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Using Differentiated Waste Fees to Encourage the Sustainable Recycling of Organic Waste

Henning Friege [1,2,*] and Maike Hentschel [2]

[1] N[3] Thinking Ahead Dr. Friege & Partners, D-46562 Voerde, Germany
[2] School of Sustainability, Leuphana University, D-21335 Lüneburg, Germany; maike.hentschel@stud.leuphana.de
* Correspondence: friege@n-hoch-drei.de; Tel.: +49-2855-3037311

Abstract

The valorisation of household and commercial bio-waste into soil improvers helps to reduce disposable waste, mitigate climate change, and improve soil resilience. While the separate collection of bio-waste is mandatory in the European Union, this remains a challenging task, particularly for large cities, due to quality problems in densely populated areas. In addition to various informational and motivational tools for households, financial incentives are becoming increasingly important. However, there is a lack of robust evidence regarding the optimal use of these incentives and their impact on the quantity and quality of collected bio-waste. We investigated the impact of different charging systems on the quantity and quality of bio-waste, basing our research on the experiences of more than twenty European cities and using a detailed questionnaire completed by the relevant administrators. The results confirm that cities, which provide financial incentives for waste sorting, yield a higher quantity of separated bio-waste. As introducing tiered fees can lead to quality issues, monitoring bio-waste and taking action against polluters seems to be unavoidable. Since the identification of polluters is very difficult in the case of multi-family homes, the results are discussed with a special focus on densely populated cities. Pilot projects for alternative options for the valorisation of organic waste, particularly in districts with high-rise buildings, should be evaluated.

Keywords: bio-waste; compost; charging system; waste collection; green waste; food waste; Polluter-Pays Principle

Academic Editors: Andrzej Biessikirski and Łukasz Kuterasiński

Received: 30 October 2025
Revised: 9 December 2025
Accepted: 16 December 2025
Published: 19 December 2025

1. Introduction

Bio-waste from households and restaurants, as well as other commercial sources, and green waste (e.g., organic material from gardens and public parks) can be processed aerobically to produce compost. Anaerobic treatment focuses on producing methane, resulting in two residues: a liquid fraction high in nutrients and a solid fraction that is further processed to yield compost. Due to its high organic carbon content, especially humus substances, compost serves as a soil improver or as a basic material for many related products like potting soil (e.g., refs. [1,2]). An increasing number of cities, e.g., Hamburg (Germany) [3], Shanghai (China) [4], Milano (Italy) [5], San Diego (CA, USA) [6], around the world are separating organic waste at source. There are many more reasons for the separate collection of organic waste, besides the production of soil improvers:

- The absence of biodegradable material drastically reduces methane emissions from landfills.

- The use of compost in soils leads to sequestration of CO_2.
- The reduction in organic waste in residual waste enhances its heating value for more efficient incineration with energy recovery.

The EU is focusing on all of these targets. According to the Waste Landfill Directive (WLD) [7], the amount of municipal waste going to landfill should be minimised to 10% by 2035. The Waste Framework Directive (WFD) [8] requires organic waste to be collected separately. Since 2024, Member States are expected to introduce suitable collection systems. The European Circular Economy (CE) strategy includes the (intermediate) target of recycling 55% of municipal waste by 2025 and finally 65% by 2035. As organic waste makes up 34% of the total household waste [9], the recycling target can only be achieved if a significant proportion of organic waste is recycled. Since 46% of European land is classified as "marginal" [10], soil improvers from bio-waste can address the lack of carbon in soils and the growing issue of soil degradation through the provision of essential nutrients and improved water, nutrient, and carbon retention, thereby improving soil's fertility and health while reducing environmental impact by replacing mineral fertilisers. Moreover, methane produced from anaerobic digestion is classified as a "RED III product" according to the amended Renewable Energy Directive [11], meaning it meets all the criteria for climate protection.

However, despite ambitious recycling targets, 18 Member States are not on track to meet their municipal waste recycling goals, while only nine are performing relatively well [12]. This disparity is partly due to the small proportion of organic waste that is collected separately. Therefore, it is necessary to increase the collection and processing of bio-waste.

1.1. Quality of Separately Collected Bio-Waste and Impacts on Compost

Once a system for collecting bio-waste has been introduced, citizens must be encouraged to separate organic waste from other materials in their homes. Food packaging materials and plastic bags used for transporting kitchen waste to the bin, as well as small plastic items from residual waste, are commonly found in separately collected bio-waste (see ref. [13] and literature cited therein), leading to far higher costs for the production of compost [14]. Impurities in bio-waste bins are considerably higher in densely populated areas compared to suburbs with detached houses [15]. Contaminants such as glass, dust, diapers, and plastic materials remain unchanged by the anaerobic or aerobic process. Plastic materials in compost are a subject of growing concern [16–18]. While large items can be removed by hand sorting or special sieving systems, milling and grinding the input material increases the number of smaller plastic pieces and cullets. Despite advanced and costly pre- and post-sorting processes, this problem remains partially unsolved. Since soil contamination by plastics should be minimised, compost must not act as a transfer medium. According to EU regulation [19] (valid from 16 July 2026), the amount of plastic particles (>2 mm) in compost is limited to 2.5 g/kg (% dry matter). Therefore, citizens must ensure that organic waste is carefully separated from other materials, particularly plastics, glass, and residual waste. Quality assurance and control during collection and processing are essential for marketing compost derived from bio-waste. Recently, Germany introduced a contamination limit of 3% for bio-waste (see a press release by the City of Jena [20]), which must be met in the organic waste before entering the biological process.

The motivation of citizens to separate waste fractions efficiently can be enhanced by providing suitable information, implementing convenient collection systems, educating special groups such as schoolchildren, and offering financial incentives [21–23]; mostly, several instruments are combined [24–26]. There is a substantial body of scientific lit-

erature that provides evidence for the multifactorial behaviour of waste producers (see refs. [27–31]). The relationship between the different factors and the instruments that lead to the desired behaviour is difficult to assess. Moreover, waste separation behaviour is influenced by local conditions such as dwelling forms, cultural attitudes towards waste, the social composition of housing areas, and other factors. In particular, the relationship between waste charges and the quantity and, especially, the quality of separately collected bio-waste is only partially understood because of the following:

- The influence of other factors on quantity and quality is difficult to distinguish from the impact of the fees to be paid,
- Municipalities rarely analyse the quality of waste,
- Anaerobic and aerobic treatment facilities reject highly contaminated waste, but do not disseminate these findings to the public,
- Scientific publications are dealing with a quality focus on compost rather than the input material.

1.2. Economic Incentives for Pre-Sorting of Waste

Economic tools like pay-as-you-throw (PAYT) tariffs and more differentiated waste charges are becoming more and more used [32] as it is generally assumed that financial incentives will lead to the desired behaviour of companies or individuals, i.e., choosing the environmentally friendly option [33]. Financial incentives aim to reduce waste and environmental damage [32,34]. Such incentives come in different forms, negative incentives such as penalties, and positive incentives such as refunds or discounts. Incentives can also be used to address social issues [35].

Waste separation at source can be incentivised by higher prices for residual waste compared to recyclable fractions. In line with the Polluter-Pays Principle (PPP), fees based on the mass or volume of waste encourage citizens to reduce the amount of waste. According to a review by Alzamora and Barros [36], PAYT charging systems are widely used in industrialised countries, whereas developing countries often rely on flat rates for waste management or finance this service from general revenues. PAYT incentive schemes [37,38] increase the amount of pre-sorted waste, reflecting a change in the behaviour of households [39,40], leading to lower overall costs for waste management [41,42]. Comparisons between municipalities that introduced PAYT systems and those with traditional systems show an increase in the rate of separately collected recyclables [43]; this also applies to bio-waste [44,45]. Other studies observed that the specific amount of mixed waste and organic waste, or only organic waste per household, decreased thanks to PAYT systems [46]. An explanation for this effect could be that "the tariff may lead households to plan their food consumption better, resulting in less food being discarded." [46]. Deviating from the majority of publications, a comparative study of Swedish municipalities revealed a decline in residual waste, but no substantial rise in recyclables [47]. Gautier and Salem [48] focused on the price elasticity for residual and organic waste by evaluating statistical data from all Wallonian municipalities (Belgium) between 2009 and 2018. They found significant own-price elasticity and a cross-price elasticity for residual waste, but a limited own-price elasticity for organic waste.

