materials in the composting feedstocks (Kawecki et al., 2021). Improper materials are non-biodegradable fractions, mainly plastics, paper, glass, metals, and stones, often collected together with biowaste feedstocks used for composting. The occurrence of improper materials in composting feedstocks is linked to the occurrence of physical contaminants in the final compost (Cattle et al., 2020; Sharifi and Renella, 2015) as fragments or whole pieces of plastics, glass, metal, or stones, lowering compost quality. Besides, their occurrence in feedstocks may transfer hazardous contaminants to organic matter during degradation, and may interfere with the composting process by affecting the water, air, and nutrient-balance requirements (Malamis et al., 2017). Several studies have demonstrated physical contaminant problems in MSW compost or its feedstocks to be significantly huge. In Spain, at least 10% of biowaste composting feedstocks were reportedly improper materials (Rodrigues et al., 2020). Table 1 shows the composition of MSW compost, including physical contaminant fractions reported in various literature.

While previous attention in MSW compost focused mainly on its fertilizing and agronomic quality (Vázquez et at., 2015), there is a growing concern to consider physical contaminants in compost for agricultural or horticultural use. This is important since compost can contribute significantly to physical contaminant input in amended soils. Some previous review studies have documented the occurrence of contaminants in soil amendments including compost. O'Connor et al. (2022) reviewed the physical, chemical, and microbial contaminants in compost but only of food waste origin. Porterfield et al. (2022) reviewed microplastic contaminants in composts, digestates, and food wastes. However, the study lacked discussions of macroplastics and other traditional physical contaminants in compost. As far as we know, there is a lack of a comprehensive systematic summary describing physical contaminant occurrence in MSW compost and their implications. This work thus consolidates widely scattered knowledge on sources, occurrence, implications, and fate of physical contaminants in MSW compost. More precisely, the aims of the review are to 1) describe the sources and occurrence of physical contaminants in MSW compost; 2) discuss the environmental and ecological impacts of physical contaminants in compost on amended soils; 3) discuss the fate of physical contaminants in MSW compost; and 4) propose strategies to mitigate physical contaminants in compost. The work thus consolidates evidence-based

**Table 1**
Composition of MSW compost including physical contaminant fractions.

| Compost | Origin | Composition | Percent fraction | Country | Reference |
|---|---|---|---|---|---|
| MSW compost (0-40 mm) | Green waste | Organic matter | 87.2% | United Kingdom | Echavarri-Bravo et al., 2017 |
| | | Glass (>2 mm) | 0.1% | | |
| | | Metal (>2 mm) | 0.1% | | |
| | | Plastic (>2 mm) | 0.1% | | |
| | | Stone (>4 mm) | 12.3% | | |
| | | Other materials | 0.2% | | |
| MSW compost | Source-separated or mixed MSW or both | Organic matter | Variable, depending on inert content | United Kingdom | Dimambro et al., (2007) |
| | | Glass | 0.0-16.8% | | |
| | | Plastic | 0.0-4.2% | | |
| | | Metal | 0.0-0.4% | | |
| | | Stone | 1.1-7.3% | | |
| Stabilized fraction in 10 Mechanical Biological Treatment (MBT) plants | MSW | Organic matter | 78.2% | Castile & Leon region of Spain | Montejo et al., (2010) |
| | | Paper and cardboard | 5.9% | | |
| | | Plastics | 5.9% | | |
| | | Glass | 6.5% | | |
| | | Metals | 0.8% | | |
| | | Textiles | 0.4% | | |
| | | Wood | 0.4% | | |
| | | Non-combustible | 1.9% | | |
| MSW compost | Mixed MSW | Organic matter | 70.4% | Iran | Sharifi and Renella, 2015 |
| | | Glass | 11.1% | | |
| | | Stones | 18.2% | | |
| | | Plastics | 0.3% | | |
| MSW compost | Mixed MSW | Organic matter | 88.5% | Turkey | Sezer and Arikan (2011) |
| | | Glass | 4.2% | | |
| | | Stones | 5.8% | | |
| | | Textile, plastic, and metal combined | 1.5% | | |
| MSW compost (<25.4 mm) | Mixed MSW | Organic matter | 89.0% | Across North America | Brinton Jr (2005) |
| | | Glass | 5.2% | | |
| | | Metal | 0.2% | | |
| | | Plastic | 3.9% | | |
| | | Textiles | 1.7% | | |

information on physical contaminants in compost and their environmental and ecological implications that catalyze stakeholder interests and interventions at the local and global levels.

## 2. Strategy for the literature review

### 2.1. Scope

This literature review comprehensively presents physical contaminants in MSW compost and their implications on compost-amended soils and related ecosystems. Although contaminants in compost may be physical, chemical, or biological, this review focuses only on physical contaminants *inter alia* plastics, glass, paper, metals, and stones in MSW compost. Physical contaminants, mainly plastics, have recently gained notoriety in MSW management systems, complicating the recycling of OFMSW through composting. Physical contaminants in compost include macro- and micro-particles (Judy et al., 2019; Wahl et al. 2024), including nanoparticles. The review is also limited to compost of MSW origin. While compost is obtained from diverse sources including industrial, agricultural, and livestock wastes, our review focuses on compost from MSW only. MSW originates from households, commercial establishments, streets and parks, industries, and institutions (Babu et al., 2021; Farrell and Jones, 2009).

### 2.2. Data collection and analysis

A structured literature search was performed by collecting and reviewing articles from Google Scholar, Scopus, and ScienceDirect scientific databases published between 2005 and April 2023 for physical contaminants in MSW compost. MSW composting has only recently gained considerable global attention due to the challenges of large-scale MSW management, circular economy thinking, and growing interest in the use of organic fertilizers. The criteria for preliminary screening of articles included the title, abstract, keyword, and document type. To gain an understanding of physical contaminants in MSW compost, the keywords "compost" AND "physical contaminants" OR "foreign matter" OR "improper materials" OR "extraneous matter" were used for the initial literature search (See Fig. 1). This yielded 1,660 results on Google Scholar in April 2023, of which 982 (59%) were published between 2015 and 2023, indicating the increasing scholarly interest in the topic lately. A further search was conducted using the following keywords across databases: 'municipal solid waste', 'compost', 'contamination', 'physical', 'pollutant', 'plastic', 'macroplastics', 'microplastics', 'nanoplastics', 'glass', 'textile', 'stone', 'paper', 'paperboard', 'wood', 'stone', 'emerging', 'contaminant', 'environmental', 'ecological', 'risk', 'source', 'fate', 'short-term', 'long-term', 'accumulation', 'degradation', 'transport'. These keywords were used in various combinations using 'AND' and 'OR' Boolean operators. The obtained articles were screened for eligibility, with irrelevant and duplicate articles abandoned. Further, letters and reviews were not considered. In addition, references to the literature of selected articles were traced for further relevant literature. Finally, about 85 journal articles were eligible for full-text review.

## 3. Sources of physical contaminants in MSW compost

Improper materials in MSW biowaste are heterogeneous and varied, including mainly plastics, metals, glass, stones, paper and paperboard, and textiles (Table 2), originating from residential, commercial, institutional, and industrial waste collection systems (Farrell and Jones, 2009; O'Connor et al., 2022). MSW collection may occur either through source separation of the different waste fractions, facilitating recycling of the desired fractions, or through mixed waste collections where all fractions are collected together, for example, in the same bin. Both systems of waste collection may also be employed in some places. Carefully designed MSW collection systems employing source separation are common in developed countries e.g. Europe (Wang et al., 2020), and are responsible for their high level of solid waste recycling and recovery (Han and Zhang, 2017). In mixed MSW collection systems, such as is commonly practiced in developing countries, improper materials in biowaste are the most limiting factor in the recycling of OFMSW through composting or anaerobic digestion. Composts originating from such collection systems are often more contaminated with physical

