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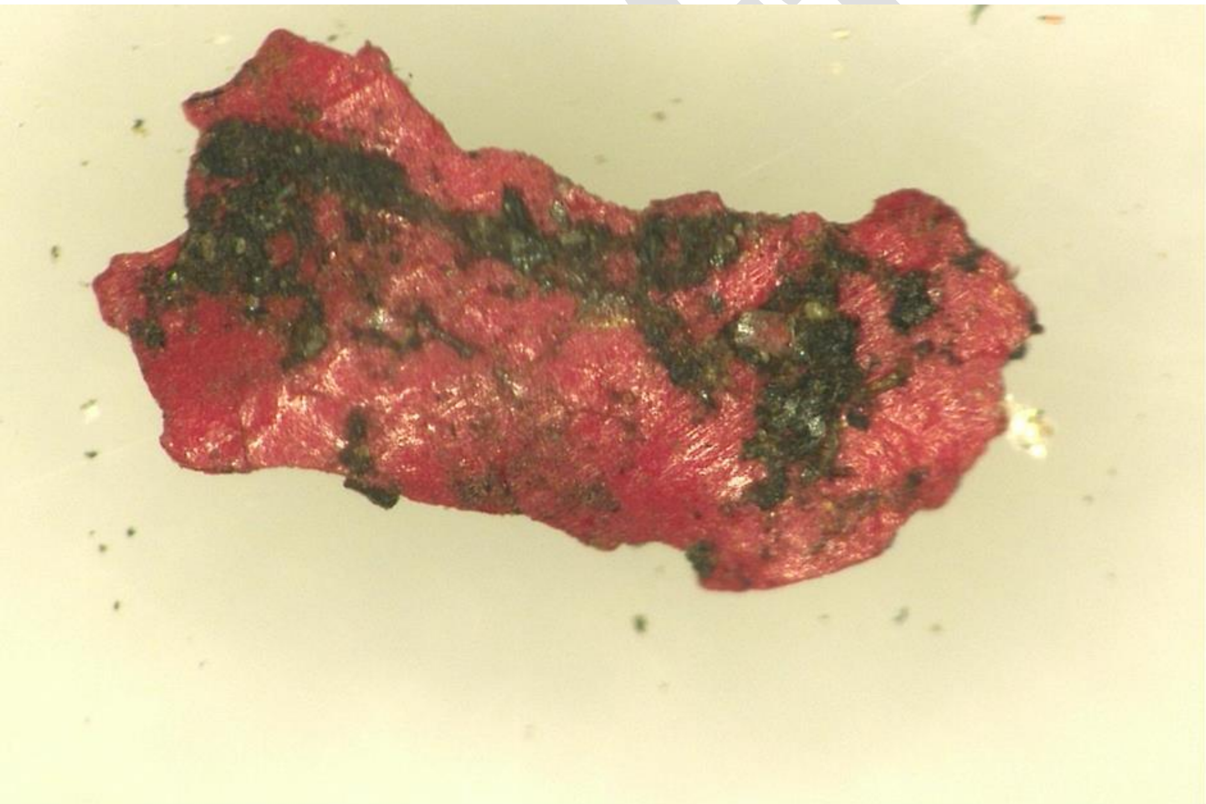
Study on composts from four North German facilities



Report in the SOILCOM-Project:
Sustainable soils by quality compost with defined properties

Workpackage 5:
Compost production and quality indicators

Technische Universität Hamburg, 2023

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Microplastic in composts from different composting facilities -
Study on composts from four North German facilities, TUHH, 2023

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Title photo: Sophie Hasert (2021): Red particle from EBL compost sample of the fraction 0.5-1 mm

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List of abbreviations

DüMV:	German Fertilizer Regulation (Düngemittelverordnung)
BioAbfVO:	Biowaste Regulation (Bioabfallverordnung)
BGK:	Compost Quality Association of Germany (Bundesgütegemeinschaft Kompost e.V.)
DIN:	German Institute for Standardization (Deutsches Institut für Normung)
EBL:	Entsorgungsbetriebe Lübeck (Lübecks municipal waste managment companies)
GBB:	Gräflich Bernstorff'sche Betriebe (Organic farming company with composting company)
STR:	Landwirtschaftlicher Betrieb Wilhelm Struck (Horse breeding with composting company)
SRH:	Stadtreinigung Hamburg AöR (Municipal waste management authority Hamburg)
FM:	Fresh matter
DM:	Dry matter
TUHH:	Technische Universität Hamburg (Hamburg University of Technology)
WC:	Water content
NSR:	Northsea Region
MBT:	Mechanical-biological waste treatment

Definitions

Biowaste:	Organic waste fractions as defined in BioAbfVO (2022)
Green waste:	Biowaste separately collected from gardens, park's and landscaping
Biobin waste:	Biowaste separately collected from households; includes kitchen waste and mostly garden waste
Foreign material:	Refers to plastically deformable plastics, glass, metals and non-plastically deformable plastics together, stones as defined
Pile:	Material bulk for composting is not turned
Windrow:	Material bulk for composting is turned

1 Farmer’s concerns with composts

At the beginning of the SOILCOM project, German farmers applied composts with hesitations. A major reason was their concern of pollutants, specifically plastics. However, most farmers were aware of the compost’s benefits. These findings were concluded from the SOILCOM questionnaire distributed in 2020 to farmers. It aimed to find out whether they use compost and what considerations they have regarding its usage, respectively to understand the reasons if they do not use compost.

The questionnaire

The questionnaire was published in July 2020 via the agricultural blog *Bauer Willi* and additionally was distributed by Stadtreinigung Hamburg (SRH) to various agricultural chambers in the North Sea Region (NSR) for their further distribution to farmers. The questionnaire contained multiple questions to following topics: General issues, compost quality, effects of compost usage, and laws. It contained various types of questions by structure such as multiple choice options presented in matrix format, responses requiring a simple “yes” or “no” and open text boxes for elaborative answers.

General results

133 complete answered questionnaires were submitted by German growers, which formed the basics for general evaluation. The distribution of the origins of the responding farmers is shown in Figure 1.

Figure 1: Origin of the responding plant growers

(left: German Federal State; right: Sub-region) (Ortiz, I.Z.A., in: Krishnakumar et al., 2021)

Roughly fifty percent of the participants were contacted through blog, while the remainder were reached via agricultural chambers. However, the majority of the respondents were from the NSR (Schleswig Holstein, Niedersachen), with a notable concentration hailing from the region of Segeberg. This result is a compliment for remarkably proactive agricultural chambers and their interconnected network of farmers. The answers cannot be considered as statistically representative, but they give some insights on the issue of compost application on farms.

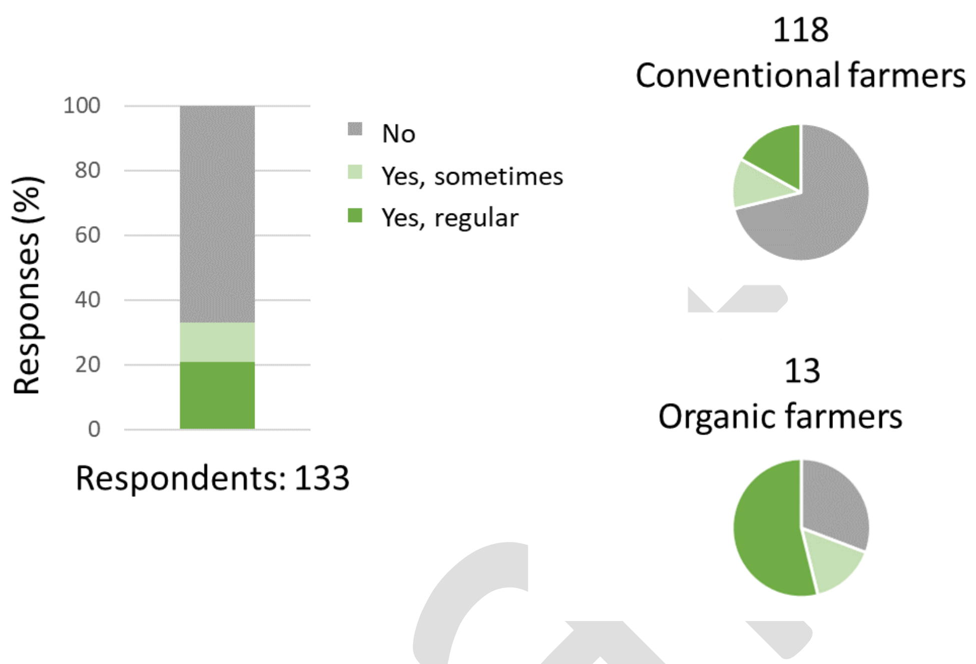

Figure 2: Use of compost by the responding plant growers and their farm type

Around 90% of the farmers utilized conventional methods for crop production, whereas 10% were ecological farmers, and only a single farm reported employing both approaches. Among the respondents, 89 farmers opted not to incorporate compost on their land, while 44 farmers did utilize compost. From the non-users, 84 adhered to conventional farming practices and 4 were ecological farmers. In contrast, out of the group of compost users, 35 followed conventional farming, while 9 pursued ecological farming methods (Figure 2). The most of the ecological farms were located in the NSR.

The majority of applied composts were sourced from municipal feedstock - from green waste or a mixture of green and biobin waste. Only 25% of the growers used self-made composts and a small fraction of compost originated from other farms. Roughly 70% of the regular treated areas ranged in size from 10-100 ha.

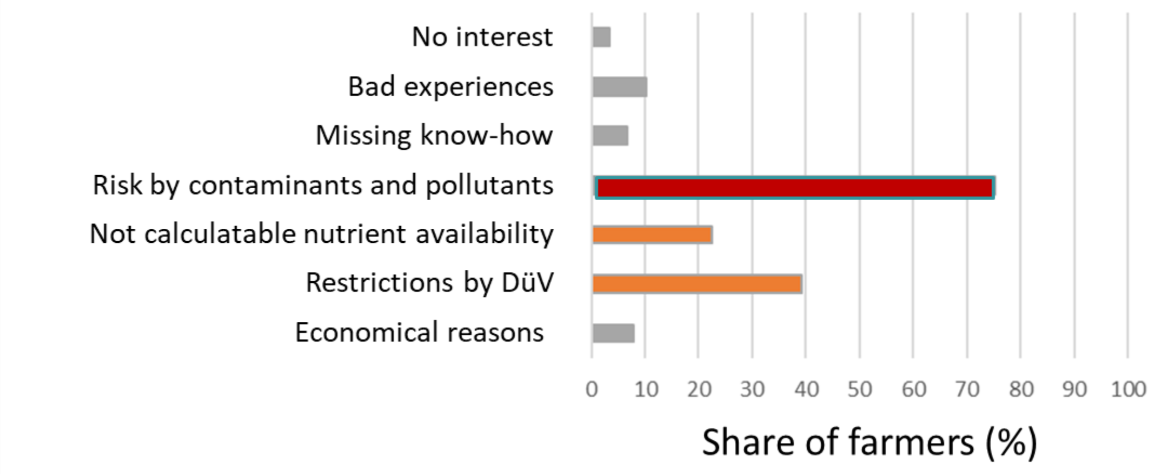

Figure 3: Reasons of the responding plant growers not to use compost

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The main reason provided for not using compost on crops was the apprehension of potential risks related to damages and pollutants (Figure 3). Additionally, concerns about limitations imposed by the fertilizer ordinance were frequently mentioned, particularly in the NSR. The least selected reason was no interest, suggesting that farmers might indeed be interested in using compost, but certain concerns need to be addressed. The most relevant aspect was determined through an analysis of the text responses, as depicted in Figure 4. Therefore, a deeper investigation was conducted into the issue of plastics.

Figure 4: Most mentioned concerns regarding compost quality of the responding farmers (Ortiz, I.Z.A., in: Krishnakumar et al., 2021)

NSR results

In the following, the answers of the 97 crop growers from NSR are evaluated. NSR is the target region of SOILCOM. Some aspects from the answers from NSR respondents were different from the respondents from other German regions. The average farmland size of the NSR respondents was 147 ha, which was clearly above the NSR average. The majority of the NSR farmers (74%) do not use compost, 12% apply occasionally, approximately once every two to seven years, while 13% utilize compost regularly at least once a year. Notably, the rate of compost usage in the NSR was slightly higher when compared to the rest of Germany.

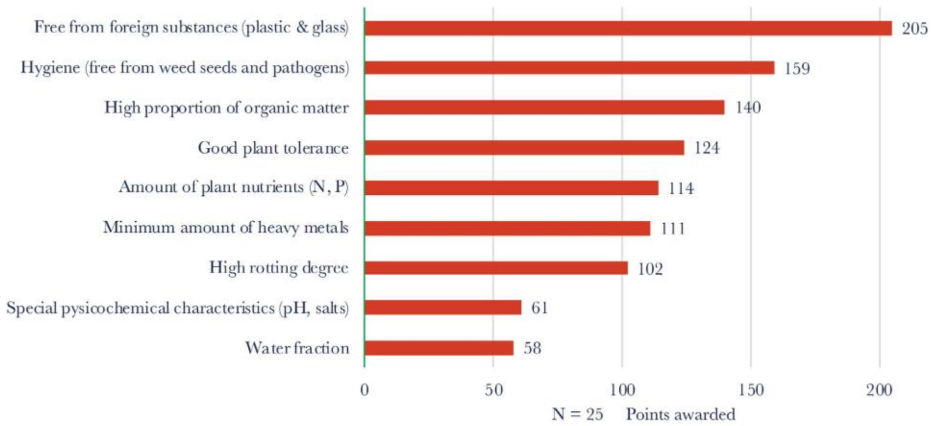

Figure 5: Compost quality characteristics with importance for NSR farmers (Oritz-Cabrera, 2020)

The majority of farmers acknowledged the benefits of compost. Among the benefit ranking, the most widely agreed-upon was the increase of soil humus content (81%), followed by improving soil structure (78 %) and water holding capacity (74%). When it comes to purchasing compost, quality emerged as a crucial factor for farmers. All the compost-users were familiar with and acknowledged the significance of RAL certificate. More than half of these farmers find it essential.