As outlined above, there is a bundle of different influences that lead to the multiple and combined approaches mentioned above. Besides the importance of intrinsic motivation [49], convenience issues [50] must be taken into account in the case of the introduction of new waste collection schemes. Citizens not only recognise cost savings with respect to waste charges, but also the additional time and inconvenience involved in sorting. Financial incentives can also have negative effects. For example, free-of-charge bins intended for packaging waste are widely misused, i.e., filled with residual waste [51]. Illegal dumping

could be another unintended consequence, as it helps to minimise tax burdens [30,52]. Van Beukering et al. [24] concluded that differential and variable rates are a cost-effective instrument for reducing waste and increasing recycling. However, they also advocated conducting pilot experiments in highly urbanised areas to assess behavioural responses.

Though the quality of separated material is key for a good compost, reasons for contamination of bio-waste are rarely in the focus of researchers. According to Alvarez et al. [15], separately collected bio-waste in about 200 Spanish municipalities contained between 10% and 20% of "undesirable material" in the mean, with maximum levels up to 40%. The amount of undesirable waste in the bio-waste fraction increased linearly in relation to the population density. Moreover, correlations of contamination with gross disposable household income (negative), unemployment, and illiteracy (positive) were found. Kranert et al. [53] reported a range from 0.9% to 12% misplaced materials in bio-waste from numerous German cities, partially depending on the population density. Only in very few publications is the quality of the collected organic waste in relation to waste charges mentioned. Hadzi-Nikolowa et al. [54] reported on a pilot project in the Republic of North Macedonia, yielding high-quality compost from two decentralised composting units located in the urban area. In this case, a PAYT system was introduced whereby the disposal of waste could be assigned to the respective users. An evaluation of numerous Italian cities with and without PAYT systems showed a reduction in residual waste of 10% or more, as well as an increase in separately collected paper, cardboard, and organic waste. The authors of this study found an indication for better quality of recyclable fractions but did not find data for the quality of organic waste [55]. Interviews with experts from municipalities with very low contaminated bio-waste (0.5–3.7%) revealed "Too high differences in the fees between organic and residual waste" as a reason among other factors, which lead to incorrect sorting [13].

1.3. Scope of This Study

These partially contradictory research findings and the scarcity of studies to date on the effect of financial instruments on the quantity and, above all, the quality of bio-waste, are the motivation for this paper. With this paper, we aim to answer the following questions:

1. What is the current status of organic waste collection in European cities?
2. How does the charging system affect the amount of organic waste collected?
3. What impact does the charging system have on the quality of the collected material?

Clearly, an experimental approach in pilot areas would encounter political concerns, a lack of standardised waste producers, and the need for follow-up over a period of one year or more. Therefore, we have evaluated the experiences of a number of cities with different charging systems for collecting bio-waste separately in order to learn more about the relationship between financial incentives and organic waste delivered to processing facilities in terms of quantity and quality. We took the following steps:

- Presented a questionnaire for cities,
- Explained the methodology for the evaluation,
- Presented and discussed the results with respect to local conditions (e.g., population density, waste fee system, quality monitoring, regulatory framework), and drew conclusions for the European framework, the introduction of differentiated waste charges, and the need for further research in this field.

2. Methods

2.1. Data Sources

The approach of data collection involved a structured questionnaire (see Table S1), which served as the primary data source, asking cities for a detailed description of their

bio-waste collection system, including figures on quantities collected and quality indicators, the financing and fee structure of their system, and an outline of their legal frameworks and responsibilities for waste administration, collection and treatment. In the case of implausible or missing data, details were clarified by a review of publicly available documents, such as financial reports or official websites from the waste management authority, or by consulting the respondents who submitted the questionnaires.

2.2. Participant Selection

In terms of participants, an even distribution across Europe was aimed for, focusing mostly on European capitals or larger urban areas, as these were more likely to pose greater operational challenges arising from waste charging systems due to higher population density. The research was conducted in collaboration with the EU-funded Bin2Bean project [56], whose network of European cities supported outreach. Active project partners and members from the stakeholder forum participated in the study. In total, 76 cities were contacted, resulting in 27 responses with a response rate of 35.5 percent. While an even geographical distribution was sought, responses from Northern and Middle Europe were comparatively higher than those from Eastern and Southern Europe. The non-randomised, network-based sampling approach was considered appropriate, as it led to the representation of a variety of waste charging systems and population densities. Regions were included in case of a supervising authority, which provides complete data for all cities. To simplify further descriptions, all entities are referred to as "cities" and only in applicable cases as the more fitting description of municipality, county, or state.

Data collection was conducted from June to September 2025. Requests were sent to either waste departments or waste management companies, and questionnaires were provided in English, German, and French to maximise participation. Most respondents represented municipal waste management authorities; however, their specific position could not be recorded for data protection reasons. Data for Amsterdam, Hamburg, and Egaleo were provided by representatives of the three Bin2Bean project partners. For data evaluation, three cities that responded to our request were excluded from further analysis since no separate bio-waste collection system was implemented. One city wished to be excluded from publication, since it originally participated in preceding non-published research. This resulted in 23 cities being considered in the analysis, from which two participants requested that their names be anonymised. The location of the participating cities is shown on a map, with the exception of the two districts in Germany that remain anonymous (see Figure 1, created with https://umap.openstreetmap.fr, accessed on 17 November 2025).

2.3. Data Evaluation

The resulting dataset combined both quantitative and qualitative elements. Data analysis was performed combining inductive and deductive category development with descriptive quantitative analysis. All results were compiled into a matrix, creating a clear overview of how each case was classified across topics such as collection systems, fee models, and reported impacts (e.g., kilograms of bio-waste collected per capita). This structure enabled descriptive comparison, combining qualitative assessments alongside quantitative indicators, and resulted in the identification of common patterns.

Given the small number of cases and the limited availability of comparable quantitative indicators, the statistical analysis was carried out in an exploratory manner. Two preliminary analyses, based on Pearson's correlation coefficient, were conducted to check whether basic relationships existed between population characteristics (total number of inhabitants and population density) and waste generation (total bio-waste collected and

bio-waste collected per capita). Such analysis provides an appropriate and robust exploratory measure for detecting linear associations between two continuous variables in small, heterogeneous samples.

Figure 1. Municipalities included in the survey (names given in the respective national language).

To assess whether different charging systems are associated with different amounts of collected bio-waste and residual waste, additional comparative analyses (Kruskal–Wallis test with post hoc comparisons) were conducted. Because the distributions of waste quantities varied considerably between cities, methods appropriate for small and unevenly structured datasets were used. These analyses compared the four charging-system groups (see below) and, where meaningful differences appeared, follow-up checks were carried out to identify which systems differed most clearly from one another. All technical details and full statistical output are provided in Tables S2–S5.

The indicators above were selected because they were the most comparably reported across cities and allowed for the construction of a consistent numerical dataset. Information on quality was provided by 12 cities, allowing only an indicative evaluation.

2.4. Classification of Waste Charging Systems

The classification of the numerous systems for financing waste management, which vary from city to city, followed a system published by Lüssenhoop et al. [57], which distinguishes between four categories:

"Flat": A flat fee is based on the characteristics of a dwelling (e.g., per household, according to the number of residents, the property's size, or its value). All citizens pay the same relative amount of fees or taxes, regardless of the actual amount of waste generated.