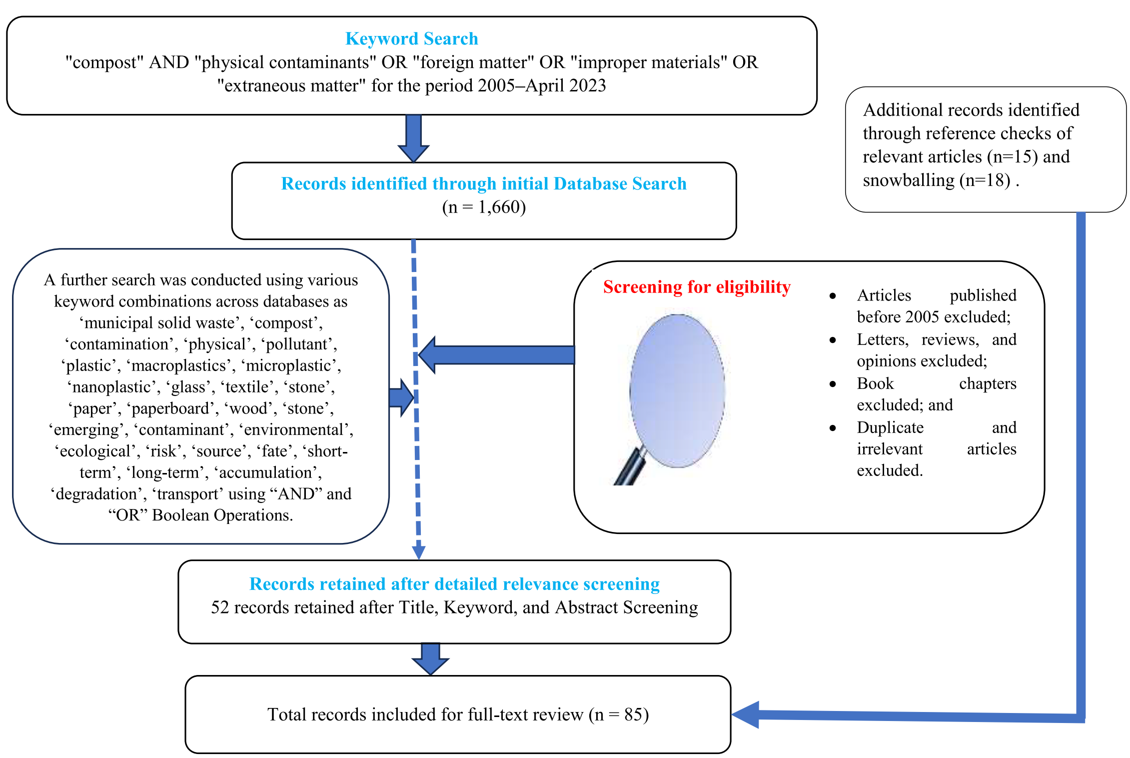


**Fig. 1.** General search procedure and results for the literature search decision-making process

**Table 2**
Composition of MSW in selected countries showing improper material fractions.

| City/Country | Organic matter (%) | Plastic (%) | Paper and paperboard (%) | Glass (%) | Metal (%) | Textile (%) | Wood (%) | Other (%) | Reference |
|---|---|---|---|---|---|---|---|---|---|
| Nur-Sultan City, Kazakhstan | 46.3 | 15.2 | 12.8 | 4.9 | 1.9 | 3.7 | 0.8 | 14.4 | Abylkhani, 2021 |
| Suzhou City, East China | 65.7 | 8.9 | 14.3 | 2.1 | 1.5 | 2.3 | 0.4 | 4.9 | Gu et al., (2015) |
| Shalimar Town, Pakistan | 81.0 | 6.0 | 5.0 | 2.0 | - | - | - | 5.0 | Kamran et al., (2015) |
| Riihimäki City, Finland | 48.4 | 15.8 | 14.2 | 1.6 | 2.3 | 5.1 | - | 12.6 | Liikanen et al., (2016) |
| Kuwait, Iraq | 45.8 | 18.2 | 6.7 | 6.1 | 4.0 | 6.2 | 3.8 | 8.4 | Al-Jarallah and Aleisa (2014) |
| Castile & Leon, Spain | 64.1 | 9.1 | 9.2 | 10.9 | 2.0 | 0.5 | 1.1 | 3.1 (including household batteries) | Montejo et al., (2010) |
| Gaza Strip, Palestine | 54.0 | 12.0 | 11.0 | 3.0 | 3.0 | - | - | 17.0 | Abd Alqader and Hamad, 2012 |
| Italy | 92.0 | - | 1.8 | - | - | - | - | 6.2 (total for plastic, metal, and other inert materials) | Cesaro et al., (2019) |
| Sangamner City, India | 61.0 | 6.0 | - | 2.0 | 5.0 | - | - | Bone 1.0; Rubber and leather 2.5; rocks, sand, bricks, stones 12.5; Other inorganic materials 10.0 | Thitame et al., 2010 |
| Kampala, Uganda (dry season) | 88.5 | 6.6 | 2.2 | 0.9 | 0.2 | 0.7 | - | 1.0 | Komakech et al., (2014) |
| Kampala, Uganda (rainy season) | 94.8 | 3.4 | 0.7 | 0.3 | 0.1 | 0.3 | - | 0.3 | Komakech et al., (2014) |
| Sisimiut City, Greenland | 42.8 | 2.4 | 11.4 | 7.1 | 2.0 | 1.8 | 1.0 | 31.5 (diaper, packaging, hygiene articles) | Eisted and Christensen (2011) |

contaminants than those from source-separate collection or garden waste or green cuttings (Colombini et al., 2022; Dimambro et al., 2007; van Schothorst et al., 2021).

Such composts (from mixed collection) are not recommended for agricultural use and should be subject to alternative disposal pathways other than agriculture (Farrell and Jones, 2009). Wei et al., (2017) argued that MSW composting for agricultural use should go hand in hand with the source separate collection of biowaste. Nevertheless, even biowaste or compost originating from source-separated biowaste from MSW collection is reportedly contaminated with physical contaminants, as users often breach the system either through negligence or lack of knowledge on where to dispose improper materials (Sholokhova et al., 2021). Thus, municipalities and cities performing source collection may differ in the levels of improper materials in the biowaste. Fig. 2 shows the general flow scheme of composting with indications of improper materials in MSW destined for composting.

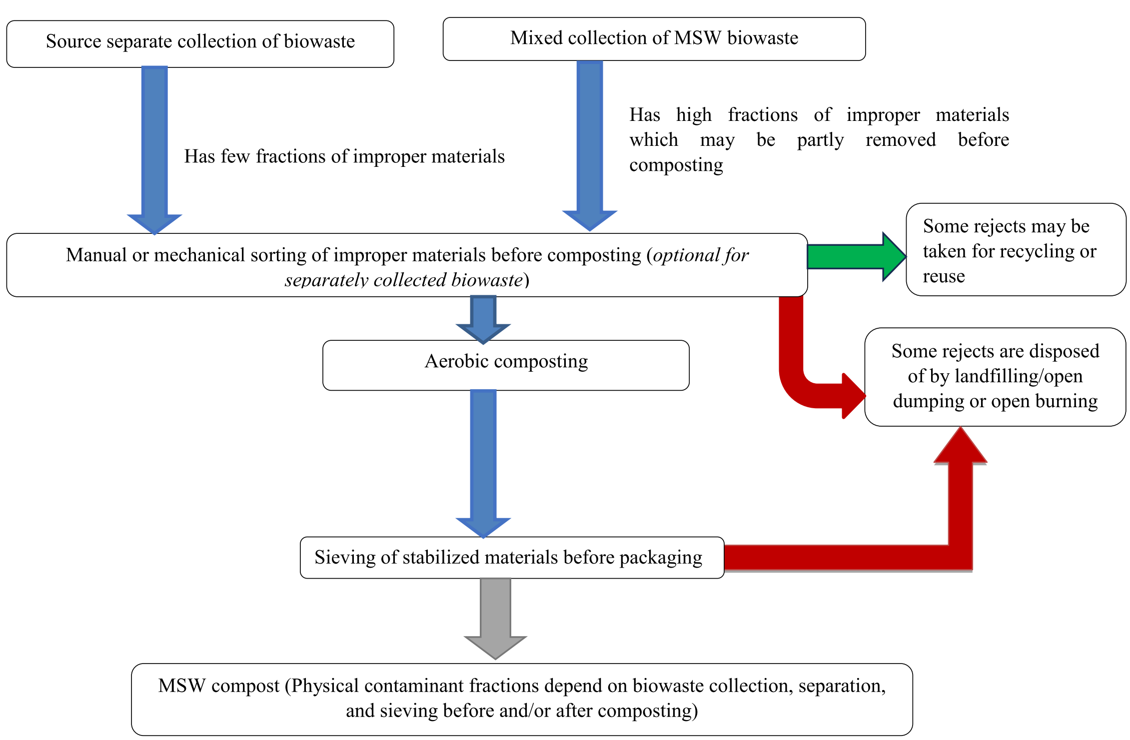


**Fig. 2.** General flow scheme of a typical MSW biowaste composting with remarks on improper material flow

Plastics are arguably the most widespread physical contaminant in MSW compost today due to their enormous occurrence and diversity in solid waste, having become a rapidly growing fraction in MSW systems. In many places, plastics are used for biowaste collection and disposal (Cesaro et al., 2015; Rodrigues et al., 2020), and are often unsatisfactorily removed using composting plants' manual or mechanical separation systems. Other sources of plastics in solid waste collection include food and other consumer product packaging, plastic liners, films, stickers, tea bags, and plastic-coated items. During composting, synthetic plastics in biowaste may disintegrate due to the turning events and high temperature achieved, releasing macro-, micro-, and nanoplastic particles (Gadaleta et al., 2023; Ruggero et al., 2021). These plastics contaminate the finished compost and subsequently amended soils where compost is applied.