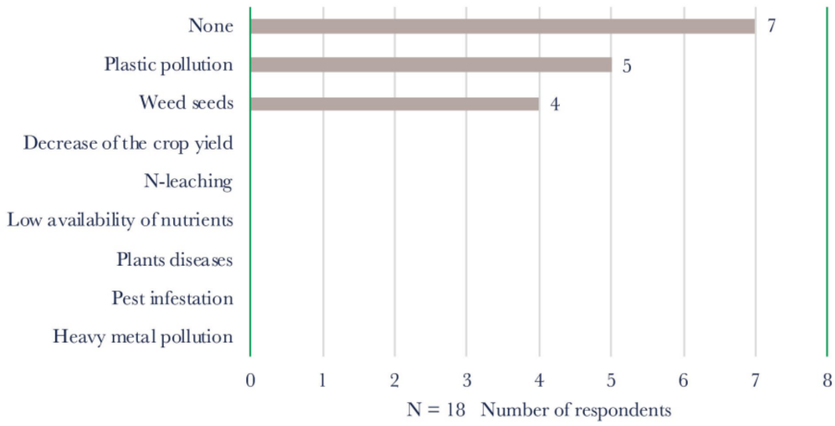

Figure 6: Problems after compost applications reported by NSR farmers (Oritz-Cabrera, 2020)

Based on the selected responses presented in Figure 5 it can be concluded that farmers prefer compost that is devoid of foreign matter, especially plastics. The most important reason that farmers decide not to apply compost in their farmlands was the concern of introducing pollutants, the second most important factor was the complex and bureaucratic nature of German fertilizing regulation. From the 18 farmers, which use compost regularly (Figure 6), 39% reported no issues. However, 28% encountered problems related to plastics on their fields, while 23% reported issues with weeds.

Conclusion

Only a minority of the questioned farmers used compost regularly. From the ones which use compost, the ecological farmers are dominant. They mostly either use self-made compost or green waste compost. The conventional farmers used mainly compost made from municipal composting facilities. In order to increase the acceptance, plastics in the compost plays an important role. For that reason, this issue was investigated in more detail considering composts produced in municipal as well as agricultural composting.

2 German regulations and guidelines on compost quality

The quality requirements related to foreign substances in compost are regulated by the German Biowaste Regulation (BioAbfVO, 1998) in §4(5), specifically for facilities with an annual input exceeding 2000 Mg. The DüMV (Düngemittelverordnung, 2021) stipulates the collection of foreign substances in compost from a size of 1 mm or larger, while the BioAbfV (Biowaste Regulation, 2022) sets the threshold at 2 mm. Additionally, the Federal Quality Association Compost (BGK) verifies and issues quality certificates based on an extended compost standard. The BGK distinguishes between three compost types: fresh compost, mature compost, and substrate compost, each with specific quality requirements that align with the aforementioned regulations. It is important to note that these regulations only apply to facilities that sell or distribute compost to external stakeholders and do not apply to compost used for internal purposes.

2.1 Biowaste Ordinance

The *German Biowaste Ordinance* (BioAbfVO, 1998, 2022) applies for the characteristics and treatment of biowaste, and the use of untreated or treated biowaste on soils from agriculture, forestry or horticulture. During SOILCOM, the ordinance (BioAbfVO, 1998) has been updated (BioAbfVO, 2022) and is valid since 01.05.2023. The revision intents to enhance and improve biowaste management practices specifically to reduce plastic inputs into the environment. Regulations to reduce foreign materials, particularly plastics, in biowaste treatment were introduced. These include an input control value for the plastic content in biowaste. Furthermore, specifications for biowaste collection bags made of biodegradable plastics have been added. The BioAbfVO (2022) also defines pollutants and foreign matter in products such as composts. In § 4 (4) the parameters and limiting values are regulated with regard to foreign matter. The relative proportion within a sieve passage of >1 mm and >10 mm must not exceed following limits (expressed as a percentage of DM from the product to be applied):

- Deformable plastic foils (>1 mm) - 0.1%
- Other foreign matter
  (in particular glass, metals, non-plastically deformable plastics, >1 mm) - 0.4%
- Stones (> 10 mm) - 5%

In the former BioAbfVO (1998) the sieve passage limit for plastically deformable and other foreign matter was set at >2 mm.

2.2 Fertilizer Ordinance

Stricter limits for plastics and foreign substances in finished composts and biowaste-containing materials have been incorporated from the amended German Fertilizer Ordinance (DüMV, 2019) already before the revision of the BioAbfVO (2022). The German Fertilizer Ordinance specifies the requirements for good agricultural practices in fertilization and regulates how to reduce risks associated with fertilization. Fertilizers must be approved and applied according to good agricultural practices includes aligning the type, quantity, and timing of application with the needs of plants and soil. When used correctly, fertilizers must not harm the health of humans and animals or endanger the natural environment. The Fertilizer Ordinance specifies these legal requirements by regulating the manufacturing, composition, and labelling of fertilizers. The regulation includes provisions on permitted raw materials, nutrient content and efficacy, as well as setting restrictions on undesirable substance levels. The regulation also specifies the percentage of foreign matter in fertilizer as follows in § 4 (3) (expressed in percentage of fertilizer's DM to be applied):

- Waste paper, cardboard, glass, metals and non-plastically deformable plastics (>1 mm): 0.4%
- Other not degraded plastics (>1 mm): 0.1%
- Stones (>10 mm): 5%

The BioAbfVO (2022) follows this classification, but with modifications in terminology specifically regarding the inclusion of wastepaper and cardboard as foreign matter. The DüMV (2019) gives a specification. After that avoidable paper fractions such as packaging material are foreign matter, but not paper-fractions in products from made from biowaste (DüMV, 2019, Annex 2, Table 8.3.9, Table 7).

2.3 RAL quality certification

The German Compost Quality Association (Bundesgütegemeinschaft Kompost e.V, BGK) has set up a RAL quality management system. This system ensures RAL quality of assessed composts and labels them (BGK, 2023). Furthermore, the BGK is certified according to DIN EN ISO 9001:2015 standard.

Analytical methods for manifold chemical, physical and biological parameter are documented in the BGK *Method Book* (Method book for the analysis of organic soil improvers, fertilisers and substrates, 5th edition 2006 with 6 supplementary deliveries). The analytics needs to be carried out by a certified laboratory.

Regarding mass of impurities, BGK uses the DM-based limit values from DüMV (2019) and BioAbfVO (2022). However, BGK introduced the additional quality parameter, surface area of impurities. It is a visual parameter describing the compost optics. The impurities >2mm are indicated by their area sum. The limit value of the impurity level varies among the different compost types (Table 1). It is stricter for substrate compost compared to fresh and mature compost.

Table 1: Overview on the BGK guidelines regarding impurities and stones

Parameter	Unit	Fresh compost	Mature compost	Substrate compost	BGK-Method Book
Degree of decomposition		II, III (IV, V)	IV, V	V	Kap. IV. A 1[1]
Mass of impurities (>1 mm)	% DM				Kap. II. C 1[2]
o Deformable plastic (foils)		≤0.1	≤0.1	≤0.1	
o Other		≤0.4	≤0.4	≤0.4	
Mass of impurities (>5 mm)		-	-	≤0.1	
Stone mass (>10 mm)	% DM	≤5	≤5	≤0.5	Kap. II. C 2[1]
Stone mass (2-10 mm)		-	-	≤5	
Surface area of impurities (>2 mm)	cm^2/L FM	≤15	≤15	≤10	Kap. II. C 3[3]

1 Original book, 2006
2 Method book, 5th supplement delivery 2, 2020
3 Method book, 4th supplement delivery 12, 2015
Source: BGK 2023a

The values provided in Table 1 are valid since 01.01.2021. Before that date, the mass of impurities was referring to particles >2 mm.

3 Characteristics of the studied composting facilities

The company information has been verified by the respective companies. The auditors are listed at the first page of this report.

3.1 Facility overview

Two facilities from the municipal sector, located in Lübeck and Hamburg, and two from the agricultural, located in Groß Gusborn and in Gartow, were investigated regarding microplastic in their composts. All companies are located in the German North Sea Region (NSR):

- *Entsorgungsbetriebe Lübeck (EBL):* In 2019, the company processed 54,500 Mg separately collected biowaste and green waste to 12,000 Mg composts. The man input into the *Biomass Plant* for composting, which is in operation since 1996, is digestate from separately collected biowaste. It is received from the *Mechanical-Biological Waste Treatment Plant (*MBT, commissioned in 2005) which treats source-separated biowaste received from biobins by anaerobic digestion. Besides the biobin waste, the MBT has another one for residual waste. The total waste input into both lines is about 100,000 Mg waste per year, and the product is biogas (about 6 Mio m³ per year) which is further transformed into electricity and heat in a combined heat and power plant (CHP).

- *Stadtreinigung Hamburg (SRH):* The approved total capacity of the SRH facility is 90,000 Mg per year (70,000 Mg/a biowaste and 20,000 Mg/a green waste). The current throughput amount is 55,000 Mg/a with an alignment to the approved capacity in the near future. The current facility consists of the original composting plant, which is in operation since 1995. This moving tabular windrow system was acquired by SRH in 2008. An anaerobic digestion stage was added in 2011 as pre-treatment for composting. From the produced biogas biomethane is produced and provided into the public gas grid. Currently about 35,000 Mg of compost and 1.3 Mio m³ biomethane are generated each year.

- *Landwirtschaftlicher Betrieb Wilhelm Struck (STR):* STR, located in Groß-Gusborn, is a certified organic farm with horse breeding, organic crop production and field composting. The latter is an open agricultural composting facility using the static pile system. Yearly about 650-700 m³ respectively 350-400 Mg horse manure are generated and used as feedstock. It is mixed with external green waste. The estimated amount is estimated with about 500-650 m³ yearly. The composting time varies between 12 and 20 weeks. The piles are irrigated on demand. The compost production is about 900-1100 Mg per year and the whole amount is applied on own fields.

- *Gräflich Bernstorff'sche Betriebe (GBB):* GBB, located in Gartow, is an agriculture and forestry business with organic livestock and arable farming. Since 2014 it is following the Bioland association principles. It carries out composting with cattle manure and green waste. A composting cycle lasts about 12 weeks. The input material mixtures are composted in an open field composting system with windrows of 70 - 100 m length. They are turned regularly using a special compost turning machine with an implemented irrigation system. About 3000 - 4000 Mg of compost are produced per year. The compost is applied to own crops and vegetables.

The municipal composting facilities produce RAL-certified compost for selling to agriculture respectively substrate production considering the guidelines of BGK (Chapter 2.3). For the proof of hygienisation they follow BioAbfVO (2022) after which the temperature of each batch has to be > 60°C for at least 1 week or > 65°C for at least 72 hours. The agricultural facilities produce compost for own use. They do not hold RAL certification. However, GBB also measures the temperature to control the process, but not so STR.

3.2 Municipal facilities

3.2.1 Biogas and composting facility in Lübeck

EBL obtains green waste from various sources and biobin waste from households from the 214 km^2 catchment area of the city of Lübeck with around 215,000 inhabitants. They use it to produce different composts in different process lines (Figure 7, Figure 8, Figure 9).

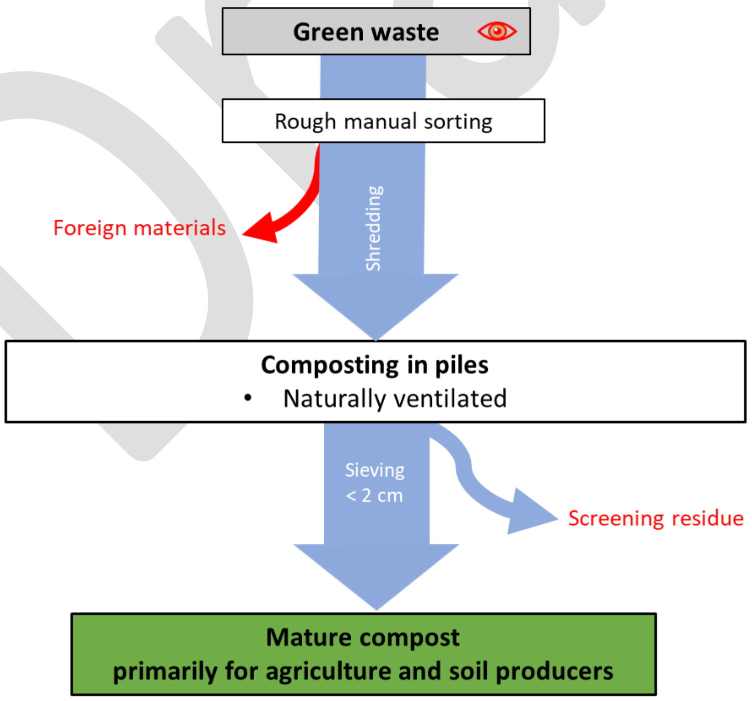

Figure 7: Plastic discharge in the EBL process for green waste

(red arrow: pathway from special importance; red text: plastics discharge as minor part of the stream)

In one approach, mature compost is produced purely from green waste (Figure 7). In the other, compost is generated following a sequence where a portion of biobin waste undergoes a 15-21-day anaerobic wet fermentation process with the recirculation of process water. Subsequently, portions of biowaste digestates are mixed with green waste (Figure 8, Figure 9). Until 2021, mature compost production was carried out based on these respective procedures showing in Figure 8. Since 2022, EBL is using an expanded process with a downstream air classifier, in which impurities can be further separated from compost by a wind classifier (Figure 9), so that substrate compost quality is achieved. While the green waste line produces exclusively compost, the line with portions of biobin waste also supply biogas as a co-product.