"Flexible" (in the following "Flex"): Users have one choice regarding the waste charge they pay, usually by selecting a container size, which is charged at a different rate (larger containers cost more than smaller ones). A minimum container size relative to household size may be stipulated.

"Flexible+" (in the following "Flex+"): Users have more than one option for paying the waste charge, usually by selecting a container size and collection frequency. A minimum container size or collection frequency relative to household size may be stipulated.

"PAYT": Users are charged for each kilogram of waste collected, or for each waste bin collection. Collections are counted via sensors in the bins, or via stickers or bags, which households must purchase in advance. A minimum number of collections may be stipulated.

3. Results

Twenty-six out of the seventy-six selected regions, cities, and counties completed the survey fully or partially. Six cities and counties are situated in Germany. Two cities can be found in each of the following countries: The Netherlands, Italy, France, Switzerland, and the UK. One city or region is located in each of the following countries: Austria, Finland, Spain, Latvia, Croatia, Denmark, Portugal, Belgium, Estonia, Greece, and the Czech Republic. Key information, such as the number of inhabitants, population density, and the amount of waste and bio-waste collected, is summarised in Table 1 in descending order with regard to the number of inhabitants. Data on inhabitant numbers and population density were taken from official statistics on the internet. About 17 million inhabitants were involved in this survey, i.e., about 3.5% of the population in the EU, UK, and Switzerland.

Table 1. Amount of residual waste, organic waste, and green waste (mostly included in the sixth column) collected.

Name	No.	Inhabitants	Population Density [inh km^{-2}]	Residual Waste [Mg]	Separately Collected Organic Waste [Mg]	Separately Collected Green Waste [Mg]	Type of Financing
Berlin, Germany	1	3,685,000	4136	939,793	120,000	included	Flex+
Vienna, Austria	2	2,006,000	4835	526,000	120,000	included	Flex+
Hamburg *, Germany	3	1,863,000	2466	414,757	77,273	20,000	Flex+
Helsinki cap. area, Finland	4	1,582,000	2213	150,500	50,769	18,793	Flex+
Amsterdam *, The Netherlands	5	932,000	4953	230,000	800	included	Flat
Zagreb, Croatia	6	771,000	1196	140,000	32,000	included	PAYT
Copenhagen, Denmark	7	659,000	7254	93,943	18,127	11,039	Flat
Riga, Latvia	8	599,000	1969	173,840	13,977	Included	Flex
Lisbon, Portugal	9	576,000	6781	232,472	24,111	included	Flat
Arrondissement County Turnhout	10	548,000	370	40,481	50,969	18,793	PAYT
Lyon, France	11	522,000	10,909	300,000	10,000	included	Flat
Tallinn, Estonia	12	458,000	2874	80,761	17,245	included	Flex+
Zürich, Switzerland	13	450,000	5000	66,000	19,000	included	PAYT
Brno, Czech Republic	14	401,000	1741	67,113	6245	included	Flat
Utrecht, The Netherlands	15	377,000	4020	101,000	11,700	included	Flat
Wandsworth, London, UK	16	334,000	9752	62,120	0	200	
Anonymous 1, Germany	17	276,000	1625	48,580	26,955	included	Flex+
Anonymous 2, Germany	18	259,000	402	22,000	13,000	included	PAYT
Krefeld, Germany	19	237,000	1720	53,848	13,918	10,324	Flex+
Parma, Italy	20	198,000	760	21,381	20,409	15,161	PAYT
Richmond, London, UK	21	198,000	3444	43,000	0	10,385	
County Höxter, Germany	22	144,000	116	13,700	21,500	included	Flex
Egaleo, Greece	23	65,000	10,000	27,000	<100		Flat
Liechtenstein	24	40,000	249	8000	8000	included	PAYT
Albano Laziale, Italy	25	40,000	1670	3574	6000	included	PAYT
Argentona, Spain	26	13,000	509	709	1796	included	PAYT

* Three of the cities mentioned are partners of the Bin2Bean project: Hamburg (No 3), Amsterdam (No 5), and Egaleo (No 23).

Three municipalities were excluded from the further presentation of results: Wandsworth (No. 16) and Richmond (No. 21) because both cities collect mostly green waste and do not

have their own charging systems, and Egaleo (No. 23) was excluded because the collection of organic waste started at the end of 2024 as a pilot project.

Cities cannot control whether green waste is mixed with kitchen waste. Therefore, even if they offer additional drop-off points for garden waste, most cities collect green waste together with kitchen waste. Ultimately, depending on the ratio of kitchen and garden waste, all this material can be composted or fermented. In what follows, the terms 'green waste' and 'garden waste' are used interchangeably, whereas 'bio-waste' or 'organic waste' includes green waste.

3.1. Collection Systems

In a first attempt to understand how the cities organise their waste management infrastructure, a simplified overview of the responsible institutions for each stage of waste management (waste administration, (bio-)waste collection, and bio-waste treatment) is set up. Since some cities indicated multiple institutions for each stage, the number of times a certain institution is mentioned was considered. In terms of waste administration, most cities are directly responsible for administrative tasks, such as planning and organisation, data management, or budgeting. Usually, waste administration is a task performed by a department of the city, i.e., the waste department. In larger cities, such as Amsterdam, each city district sometimes has its own waste department. In the case of Helsinki and Lyon, a metropolitan authority is responsible for all administrative tasks. It is less common for the administration part to be executed by municipally owned or private enterprises. The responsibility starts to shift when it comes to waste collection tasks. More local governments are dealing with waste collection, but are shifting this responsibility towards municipal and sometimes private enterprises. An even greater shift then sets in for bio-waste treatment responsibility where a wider variety of institutions is visible. Mostly companies, municipally or privately owned, will deal with bio-waste treatment and processing.

Table 2 provides an overview of the collection systems in the cities under evaluation. 18 cities mainly provide a door-to-door collection Via bio-waste bins to households, collecting mostly food waste and fine garden waste. An exception is the City of Copenhagen, which explicitly collects food waste and garden waste separately. One of the anonymous municipalities in Germany offers door-to-door collection not for bins but for special bio-waste bags. A voucher for 60 15 L waste bags is offered to each household, which is considered to cover annual bio-waste generation. Additional bio-waste bags must be bought and paid for by citizens. Utrecht and Amsterdam offer door-to-door collection Via bio-waste bins only in some districts, while other districts, such as the historic city centres or large apartment buildings, have no option for bio-waste disposal. In Utrecht, plans are developed to introduce centralised collection systems Via above-ground containers for areas with large apartment buildings. In Amsterdam, some large apartment buildings have small enclosures 'cocons', which store common household-sized bins and can only be accessed Via an access card.

Table 2. Collection systems in the cities (sorted according to the type of collection scheme).