Besides plastics, other improper materials in MSW collection systems that lower compost quality include metals, glass, rocks/stones, textiles, and paper and paperboard (Echavarri-Bravo et al., 2017; Thakali et al., 2022). In general, physical contaminants in compost originate from inadequate solid waste collection and disposal practices for biowaste. While manual or mechanical sorting of improper materials in mixed waste collection may reduce the content of improper materials in biowaste, the resulting compost still tends to be low quality (Wei et al., 2017).

Although regulations governing physical contaminants in compost exist in some countries (Table 3), there are currently no regulations governing small-sized physical contaminants less than 2 mm in compost (O'Connor et al., 2022). Small-sized physical contaminants <2 mm, including MPs, are largely unregulated, mainly due to the difficulty in conducting quick, affordable, and reliable analytical determinations of such contaminants in compost. In addition, regulations governing physical contaminants in compost differ widely between countries, limiting compost marketing between countries. Existing regulations are often based on the visual appearance of physical contaminants, and counting and weighing particles of a minimum size (Zorpas, 2016). Recently, there has been an increasing research interest in physical contaminants in MSW compost and amended soils (Fig. 3), with MPs gaining tremendous scholarly interest in the last few years as an emerging contaminant.

## 4. Occurrence and implications of physical contaminants in MSW compost

The occurrence of physical contaminant materials in MSW compost is common, especially where there is improper management in biowaste collection systems, as already described. The following describes physical contaminants in compost that limit its suitability for agricultural use.

### 4.1. Plastics in MSW compost

Plastics are ubiquitous, often found in almost every aspect of our daily lives, including product packaging, construction, electrical and electronic products, automotive, agriculture, textiles, and consumer marketing. The most commonly produced plastics are carbon-based polymers including polypropylene, polyethylene, polystyrene, polyvinyl chloride, and polyethylene terephthalate, with polyethylene being the most widely used plastic worldwide (Huang et al., 2021). Although advantageous in many aspects, plastics form a considerable fraction of MSW collection systems and are often inappropriately disposed of at the end of their life.

Plastics pose several adverse environmental effects, including pollution of soil, marine, and freshwater ecosystems. Previously considered a problem only in marine ecosystems, there is growing scientific evidence of plastic abundance in terrestrial and aquatic ecosystems, including agricultural soils (de Souza Machado et al., 2018a). It is postulated that agricultural soils could be harboring more plastics than oceans (Nizzetto et al., 2016), mainly due to the increasing use of materials or additives containing plastics for nutrient replenishment and pest, disease, and environmental management. The use of organic fertilizers including MSW compost is one of the main pathways of plastic input to the soil (Edo et al., 2022). Although MSW compost contributes a significant plastic input to agricultural soils, there is still a knowledge

**Table 3**
Legal limits of physical contaminants in compost for agricultural use in selected regional and national standards.

| Parameter | EU [A] | Austria [B] | Australia [C] | Belgium [D] | France [E] | Germany [F] | Italy [G] | UK [H] | Canada [I] |
|---|---|---|---|---|---|---|---|---|---|
| Stones and clay lumps (% dw) | - | - | ≤5% | <4% of stones >5 mm | - | <5% of >5 mm | ≤5% for stones ≥5 mm | ≤8% of >4 mm | - |
| Glass, plastic, metal (% dw) | ≤3 g/kg of macroscopic impurities >2 mm;<br>≤5 g/kg for a total of glass, metal, plastic | ≤0.4% of >2mm for a total of glass, metal, and plastic;<br>≤0.1% for plastic >2mm;<br>≤0.2% for metal >2mm;<br>≤0.2% for glass >2mm | ≤0.5% with light flexible plastic ≤ 0.05% | <0.8% for impurities >2 mm | <2.0% for glass and metals >2 mm;<br><0.3% for plastic films and polystyrene >5 mm;<br><0.8% for other plastics >5 mm | ≤0.5% for >2 mm | ≤0.5% for total impurities ≥2 mm | ≤0.25% of which ≤0.12% is plastic >2mm | No sharp foreign matter >3 mm per 500 ml<br>≤3 pieces of sharp foreign matter >12.5 mm per 500 ml<br>≤1 piece of foreign matter ≥25 mm per 500 ml<br>≤2 pieces of foreign matter ≥25 mm per 500 ml |

[A] European Commission (2019)
[B] BMSGPK (2004)
[C] Biala and Wilkinson (2020)
[D] VLACO (2011)
[E] AFNOR (2006)
[F] Siebert (2012)
[G] CIC (2017)
[H] PAS (2018)
[I] CCME (2005)

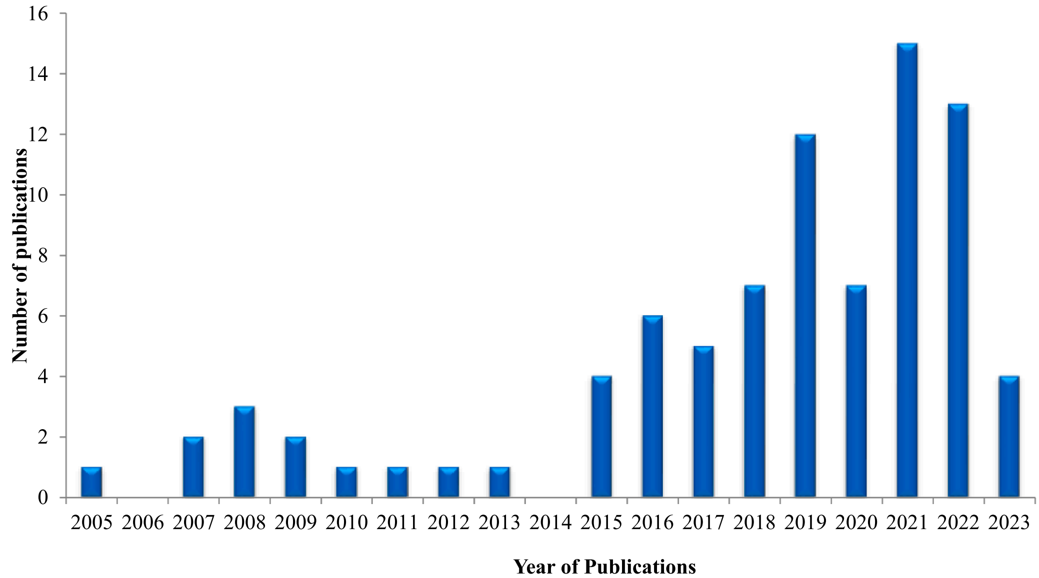


**Fig. 3.** Number of research studies on physical contaminants in MSW compost or amended soils for the period 2005–April 2023

gap on the extent of plastic contamination and its impacts on amended soils.

*4.1.1. Occurrence and quantification of plastics in MSW compost*

Plastics in MSW compost and other ecosystems may exist in any of three forms: as large particles of at least 25 mm, termed macroplastics (Romeo et al., 2015); as medium-sized particles of 5–25 mm, termed mesoplastics (Braun et al., 2021); or as minute particles of <5 mm termed microplastics (Thompson et al., 2004). While visibly large-sized plastics (macroplastics and mesoplastics) are more likely to receive considerable attention than small-sized ones from compost users, microplastic contamination deserves more attention (Gui et al., 2021), due to the dangers that it poses to the soil ecosystem. The amount of small-sized plastics entering the soil through soil amendment use can be significantly enormous. A recent study in Germany estimated that between 35 billion to 2.2 trillion MPs enter agricultural land annually through organic fertilizer use alone (Weithmann et al., 2018). A more recent study of fields fertilized with MSW compost 12 years ago in Germany reported 0-64 microplastic particles/kg, corresponding to stocks of 38.2 million to 171.4 million microplastic particles/ha in the soil (Braun et al., 2023). These are significant magnitudes of plastics in the soil and could be much higher in other countries since Germany's regulations of compost quality are regarded as one of the strictest in the world.

Until recently, the soil input of plastics through compost application received little attention, but interest has been increasing in the past few years, pointing to the realization of the problem. The first study that quantified plastics in MSW compost was an undergraduate thesis research, which reported up to 1,200 mg plastics/kg in a Slovenian compost (Gajst, 2016). Another study later reported MSW compost in Germany to have much lower plastic contents than the Slovenian compost, ranging from 2.38-180 mg/kg (Bläsing and Amelung, 2018). Since then, several scholarly outputs (Table 4) have emerged providing evidence of the abundance of plastics in MSW compost in different countries.

Braun et al., (2021) evaluated the potential plastic loads (mesoplastics and MPs) of MSW compost originating from composting facilities and hardware stores in Germany. All the investigated compost contained plastics averaging 12-46 particles/kg, amounting to plastic weights of 50–1,360 mg/kg. This study estimated that such composts applied at a recommended rate of 7-35 tonnes/ha would input 84,000-1,610,000 plastics/ha/year in the soil, equivalent to 0.34-47.53 kg of plastics/ha/year respectively. In Finland, Scopetani et al., (2022) studied the occurrence of macroplastics, mesoplastics, and MPs in compost from mixed MSW biowaste. The concentration of macroplastics/mesoplastics in the compost was 6,530 mg/kg, while MPs averaged 6,600 items/kg. Compared to the study of Braun et al., (2021), Scopetani et al., (2022) showed that plastic input into agricultural soils from MSW compost could be much higher than previously estimated. Table 4 shows evidence of plastic occurrence and abundance in MSW compost and the potential soil input that may result from compost use. Generally, in most evaluated compost, plastics of different size fractions occur in the compost.