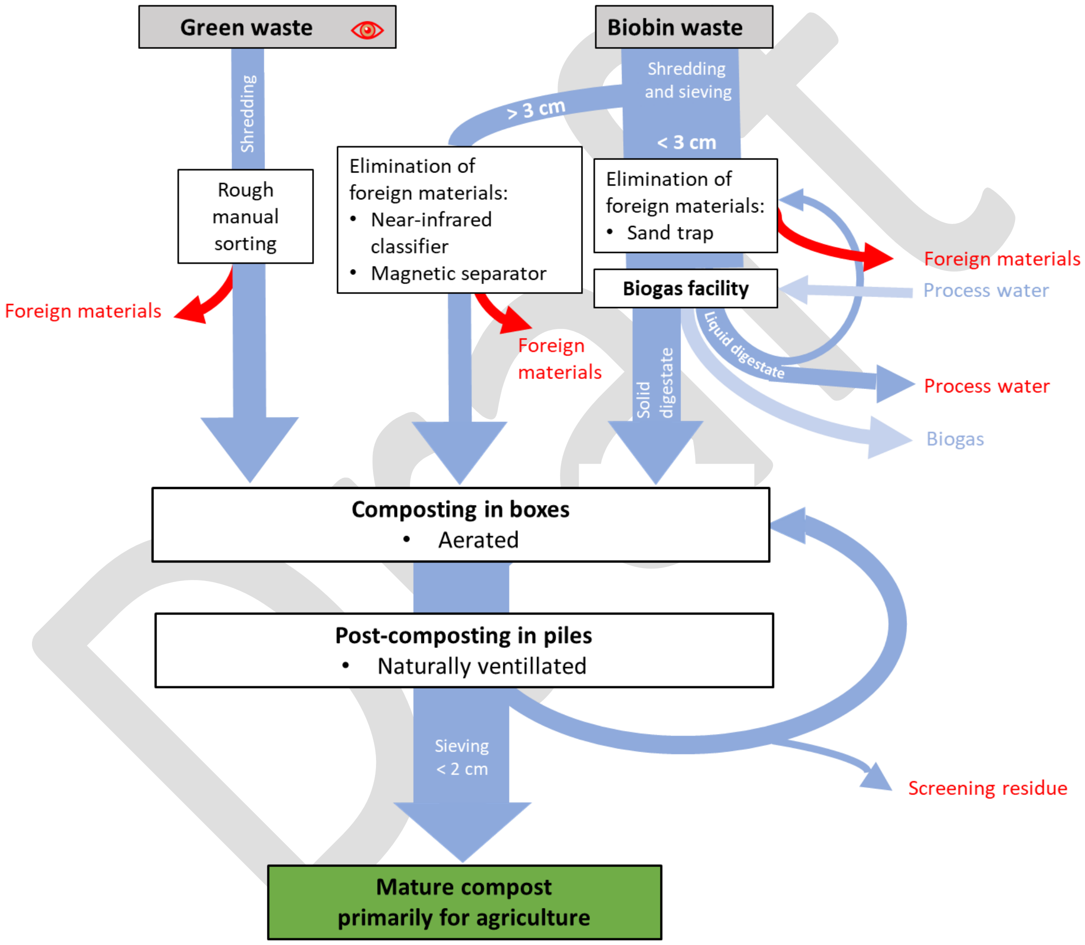

Figure 8: Plastic discharge in the EBL process till 2021 for biobin and green waste

(red arrow: pathway from special importance; red text: plastics discharge as minor part of the stream)

With regard to the separation of foreign materials, the different inputs into the composting in piles (Figure 7) and boxes (Figure 8, Figure 9) are characterised as follows:

○ The green waste from gardening and landscaping is delivered by private individuals and companies. At EBL, a sporadic visual inspection is carried out, during which larger plastic contaminants are removed manually, or acceptance is refused if the proportion is too high. After storage on a heap, shredding is done with a chipper.

- The biobin waste is first mechanically crushed using an impact mill and thereafter sieved into a coarse (>3 cm square meshes[1], around 10 vol.%) and fine fraction (<3 cm; around 90 vol.%). Among others some of the plastic impurities are removed from the coarse fraction by means of near-infrared classifier. In addition, magnets are used for metal removal.
- The fine fraction of the biobin waste is mixed with liquid digestate and process water. After the separation of heavy materials such as sand and stones by a sand trap, the cleaned mixture is send to wet fermentation. The digestate remaining after the biogas process is dewatered. The solid portion is fed into box composting. Some of the liquid is recirculated. Another part is discharged as process water and used in residual waste fermentation. The process water may also contain microplastic particles.

The input of composting in the green waste variant (Figure 7) consists exclusively of shredded green waste. It is composted in naturally ventilated open piles for at least 4 weeks. In the biobin variants (Figure 8, Figure 9), a large share of the input consists of solid digestate from biobin waste fractions. The remainder is shredded green waste and recycled screenings. The mixtures are composted in aeration-controlled rotting boxes with a volume of 100 or 400 m^3 for minimum one week to 10 days.

Subsequently, the rotted material is moved to open windrows where it undergoes further decomposition for a minimum of one additional week. The composting time in the open windrows in all variants depends on the waste quantities delivered and the compost amount required. Thus, it varies according to the season. The rotted material from the windrows is finally screened in all three variants with a drum sieve. The cleaned screening residue is recirculated. A part of the screen residue can also be incinerated externally. Light impurities including microplastic are removed from the fine fraction by means of an air classifier in the extended system (Figure 9).

The fine fraction in each case is a mature compost, and it is marketed with RAL quality certificate. Since 2022, the extended process variant with the air classifier (Figure 9) has been delivering composts with reduced plastic impurities, which correspond to the higher quality of a substrate compost (Chapter 2.3). Likewise, the composts produced from pure green waste (Figure 7) are also of substrate quality, while the second process variant (Figure 8) resulted in mature composts only. In 2022, approx. 45% of the compost was delivered to soil producers and 55% to farmers, horticulturists or private customers.

[1] refers to the diagonals of the square mesh

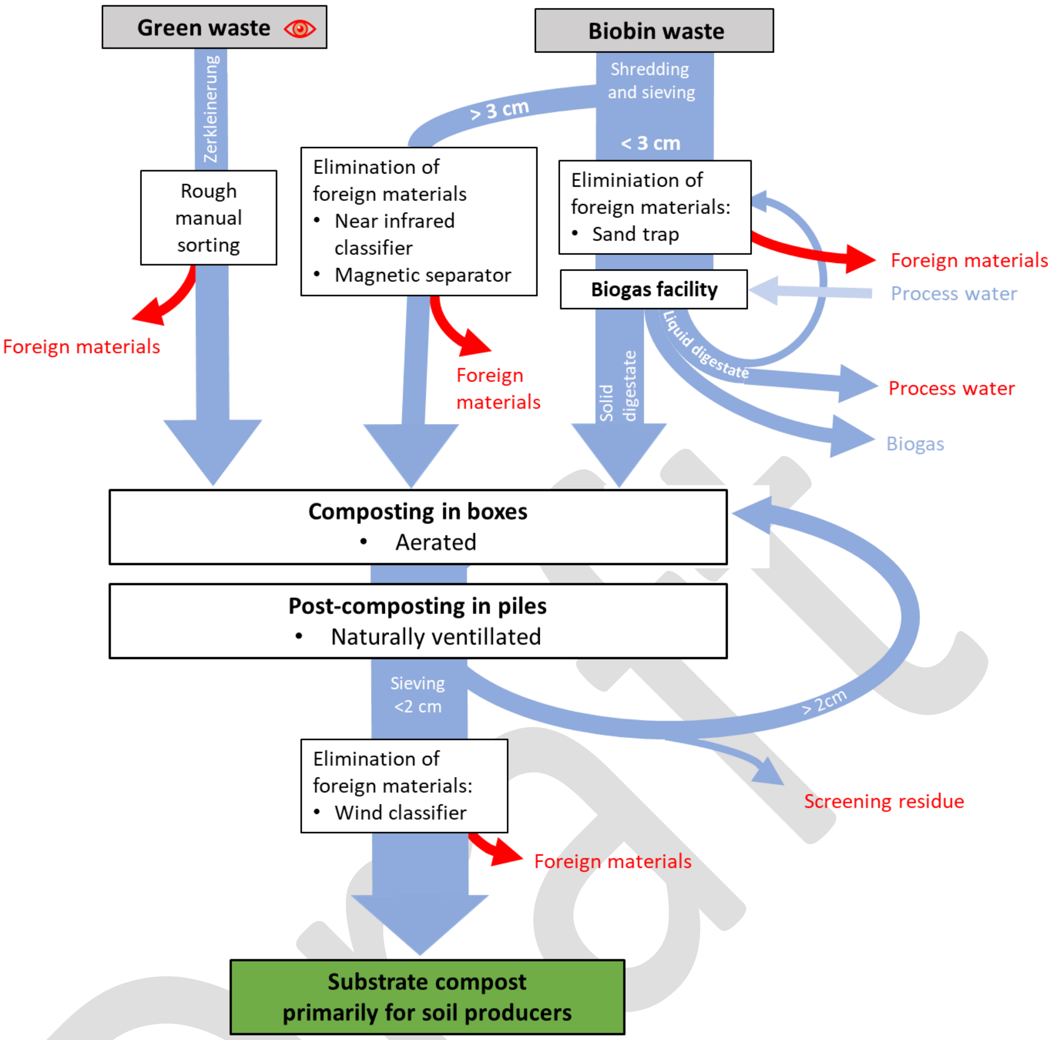

Figure 9: Plastic discharge in the EBL process from 2022 onwards for biobin and green waste

(red arrow: pathway from special importance; red text: plastics discharge as minor part of the stream)

3.2.2 Biogas and composting facility in Hamburg

Stadtreinigung Hamburg AöR (SRH) is the public waste management company of the Federal State and the City of Hamburg. It operates a biogas and composting plant in Bützberg for biobin waste and some garden and park waste. The plant is located in the Federal State of Schleswig-Holstein, but close to the Hamburg border. The biowaste volume fed into the facility consists of around 95% biobin waste from separate collection of private households. The catchment area covers whole Hamburg (about 755 km^2 and 1.8 million inhabitants). Furthermore, individuals and small businesses bring green waste to Hamburg's recycling centers, which is then transported to the Bützberg plant (Figure 10). There RAL certified mature compost as well as biogas is produced in a discontinuous dry fermentation with percolation. The biogas is refined into biomethane by CO_2 separation and fed into the gas grid.

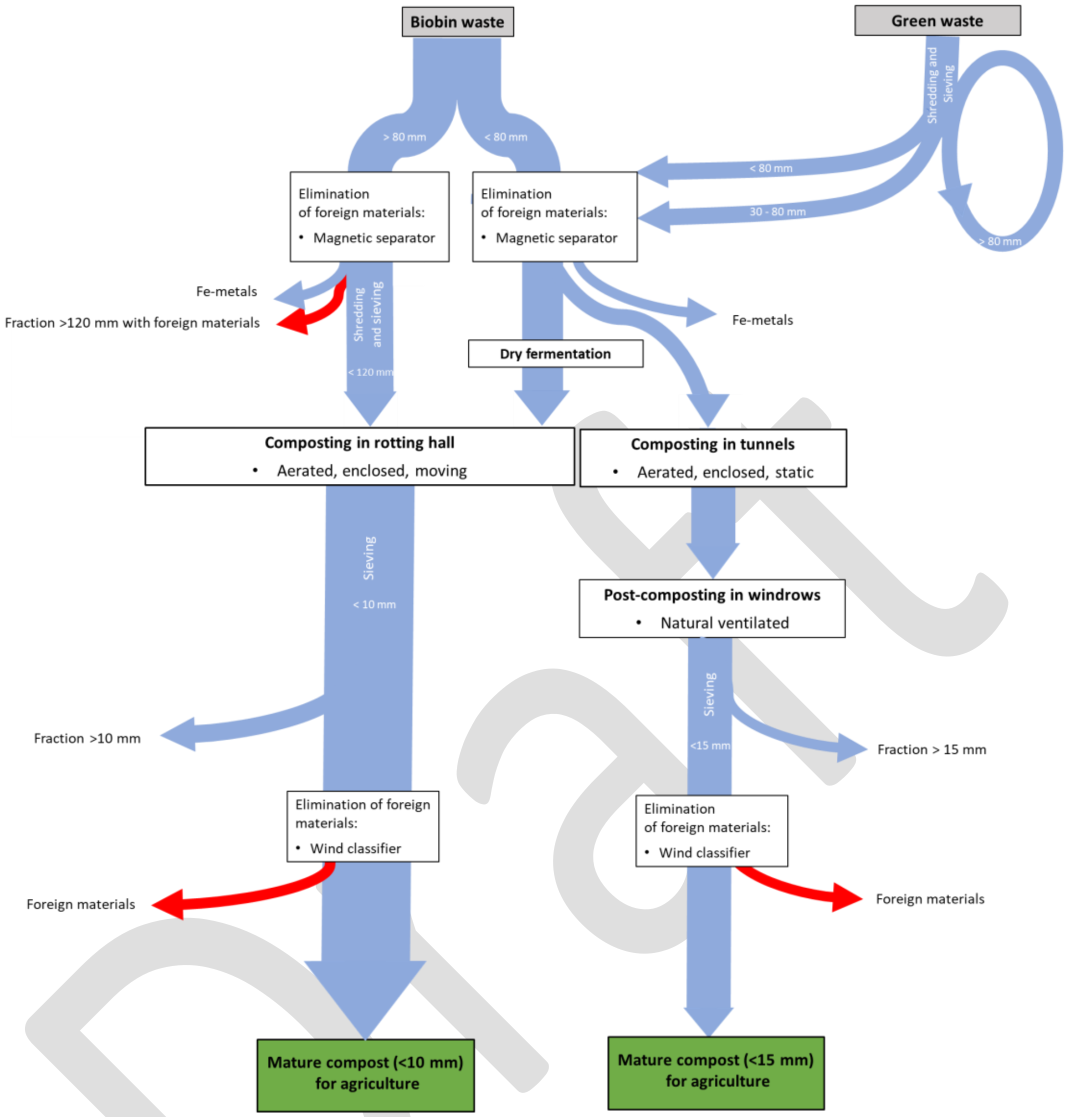

Figure 10: Plastic discharge in the SRH process from 2008 onwards with biobin and green waste