Name	No.	Household Bio-Waste (Food and Garden Waste)	Green Waste	Commercial Waste
Anonymous 2	18	DtD Via bag	Recycling centres	/
Turnhout	10	DtD Via bin	Recycling centres	/
Liechtenstein	24	DtD Via bin	Drop-off points, Composting facilities	/

Table 2. *Cont.*

Name	No.	Household Bio-Waste (Food and Garden Waste)	Green Waste	Commercial Waste
Albano Laziale	25	DtD Via bin		DtD
Parma	20	DtD Via bin	Street containers, recycling centres	DtD Via bin
Anonymous 1	17	DtD Via bin	Recycling centre	DtD Via bin
Berlin	1	DtD Via bin	Recycling centres, an optional seasonal bin for garden waste	No commercial waste collection
Helsinki	4	DtD Via bin	Recycling centres	No commercial waste collection, except for municipalities' administrative and service functions
Tallinn	12	DtD Via bin	Drop-off points	DtD
Vienna	2	DtD Via bin	Street containers, Recycling centres	DtD Via bin for SMEs
Krefeld	19	DtD Via bin	Recycling yards, Mobile drop-off points twice per year	/
County Höxter	22	DtD Via bin	DtD on request. Drop-off points	/
Riga	8	DtD Via bin	DtD	DtD
Argentona	26	DtD Via bin	Recycling hub	DtD
Zürich	13	DtD Via bin	Recycling centre	No commercial waste collection
Amsterdam	5	DtD Via bin (in a few districts), underground containers	Recycling centres, DtD on request	No commercial waste collection, smaller companies' waste is all mixed waste
Utrecht	15	DtD Via bin (not all districts), above-ground container (being developed)	Recycling hubs	DtD Via bin (only if contracted)
Copenhagen	7	DtD Via bin (only food waste)	DtD fixed for single-family households, DtD on request for multi-family houses, Recycling station	
Zagreb	6	DtD Via bin, drop-off collection from underground containers; recycling yards	DtD, recycling yards	DtD
Lisbon	9	DtD Via bin, street containers, drop-off points	DtD (by request), street containers, drop-off points	DtD, Street containers, Drop-off points
Hamburg	3	DtD Via bin, underground containers	Recycling centres	No commercial waste collection
Lyon	11	Drop-off points (kitchen waste)	/	/

Table 2. *Cont.*

Name	No.	Household Bio-Waste (Food and Garden Waste)	Green Waste	Commercial Waste
Brno	14	Drop-off points, DtD (one district)	Recycling centres, mobile containers	/

DtD = door-to-door collection.

Zagreb and Lisbon provide additional possibilities for door-to-door collection, which do not cover all households, such as recycling centres or some drop-off points, either underground or above-ground containers, distributed throughout the city. In the case of Hamburg, underground containers are only available to residents from high-rise buildings who have no option for small bio-waste bins for each household.

The City of Vienna offers a similar type of door-to-door collection, which involves a full-service backyard collection, meaning that households do not need to bring their bins to the curb. Since most of Vienna's housing structures are larger apartment buildings, these bins are often shared collectively. There is also a small number of openly accessible containers to which residents may bring their organic waste, which is less frequent and mainly used for garden waste.

Only two cities do not offer door-to-door collection as their main collection method. In Lyon, households can take their bio-waste to one of 2700 collection points located throughout the city. Meanwhile, in Brno, public street containers and bins are used for collection, with the exception of one district with door-to-door collection.

In terms of green waste, different approaches are also used. Specifically, Zagreb and Riga collect green waste from households and other locations Via door-to-door collection. Lisbon and Copenhagen also offer recycling centres as drop-off points for households, in addition to door-to-door collection. Ten cities have drop-off points for green waste distributed throughout the city, which are also partially used for other waste fractions (recycling yards). There are also other options available to citizens, for example, additional mobile containers or optional green waste collection bags, depending on the season. Ten cities did not provide any information regarding separate green waste collection.

3.2. Regulatory Frame

Almost three-quarters (74%) of the cities indicated that they have mandatory bio-waste collection in place. However, exceptions are often made for specific cases. For example, in Riga, separate bio-waste collection is mandatory for apartment buildings with more than ten apartments, whereas in Vienna, it is only mandatory if an apartment complex has a garden. Otherwise, the use of a bio-waste bin is optional. In Helsinki, separate bio-waste collection is mandatory if more than 10 kg is produced per week. Höxter, Zürich, Helsinki, and Hamburg have explicitly stated that exceptions are made if households can verify that they are performing home composting. Exceptions are also made if properties evidently have insufficient space for a bio-waste bin, as explicitly mentioned in the Dutch waste management law: "when separate collection is technically not possible or excessively expensive" (LAP3, B.3.3.2.1 in ref. [58]).

Bio-waste collection is voluntary in only six other cities. Due to many exceptions to compulsory participation in collection, the distinction between mandatory and voluntary is fluid.

The collection system for organic waste from commercial sources (e.g., hotels and restaurants) and the food industry depends on national or local regulations. Five cities claimed that they are not responsible for collecting commercial bio-waste. In these cases, it is the responsibility of the companies to find contractors to recycle their waste. The majority

(11 cities) did not provide any information on commercial waste collection. Conversely, six cities stated that they offer businesses a door-to-door collection service. In a few cases, commercial waste producers can choose between a contract with the city or with private waste companies.

3.3. Amount of Separately Collected Bio-Waste

The amount of separately collected organic waste (i.e., bio-waste, including green waste and, in some cases, green waste besides bio-waste) can be found in Table 1. For the following evaluations, the two figures were added together. This is meaningful because cities cannot exclude green waste mixed with kitchen waste, except for very small bags or bins.

In only a few cases does the amount of separately collected organic waste approach the average amount of organic waste contained in household waste (i.e., ~34% [9]). This is particularly evident in the Belgian arrondissement of Turnhout, the German county of Höxter, Argentona in Spain, and two Italian cities: Parma with a rate of over 35%, and Albano Laziale with around 50%. All of these municipalities have a low population density and are characterised by large estates with gardens.

However, due to the fact that many cities only collect bio-waste in certain districts or grant many exemptions from the obligation to collect bio-waste separately (see Section 3.2), there is no linear correlation between the amount of bio-waste and the total number of inhabitants. This is depicted in Figure 2. In the first quadrant are small and medium-sized cities from Germany and Italy, both of which have been active in bio-waste valorisation for many years. The second quadrant contains two municipalities from Spain and Belgium with far higher specific collection rates than their respective country averages. The third and fourth quadrants contain cities with more than 300,000 inhabitants, where the rate of separately collected organic waste is mostly below the national average.

Even though a linear correlation does not exist, it has to be noted that there is a strong positive correlation between the total number of inhabitants and the total amount of bio-waste collected ($r = 0.859$, $p < 0.001$), indicating that larger populations are associated with greater overall bio-waste collection.

An analysis of the relationship of the specific amount of separately collected organic waste with population density is provided in Figure 3. A significant negative correlation was found ($r = -0.579$, $p = 0.004$), indicating that municipalities with higher population density tended to collect less bio-waste per person. All municipalities with an exceptionally high bio-waste sorting rate (Albano Laziale, Argentona, Höxter, Parma, Liechtenstein, and Turnhout) are located in rural areas with comparatively low population density. It can be assumed that there is a high proportion of green waste in the bio bin. Furthermore, Parma and the arrondissement of Turnhout reported a considerable amount of green waste (see Table 1), whereas the others did not report the amount of green waste separately.

Home composting plays a role in many cities and is also supported by financial incentives in some cases (see below). However, because the quantities of at-home generated composting are very small in relation to the total amount of municipal bio-waste, these activities do not materially affect the comparative results and are therefore not analysed further.

3.4. Taxes, Fees, and Charges

The basic structure of the waste management financing system is included in Table 1 (last column). PAYT systems dominate in smaller municipalities with low population density. Apart from this observation, there are no obvious correlations between the size of the cities and their respective fee systems. In case of municipalities with a PAYT, Flex+, or

Flex system, the collection of bio-waste is either cheaper compared to residual waste (e.g., in case of Hamburg: 1/5, in Berlin 1/3 of the charge for residual waste) or even free of charge (Albano Laziale, Parma, Vienna, Krefeld and city No. 17) to incentivise waste sorting at source. Possibilities for steering sorting behaviour also depend on the allocation of fees to be paid, usually either to the property owner or directly to individual households. This usually depends on the historical development of property taxes and municipal service fees in the Member States.