*4.1.2. Influencing factors for plastics in MSW compost*

From Table 4, almost all MSW composts reportedly contain plastics to varying degrees, and this form of compost should be considered an important plastic pathway into agricultural soils. MSW compost from areas with mixed or poor biowaste collection has more plastics and other physical contaminants than those from source separation. Relatedly, Edo et al., (2022) studied five MSW composting plants in Spain and showed that plants operating door-to-door waste collection systems showed less plastic contamination than those from central or street bins where there is less control of collection management. A similar study in Catalonia provided further evidence of source separation in reducing improper materials in biowaste in door-to-door MSW collection systems (Puig-Ventosa et al., 2013). Moreover, biowaste is collected using synthetic plastic bags in many places, which easily find their way into composting plants without proper disposal management. Also, MSW composts originating from biowaste from densely populated areas contain more plastics than those from sparsely populated areas (Zafiu et al., 2023). This could be due to the difficulty in isolating plastics from source-separation biowaste collection systems in highly populated areas. Finally, the number of plastics in compost increases with a decrease in plastic particle size, supporting the argument that MPs should be given more considerable attention.

The degree of manual or mechanical separation at the composting facility before, during, and after composting is another factor that determines the physical contaminant level of compost. Composting combined with manual or mechanical separation at the facility is usually employed where source segregation of biowaste is not carried out, yet composting needs to take place for economic, social, or other reasons (Bardos, 2004). In some facilities, manual sorting may be the only available option to remove improper materials from the incoming

**Table 4**
Plastic content of MSW compost reported in literature and potential transfer/input to amended soils.

| Plastic abundance (number and/or mass of particles/kg dry weight) in compost | Compost origin | Plastic size (mm) and/or type | Potential plastic input to agricultural soil/ha/year based on annual application rate * | Country | Reference |
|---|---|---|---|---|---|
| 2.38-180 mg/kg | Household biowaste; Green cuttings | Visible plastic items (size not stated) | 0.0167-6.3 kg/ha/year | Germany | Bläsing and Amelung (2018) |
| 4,611.1 particles/kg and 10,849.2 mg/kg | Mixed MSW | 2-5 | 3.2-16.1 × $10^7$ particles/ha/year | France | Colombini et al., (2022) |
| 3,783-5,733 particles/kg | Food waste and green-cuttings | 1-5 | 2.65-20.1 × $10^7$ particles/ha/year | Lithuania | Sholokhova et al., (2021) |
| 17,407 and 15,400 particles/kg for autumn and winter compost respectively | Mixed MSW | 1-5 | Average of 11.5-57.4 × $10^7$ particles/ha/year | Lithuania | Sholokhova et al., (2021) |
| 7-232 macro- and microplastic particles/kg | Household biowaste from urban settings | >0.2; dominated by polypropylene (39%); polyethylene (20%), polyacrylic acid (11%), polyurethane (5%), polyethylene terephthalate (5%), and biodegradable plastics (5%) | 4.9-812.0 × $10^4$ particles/ha/year | Austria | Zafiu et al., (2023) |
| 2,400 particles/kg | Rural domestic waste | 0.05-5 | 1.68-8.4 × $10^7$ particles/ha/year | China | Gui et al., (2021) |
| 1,200 mg/kg | MSW | - | 8.4-42 kg/ha/year | Slovenia | Gajst (2016) |
| Macroplastics/mesoplastics 6,530 mg/kg<br>MPs 6.6 particles/kg | Biowaste from households, restaurants, and industry | Macroplastics/mesoplastics (5-150): Dominated by polypropylene (58.3%) and polyethylene (36.1%);<br>MPs (<5): Dominated by polyethylene terephthalate (44.2%), polyethylene (25%), acrylates (9.6%), ABS (7.7%), polypropylene (5.8%), and polystyrene (3.9%) | 45.7-228.6 kg macroplastics & mesoplastics/ha/year<br>4.6–23.1 × $10^4$ MPs/ha/year | Finland | Scopetani et al., (2022) |
| Mesoplastics and macroplastics 1,000–15,300 mg/kg | Household waste | >5 | 7–536 kg plastics/ha/year | Italy | Watteau et al., (2018) |
| 12-46 particles/kg, corresponding to plastic weights of 48-1,360 mg/kg; Compost from green cuttings had the least amount of MPs. | Household biowaste; Green cuttings | <1-25;<br>more fragments (68–91% of all plastic items) than fibers (5–13 of all plastic items) | 8.4-161.0 × $10^4$ plastic items/ha/year, amounting to an input of 0.34-47.6 kg plastic/ha/year; | Germany | Braun et al., (2021) |
| 20-24 particles/kg | Household biowaste; Green cuttings | >1;<br>Polymer abundance was styrene-based polymers (42–60%) followed by polyethylene (30–33%), and polypropylene (0–17%) | 1.40–8.4 × $10^5$ particles/ha/year | Germany | Weithmann et al., (2018) |
| Total plastics were 10,000-30,000 particles/kg, mostly <5 mm (about 5,000-20,000 MPs/kg); | OFMSW | <0.1->10;<br>Polyethylene, polystyrene, polyester, polypropylene, and PVC accounted for 94% of all plastic items | 7–105 × $10^7$ particles/ha/year | Spain | Edo et al., (2022) |
| 13-111 particles/kg; <0.1-2,900 mg/kg) | Biowaste from urban centers | 0.63-10<br>Mainly low-density and high-density polyethylene, polypropylene, and polypropylene/polyethylene blends | 9.1–388.5 × $10^4$ particles/ha/year | Austria | Zafiu et al., (2020) |
| 2,800 MPs/kg and 1,253 MPs/kg for OFMSW compost and green cutting compost respectively | OFMSW; Green cuttings | 0.03-2 (polyethylene; polypropylene) | OFMSW compost: 1.96–9.8 × $10^7$ MPs/ha/year;<br>Compost from green cuttings: 8.8-43.9 × $10^6$ MPs/ha/year | Netherlands | van Schothorst et al., (2021) |
| 39–102 particles/kg | Anaerobic digestate of OFMSW | 1-5 | 2.73-35.7 × $10^5$ particles/ha/year | Germany | Schwinghammer et al., (2021) |
| 200–1,300 particles/kg | OFMSW | 0.5-34 | 1.4-45.5 × $10^6$ particles/ha/year | British Columbia, Canada | Smith (2018) |

* Soil Plastic input in Table 4 is calculated based on the generally recommended compost application rate of 7-35 tonnes of compost/ha/year for agricultural land (Braun et al., 2021). However, compost application regulations differ between countries. For example, in Germany, compost application rate is restricted to 20-30 tonnes/ha within three years (Siebert, 2012)

feedstock. However, separation at composting facilities is often ineffective as most improper materials are often not removed (Gamble et al., 2022). Further, manual separation of contaminants may expose workers to safety hazards including pathogens and sharp objects that may be present in the feedstock.

While synthetic plastics in biowaste threaten compost quality for agricultural use, the use of biodegradable plastics for biowaste collection emerged as a promising alternative. There is available evidence showing that compost quality is unaffected by biodegradable plastics as these degrade during the thermophilic composting conditions, albeit at different rates (Kalita et al., 2021; Ruggero et al., 2021). However, some lab-based experiments have shown these not to undergo full degradation during composting (Bagheri et al., 2017; Gadaleta et al., 2022; Sintim et al., 2020). Biodegradable plastics in composting may thus not necessarily reduce the plastic content of compost.

### 4.2. *Implications of plastics on compost-amended soils and related ecosystems*

Plastics in compost enter the soil as macroplastics, mesoplastics, and

MPs, as already described in Section 4.1.1. Generally, plastics in compost may be of at least 25 mm (called macroplastics), or 5–25 mm (called mesoplastics), or <5 mm (MPs including nanoplastics), and are transferred to agricultural soils when plastic-contaminated compost is used for soil amendment. When plastic-contaminated composts are used for soil amendments, the plastics remain in the soil for a long time, slowly disintegrating physically and mechanically into MPs or nanoplastics (Zafiu et al., 2023). Although plastics in compost started gaining research visibility only recently, there is increasing evidence of its abundance in MSW compost-amended soils (Table 5).

The environmental and ecological implications of plastics in agricultural soils are multifaceted and depend on several factors, including polymer type, concentration, size, shape, and soil characteristics (Gharahi and Zamani-Ahmadmahmoodi, 2022; Porterfield et al., 2022). Plastics generally alter the physical, chemical, and biological properties of agricultural soils with severe consequences on crop performance. While recent studies of plastic implications in agricultural soils have been investigated mostly for MPs, plastics generally impose negative impacts on soils and crops in multiple ways as described in the next section.