(red arrow: pathway from special importance; red text: plastics discharge as minor part of the stream)

The whereabouts of the impurities and the input streams into the composting processes are characterised as follows:

- The initial preparation of the biobin waste is carried out with a drum screen (round hole 80 mm). Long parts, which may also contain plastic, are removed from the fine fraction using a long parts separator. The fine and the coarse fraction pass through magnetic separators to remove Fe-metals eventually with some plastic particles attached. The coarse fraction is then shredded (3-shaft shredder) and sieved (star screen 80/120 mm), impurities (>120 mm) including plastics are removed. The major part of the conditioned fine fraction (<80 mm) is fermented (17 days) and then fed into the rotting hall, while a minor is fed into intensive rotting tunnels (21 days).

- Sporadic visual inspections of green waste are carried out at the recycling centers, where larger plastic impurities might be removed manually or acceptance refused. In the Bützberg facility, the green waste is shredded and screened (mobile star screen: 30/80 mm) by an external service provider. The coarse fraction (>80 mm) is shredded again. The medium fraction (30-80 mm) is mostly an input stream into the rotting hall, but can optionally also be added to the biowaste or fermentation. The fine fraction (<30 mm) is mainly added to the biowaste, but can also be fed directly into the rotting hall if required. Plastics are not discharged in these processes.

These different biowaste fractions are mainly composted in a rotting hall (35 days) with a moving tabular windrow. A partial stream can also be composted in an intensive rotting process in tunnels (21 days), followed by a subsequent rotting process in triangular windrows (14-48 days). The fermented fine fraction always goes into the rotting hall, where it is mixed with certain unfermented fractions. The respective proportions depend on the quantities delivered and their qualities.

- *Rotting hall:* The moving windrow consists of an entry area for the conditioned biowaste, which is filled twice a week. Then the mixture enters the composting area. One run lasts a total of 35 days. Transport and mixing is carried out with a paddle-wheel converter, which brings the rotting material from the entrance to the exit of the hall. The rotting loss is approx. 50 % by volume. There are aeration fields under the windrow, which can supply air as needed (at the begin: 6-fold, at the end: 1-fold air exchange per hour). After being turned 10 times, the finished compost is discharged with the help of the turning device and fed to the fine processing unit via conveyor belts.
- *Rotting tunnels with post-composting:* A total of 7 intensive rotting tunnels are available. The residence time in a tunnel is 21 days. Afterwards, the discharged material is loosened and composted in an open triangular windrow for 14-48 days. The rotting material is turned twice.

In both systems, the oxygen supply is adapted to the process and the temperature is monitored. Generally, temperatures of over 70°C are reached over a longer period of time to allow hygienisation. After composting, the rotted material is passed through a drum screen (10 mm round hole; sometimes 15 mm for material from triangular windrows). Foreign matter is removed from the coarse fraction by means of an air classifier, whereas the light fraction in particular contains plastics in significant shares. The conditioned coarse fraction passes through another drum screen (30 mm round hole). The screen overflow is partly reused as structural material, the medium sized fraction for composting; or partial fractions might be also discharged from the system.

The fine fraction is of finished compost. It is stored in roofed heaps until distributed. The main part (approx. 82%) is sold to farmers in Schleswig-Holstein, the rest is packed and delivered to Hamburg's twelve recycling centres, where the bags are purchased by private individuals.

3.3 Agricultural facilities

3.3.1 Horse breeding with on-site composting in Groß-Gusborn

In the STR composting plant, manure from the company's own horse farm is the main input. The manure from about 40 horses is used for composting and comes from the stable. It consists of the horses' excrement soaked into the straw bedding material in the stable. As the horses graze on a large pasture from spring to autumn, the amount of manure is higher in winter than in the other quarters of the year. The manure is removed from the stable about once a month.

External green waste is used as a co-substrate in greater quantities than the main substrate. The mixing ratio is about 3:2 on volume base. The type of green waste varies. STR is still in the experimental phase to determine the most suitable sources. If necessary, the delivered co-substrate is manually cleaned of particularly large or obvious plastic particles before it is mixed with the horse manure.

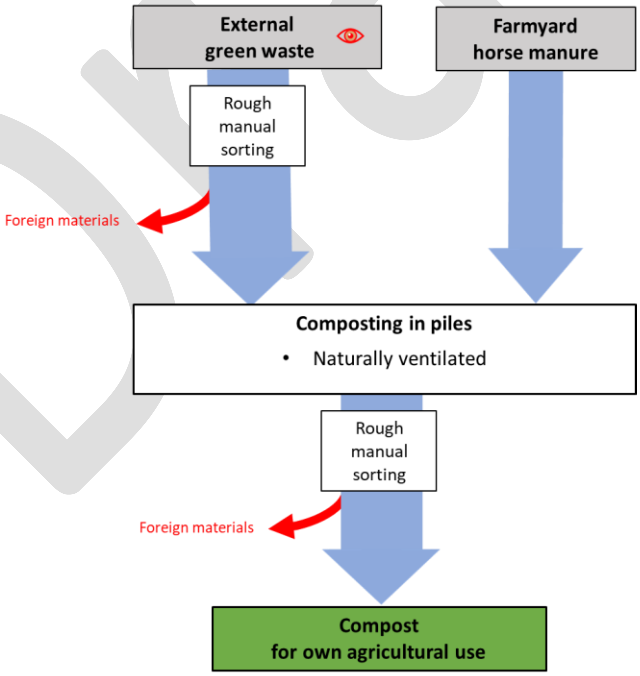

Figure 11: Plastic discharge in the STR process with horse manure and green waste

(red arrow: pathway from special importance)

The following substrates have been considered during the SOILCOM period and have been rated as follows by the farmer in terms of foreign matter:

- Horse manure coming directly from the farm's stables is assumed to be plastic free.
- Shredded green waste from private gardens was picked up from the collection points of the regional machinery ring. It was reported to contain plastic contamination.
- Other co-substrates used were tree prunings from ditches cared by the water and soil accociation, and 120 Mg pressed digestate from an agricultural biogas facility. Additionally, lime (Carbo-Kalk) from sugar production from sugar beets was used once as amendment. All substrates were reported to be optically free from plastics.
- Heather residue from heather landscape maintenance and moss from nature reserves are substrates under discussion, but are not applied yet.

The process flow is shown in Figure 11. The two initial substrates are mixed using a manure spreader. The mixtures are placed in piles with 2 m wide, 1.0-1.3 m high and of variable length. The piles are moved and turned at most once during the composting process. As open field piles without a roof, they are exposed to the weather conditions. Rainwater can seep into the piles. If a pile too dry, it is manually watered according to the initial moisture of the mixture and the weather conditions during composting with a water hose. After a composting period of 12-20 weeks, the compost is used to spread on the farm's own crop land. The produced crops are mainly rye, oat and barley as feed for the own horses and selling for food or feed production.

3.3.2 Organic farming with on-site composting in Gartow

In the GBB composting plant, manure from the company's cattles is the main input. About 600-800 Mg of manure per year from about 150 cattles are generated in the stables. It consists of cattle excrement soaked into the bedding material straw. The manure is removed from the stables and stored in a pile between 5 and 15 weeks. As the cattles graze on a large pasture the most of their time, only a limited share of the excrements is collected and used for composting. How much and the timing is depending on the housing system (Feeding area of suckler cows 1 x weekly and only in winter; lying area of suckler cows every 3 months and only in winter; lying area for fattening bulls 2 times in a year; calf stable 1x a month and in winter only). GBB owns about 425 ha grassland, but only a part is used for grazing.
Besides the own manure, also external cattle manure delivered by farmers from the surrounding is used. External manure from feed cooperation from about 500 Mg a year were used. Furthermore, external or internal green waste is used with a share of about 40 vol. %. The following substrates have been considered during SOILCOM and have been rated by GBB in terms of foreign matter:

- Cattle manure is generally considered to be plastic-free. However, some batches showed a high level of contamination with plastic fibers originating from plastic nets used to hold straw bales together.

- External green waste is chopped and screened. It is delivered by the machinery ring of the region and consists mainly of private garden waste. It may contain plastic contamination.
- Since 2023 also grass clippings from own landscaping fields are tested to substitute external green waste. They are optically free of plastics contamination.
- Partly clay-like material from own fields was used as amendment (up to 10 Vol. %) with the intention to build up clay-humus complexes already during composting. This method was postponed since the material was not rich in clay and contained mostly sand. However, it was optically free of plastic pollution.

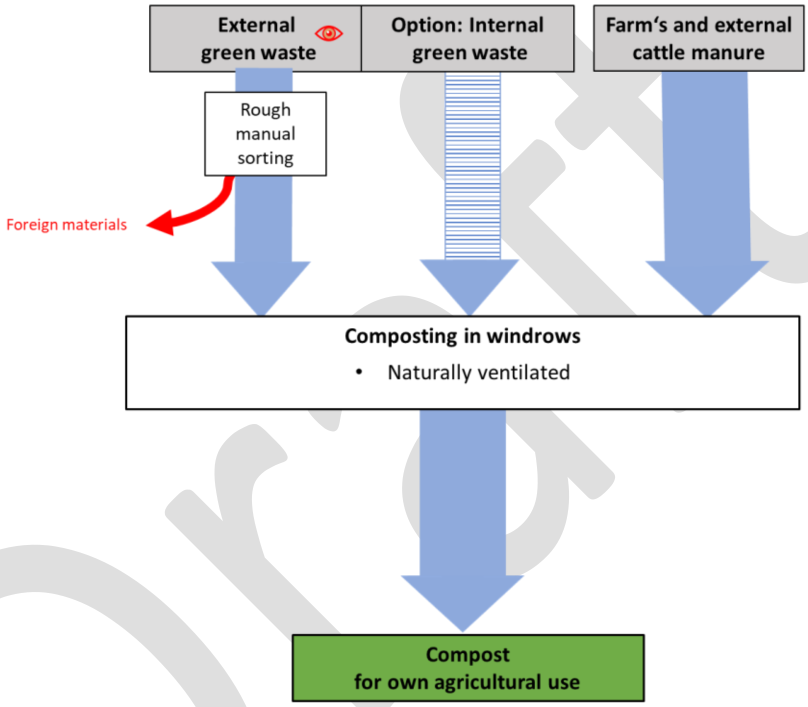

Figure 12: Plastic discharge in the GBB process with cattle manure and green waste

(red arrow: pathway from special importance)

The volume ratio of manure to green waste was approximately 3:2. The different substrates were stored in piles at the composting site until needed for composting. To start the composting process, they were alternately stockpiled with an excavator into parallel windrows, which were 2 m wide, 1.5 m high and up to 120 m long. At the start of the composting process, the windrows were turned completely once a week using a tractor-drawn compost turner with an attached irrigation system. Watering was carried out according to the weather conditions and the moisture level of the substrate. Towards the end of the composting process, turning was reduced to once every fortnight. A composting cycle therefore includes seven to nine turning operations. The windrow temperature was monitored to control the process.

No specific measures were taken to remove contaminants such as plastics from the compost, but the external green waste was checked on delivery and large contaminants were sorted out if the material was obviously contaminated.

The compost was produced exclusively for the farm's own agricultural use. The agricultural area was about 425 ha, but not all of it was treated with compost. Compost was added to cereals (spelt, rye, wheat, oats) and vegetables (carrots, beetroot, potatoes), but not used, for example, on clover grass and legumes such as peas and beans.

4 Compost quality certification in the municipal facilities

4.1 BGK quality control data

On a regular basis, municipal composting facilities conduct plastic analytics as a part of the BGK quality control process (Chapter 2.3). Regular taken samples are analysed by a certified laboratory in accordance with the BGK parameters and procedures.