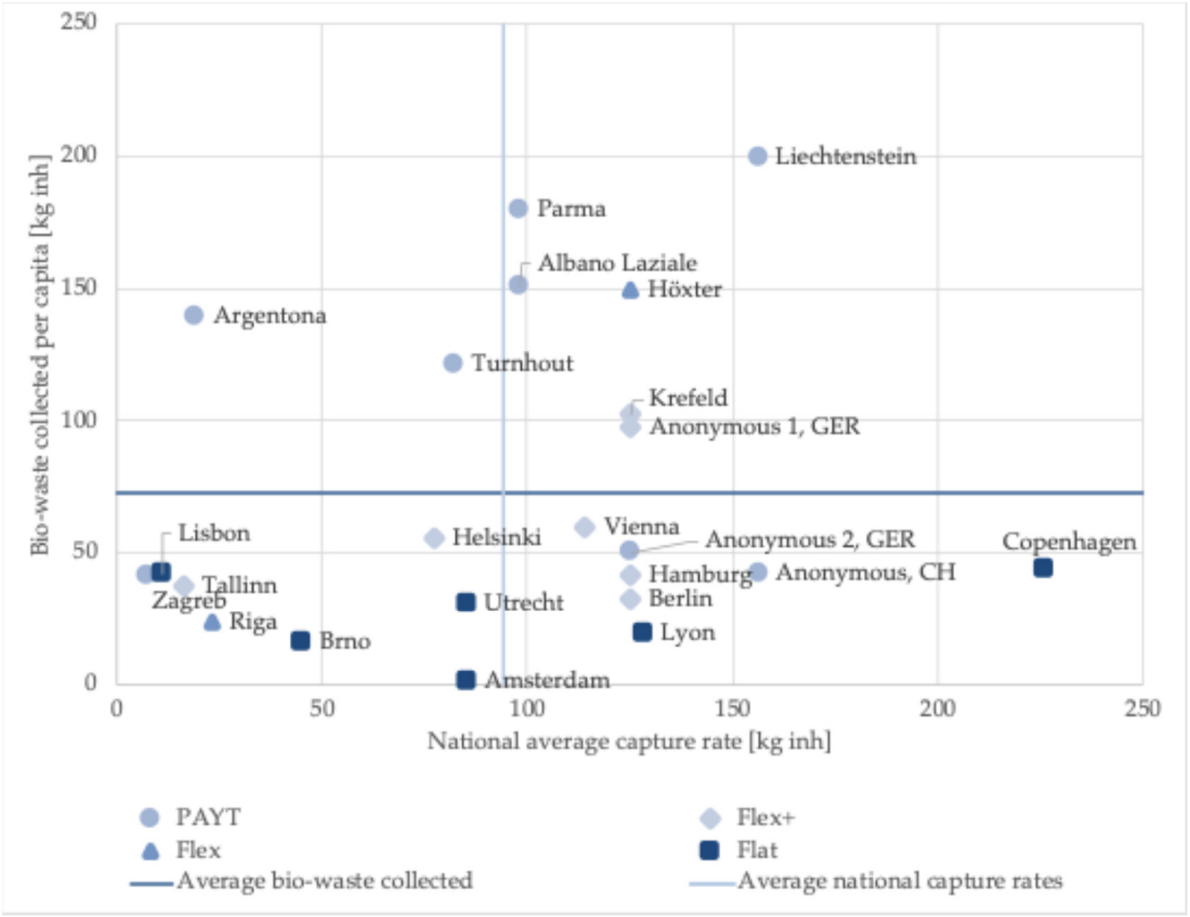

Figure 2. Relationship between the specific amount of separately collected organic waste and the national average.

Some municipalities support home composting with different measures to allow citizens to save money:

- Free construction kits for composters.
- Waiving the obligatory bio-waste bin and therefore also the fee for this bin.
- Reduction in the collection frequency or the obligatory volume for residual waste.

A total of nine cities declared that there are no financial incentives for home composting. As on-site inspections (in County Höxter and the City of Hamburg) have shown, most households dispose of their kitchen waste in residual waste bins rather than in compost bins due to the fear of vermin. Therefore, there is a tendency either to reduce financial incentives or to install obligatory bio bins, provided that residents use the composters exclusively for garden waste.

As fee systems influence the amount of both bio-waste and residual waste collected, the difference between the two waste fractions should relate to the charging system in place. The outcome of this comparison can be seen in Figure 4. Clearly, cities that use a

PAYT system to provide financial incentives collect more organic waste and less residual waste than those that use taxes or flat fees. The differences between simple Flex and Flex+ systems are less obvious because there are only two examples of the Flex case. As shown in Figure 4, these effects tend to be more pronounced in smaller rural cities than in densely populated urban areas. This will be discussed in more detail in the next section.

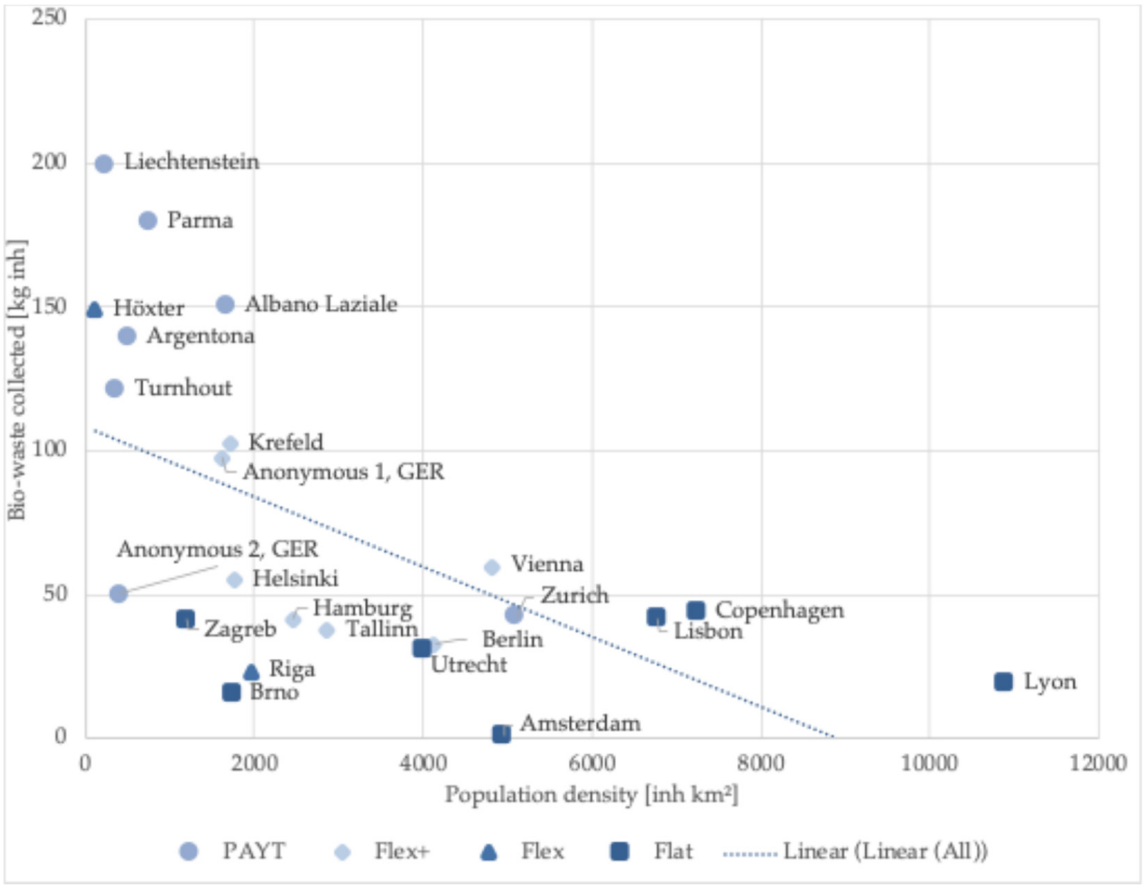

Figure 3. The relation between the specific amount of separated organic waste and the population density.