**Table 5**
Plastic contents of soils amended with MSW compost.

| Description of compost applied | Plastic content of compost-amended soil | Plastic size (mm) | Country | Reference |
|---|---|---|---|---|
| Urban biowaste compost, biowaste-green waste compost, and sewage sludge-green waste compost, each separately applied | MPs were 26.9-417 kg/ha depending on compost type after 22 years of bi-annual application (every 2 years). | 2-5 | France | Colombini et al., (2022) |
| Domestic waste compost applied in a maize-wheat rotation at 8.4 tonnes/ha/year for 13 years | 2,462±247 MPs/kg | <5 | China | Zhang et al., (2022) |
| MSW compost and green waste compost applied at 10 tonnes/ha/year for 7 years | 0-10 cm: 903±430 MPs/kg<br>10-30 cm: 848 ±586 MPs/kg | 0.03-2 | Netherlands | van Schothorst et al., (2021) |
| MSW compost applied yearly at 10 tonnes/ha/year for 20 years | 0-10 cm: 650±245 MPs/kg<br>10-30 cm: 1,107 ±587 MPs/kg | | | |
| MSW compost applied yearly for 10 years | Plastics were 1,000–15,300 mg/kg in amended soils, while absent in non-amended soils. | >5 | France | Watteau et al., (2018) |
| Fields amended with MSW compost for at least 5 years | MPs were 59,900-890,300 particles/kg in compost-amended soils and 40,200-342,600 particles/kg in non-amended soils. | 0.001-5 | Netherlands | Lwanga et al., (2023) |
| MSW compost and garden compost applied at rates ranging from 0-200 t/ha | 1.3% of soils contained physical contaminants mainly rigid and film plastics 13 months after compost use. | >2 | Australia | Cattle et al., (2020) |

*4.2.1. Release and adsorption of toxic substances*

The most apparent risk of plastic-contaminated compost is the ecotoxicity of plastics and their associated contaminants or metabolites in the soil. Plastics can transfer and release adsorbed toxic substances during their life cycle (Kim et al., 2020; Scopetani et al., 2022). As plastics undergo further degradation in the soil, micro-impurities and chemical contaminants are released which may be harmful to ecosystem health (Rillig et al., 2021). Besides the polymer and copolymer materials, plastics contain additive materials such as plasticizers, heavy metals, antioxidants, pigments, flame-retardants, and fillers incorporated during manufacture to confer desirable plastic properties (Liwarska-Bizukojc, 2021). These additives, which can reach up to 70% of the plastic mass (Nizzetto et al., 2016), or their metabolites, may leach out during the plastic disintegration (Hahladakis et al., 2018). This leaching is of concern as several of these additives are known for their potential endocrine disruption in some vertebrate and invertebrate species (de Souza Machado et al., 2018a). Scopetani et al. (2022) demonstrated that soils amended with plastic-contaminated compost showed higher concentrations of specific organic chemical contaminants (DEHP, acetyl tributyl citrate, dodecane, and nonanal) compared to non-amended soils.

Besides releasing toxic chemical substances, synthetic plastics can sorb hazardous environmental contaminants such as heavy metals, pathogens, pesticides, xenobiotics, pharmaceuticals, and persistent organic pollutants onto their surface (Guo et al., 2020; Hahladakis et al., 2018; Zou et al., 2020), which are thereafter released to the environment. Plastics in the soil can thus provide a surface upon which heavy metals and other pollutants bind and release to the environment. Such contaminants become bioavailable and can be translocated to the plant through plant uptake (Zou et al., 2020), becoming a risk to higher-level organisms through trophic transfer.

*4.2.2. Effects on soil physical properties*

Due to their distinct physical structure and chemical characteristics, plastics are known to alter the physical environment of agricultural soils, affecting the soil-plant-water relationships and hence crop performance (de Souza Machado et al., 2019). Some of the soil's physical properties and processes affected by plastic contamination include bulk density, porosity, infiltration, aggregation, moisture, and evapotranspiration (Guo et al., 2020). Table 6 describes how some of these properties are impacted by plastic contamination. There is generally decreased soil bulk density due to plastic contaminations (de Souza Machado et al., 2018b; de Souza Machado et al., 2019), and in some cases, the effect is dose-dependent. Reduced soil bulk density by plastic contamination may be attributed to plastic particles being less dense than predominant soil particles. Decreased bulk density may offer some temporary benefits by increasing soil aeration, porosity, and improving root penetration. Some studies, however, have reported increased soil bulk density due to plastic contamination (Wang et al., 2017) (Table 6). Higher bulk density reduces soil porosity, negatively affecting water and air flow in the soil.

Plastics have also been shown to alter the aggregation of soil particles, possibly by loosely or tightly binding to soil mineral and organic components (de Souza Machado et al., 2019; Lei et al., 2018). Soil aggregate stability is naturally enhanced by organic matter, however, plastic contamination generally decreases soil aggregation. Liang et al. (2021) observed that MPs of polyester and polyacrylic acid fibers substantially decreased water-stable aggregates in soils with organic residues, but not in those without residues. Agricultural soils thus have a tendency to disintegrate with increasing microplastic contamination (Liang et al., 2021), since loss of water-stable aggregates exposes the soil to disintegration. This may expose the soil to external vulnerabilities including water and wind erosions. Contrarily, Lozano et al. (2021a) reported increased soil aggregation in polyester fiber-contaminated soils (Table 6). Generally speaking, aggregation influences the soil physical

**Table 6**
Impacts of soil plastic contamination on agriculture-related soil performance parameters

| Soil property | Parameter | Form/type of plastic contamination | Plastic size (mm) and length of soil contamination | Induced changes in the soil | References |
|---|---|---|---|---|---|
| Soil chemical properties | pH & EC | High-density polyethylene, polyester fibers, and polyacrylic MPs | 0.1026, 30 days | Soil pH decreased relative to non-exposed soils but only significant for high-density polyethylene. | Boots et al., (2019) |
| | | Polyethylene terephthalate MPs | <5, 30 days | Soil pH considerably decreased; higher plastic concentrations caused more decrease in pH than lower concentrations. | Gharahi and Zamani-Ahmadmahmoodi (2022) |
| | | Low density polyethylene | 0.002-0.016, 100 days | Soil plastic contamination (1–7%) significantly decreased soil pH and increased electrical conductivity. | Palansooriya et al., (2022) |
| | | High-density polyethylene and polystyrene MPs | 0.039-0.08, 120 days | Low dose MPs (0.2%) did not significantly change soil pH, but high dose (2%) decreased soil pH. | Feng et al., (2022) |
| | Soil organic matter and carbon | Polylactic acid, high-density polyethylene, polystyrene, polyamide, and polybutylene succinate | 0.039-0.08, 120 days | Increased soil dissolved organic carbon content; 2% polylactic acid resulted in the greatest increase. | Feng et al., (2022) |
| Soil physical properties | Soil bulk density | Polyamide beads, polyester and polyacrylic fibers, and fragments of HDPE, polypropylene, polyethylene terephthalate, and polystyrene MPs | 0.222-5, 2 months | General decrease in soil bulk density. | de Souza Machado et al., (2019) |
| | | Polyethylene granules | Size not stated; 8 weeks | Increased soil bulk density in contaminated soils. | Atuanya, 2012 |
| | Soil aggregation | High-density polyethylene and polylactic acid MPs | 0.1026, 30 days | Soil aggregate stability generally decreased in soils exposed to MPs; Altered soil macro-aggregate and micro-aggregate fractions (Decreased large macro-aggregates (>2 mm); Increased micro-aggregates (0.25–0.063 mm); Decreased small micro-aggregates (<0.063 mm). | Boots et al., (2019) |
| | | Polyester and polyacrylic acid fibers | 0.008-0.03, 42 days | Water-stable aggregates in soils with organic residues decreased by 26.2–37.6%; soil without organic materials were unaffected. | Liang et al., (2021) |
| | | Polyester fiber MPs | 0.03, 2 months | Soil aggregation increased by 15% and 21.7% in plastic-contaminated soils in well-watered and dry conditions respectively. | Lozano et al., (2021a) |
| | Soil evaporation and crop evapotranspiration | Polyethylene film of different sizes | 2-10, 50 hours | Soil evaporation rate profoundly increased in plastic-contaminated soils; Evaporation rate increased with increasing plastic concentration; Small-sized plastics (2 mm) induced more evaporative effect than 5 mm and 10 mm plastics. | Wan et al., (2019) |
| | | Polyamide beads, polyester fibers, and fragments of high-density polyethylene, polyethylene terephthalate, and polystyrene MPs. | 0.222-5, 2 months | Evapotranspiration of spring onion increased by ~35% and ~50% in soils contaminated by polyamide and polyester MPs respectively; smaller increases occurred with high-density polyethylene, polyethylene terephthalate, and polystyrene MPs. | de Souza Machado et al., (2019) |
| Crop performance | Seed germination | Clothing fibers and biodegradable polylactic acid | 0.1026, 30 days | Soils exposed to clothing fibers and biodegradable polylactic acid MPs showed fewer seed germination; Fibers and PLA MPs led to a 7 and 6% reduction in germination respectively. | Boots et al., (2019) |
| | | Polyethylene terephthalate MPs | <5, 30 days | Fewer seeds germinated in soils exposed to MPs. Soils with 1, 3, and 5% MPs showed a 2.8, 10.6, and 18.6% germination reduction respectively. | Gharahi and Zamani-Ahmadmahmoodi (2022) |
| | Plant biomass, yield, and plastic entry | Polyester, polyamide, polypropylene, low-density polyethylene, polyethylene terephthalate, polyurethane, polystyrene, and polycarbonate | <4, 1 month | Shoot mass of carrots increased by between 27-60% for all investigated MPs; Root mass increased by 51-77% for foam, film, and fragment shapes of investigated MPs. | Lozano et al., (2021b) |
| | | Polystyrene and polymethylmethacrylate MPs | 0.002 | Crack entry of MPs through lateral roots resulted in uptake of MPs and resultant translocation from roots to shoots in wheat. | Li et al., (2020) |

and chemical processes and activities, which contribute to long-term soil fertility, performance, and productivity (Zhou et al. 2020).