Data sheets of the complete sets of measurement results were provided to TUHH for evaluation by EBL for the years 2018-2022 as well as by SRH for 1998-1999 and 2020-2022. The parameters selected for evaluation in this study included the ones with relevance for describing compost impurities:

- Deformable plastic mass (>2 mm, since 2021 >1 mm)
- Other foreign matter mass (>2 mm, since 2021 >1 mm)
- Surface area of impurities (>2 mm)
- Stone mass (>10 mm)

The sieve fractions used for the mass determination of deformable plastic and other foreign matter were >2 mm before 2021, and >1 mm after, since the BGK demanded the smaller value since that 01/2021 (Chapter 2.3). Regarding BioAbfVO (2020) the smaller particle size is demanded since 05/2023 (Chapter 2.1).

4.2 Impurities in composts from Lübeck and Hamburg

The results from the quality control data sheets of EBL are summarized in Table 2, while those from SRH are presented in Table 3. The evaluation was done separately for the different input materials (biobin waste, biowaste mix, green waste). The biobin waste consists of 100% biobin wast in case of EBL, and mostly from biobin waste in case of SRH. There a minor amount of green waste is contained as well. The biowaste mix comprises both biobin waste from households and green waste, but in higher shares compared to the biobin waste. It has to be mentioned, that biobin waste itself is a mixture between food waste and garden waste. However, this ratios are not known.

The composts from SRH were fully mature with a degree of decomposition of V. Most compost from EBL were matured to degree V as well, but with a few exceptions having a degree of IV. In 2019 two fresh EBL composts with a degree of decomposition of II were also included for analysis. A main difference between EBL and SRH composts is seen in the grain size. EBL produced medium-grain compost, mostly with particle sizes between 0 and 15 mm. In contrast, the analysed SRH composts were fine-grained particle sizes between 0 and 10 mm.

Lübeck composts

There is a noticeable trend of improvement in impurity levels for EBL compost for the biowaste mix since 2022, as well as for the green waste category since 2019.

The enhancement in impurity reduction for the *biowaste mix* can be attributed to the additional wind classifier within the process, which removes light foreign matter from the mature compost (Figure 9). This supplementary procedure resulted in a roughly 50% reduction in impurities. The tendency is specifically seen in the results regarding the parameters “Other impurities” and “Surface area of impurities”. It is not as clearly seen for the mass on “Deformable plastic” (foils). A reduction in this aspect occurred already earlier. These improvements eventually could be assigned to improved source-separation practices at household level. EBL has carried out several of campaigns to encourage residence to more effectively segregate their bio-waste. Another reason might be the increasing proportion of green waste within the mix. The composition of green waste sourced from gardens and parks were mostly mixed with the biobin digestate, ranging from 30-70% between 2020-2022, and 20-50% prior to that period.

Table 2: Compost evaluation of EBL medium-grained compost for impurities and stones (Data given as minimum – median – maximum)

Input waste	**Time**	**Samples**	**Deformable plastic***	**Other impurities***	**Surface area of impurities**	**Stones**
Type	Year	Number	% DM	% DM	cm^2/L FM	% DM
Biobin waste	2018	3	0.03-**0.04**-0.09	0.05-**0.07**-0.09	8.0-**11.0**-15.0	0-**0**-0
Biowaste mix		3	0.05-**0.06**-0.09	0.06-**0.15**-0.17	5.0-**9.0**-15.0	0-**0**-0
Green waste		2	0.00-**0.01**-0.01	0.03-**0.04**-0.04	0.5-**6.2**-12.0	0.3-**0.6**-0.9
Biowaste mix	2019	6	0.00-**0.03**-0.04	0.03-**0.08**-0.15	3.0-**7.0**-9.0	0-**0**-0.8
Green waste		2	0.00-**0.00**-0.01	0.00-**0.03**-0.04	2.8-**3.4**-4.0	0-**0**-0
Biowaste mix	2020	8	0.00-**0.01**-0.02	0.02-**0.05**-0.12	5.4-**11.0**-19.0	0-**0**-0
Green waste		1	0.00	0.01	1.0	0-**0**-0
Biowaste mix	2021	8	0.00-**0.01**-0.01	0.00-**0.00**-0.06	0.6-**10.0**-15.0	0-**0**-0
Green waste		1	0.00	0.00	3.5	0-**0**-0
Biowaste mix	2022	11	0.00-**0.01**-0.03	0.00-**0.00**-0.00	0-**5.2**-9.3	0-**0.3**-0.95

*From 2018-2020 for particles >2 mm, since 2021 for particles >1 mm

For the *green waste*, both the impurity masses and levels remained consistently lower than those observed in the biowaste mix across all years. However, over time, the differences between them diminished. Importantly, green waste compost did not constitute the predominant product at EBL. Since 2022 the amount produced is very low, and most produced compost can be categorized as biowaste mix. However, the improvements for green waste composts since 2019 can eventually be assigned to a stricter visual inspection of the delivered wastes.

Stones were found only occasionally, and the process improvements had no influence on them. It is highly plausible that stones are introduced into the compost stream through the green waste.

Hamburg composts

In the early times of composting at SRH, the regular BGK quality control solely focused on the overall impurity content and the presence of stones. In the evaluated years (1998 and 1999), the recorded median impurity value from 10 samples was 0.1% DM. Additionally, stones were identified at levels of 0.6% and 0.7% DM, respectively.

Table 3: Compost evaluation of SRH fine-grained compost for impurities and stones (Data given as minimum – median – maximum)

Input waste	**Time**	**Samples**	**Deformable plastic***	**Other impurities***	**Surface area of impurities**	**Stones**
Type	Year	Number	% DM	% DM	cm²/L FM	% DM
Biobin waste	2020	13	00.0-**0.00**-0.00	0.00-**0.04**-0.13	1.0-**4.3**-.8.0	0-**0**-0
Biobin waste	2021	14	0.00-**0.00**-0.00	0.00-**0.02**-0.22	1.1-**3.9**-8.4	0-**0**-0
Biobin waste	2022	14	0.00-**0.00**-0.00	0.00-**0.07**-0.50	0.5-**2.2**-9.9	0-**0**-0.57

*For 2020 for particles >2 mm, since 2021 for particles >1 mm

In Table 3 for results of the more detailed analytics is given for 2020-2022. It can be concluded, that there has been an improvement in overall impurity levels, consistently remaining below the limit value of 0.4% DM for “Other impurities” with only a single outlier. However, even in the early years a high level of quality was already achieved with values significantly below the currently allowed limit.

Regarding “Deformable plastic” (foils), there was not a single detection reported by the certified laboratory in the period between 2020 and 2022 in the given accuracy level, also after the particle size was changed to >1 mm. However, the “Surface area of impurities” was positive, which likely cannot be solely attributed to other impurities. Since plastic foils are very light, they might not be measurable within the specified accuracy, but optically visible to get detected and contribute to the surface area. There is a clear trend of improvement for this parameter, with an average reduction of approximately 50% since 2020. This might be assigned to better qualities of the biobin input, since no major technical changes occurred during the period at SRH.

Stones were reported only in a single sample. Overall, the SRH composts have consistently exhibited very high quality over an extended time period.

4.3 Quality evaluation regarding impurities

When analysing composts derived from green waste in comparison to those produced from biobin waste or biowaste mixes, it is evident that the level of all impurity parameter were notably lower if same company and year is compared. The lower impurity levels in green waste compost can be attributed to its substrate's origins in gardens and parks, where contamination rate is comparatively low. In contrast, biobins often receive waste from households, leading to higher impurity levels due to improper disposal practices by residents.

The limit values for "Deformable plastic" (0.1% DM) and "Other impurities" (0.4% DM) from BioAbfVO (2020) (Chapter 2.1) were clearly undershot by both facilities, with only one outlier. According to analyses carried out within the framework of the RAL quality assurance for all BGK certified German composting facilities, the German average content of "Deformable plastic" in compost was about 0.01% DM. This is 1/10 of the legislative limit value (chapter 2.1, chapter 2.2; Kehres 2018). A more detailed evaluation of German composts is to be found in Kehres (2019) with data from 2018:

- Average "Deformable plastic" content (expressed as % compost DM): 0.008% in composts in general, thereof 0.012% in composts derived from biobin waste or biowaste mixes, and 0.004% in composts from green waste
- Average "Hard plastic" content (expressed as % compost DM): 0.024% in composts in general, thereof 0.029% in composts derived from biobin waste or biowaste mixes, and 0.018% in composts originating from green waste

Overall it can be said, the municipal composts produced by German facilities exhibit a strong adherence to the country's legislative quality standards, similarly as the studied composting facilities EBL and SRH. Comparing EBL and SRH composts, the ones from SRH were in 2022 slightly better with the "Deformable plastics", whereas, the EBL compost had lower values with the "Other impurities".

Regarding the "Surface area of impurities", EBL composts achieved substrate quality (limit: 10 cm^2/L FM) in 2022. It is the highest threshold defined by BGK (chapter 2.3). Prior to this, EBL met the BGK limit (15 cm^2/L FM) for fresh and mature composts, although there were occasional outlines. SRH composts had substrate quality already since 2020, and maybe before.

The differences between EBL and SRH composts could be caused by some differences in the cleaning technologies applied (chapter 3.2). However, the difference in the compost's grain size (SRH: <10 mm; EBL: <15 mm) seems to be specifically relevant to explain lower foil contents in SRH composts. Employing more stringent sieving, results in the removal of a higher proportion of such impurities. The disadvantage of finer sieving is reduced compost amount of final product and thus a value loss. Overall, there has been a significant improvement in compost quality from 2018 to 2022.

5 Study on microplastic in composts from four facilities

5.1 Sample overview

From the four facilities various types of samples were investigated. An overview of the analysed samples is presented in Table 4 for the municipal, and in Table 5 for the agricultural composting facilities. Specific investigations were conducted for each facility:

- EBL: different input materials, different sampling times, different process aggregates
- SRH: different grain-size compared to EBL compost
- STR: different sample locations in the pile body and, in addition from pile surface, different piles with similar substrates
- GBB: same as STR but from windrows and without surface samples, additionally, pre-rotted material

This variety aims to encompass a broad spectrum of influential factors that can affect plastic particle results.

Table 4: Overview of samples for microplastics analytics from municipal composting facilities

Sample ID	Sampling date	Input materials	Sample specifics	Code facility / student
		EBL, Lübeck (LU)		
LU1a LU1b LU1c	29.07.2021	100% Green waste	3 random samples from pile 1 with mature compost mixed and split again	E1.1M / SH E1.2M / SH E1.3M / SH
LU2a LU2b LU2c	29.07.2021	50% Green waste 50% Digestate	3 random samples from pile 2 with mature compost mixed and split again	E2.1M / SH E2.2M / SH E2.3M / SH
LU3a LU3b LU3c	11.08.2021	100% Green waste	Random samples from pile 3 with mature compost	E1.1 / SH E1.2 / SH E1.3 / SH
LU4a LU4b LU4c	11.08.2021	50-60% Digestate 20-25% Green waste 20-25% Coarse fraction	Random samples from pile 4 with mature compost	E2.1 / SH E2.2 / SH E2.3 / SH
LU5	08.12.2022	Green waste Digestate	Representative sample from pile 5 from at least 20 single samples	E1 / CN
		SRH, Hamburg (HA)		
HA1a HA1b HA1c	21.04.2023	78% Biobin waste 22% Green waste (Both partly digested)	Random samples from a bag bought at recycling center	H1.1 / ÖB H1.2 / ÖB H1.3 / ÖB

SH, CN, ÖB - Analysts initials

Table 5: Overview of samples for microplastics analytics from agricultural composting facilities

Sample ID	Sampling date	Input materials	Sample specifics	Code facility / student
			STR, Groß Gusborn (GG)	
GG1.1a GG1.1b GG1.1c GG1.1d GG1.1e	11.08.2021	60% Green waste 40% Horse manure	5 mixed samples each from 3 single samples representing different depths of pile 1: 25 cm 65 cm 50 cm (left) 50 cm (right) 120 cm	S1.1 / SH S1.2 / SH S1.3 / SH S1.4 / SH S1.5 / SH
GG2.1a GG2.1b GG2.1c GG2.1d GG2.1e	11.08.2021	60% Green waste 40% Horse manure	5 mixed samples each from 3 single samples representing different depths of pile 2: 25 cm 65 cm 50 cm (left) 50 cm (right) 120 cm	S2.1 / SH S2.2 / SH S2.3 / SH S2.4 / SH S2.5 / SH
GG1.2	31.08.2021	60% Green waste 40% Horse manure	Mixed sample from 10 samples taken from pile 1 surface	S1 A_O / SH
GG2.2	31.08.2021	60% Green waste 40% Horse manure	Mixed sample from 10 samples taken from pile 2 surface	S2 A_O / SH
			GBB, Gartow (GA)	
GA0a GA0b GA0c	11.08.2021	100 % Pre-rotted green waste	3 random samples of a heap	G3.1 / SH G3.2 / SH G3.3 / SH
GA1.1 GA1.2 GA1.3 GA1.4 GA1.5	11.08.2021	50 % Green waste 40 % Cow manure 10 % Clay	5 mixed samples each from 3 single samples representing different depths of windrow 1: 25 cm 50 cm 40 cm (left) 40 cm (right) 90 cm	G1.1 / SH G1.2 / SH G1.3 / SH G1.4 / SH G1.5 / SH
GA2.1 GA2.2 GA2.3 GA2.4 GA2.5	11.08.2021	50 % Green waste, 40 % Cow manure, 10 % Clay	5 mixed samples each from 3 single samples representing different depths of windrow 2: 25 cm 50 cm 40 cm (left) 40 cm (right) 90 cm	G2.1 / SH G2.2 / SH G2.3 / SH G2.4 / SH G2.5 / SH

SH – Analyst initials

The average compositions of the input materials presented in Table 4 and Table 5 were estimations provided by the facility operators. The exception is SRH, where the estimation was derived from basic facility data (chapter 3.1).