The pattern described above is also supported by statistical analysis (Kruskal–Wallis tests with post hoc comparisons), which showed that PAYT systems collect significantly more bio-waste than flat fee systems and exhibit a similar, though non-significant, tendency toward lower residual waste; full test results are provided in Tables S2–S5. The primary limitation of the analysis is the small sample size (N = 23), combined with unequal group sizes and substantial variance, which considerably reduces statistical power.

3.5. Monitoring the Quality of Organic Waste

Monitoring the entire process is necessary to ensure the final product is of high quality and meets legal requirements. Moreover, in a value chain, the requirements of the consumer (in this case, farmers or industry) are the most important factor in successfully marketing the product, i.e., soil improvers or fertilisers made from municipal organic waste.

Most of the bio-waste collected separately is processed into compost (21 cities) and biogas (17 cities). The type of treatment facilities varies. There are six cities that combine anaerobic and aerobic treatment on the same site, with three of these plants also producing fertiliser as a side product or CO_2 (for industrial use or greenhouses) in one case. In another eight cities, it is more common to send bio-waste to compost and biogas plants separately.

In three cases, bio-waste is sent exclusively to biogas plants, and in six cases, bio-waste is sent exclusively to composting plants.

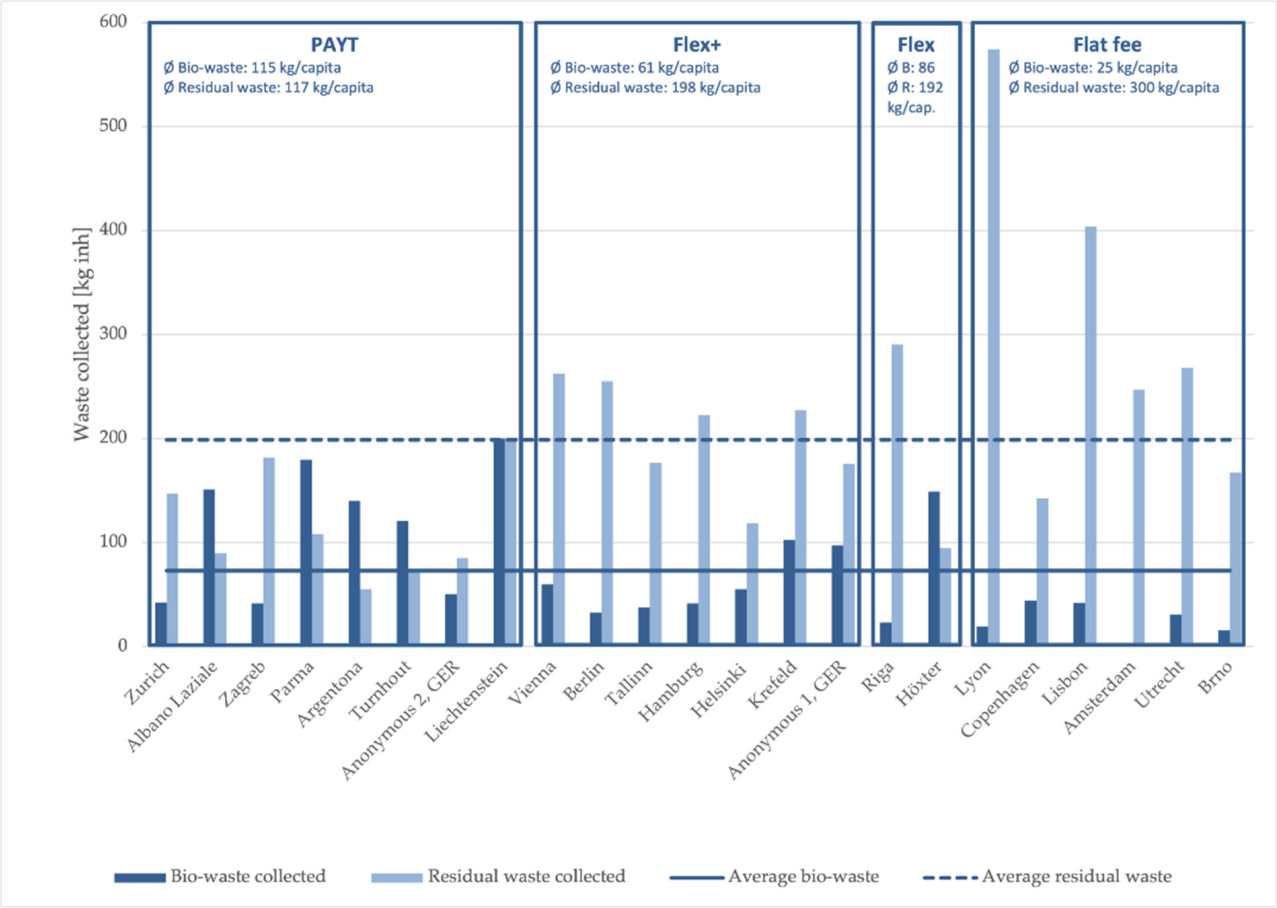

Figure 4. A specific amount of organic waste and residual waste is allocated to different waste fee systems.

Table 3 summarises the practices for measuring the quality (measured as percentage of impurities by weight or volume) of bio-waste collection in cities. A total of 18 out of 26 cities responded to this question, while only 12 were able to state numbers regarding impurities measured. Typically, quality control of organic waste is carried out at the first intervention point, i.e., before or during collection, when there are quality issues. This helps to identify the most critical areas or sources of pollution. A second intervention point is needed to prevent contaminated material from entering the process (indicated as "re-sorting upon arrival" in Table 3), as this may lead to unmarketable compost. The final intervention point serves as a quality assurance measure for the finished product. It is also noted whether cities penalise contamination of bio bins to encourage compliance. Several cities mentioned that they also remove bio bins in cases of continuous contamination. This mostly results in higher fees for the respective residents due to the installation of a larger residual waste container and the price difference between residual and organic waste. In large housing complexes, this measure may not be as effective as in areas with small houses because it is difficult to identify the person who committed the offence, as was emphasised by Vienna.

Amsterdam was excluded from the further evaluation of quality issues because the strategy for the separate collection of organic waste is still under discussion, so monitoring refers to pilot areas.

Table 3. Monitoring of the quality along the value chain and quality assessments.

Name	No	Monitoring	Quality/Rate of Contamination	Penalties in Case of Severe Impurities
Berlin	1	Visual inspection of bins	<3% by mass of foreign matter	Yes
Vienna	2	Re-sorting upon arrival, analysis of input material for composting	<2% of contaminants in the input of the plant	Yes
Hamburg	3	Re-sorting upon arrival, visual inspection of bins	Overall, very good in accordance with German regulation (i.e., <3% impurities)	Yes
Helsinki capital area	4	Measurement of rejection of input material at the plant	6.7% (calculated from mass flows)	No
Amsterdam	5	Inspections at all steps of the process	Partially high	No
Zagreb	6	Random sampling of input material	10–20% impurities (plastics, metals, residual waste)	No
Arrond. Turnhout	10	Not specified	5–6% impurities	No
Zürich	13	Visual inspection of bins and input material	3–5 reports on contaminations per month (~0.9%)	No
Utrecht	15	Measurement of impurities of the input material	<5% impurities	Yes
Anonymous1 (Germany)	17	Visual inspection of bins (by a third party), re-sorting upon arrival	<1% average plastic content, <2% total foreign matter	Yes
Albano Laziale	24	Sampling of input material, visual, and weight analysis of impurities	<5% impurities (plastics, glass, metals)	Yes
Argentona	26	Measurement of impurities of the input material (twice a year)	1.25%	Yes

4. Discussion

Due to the difficulty of distinguishing between the impact of economic incentives and that of many other factors on sorting behaviour, few attempts have been made to assess the influence of charging systems on the quantity and quality of organic waste. In this publication, we bring both issues together and try to evaluate some important frame conditions.