Regarding the soil-water relationships, plastics may affect the soil water-holding capacity by either enhancing (de Souza Machado et al., 2019) or decreasing it (Wan et al., 2019). de Souza Machado et al. (2019) showed the soil water saturation was significantly enhanced in soils contaminated by polyester fibers, while other plastics (polyethylene terephthalate, polypropylene, polystyrene, polyamide, and high-density polyethylene) did not enhance as much. While plastic contamination of soils increased the soil evaporation rate, the increases were less than the increase in water-holding capacity (de Souza Machado et al., 2019), resulting in a net gain of water availability. Contrarily, plastic contamination of soils profoundly increased the soil evaporation rate, with the rate increasing with decreasing plastic size (Wan et al., 2019) (Table 6).

It is important to note that the effect of plastic contamination may not be localized to applied soils but adjacent soils as well. Kim et al., (2021) showed in a lab-based study that microplastic contamination did not only impact contaminated soils, but also adjacent soils which showed decreased vertical flow of water despite not containing plastics themselves. In summary, the impact of soil contamination on physical properties can be positive or negative. It should, however, be viewed that there are more negative effects than positive ones.

#### 4.2.3. Effects on soil chemical properties

By releasing the chemicals that make them, plastics can induce a slow modification of the chemical composition of amended soils. Plastics have been shown to increase (Zhao et al., 2021), decrease (Boots et al., 2019; Gharahi and Zamani-Ahmadmahmoodi, 2022; Palansooriya et al., 2022), or not change soil pH (Qi et al., 2020), depending on plastic-type, shape, concentration, size and exposure time. This modification in soil pH is linked to the release of chemical compounds from plastics during its aging and disintegration process (Feng et al., 2022; Kim et al., 2020). Plastics may also selectively adsorb negatively or positively charged ions in the soil solution, inducing a change in soil pH (Feng et al., 2022). Due to changes in pH, the soil activities, processes, and microbial community and activity may be significantly affected. Besides altering pH, plastics have been shown to affect soil's electrical conductivity (EC). Soil EC was demonstrated to increase in maize fields amended with polymer-coated fertilizers at 0.1 and 1% (Lian et al., 2021). Palansooriya et al., (2022) also demonstrated increased soil EC due to low-density polyethylene in concentrations of 1-7% in the soil matrix.

Soil organic matter is another soil property affected by plastic contamination. Boots et al. (2019) showed that cloth fiber plastics increased the soil organic matter, while it decreased in soils contaminated by high-density polyethylene and biodegradable polylactic acid plastics. Plastic granules in compost fertilizers also increased soil organic matter in maize fields (Atuanya, 2012). Reduced soil organic matter due to plastic contamination may arise due to the dilution and adsorption of available soil C onto plastic surfaces (Rillig et al., 2021). The increased soil organic matter due to plastics can be attributed to the quick release of C by plastic degradation (mainly biodegradable plastics), enhancing the soil C supply. All of these are linked to increased mineralization of native soil organic matter (Zhou et al., 2020). On the other hand, plastics are C-rich but relatively difficult for soil microorganisms to use, thus reducing the mineralization and decomposition of soil organic C (Yu et al., 2021).

Further, significant decreases in soil phosphorous and cation exchange capacity induced by plastic contamination have been demonstrated (de Souza Machado et al., 2019). Plastics may also influence heavy metal availability in soils depending on plastic-type and concentration. Wen et al. (2022) demonstrated polyurethane MPs to reduce the bioavailability of Pb, Zn, Cu, and Cd while low-density polyethylene increased their bioavailability in yellow-brown soils.

#### 4.2.4. Effects on soil biological properties and crop performance

In addition to effects induced on the soil physical and chemical properties, plastics may pose direct deleterious toxic effects on the soil micro- and macro-organisms. As already stated, plastics sorb and release environmental pollutants, posing toxicity risks to soil organisms (Hahladakis et al., 2018).

Plastics are demonstrated to affect soil fauna by constraining organism growth and development, including causing mortality (Liwarska-Bizukojc, 2021). However, low levels of MPs in the soil (0–1%) were shown not to cause any significant effect on the growth and survival of earthworms (Judy et al., 2019; Lwanga et al., 2016), while high concentrations (1–60%) suppressed growth, development, and caused mortality (Cao et al., 2017; Lwanga et al., 2017). In a study by Lei et al. (2018), polystyrene MPs resulted in a decrease in the body size and lifespan of nematodes in contaminated soils, while in another study (Schöpfer et al., 2020), soil contamination by low density polyethylene and polylactic acid MPs induced reduced reproduction and body size in nematodes. Boots et al. (2019) also showed that increasing the concentrations of polyethylene and biodegradable polylactic acid in the soil decreased the population of rosy-tipped earthworms, while lowered reproductive performance in terrestrial worms occurred due to polyamide exposure in a dose-dependent manner (Lahive et al., 2019). Thus, available evidence indicates that soil contamination by different types and concentrations of plastics cause constrained organism growth, development, and in some cases causing mortality. Reduced growth and development of organisms due to plastic exposure may be attributed to histological damage and changes in gene expression (Rodriguez-Seijo et al., 2017).

Besides constraining organism growth and development, ingestion of plastics by soil fauna in contaminated soils have been reported in earthworms, snails, and nematodes (Lwanga et al., 2017; Song et al., 2019; Kiyama et al., 2012). When ingested, plastics may cause obstruction, abrasion, and damage of the organism's digestive system, constraining nutrient absorption, bioavailability, and use (Windsor et al., 2019; Setälä et al., 2016). This could be indirectly responsible for reduced organism growth, development, and ultimately undermines survival.

The soil plastic contamination is also evidenced to create an ecological imbalance in habitat for soil microorganisms, with more or fewer organisms prevailing at the soil-plastic boundary or immediate environment (Huang et al., 2021; Zhou, Gui, et al., 2021). Polyvinyl chloride and polyethylene MPs, for example, were shown to slightly increase the population of Gram-negative bacteria and decrease that of Gram-positive bacteria, with Eukaryotes increasing with polyethylene addition while actinomycetes decreased (Zang et al., 2020). However, a study by Esan et al. (2019) showed no effects on microbial diversity and community in compost due to polyethylene plastic contamination. The same could be true in compost-amended soils. Thus, although there is a general agreement that plastic contamination may alter the soil microbial composition and community, the effects vary from enhancement, inhibition, or insignificant influence.

Finally, plastic contamination of agricultural soils may adversely affect the agronomic functioning of crops and the effects vary among crops. Plastics generally have been described by Gao et al. (2022) to significantly decrease seed germination, plant height, root length, plant biomass, and crop yield. Liu et al. (2023) further demonstrated that soils with high concentrations of MPs exhibited subdued vegetative growth and nitrogen uptake in peanut plants. The exposure of spring onion to different types of MPs (polyester fibers, polyamide beads, polyethylene, polyethylene terephthalate, polypropylene, and polystyrene) also induced significant changes in plant biomass, tissue elemental composition, and root health (de Souza Machado et al., 2019). Table 6 describes evidence of the effects of plastic contamination on crop performance.

### 4.3. Glass and stones in MSW compost

Besides plastics, glass and stones are the other physical contaminants that regularly occur in urban solid waste compost (Cesaro et al., 2015). Glass and stones often occur in compost due to improper waste collection practices where they are collected together with the OFMSW. While few studies have investigated the occurrence of these physical contaminant materials in MSW compost, here we present evidence of their occurrence from literature.