5.2 Sampling procedures

5.2.1 Composts LU from Lübeck

Sampling was carried out at three different time periods and for three different substrate and process types. In total, five different windrows were investigated. Composts LU1 and LU3 were produced from green waste according to the process shown in Figure 7, while composts LU2 and LU4 were derived from waste mixtures with digestate from biobin waste according to the process shown in Figure 8. Compost LU5 was composed of green waste compost, following the process shown in Figure 9. The other part was compost from waste mixtures with digestate from biobin waste resulting from the process shown in Figure 9. In contrast to the process in Figure 8, a wind classifier removed plastic particles from the compost.

Compost samples LU1-4 were provided by EBL. Three compost samples of approximately 1 L each were taken from each windrow randomly. The three samples of one windrow from the first sampling were homogenised, and then divided into three equal parts for analysis (LU 1/2abc). At the second sampling, the three samples from different locations within one windrow (LU3/4abc) were analysed directly. The compost sample LU5 was a representative sample of the respective windrow, considering the windrow size. For LU5, at least 20 samples were taken, mixed and systematically reduced in size according to the SOILCOM protocol for representative windrow sampling.

5.2.2 Composts HA from Hamburg

A compost bag containing 30 Litres of certified compost was purchased from the Hamburg-Bergedorf recycling centre operated by SRH. It contained a compost quality representing the <10 mm mature compost resulting from the rotting-hall process line (Figure 10). The three samples were taken at random and analysed separately.

5.2.3 Composts GG from Groß-Gusborn and composts GA from Gartow

In both facilities (STR, GBB) two piles or windrows were sampled, each with similar feedstock mixtures. Samples were taken at different cross-sections and at different positions along the piles respectively windrows following the pattern shown in Figure 5. Five cross-section samples from three different positions along the length of the pile respectively windrow (front, middle, end) were taken. The five cross-section locations within the pile or windrow body had different depth below the surface (Table 5) as well as left or right leaning position. The three with similar position in the cross-section were subsequently combined into one mixed sample. This resulted in five mixed compost samples per pile respectively windrow, with each sample representing a different cross-section.

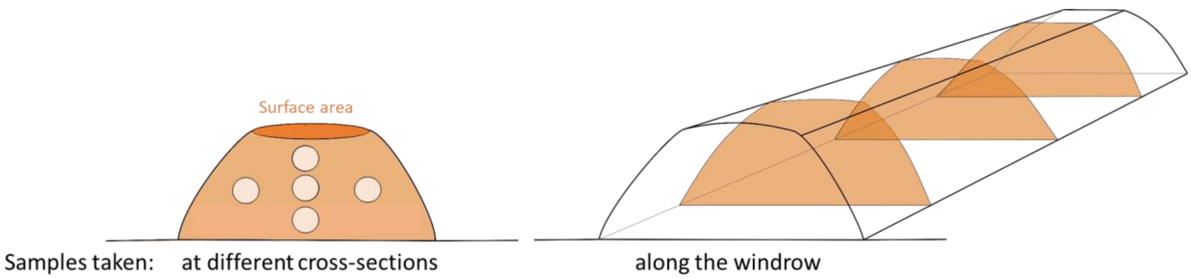

Figure 13: Sampling of compost from agricultural piles respectively windrows

Additionally, samples were collected from both STR piles (GG1.2, GG2.2) 20 days after initial sampling from the pile surfaces. In these cases, the mixed samples were prepared from approximately 10 random locations of the surface (Figure 13). The sampling depth reached up to 3 cm.

And at the GBB facility, additionally three random samples (GA0) were taken from a heap of stored green waste. Since the material had been stored for multiple days, it was considered to be in a pre-rotted state.

5.3 Determination of plastic particle numbers

The samples taken at or provided by the facilities were rather large in size. In order to receive a representative sample with a defined mass for further analytics, the quartering method was employed (Figure 14). The surplus material was utilized for the determination of the water content of the compost.

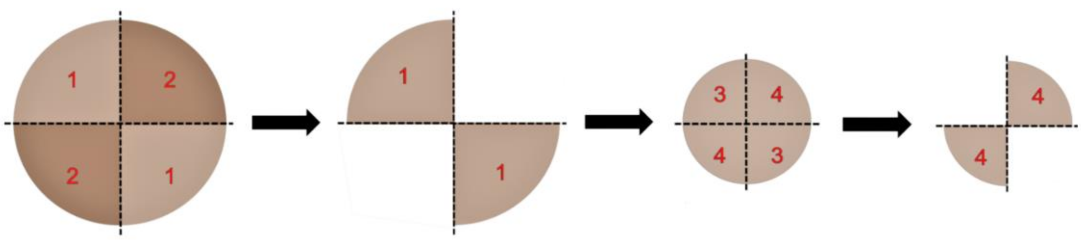

Figure 14: Preparation of a representative sample from a large amount of material

The reduced mass of fresh compost sample (about 200 g) was subjected to drying at 40°C to facilitate the sieving process. Dry sieving was conducted in a sieve tower using various sieve sizes. The resulting sieve fractions included: >5 mm, 2-5 mm, 1-2 mm, and 0.5-1 mm. The fraction <0.5 mm was excluded from further analysis. Plastic particles were isolated from all other sieve fractions using a tweezer and a lamp. More detailed procedural information is available in Annex 1. The number of the detected particles was related to the compost DM.

5.4 Evaluation of plastic particle numbers in composts

The results on plastic particles found in composts from two municipal and two agricultural composts are provided and discussed in the following. In Figure 15 and Figure 16 the total plastic particle numbers are given per kilogram of compost DM, whereas it was not differentiated between particle size. The particle numbers are cumulative including the plastic particles of following sieve fractions: 0.5-1 mm, 1-2 mm, 2-5 mm, >5 mm. In Figure 17 the parallel samples of one series were summarized, and the composts from different types were evaluated regarding the numbers of particles from different sizes. Finally, in Figure 18 a compilation of compost regarding the different input sources took place and the percentages of particles from each size in the composts were evaluated in connection with the feedstock.

Evaluation per total number of plastic particles in the different composts

Figure 15 and 16 depicts a comparison of the total number of plastic particles in the different types of composts. Following key observations were made:

- *Urban green waste composts vs. composts made with biobin waste shares* (*LU1/3 and LU4/5, HA1)***:** The green waste compost samples from EBL exhibit a clearly lower level on plastic particles compared to the biowaste mix composts produced without the use of a wind classifier. However, they where in similar range with the composts which were cleaned by a wind classifier (biowaste mix compost from EBL, LU5; biobin waste compost from SRH, HA1).
- *Rural green waste compost vs. compost made with manure shares (GA0 and GA1/2, GG1/2a-e)***:** The green waste used by GBB and by STR was private garden waste from the same provider. The share of the input mixture was 50% at the GBB and 60% at the STR facility. The pre-rotted green waste showed similar plastic particle numbers as the two types of manure compost. The results suggest that there are not substantial differences between these inputs regarding the plastic contamination. It is worth to look at the particle size for further evaluation.
- *Agricultural green waste vs. municipal green waste (GA0 and LU1/3):* The pre-rotted green waste material from GBB showed a significantly lower plastic particle number compared to the green waste composts from EBL. Both used private garden waste. It is assumed that rural garden waste might be cleaner compared to the one from urban areas, what might be attributed to larger garden sizes often found in rural settings. Another impact could be that the GA0 sample was pre-rotted, the LU1/3 samples were mature. However, the expected relative increase of plastic particle numbers due to loss of organic matter during rotting might be less influential.

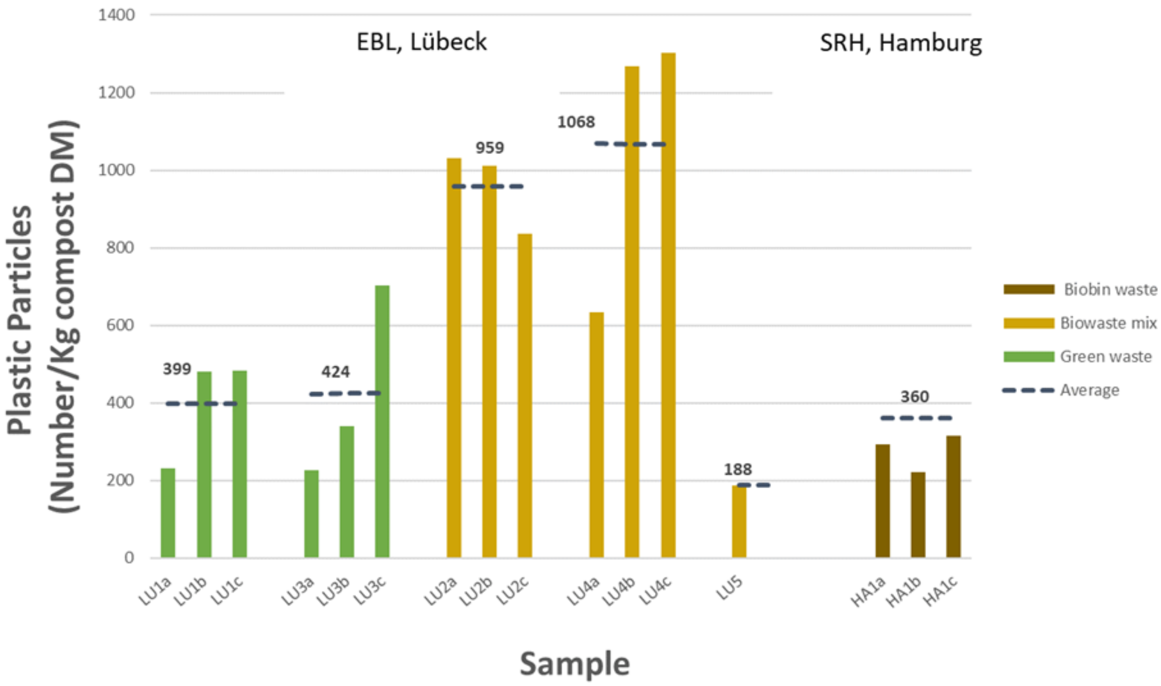

Figure 15: Plastic particles detected in composts from municipal composting facilities

Averages made from the 3 random samples taken at a pile (LU1-4) respectively bag (HA1). Exception is one sample (LU5) which was a representative sample made from more than 20 single samples (Table 4)

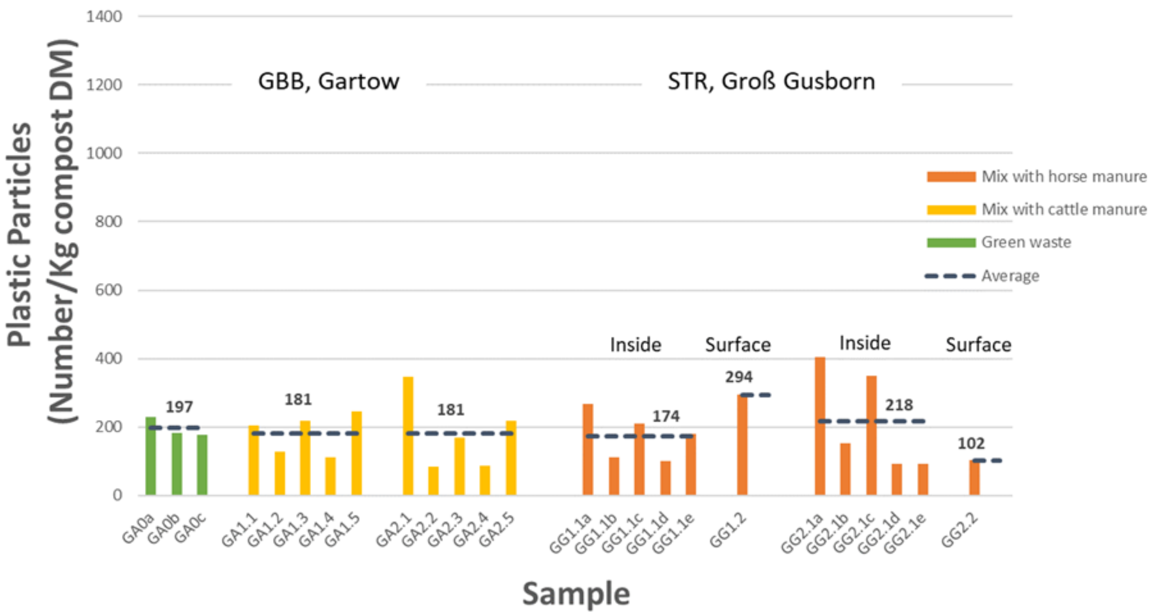

Figure 16: Plastic particles detected in composts from agricultural composting facilities

Averages made from 3 random samples (GA0), from 5 samples each made from three samples from different locations in the pile body (GA1.1-1.5, GA2.1-2.5, GG1.1a-e, GG2.1a-e), and from a mixed sample made from 10 surface samples (GG1.2, GG2.2); (Table 5)

- *Composts from pile inside vs. pile surface (GG1.1/1.2 and GG2.1/2.2):* The averages from the composts within the pile body differ from the ones from the surface. Segregation processes in different locations within the heap might have occurred but differently. The low plastic particle number in GG2.2 possibly might be caused by wind blow-out. Contrary the particle number in the surface sample GG1.2 was higher. The pile might be protected from wind. A segregation could be driven by small, more heavy compost particles moving downwards, contributing to relative plastic enrichment at the surface.