4.1. Relations Between the Amount of Organic Waste and the Type of Urban Settlement

The valorisation of municipal organic waste in Europe is an ongoing process, with some Member States leading the way and others lagging behind, according to the EEA's early warning reports [12]. It is therefore assumed that the amount of organic waste collected separately per inhabitant varies considerably between cities in different Member States. However, the amount of separately collected organic waste in cities that participated

in the survey is only partially related to their respective countries' average specific collection rates (see Figure 2).

As can be seen from Figure 3, cities with higher population density tend to collect less bio-waste per person. This is in line with recent findings by Walk [45], who evaluated statistical figures from nearly all German municipalities. In the case of cities with more than 1500 inh. km^{-2}, the sorting rate decreased by nearly by 50% compared to areas with less than 300 inh. km^{-2}. Municipalities tend to prefer DtD collection with normal bins instead of large containers because contamination levels are usually lower in smaller bins than in large receptacles. However, this results in lower collection rates in densely populated areas because containers must be used due to a lack of space. A higher level of impurity is often associated with greater anonymity [59], particularly when many people use the same container [60], and is also correlated with lower-income areas, as these households often share containers among a larger population [61].

4.2. Specific Amount of Bio-Waste in Relation to the Local System of Waste Fees

Comparing the fee systems used by municipalities with the specific amounts of bio-waste and residual waste collected (see Figure 4) demonstrates the importance of financial incentives. In cities with a flat fee, the amount of bio-waste collected separately is far below the amount of residual waste. In contrast, cities with PAYT systems and some with Flex+ systems exhibit considerably lower figures for residual waste and higher numbers for bio-waste. This result supports the outcomes of former publications [41–45,48], which highlight the effectiveness of systems that offer financial incentives for decreasing the amount of residual waste and leading to a higher amount of separately collected organic waste.

4.3. Quality of Separately Collected Bio-Waste

The results presented in Table 3 shed light on the impact of quality control and enforcement. Bio bin control is an activity that takes place after the detection of unexpected impurities at the point of delivery, i.e., at the processing facility. Contamination sources can only be identified by opening and checking the bins for impurities, or by technical means [62], such as the recently introduced AI-supported sensor system (see e.g., ref. [63]) for use in the tipping area of waste collection trucks. To eliminate critical bins from the collection, there are two options (see ref. [64] for details):

- Education of certain identifiable users or households, with the aim of improving sorting at source. This feedback is often combined with a fine for emptying the bin into a residual waste truck in the event of repeated violations of the local statute.
- Exclusion of identified polluters, or even complete areas, if the amount of impurities cannot be significantly reduced.

The 'polluter pays' principle can be used for enforcement when a PAYT or Flex+ system is in place, but hardly with taxes or flat fees. If certain waste producers are not permitted to order a bio bin, which is cheaper than a residual waste bin, because they have violated local statutes, their charges will increase considerably. Therefore, monitoring the quality of bio-waste before emptying the bin is only worthwhile if there are differentiated charges for residual and organic waste. This argument sheds light on the results depicted in Figure 5, which shows the relationship between the amount of impurities and the tools used to enforce the PPP. With one exception (No. 13, Zürich), the results suggest that achieving a level of impurities below 5% is difficult without differentiated charges and fines for violations. The deviating findings for Zürich could be related to the fact that the city will not connect its large residential complexes to the organic waste collection system until the end of 2026. Thus, the results for 2024 are mainly based on

the collection of organic waste in bins and not in large containers, which leads to a relatively lower level of impurities, as discussed in Section 4.1. The importance of control and financial sanctions in preventing bio-waste contamination is consistent with the recent evaluation of German municipalities [65]. According to this elaborate study, control plus feedback and/or sanctions are the most effective tools for improving the quality of bio-waste, but they are also costly for cities. It is also interesting to compare these insights with the experiences collected in Milan (contamination~5%), where compliance with the local waste statutes is continuously monitored by a group of employees and violations of separation requirements are subject to fines [66]. It should be remarked that Milan is planning to apply a PAYT charge on residual waste in the near future to improve recycling results [67].

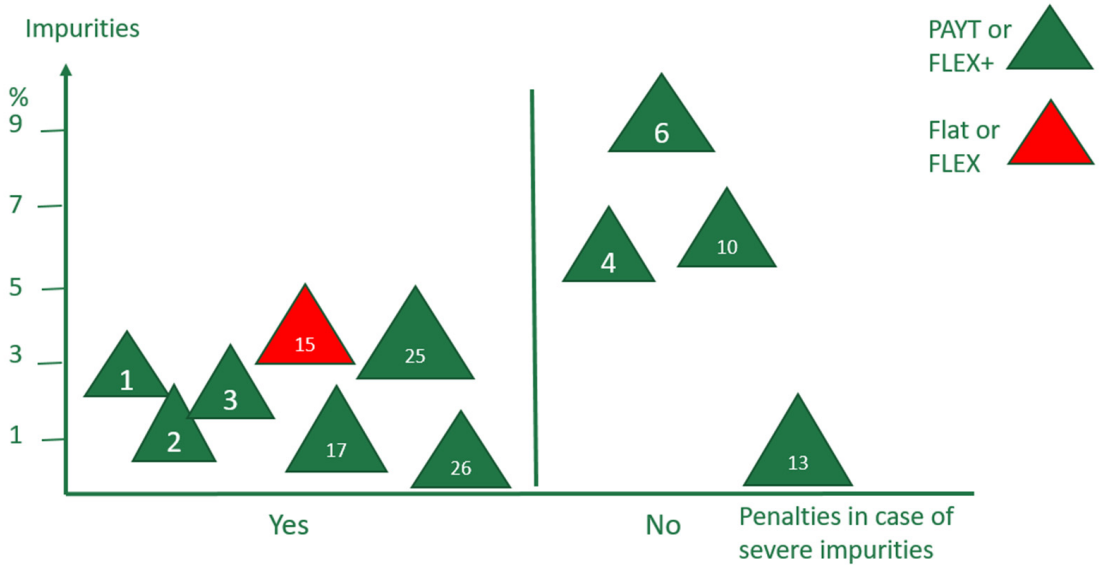

Figure 5. Level of impurities in the bio bin in relation to charging systems and penalties for violation.

4.4. Combination of the Foregoing Perceptions

As stated in Section 4.1, the amount of organic waste collected separately is negatively correlated with population density. According to the discussion in Section 4.2, municipalities that offer financial incentives for separating bio-waste (PAYT or Flex+) have higher collection rates than those with flat fees or waste services financed by local taxes. The results presented in Section 4.3 suggest that achieving further improvements in quality depends on the implementation of appropriate enforcement measures.

However, PAYT and Flex+ systems tend to be most effective in areas with detached and semi-detached houses, but not so effective in large apartment houses. This is because it is difficult to identify and charge specific users of large containers for their individual share of waste disposal. User identification is crucial for a successful PAYT scheme, as outlined by Elia et al. [35], and is also recommended as a result of the evaluation of the collection system in Catalan cities [26]. The identification of certain users is mostly based on a code card provided to individual households, which is used to unlock waste containers. The city can therefore refer to a list of users who dropped waste into the container within a certain timeframe. According to additional information gathered in the Bin2Bean project, the City of Amsterdam withdrew an installed system of this type due to personal data security concerns. The City of Hamburg abstains from technical tools of this type due to the high installation and maintenance costs, besides concerns about data security. In the latter case, cooperation with homeowners (mostly large companies partially owned by the city) and providing residents with more convenient sorting and transport of kitchen waste

is preferred [64]. Therefore, practitioners need guidelines on how to identify residents who dispose of waste in containers provided at their homes, in line with the European General Data Protection Regulation [68].