Sharifi and Renella, 2015 studied the occurrence of physical contaminants in compost from a composting plant in Kurdistan province, Iran. Only 70.4% of the final stabilized material (compost) was organic matter, the rest being physical contaminants, mainly stones (18.2%) and glass (11.1%). Glass and stone impurities in the compost exceeded the local legal limits by 22.2-fold and 1.4-fold respectively (Sharifi and Renella, 2015), rendering such compost unsuitable for agricultural use. In Istanbul Metropolitan Composting and Recycling facility (Turkey), only 88.5% of the final composting output was organic matter, while the rest were physical contaminants, mainly glass (4.2%) and stones (5.8%) (Sezer and Arikan, 2011). In a study of 30 MSW compost-like output from 10 MBT plants in Castile and León, Spain, only 78.2% of the final stabilized fraction was organic matter while the rest were physical contaminants, 6.5% of which was glass (Montejo et al., 2010). In this study, the composting inputs contained 64.1% biodegradable matter with the rest being improper materials including glass (10.9%). Montejo et al., (2015) further investigated the final stabilized material of 30 compost samples from different MBT plants in Castle and Leon, Spain, and found physical contaminants >2 mm to be 5% (ranging from 0.8–15.0%), including plastics, gravel, stones, or glass.

The analysis of data from a MSW composting plant in Seville, Spain for the 2006-2012 period showed glass fraction in compost to be 2.6%, which was an improvement from 14.8% fraction for the 2000-2004 period (López et al., 2015). This improvement was mainly due to the adoption of source separation in biowaste collection in the second period of data analysis. In the UK, Dimambro et al. (2007) evaluated compost quality from 12 different composting facilities processing source-separated, mixed MSW, or both. The compost contained between 0.0–16.8% glass and 1.1–7.3% stones besides other physical contaminants.

Malamis et al., 2017 also reported up to 2.1±0.9% of the final stabilized material of MSW composting in 2 Municipalities of Attica Region, Greece to be physical contaminants, 80% of which was glass. The physical contaminant levels were low compared to other studies. In Brazil, a study of compost from 14 MSW composting plants from different Brazilian Cities reported 4.8-17.2% of compost to be glass fractions, and 1.0-3.1% to be plastic (Barreira et al., 2008). Glass was the main physical contaminant in the Brazilian compost.

Like plastics, glass is an inert material that does not undergo biodegradation during the composting process or thereafter but often undergoes physical or mechanical degradation. Glass and stones in composting feedstocks tend to break into fragments due to the turning events of composting (Malamis et al., 2017). These broken glass and stone pieces tend to remain in the final compost even after sieving. Unlike plastics, glass and stones do not release toxic substances and, therefore, do not chemically contaminate amended soils. However, glass or its fragments present a physical safety hazard in compost handling by farm workers. Accidental risk such as work injuries may be sustained while handling such compost (Cerda et al., 2018). This is even more concerning when compost is used as a growing media as there is often direct contact workers have in handling the material. Due to this, glass and other sharp objects may deter the use of organic fertilizers in agriculture (Dimambro et al., 2007). One of the remediation approaches for glass is fine milling of the compost before field application (Sharifi and Renella, 2015).

### 4.4. Paper and paperboard in MSW compost

Paper and paperboard typically constitute a significant component of MSW and originate mainly from newspapers, packaging boxes and wraps, and writing and printing papers. In all compost regulations, paper and paperboard are not included among physical contaminants in compost. However, paper and paperboard have been reported in urban waste compost, indicating biowaste materials that have not undergone full degradation. In the study of Dimambro et al. (2007), for example, paper and paperboard formed a significant fraction of the MSW compost in at least 5 of 12 composts investigated in the UK. These materials may require special treatments before composting so they do not compromise the composting process and compost quality (WRAP, 2007). Besides, paper and paperboard may contain dyes, inks, steel staples, overly packaged cardboard, and non-biodegradable coatings (AforR, 2006), and their inclusions in composting could indirectly lower compost quality. Further, there is a concern when plastic-coated paper products are used as feedstocks for composting as these produce macro-and micro-fragments of non-biodegradable plastics, contaminating finished compost (Brinton, 2019).

Paper and paperboard may also contain high content of lignin which may retard biodegradation during composting (Montejo et al., 2010). Despite being an organic polymer, lignin is only slowly biodegradable and thus reduces the rate of composting. There is, however, a lack of guidance on the length of time for paper and paperboard with such composition to be sufficiently degraded during composting (Echavarri-Bravo et al., 2017). The study of Alvarez, 2009 showed that paper and paperboard differ in their degradation rates, with some paper materials unable to undergo complete degradation after 45 days of composting.

### 4.5. Metals and other physical contaminants in MSW compost

Metals or their fragments are regularly reported in MSW compost studies. Metals in MSW compost are reported to range in compost fraction from 0 to 1.5% (Brinton, 2005; Echavarri-Bravo et al., 2017; Montejo et al., 2015; Sezer and Arikan, 2011). However, due to advancements in industrial composting, metals are often removed during the separation stage using magnetic or eddy current separators (Cesaro et al., 2019; Sezer and Arikan, 2011).

Other physical contaminants in MSW compost include household batteries, textiles (Montejo et al., 2010; Sezer and Arikan, 2011; Papadimitriou et al., 2008), and pharmaceuticals and personal care products (Bourdat-Deschamps et al., 2017; Lederer et al., 2017). Household batteries in compost or its feedstocks are highly hazardous and release high levels of heavy metals mainly Hg and Zn in recycled fertilizers (Papadimitriou et al., 2008), limiting their agricultural use. Pharmaceuticals and hygiene items, including syringes in compost, may pose a physical or biological safety hazard to farm workers involved in compost handling.

## 5. Fate of physical contaminants in compost-amended soils

Physical contaminant input into agricultural soils through compost application and other pathways may have their fate through accumulation, degradation, and transportation by biotic and abiotic agents.

### 5.1. Accumulation in the soil matrix

Following the application of physical contaminant-infested compost, the most apparent fate is soil contaminant accumulation, since soils act as a sink for physical contaminants (Ng et al., 2018; Wang et al., 2023). Physical contaminants accumulate in the soil matrix at rates dependent on compost contamination, application rate, soil type, and land use. Because physical contaminants, mainly plastics and glass, have a long residence time in the soil, contaminated compost application leads to long-term soil accumulation (Bläsing and Amelung, 2018; Wang et al., 2023). Cattle et al. (2020) observed increased soil accumulation of physical contaminants, mainly glass and plastics, within the depth of incorporation following mixed MSW compost application, the degree of accumulation dependent on the compost rate applied. Contrarily, fields that received garden waste compost showed little or no accumulation of physical contaminants compared to those amended with mixed waste compost (Cattle et al., 2020).

Regrettably, plastics are the most notorious among all physical contaminants for their extremely long residence time in the soil (Chamas et al., 2020), which can be up to hundreds to thousands of years (Barnes et al., 2009). Due to their relatively stable chemical structure, synthetic plastics can resist degradation which is responsible for their long-term soil accumulation and persistence (Ali, 2021). Indeed, there is increasing evidence of plastic accumulation in soils amended with MSW compost over the years (Table 5). Physical contaminants that accumulate in the soil are often primarily large particles that cannot easily be leached or transported to other points.

### *5.2. Degradation to smaller particles*

Physical contaminants undergo degradation during composting, forming small-sized particles in compost (Le et al., 2023). Following compost application containing physical contaminants, these undergo further degradation in the soil at rates dependent on contaminant type, soil type and activities, and environmental conditions (Pathan et al., 2020). Environmental conditions such as ultraviolet radiation, mechanical abrasion, and high temperature have been shown to increase the plastic degradation rate (Eubeler et al., 2010; Song et al., 2017). However, not all these conditions may be present in the soil; thus, plastic degradation can be prolonged, with studies showing less than 1% weight loss in different plastics after several years in the soil (Arkatkar, 2009; Santana et al., 2012). Accordingly, plastics may degrade slowly over several years, forming MPs or nanoplastics (Chamas et al., 2020; Wahl et al., 2024). Some plastics have, however, been shown to undergo accelerated degradation under abiotic (hydrolysis and photodegradation) or biotic (enzymes or certain microorganisms) conditions (Alshehrei, 2017; Eubeler et al., 2010).

While synthetic plastics threaten the quality of compost because of their slow degradability, there is a thin ray of hope as some biodegradable plastics may fully degrade during composting, albeit at different rates (Edo et al., 2022; Unmar and Mohee, 2008). There is available evidence indicating the vast majority of biodegradable plastics (e.g. blends of starch-based polymers, polylactic acid, polyhydroxyalkanoate, cellulose) to undergo degradation under the thermophilic composting conditions (Kalita et al., 2021; Ruggero et al., 2021). However, their inclusions in composting feedstocks are still constrained by limited research, and the release of heavy metals and other contaminants (Kubowicz and Booth, 2017; Markowicz and Szymańska-Pulikowska, 2019), slow rate of decomposition beyond the composting period, and lack of understanding about their further degradation once introduced in the soil (Le et al., 2023; Accinelli, 2020).