There were clear differences in the plastic particle numbers between compost samples from the different origins, but also within one facility in dependence of the input substrate and the position in a windrow or a pile due to segregation.

Evaluation of plastic particle numbers of different sieving fractions

In Figure 17 and 18 the plastic particle numbers are presented considering their respective size. The particle >5 mm and between 2-5 mm are the ones counted in the parameter "Surface area of impurities", which is demanded for the BGK certificate. Additionally, 1-2 mm particles are included in the mass parameters "Deformable plastic" and "Other impurities" demanded by BioAbfVO (2020) and DüMV (2021). Particles between 0.5-1 mm are so far not covered by legislation or quality guidelines.

Following findings are derived from Figures 17 and 18 regarding the different plastic particle sizes:

- *Fraction >5 mm:* These large particles are slightly present in a higher number in municipal composts (0-27 particles per kg compost DM) compared to agricultural composts (0-18 particles per kg compost DM). The biggest particle was found in a GBB compost. It measured 725 mm² (determined with picture analyses; corresponds to a 3 cm diameter if a circular shape is assumed). In SRH composts no particles >5 mm were found. The difference between SRH and EBL composts could partly caused by the different grain size of compost produced.
- *Fraction 2-5 mm:* In municipal composts (25-182 particles per kg compost DM) higher number of particles were detected compared to the agricultural ones (12-38 particles per kg compost DM). The upper range of the later can be assigned to the pre-rotted green waste, which is similar to the situation in municipal green waste composts. However, green waste composts had only less 1-2 mm particles compared to the composts made from biowaste mixes, if no wind classifier was applied. It seemed to be very effective for this particle size. Comparing the different types of manure, composts with horse manure contained more particles compared to the ones with cow manure.

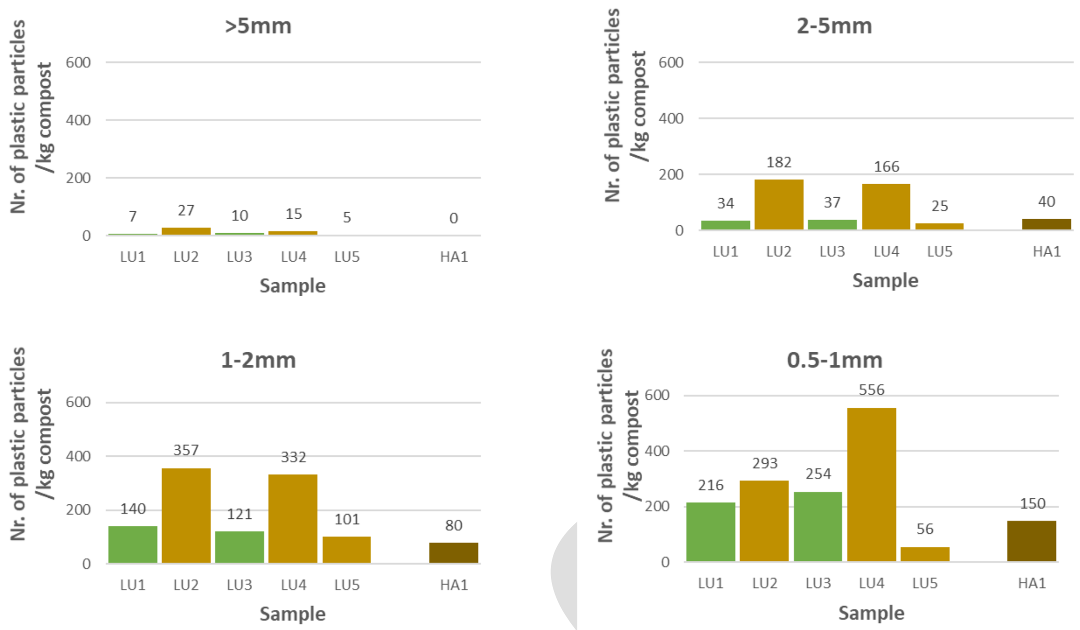

Figure 17: Numbers of plastic particles in different size categories in the municipal composts

Averages were calculated from the number of samples similarly as described in Table 15.
Note: The scale from Figure 17 and 18 are different.

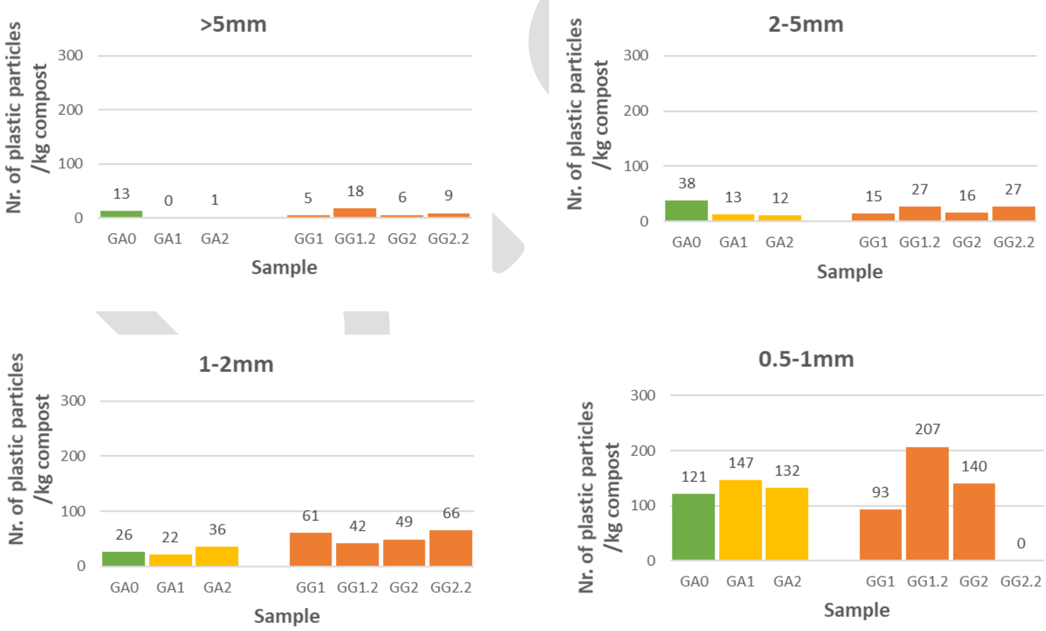

Figure 18: Numbers of plastic particles indifferent size categories in the agricultural composts

Averages were calculated from the number of samples similarly as described in Table 15.
Note: The scale from Figure 17 and 18 are different.

- *Fraction 1-2 mm:* In this fraction, the picture was quite similar to the 2-5 mm fraction, but the total number of particles found was much higher. In the municipal composts the number of particles were about 5 times higher (101-357 particles per kg compost DM) compared to agricultural composts (26-66 particles per kg compost DM). A new aspect is that the rural green waste material seemed to contain less of these particles compared to the urban green waste compost. This could be due to the fact that less mechanical work was done on the material during processing. The municipal composts were screened and turned several times, but the pre-rotted green waste was not.
- *Fraction 0.5-1 mm:* The trend is the same as described above for the 2-5 and 1-2 mm fractions, but with two notable exceptions. The agricultural compost from the pile surface 2 at STR did not contain any small plastic particles. It is likely that the very fine and light particles were blown away by the wind. A similar observation was made with the municipal compost from EBL, where a wind classifier was used. Only 56 particles were counted per kg of compost DM. A wind classifier was also used to clean SRH compost, but the specific techniques used there, which are much older, may not be as effective. The general level of the small particles was very high and again more were contained in municipal (56-556 particles per kg compost DM) than in agricultural composts (0-207 particles per kg compost DM).

It's important to note that there are uncertainties when identifying plastic particles in compost, particularly as particles become smaller. In Hasert (2021), the accuracy level of detection was investigated using microscopy to differentiate plastic particles from particles, which look like plastic. She reported different accuracy levels in the different fractions with increasing uncertainty as smaller the particles get. In the smallest group (0.5-1 mm) the uncertainty was up to 75%, large particles could be assigned well. However, it can be stated, that the number of plastic particles increase as the particles get smaller. Therefore, it is probable to assume, that a significant number of particles smaller than 0.5 mm exist. But they cannot be counted using the method applied in this study.

Evaluation of the share of plastic particles of different sizes

Figure 19 shows the percentual particle size distribution. It provides an insight into the trend of particle distribution under the influence of specific factors, resulting in distributions that deviate from the norm. The general trend observed in most of the plots is that smaller particles are more abundant. However, three of the samples deviate from this general finding:

- *Mixed bio-waste LU5:* The influence of wind classifier employed by EBL had a significant impact on the distribution. This effect resulted in a lower percentage of the 0.5-1 mm fraction (30%) compared to the 1-2 mm fraction (54%). Although SRH also used a wind classifier, this trend was not observed in the HA1 sample. It's worth noting that the EBL wind classifier was not used just once on the LU5 sample, moreover, it was a newer and probably more advanced classifier.

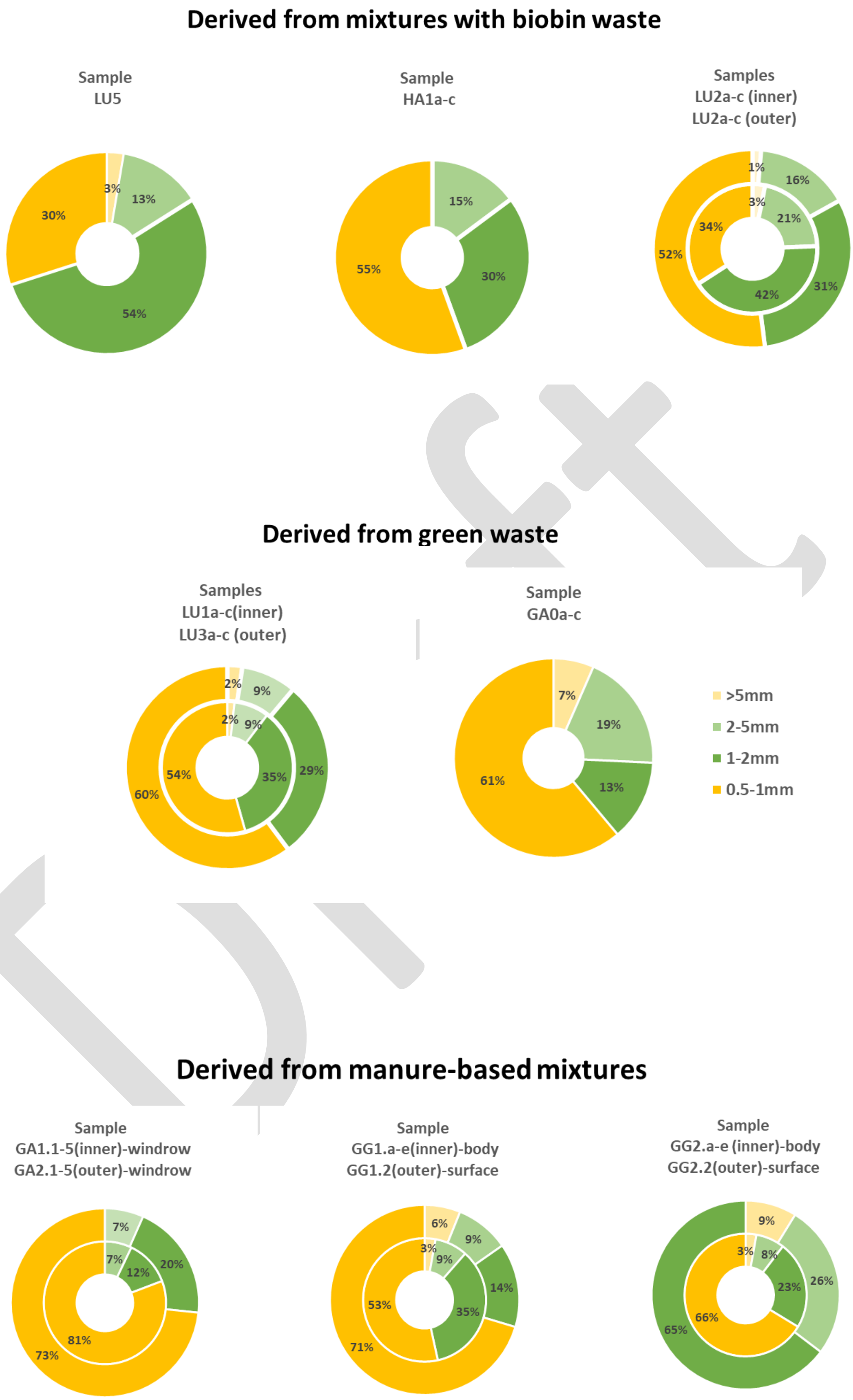

Figure 19: Share of microplastic particles in the composts derived from different feedstock

- *Pre-rotted green waste GA0:* In the GA0 sample of GBB, the 1-2 mm fraction accounting for a lower proportion (18%) than the 2-5 mm fraction (20%). One possible explanation for this observation is that this pre-rotted material undergo minimal processing (shredding, transport and piling). Despite some degree of decomposition, it retains characteristics more akin to input material rather than a compost. Contrastingly, examples such as green waste compost from EBL underwent an additional phase of refinement, involving a final screening through a drum sieve. In such cases, both the mechanical agitation and the effects of decomposition could potentially lead to the breakdown of larger particles into smaller ones.
- *Pile surface sample GG2.2:* Among the samples analysed, the most outstanding sample was-the surface samples from a STR pile. An interesting observation was the complete absence of particles within 0.5-1 mm range. Consequently, all other fractions exhibited relatively high proportion compared to all other samples. As mentioned above, this could be due to windblown particles. However, further investigation is needed to verify this, and rule out the possibility of analytical errors.