This makes it clear that the separate collection of organic waste will not necessarily be successful if PAYT systems are introduced. Further activities are necessary to prevent impurities in the organic waste bin, as the quality of compost and related products depends on the quality of the input material.

4.5. Sustainability

Though the collection of organic waste is a challenging task and requires a great deal of effort with respect to communication with citizens and monitoring, the importance of the valorisation of organic waste for sustainable development should not be underestimated. Soil improvers based on organic waste with good quality contribute to many of the Sustainable Development Goals (SDGs) [69]. They combat soil degradation (target 15.3) and mitigate climate change (target 13.2) by sequestration of carbon. The separate collection of bio-waste reduces the amount of waste that needs to be disposed of (target 12.5), also avoiding methane emissions (target 13.2). The valorisation also helps to reduce damage to the urban environment (target 11.6).

4.6. Limitations

This study is subject to several limitations that should be taken into account when interpreting the results. The network-based sampling approach and the reliance on voluntary participation introduced selection bias. The sample is geographically imbalanced, with a strong concentration of cities from Northern and Middle Europe due to a higher willingness to participate (see Figure 1). Lower participation from Southeastern and Eastern Europe is probably also due to the delayed introduction of the separate collection of organic waste (see also ref. [12]).

The completeness and level of detail in the responses to the questionnaire varied considerably. Missing data were particularly common for contamination indicators, participation rates, and percentages of green waste. The comparison of contamination levels gives only a first impression, as monitoring methods differed across cities, affecting both comparability and interpretability. Information on waste management costs was also frequently omitted and, due to differing financial reporting practices, was not considered in this paper; it had been included in the questionnaire mainly to provide contextual background. Similarly, the concluding question addressing the relevance of mechanisms beyond charging systems was excluded from the analysis, because we received uniformly affirmative responses with limited explanatory value.

As already mentioned in the introduction, there are many factors that influence the waste separation behaviour of citizens. The effectiveness of an elaborated charging system, including monitoring and enforcement, also depends on other measures like awareness raising, convenience, and infrastructure.

5. Conclusions

This contribution highlights the increasing importance of maximising the value of organic waste in Europe as an important activity to promote the CE and the production of soil improvers. It focuses on the relationship between the quantity and quality of separately collected bio-waste, and the relevant conditions that influence its management in European cities. Although regions in Northern and Central Europe are overrepresented in the study, the survey results generally reflect the current situation in Europe because many Member States in Southern and Southeastern Europe are not yet meeting targets

for separating recyclable waste fractions [12], i.e., 55% recycling or preparation for re-use in 2025 according to the WFD. Our results suggest that the process of turning organic waste into soil improvers is in the early stages of development and poses a significant challenge, particularly for urban areas with high population density. In many municipalities, separate collection is still in its infancy. This is reflected not only in the relatively low amounts of organic waste, but also in the fact that 50% of the cities participating in the survey do not yet monitor the quality of bio-waste. The use of standard procedures and further technical improvements for the inspection of bio bins for impurities would be helpful.

We found an inverse relationship between the amount of bio-waste collected separately and population density. Large cities tend to introduce the collection of organic waste in areas with detached and semi-detached houses first. This strategy focuses on 'low-hanging fruit' because quality problems usually increase with higher population density. This is one reason, among others, for the low percentage of impurities found in several large cities (see Table 3), i.e., <5% or even <3%. These cities face a real challenge of increasing the amount of compost without compromising on quality.

Furthermore, cities with differentiated charging systems show a higher specific amount of organic waste than those that do not financially motivate households to separate their waste (see Figure 4). However, it cannot be concluded that the introduction of PAYT or Flex+ systems is key to a high amount of usable compost. There is a risk of decreasing quality if financial motivation leads to misuse of the brown bin, i.e., dropping residual waste into the organic waste to save money (see e.g., refs. [51,60,65]). According to the results presented here, control mechanisms should be in place to ensure good quality bio-waste in any case (see Figure 5). This makes it clear that the valorisation of organic waste into soil improvers requires significant political support, particularly in large cities. Efforts to avoid contamination in the final product, such as monitoring bio-waste and installing pre- and post-sorting devices in composting facilities, increase the cost of the process, whereas revenues for compost or fertilisers are often low despite their undisputed value for healthy soils. Municipalities should use the findings from this study and the literature cited therein to coordinate and optimise their instruments for high-quality bio-waste collection. The local situation, including the cultural background of the relevant citizens, must be carefully considered [24,31].

Nevertheless, future targets for the recovery of municipal waste (i.e., 60% by 2030 and 65% by 2035) can only be achieved by collecting a significant proportion of organic waste. Although landfilling biodegradable waste is still common in some Member States, it will only be permissible to a certain extent until 2035. This regulatory framework is in line with sustainability principles and will encourage the separate collection of bio-waste. However, obtaining high-quality input material in high-rise buildings and other multi-family homes requires enormous effort. Therefore, it is useful to consider alternative technical methods. In the Bin2Bean project, a 'Kitchen Sink Grinder' (KSG) is being developed [70], which could be installed in newly constructed high-rise buildings. The KSG will collect food waste at the household level, separating it into liquid and solid streams. The liquid stream is intended for discharge into the sewage system, while the solid stream will be collected and sent to a central anaerobic digestion plant. This method would largely prevent contamination. However, the loss of carbon compared to the collection of solid organic waste should be investigated. Furthermore, a separate pipe system is needed. Experience from a pilot installation in Seoul based on a similar system could provide valuable insights for discussions in Europe [71]. Comparative life cycle assessments, including energy and mass balances for carbon, nitrogen, phosphorus, etc., and economic considerations along

the entire process chain, from households to products, are necessary in order to select the most sustainable option depending on population density.

Summing up, there is no silver bullet for the collection of clean bio-waste from densely populated areas. More research and practical experience on-site are necessary to find suitable solutions.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su18010052/s1, Table S1: Questionnaire; Table S2: Pearson's Correlations; Table S3: Descriptive Statistics; Table S4: Group comparison of charging systems for bio-waste; Table S5: Group comparisons of charging systems for residual waste.

Author Contributions: Conceptualization: H.F.; methodology: M.H.; investigation: M.H.; data curation: M.H.; writing—original draft preparation: H.F.; writing—review and editing: H.F.; visualisation: M.H.; project administration: H.F.; funding acquisition: H.F. All authors have read and agreed to the published version of the manuscript.

Funding: Part of this research was co-funded by the European Union (project "Bin2Bean", grant number 101113011). Views and opinions expressed are, however, those of the authors only and do not necessarily reflect those of the European Union or REA. Neither the European Union nor the granting authority can be held responsible for them.

Institutional Review Board Statement: No personal or sensitive data were used in this study. Therefore, ethical review and approval were waived by the Institutional Committee, as the study did not involve the processing of personal data within the meaning of § 1 of the German Federal Data Protection Act (BDSG) and Article 4 and Recital 26 of the European General Data Protection Regulation (GDPR).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: More data and results can be found in the publications from the Bin2Bean project (www.bin2bean.eu, accessed on 15 November 2025) and in Maike Hentschel's Master's Thesis (will be made available at PubData after examination).

Acknowledgments: This is a part of Maike Hentschel's Master's Thesis. The authors are indebted to Yannick Schrik (University of Wageningen) for valuable ideas and discussions and to Steffen Walk, Technical University of Hamburg, and the European Compost Network, for generous information. We would like to thank the employees of the cities surveyed in this study for completing the extensive questionnaire.

Conflicts of Interest: Henning Friege is a partner of N3 Thinking Ahead Dr. Friege & Partners. The authors declare no conflicts of interest. The funding body had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

CE	Circular economy
EEA	European Environment Agency
EU	European Union
inh.	Inhabitant
KSG	Kitchen sink grinder
PAYT	Pay as you throw
PPP	Polluter-Pays Principle
WFD	Waste Framework Directive
WLD	Waste Landfill Directive

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