Like plastics, glass and other physical contaminants undergo slow degradation in the soil through physical and chemical means, forming small-sized fragments (micro- and nano-particles) (Kumari et al., 2022). Degradation of glass in the soil, for example, may occur through the turning process of tillage, high temperature, weathering, and chemical degradation (Kumari et al., 2022). Little, however, is known about the effects of micro- and nano-glass particles in the soil and related ecosystems.

### *5.3. Transportation to other points and ecosystems*

Physical contaminants may not stay static in the soil; they can be transported vertically or horizontally via biotic and abiotic processes. Biotic transport includes ingestion and dispersion by soil fauna, direct transport by fauna movement, and contaminant adherence to fauna external surfaces (Rillig et al., 2017a; Xu et al., 2020). There is available evidence of physical contaminant (MPs) ingestion and possible dispersion within the soil profile by soil fauna including earthworms (Lwanga et al., 2017), snails (Song et al., 2019), and nematodes (Kiyama et al., 2012). The biotic transportation rate depends on the type, size, and shape of the particles, with small-sized contaminants more rapidly transported (Lwanga et al., 2022) than large ones.

The abiotic transportation of physical contaminants occurs through wind/water erosion, runoff, leaching to groundwater, and the main drivers are topography, land use, climate, and vegetation (Lwanga et al., 2022). Since soil is made up of numerous pore spaces, these allow the migration of physical and chemical substances within them. Physical contaminants may be transported through these pore spaces by leaching, gravity, or physical turning activity. Transportation through leaching is, though, only possible for extremely small physical contaminants (Bläsing and Amelung, 2018), with the leaching rate dependent on the number and size of pores, interconnectivity, and soil physiochemical characteristics. van Schothorst et al. (2021) observed more small-sized MPs in the deeper soil layers than topsoil in compost-amended soils, suggesting transportation to deeper soil layers and retention of larger particles in the topsoil. However, leaching of physical contaminants is only possible to a few soil depths, rarely exceeding a meter, and may not pose a severe problem except in areas with shallow groundwater (McGechan, 2002). Plant roots could also influence physical contaminant transport through root movement, expansion, and soil disturbance (Gabet et al., 2003). Further, decomposition or removal of plant roots leaves large soil macropores, facilitating the downward transportation of contaminants. Soil mechanical disturbance through tillage, for example, may bring about soil inversion and hence physical contaminants, causing their movement and transportation within the soil profile (Rillig et al., 2017b; Wahl et al., 2024). Also, surface cracks may appear in the soil in dry climates, providing a pathway for physical contaminant transport downwards in the soil layers. Lastly, physical contaminants may be dispersed through runoff in sloping agricultural lands, depending on the soil surface conditions; they may also be dispersed by wind (van Schothorst et al., 2021).

## 6. Strategies to mitigate physical contaminants in MSW compost

Reducing physical contaminants in MSW compost is necessary to guarantee high-quality, nutrient-rich organic fertilizer free from inert impurities. Deliberate attempts to eliminate improper materials in biowaste collection for composting should be the most critical strategy to eliminate physical contaminants in MSW compost (Wei et al., 2017).

If it is impossible to eliminate improper materials in biowaste during collection, manual or mechanical separation and sieving of improper materials before, during, and after composting are highly recommended to reduce physical contaminants in finished compost to acceptable limits (Cesaro et al., 2019; Colombini, et al., 2022). However, these procedures are ineffective in removing small-sized particles such as MPs and glass fragments, which dominate physical contaminant fractions in compost (Braun et al., 2021). Removal of improper materials in biowaste at the composting facility is less effective in mitigating physical contaminant problems in compost since removing most of these materials is impossible.

Plastics commonly used in biowaste collection arguably present one of the most significant challenges in biowaste recycling through composting. The use of biodegradable and degradable plastics for biowaste collection emerged as a sustainable alternative to synthetic plastics in waste management. Biodegradable plastic inclusions in composting, however, may not necessarily reduce the plastic content of compost (Gadaleta et al., 2022; Accinelli, 2020), as incomplete degradation has been reported for some biodegradable plastics at the end of composting (Unmar and Mohee, 2008). Thus, while it is safe to conclude that degradation is faster for biodegradable plastics than conventional plastics, the time required to attain complete degradation is still unknown. Further, MPs (including nanoplastics) may be released following their degradation (Markowicz and Szymańska-Pulikowska, 2019; Sintim et al., 2019; Qin et al., 2021). The long-term fate of released MPs in amended soils is not clearly understood and needs further investigation. Besides, many plastics labeled and marketed as biodegradable may not be completely degradable (Dai et al., 2022), and may be broken down to smaller plastic particles that retain their original polymer characteristics. The use of bioplastics in biowaste collection should thus be encouraged, but further investigations of their inclusions in composting, including long-term fate in amended soils, should be evaluated.

Finally, regulations and directives specifying maximum physical contaminant limits in compost and the quality of OFMSW for composting should be in place to guide all the relevant stakeholders (Braun et al., 2021). While Regulations specifying physical contaminant limits exist in many States and Regions, mainly in Europe, there are several countries with no regulations guiding urban biowaste composting and physical contaminant standards in compost. In these countries, MSW composts with huge incidences of physical contaminants continue to be generated and used in agriculture, posing significant current and future environmental implications. There is a need to develop regulations to guide recycling OFMSW through composting for agricultural use.

## 7. Limitations and recommendations

Plastics in compost present the most critical concern today due to their wide occurrence and potential environmental implications. Our review reiterates the general claim of difficulty in comparing studies of plastic contamination in compost. The different reviewed studies suffer gaps regarding comparable units of plastic quantification in compost. These studies employ the count per weight (number of plastics per compost weight), the weight per weight (weight of plastics per compost weight), or both. Among the reviewed articles, only 20% used weight per weight basis, 53% used count per weight basis, and 27% employed both units. There is presently no standardized unit for reporting plastic contamination in compost or amended soils (Porterfield et al., 2022). It is best to say that the count per weight method of plastic quantification should be less merited in compost quantification mainly due to two reasons: 1) most ecotoxicity risks of plastics are specified on a per-weight basis and not on the number of plastics (Boots et al., 2019; Samadi et al., 2022), and 2) the count per weight presents an additional challenge as plastics in compost and other matrices are capable of disintegrating into small-sized particles. Thus, the count per weight values of plastics in compost or amended soils may vary in time and space compared to the weight per weight estimation.

While this review has indicated adverse implications of plastics in soils, most studies are short-term, lasting only days to a few months (Boots et al., 2019; de Souza Machado et al., 2019; Zang et al., 2020). Studies evaluating the implications of plastic contamination in soils for more than a year were scanty in our literature search. There is a need to conduct long-term studies of impacts of plastic contamination on the physical, chemical, and biological properties of soil.

Lastly, most studies of plastic contamination in compost and implications in amended soils focus mostly on MPs, with limited investigations conducted for meso- and macroplastics. The characterization and identification of large-sized plastics >5 mm in compost and amended soils is important as these frequently occur in compost, yet their impacts in amended soils are not clearly understood. While large-sized plastics degrade to form MPs and nanoplastics, the immediate and long-term impacts of these large plastics need investigation.

## 8. Conclusions

The present work describes and quantifies physical contaminants in compost of MSW origin and their sources, implications, and fate in amended soils. Despite the growth in composting to valorize the OFMSW, compost derived from MSW biowaste may largely remain wastes (instead of compost) from a legal perspective if its physical contamination exceeds the maximum specified value. The review provides evidence of the abundance and heterogeneity of physical contaminants in MSW compost. Physical contaminants, no doubt, remain the most critical limiting factor in the recycling and reuse of OFMSW through composting.

The degree of physical contaminants in compost depends on the quality of feedstocks used, with compost from mixed MSW biowaste having significantly high physical contaminant levels. Plastics, mainly MPs, are arguably one of the most concerning physical contaminants in compost today, but face quick analytical challenges and lack of standardized units in measurement. When plastic-contaminated composts are used for soil amendment, the contamination persists for a long time, posing severe physical, chemical, and biological impacts on the soil ecosystem.

Repeated application of contaminated MSW compost may lead to the accumulation of physical contaminants in soils. Physical contaminants in amended soils may be degraded into small-sized particles, releasing additives or their metabolites; they may be transported horizontally or vertically through leaching, runoff, wind, or fauna, causing secondary pollution effects. Considerable attention should be taken to minimize physical contaminants in MSW compost. Mitigating this problem is a multifaceted task, requiring improving source separation of biowaste, proper operations of composting facilities, and having strong regulatory systems guiding the recycling of OFMSW for agricultural use.

## CRediT authorship contribution statement

**Francis Okori:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Jakob Lederer:** Conceptualization, Data curation, Funding acquisition, Methodology, Project administration, Supervision, Validation, Writing – review & editing. **Allan John Komakech:** Formal analysis, Investigation, Supervision, Validation, Writing – original draft, Writing – review & editing. **Therese Schwarzböck:** Funding acquisition, Project administration, Resources, Writing – review & editing. **Johann Fellner:** Funding acquisition, Methodology, Supervision, Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

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