The samples that followed the general trend were partly different. For example, municipal and agricultural composts were distinguished as follows, if the three outstanding samples are excluded:

- *Fraction >5 mm:* municipal composts – 1-3%, agricultural composts – 0-6%
- *Fraction 2-5 mm:* municipal composts – 9-19%, agricultural composts – 7-9%
- *Fraction 1-2 mm:* municipal composts – 29-37%, agricultural composts – 15-35%
- *Fraction 0.5-1 mm:* municipal composts – 41-60%, agricultural composts – 56-78%

Particles exceeding 5 mm are classified as macroplastics. The distribution of macroplastics was notably more uniform within the municipal composts. In case of agricultural compost, this proportion varied depending on the composition of input material. The presence of microplastics in compost can be minimized if effective measures can be taken and properly supervised by the farmer. The larger proportions were reported by the farmer as coming from packaging residues from straw packaging used for cow bedding. If the source is known, it also can be avoided. Another observation relates to the proportions of very small particles within the 0.5-1 mm range. These particles are likely associated with manure, with a difference between horse and cow manure. The higher proportion of these particles could potentially be attributed to the passage of larger plastic fragments through the animals' digestive systems. This tendency might be more pronounced in cows due to their ruminant physiology. It is important to note that this is an initial assumption that requires further detailed investigations for validation.

6 Options to lower microplastic content in composts

Microplastic is typically defined for particles sizes ranging from 1 µm to 1 mm. Particles in the range of 1-5 mm are often categorized as large microplastic. To provide more precise distinctions within the smaller size range further subdivisions are suggested: 1000-500, 500-100, 100-50, 50-10, 10-5, and 5-1 µm (Kehres, 2019). Above 5 mm it is macroplastic. Such were also detected in this study.

Regarding microplastic, this study looked specifically at large microplastic (1-5 mm), as well as at microplastic in the upper range (0.5-1 mm). Smaller particles occurred most likely in the composts as well. The effects of microplastics in soils are currently poorly understood (Bertling et al., 2021). However, there is evidence that soil chemistry, biology and physics are affected. In particular, the very small particles may be of concern, as there is evidence that they can enter the cells of organisms. For example, Horvatis et al. (2022) found microplastic in human liver tissue. As there are still many questions, precautionary protection requires a reduction of microplastics to avoid long-term consequences.

Agricultural composts tended to have lower levels of microplastics, while municipal composts had a wider range, but with some in the range of agricultural composts. The differences were due to different input materials: green waste, biobin waste, cow and horse manure, all with different initial plastic levels. Differences in the composting processes of agricultural and municipal facilities also contributed. Of particular importance following technical steps are seen: manual removal, shredding, screening, wind classifing and turning, all of which have an impact on the size reduction from large to small particles or removal of microplastic particles.

The options for reducing the microplastic contents in municipal and agricultural composts are partly different:

- *Municipal composts:* The most important starting point is to improve the quality of biobin waste. Impurities in biobins are typically between 1 and 3% by mass. A reduction is expected as the new BioAbfVO (2022) now requires a control of the input into a composting plant. Deliveries with more than 1% will have to be rejected. Improved collection systems could help. Research in Lübeck has shown that providing households with specific collection vessels can reduce the impurity in kitchen waste, the major source of impurities, to well below 0.5%. Most households sorted correctly and the impurities came from only a few individual households (Angouria Tsorochidou et al., 2022). There is concern about new sources of microplastic, possibly introduced by biodegradable biowaste collection bags. These bags may not fully degrade during industrial composting and therefore should not be allowed in the municipal biowaste collection system.
- *Agricultural composts:* In agriculture, one way of reducing impurities is to carefully select external input materials and visually inspect deliveries. For example, green waste from

nature reserves or parks may contain less plastics than that from private gardens or roadsides. However, the most important input materials handled are those produced on the own farm. There are some starting points for these as well. Plastic packaging materials for straw or silage bales could be a source of plastic particles, and should be avoided. These could be introduced directly into the composting input or indirectly via the manure. The ubiquitous contamination of feed and grassland with microplastic particles may also be relevant, but can only be partially influenced by the farmer. However, avoiding agricultural films that may degrade over time and release particles could be an option for reduction on the own site.

In summary, there are many ways to lower the microplastic in compost. Contributions should be made in all of the following areas: More clean input materials, improved removal techniques, and also routine quantitative and qualitative analysis of microplastic in composts and other environments, including smaller particles <1 mm.

7 Conclusion

The findings of our study on microplastic in composts revealed multifaceted challenges, issues, and potential solutions. Among the noteworthy observations is the cautious stance of German farmers towards compost utilization due to concerns of plastic pollution, and lack of hands-on experience with both, agricultural and municipal composts. Nevertheless, they emphasize the significance of compost quality, with the BGK certification receiving significant recognition. An encouraging outcome from our study is that the investigated composts consistently fall well below the limits of microplastic related BGK quality parameters. This aspect may enhance farmers' perceptions of compost. Coupled with the numerous advantages linked to compost use, such as nutrient enrichment, enhanced water retention, carbon sequestration, and improved soil vitality, there is clear potential for increased compost use in agriculture.

However, a new challenge has emerged due to a substantial increase in mineral fertilizer prices, driven by geopolitical factors. This situation has triggered a high demand for composts among farmers. Composting facilities prioritize deliveries currently to substrate producers, often leaving little room for new customers. The primary bottleneck for more municipal composts is seen in the limited availability of source-separated biowaste. Nonetheless, a large untapped potential exists, as substantial quantities of biowaste are incorrectly disposed of with the residual waste. This necessitates improved waste segregation practices, closely linked to enhanced quality standards aimed at reducing plastic pollution.

Within the agricultural sector, legislative constraints stand out as a significant hurdle. Agricultural composting operations encounter often approval challenges and navigating costly requirements that don't always align with ecological benefits. Overcoming these obstacles is crucial, requiring a demonstration of the ease and cost-efficiency of agricultural composting methods while also showcasing their positive ecological impacts. While the levels of plastic impurities have been relatively low, there is still room for improvement in this aspect. Attention should be paid regarding the origin of external co-substrates, particularly plastic-based packaging for agricultural products, and the limited use of agricultural films. Additionally, gaining a better understanding of the extent and distribution of plastic within manure is important.

Both, agricultural and municipal composts from the 4 studied facilities have demonstrated a very low level of impurities far below the requirements outlined in the Fertilizer and Biowaste Ordinances (DüMV, 2021, BioAbfVO, 2020). But it's worth noting that numerous opportunities exist to further reduce microplastic content in composts. Such measures support the broader objectives of ecological conservation, sustainable agricultural practices, and the long-term well-being of our soils, the overall environment, and ourselves.

Acknowledgement

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Literature

Angouria Tsorochidou, E., Walk, S., Koerner, I., Thomsen, M. (2022): Bio-waste Source-Separation and Valorization: Upstream Determinants for Environmental and Economic Performance, SSRN Electronic Journal, DOI: 10.2139/ssrn.4058128

Bertling, J., Zimmermann, T., & Rödig, L. (2021). Kunststoffe in der Umwelt: Emissionen in landwirtschaftlich genutzte Böden. Fraunhofer UMSICHT, 220. https://doi.org/10.24406/UMSICHT-N-633611 (letzter Zugriff: 05/2022)

BioAbfVO, 2022: Verordnung über die Verwertung von Bioabfällen auf landwirtschaftlich, forstwirtschaftlich und gärtnerisch genutzten Böden (Bioabfallverordnung in der Fassung der Bekanntmachung vom 4. April 2013 (BGBl. I S. 658), die zuletzt durch Artikel 1 der Verordnung vom 28. April 2022 (BGBl. I S. 700) geändert worden ist, https://www.gesetze-im-internet.de/bioabfv/ (letzter Zugriff: 05/2022)

BioAbfVO, 1998: Verordnung über die Verwertung von Bioabfällen auf landwirtschaftlich, forstwirtschaftlich und gärtnerisch genutzten Böden (Bioabfallverordnung in der Fassung der Bekanntmachung vom 4. April 2013 (BGBl. I S. 658), die zuletzt durch Artikel 1 der Verordnung vom 28. April 2022 (BGBl. I S. 700) geändert worden ist, https://www.gesetze-im-internet.de/bioabfv/ (letzter Zugriff: 05/2022)

Horvatis, T., Tamminga, M., Liu, B., Sebode, M., Caramia, A., Fischer, L., Püschel, K., Huber, S., Fischer, E. (2022): Microplastics detected in cirrhotic liver tissue. eBioMedicine, Vol. 82, 104147, https://doi.org/10.1016/j.ebiom.2022.104147 (letzter Zugriff: 08/2023)

Krishnakumar, B. Suresh, I. Z. A. Ortiz, S. Desai (2021): Microplastic pollution in compost. Exercise in the TUHH-course “Bioresources and Biorefineries”, Internal document

Ortiz Cabrera, R. (2020): Compost quality and impacts of its application - A case study of the German North Sea Region. Master thesis at TUHH, Internal document

DüMV, 2021: Verordnung über die Anwendung von Düngemitteln, Bodenhilfsstoffen, Kultursubstraten und Pflanzenhilfsmitteln. https://www.gesetze-im-internet.de/d_v_2017/D%C3%BCV.pdf

DüMV, 2019: Verordnung über das Inverkehrbringen von Düngemitteln, Bodenhilfsstoffen, Kultursubstraten und Pflanzenhilfsmitteln1, Ausfertigungsdatum: 05.12.2012 - "Düngemittelverordnung vom 5. Dezember 2012 (BGBl. I S. 2482), die zuletzt durch Artikel 1 der Verordnung vom 2. Oktober 2019 (BGBl. I S. 1414) geändert worden ist"

BGK (2023a): Schwellenwerte und Grenzwerte. Dok. 251-006-4 p.2, https://www.kompost.de/guetesicherung/guetesicherung-kompost/download

BGK (2023b): Merkblatt zu Umfang und Häufigkeit von Untersuchungen im Rahmen der RAL-Gütesicherung Kompost (RAL-GZ 251) Dok. 251-008-1 Stand: 01.01.2021 https://www.kompost.de/guetesicherung/guetesicherung-kompost/download

Kehres (2018): Kunststoffe in Kompost und Gärprodukten. Quelle: H&K aktuell Q4 2018, pp. 4-6: Dr. Bertram Kehres (BGK e.V.)

Kehres (2019): Kunststoffe in Kompost und Gärprodukten. Herkunft - Bedeutung – Vermeidung. BGK Informationen.https://www.kompost.de/fileadmin/user_upload/Dateien/Themen_Positionen/5.3.16_Thema_Kunststoffe_in_Kompost_und_Gaerprodukten_final_2018_12_12.pdf

Hasert (2021): Mikroplastik im Kompost - ein Vergleich der Kontamination in städtischen und landwirtschaftlichen Kompostierungsanlagen. Bachelor thesis at TU Freiberg in cooperation with TUHH, internal document

Annexes

Annex 1: Instruction for the determination of microplastic particle numbers in compost

A. Sample preparation

1. Thoroughly mix the compost samples taken from different locations in the windrow.
2. Take a representative sample of 200g (Figure 14).
   - Spread the entire mixed sample evenly and flatten it.
   - Divide the flattened sample into four equal parts, then remove two opposite quarters from the divided sample and put them back for other uses.
   - Mix the remaining two quarters again by spreading them flat and divide the mixed sample with a cross pattern into four equal parts once more.
   - Remove the other two opposite quarters and also place them back for further uses.
   - Continue repeating this procedure until the remaining amount of compost is approximately 200g.
   - This is the sample for plastic screening.
3. Dry the representative sample in at 40°C overnight. In case of a high initial moisture content, extend the drying duration accordingly.
4. Mortar the sample for about 2 minutes to break down large lumps and aggregates.

B. Preparation of sieve fractions

1. Sieve the sample using a sieving machine with sieve of sizes 5, 2, 1 and 0.5 mm along with a catch tray for a total sieving time of 5 minutes
   - Sieve for the first 2 minutes at an amplitude of 2.5 mm (80% intensity)
   - In the 3rd minute, increase the amplitude to 3 mm (100% intensity)
   - Continue sieving in the last minutes at an amplitude of 3 mm (100% intensity)
2. After sieving, store and label the sieve fractions of the sample
   - provide sample name, sieve fraction, date, and analyst name
   - use suitable vessels for storing these fractions (laboratory hard plastic bottles)
   - Do not use foil bags as they may cause electrostatic charging, leading to particles sticking to the bag

C. Separation of plastic

1. Divide the material from a sieve fraction into three parts
   - Place the three sub-samples from each sieve fraction on 3 petri dishes
   - Distribute the entire material, or a defined share, if the portions are to large

- About 2 g of material in a petri dish for smaller sieve fractions, more material for larger sieve fractions (>5mm, 2-5mm)

2. Separate plastic particles found from each petri dish and place them in a separate petri dish
   - using a pair of tweezers and a good lamp
   - slide the sample to one side of the petri dish
   - carefully examine the sample by transferring parts to the other side using a tweezer
   - separate the plastic particles found
3. Count the plastic particles and store them in well-labelled Eppendorf tubes
4. Repeat the same process with the material from all sieve fractions