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Decision making methodology for biowaste management planning support: Addressing an EU directive

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ABSTRACT

In the European Union (EU), biowaste accounts for 34 % of municipal waste generated. The EU Directive 2018/851 established a mandatory separate collection of biowaste by the end of 2023. The Directive allows for derogation in case the collection of waste is not technically, economically, or environmentally feasible. This study proposes a decision-making methodology to assess the technical feasibility of separate collection of biowaste. Two new indicators are proposed: the "Artificial Urban Area" indicator, which assesses the size of the built-up area where biowaste is generated, and the "Generation" indicator, which estimates the quantities of biowaste to be collected. To demonstrate its applicability, the methodology is applied to a national case study. Our results conclude that waste collection is technically viable in 44 % of national parishes, representing 85 % of the country's total biowaste generation. This study provides insight into where biowaste generation is concentrated, thus supporting an efficient allocation of waste management resources.

1. Introduction

Biowaste accounts for more than 34 % of municipal waste generated in the European Union, making it a significant economic, environmental and social burden (EEA, 2020). However, this waste stream has the potential to contribute to a stronger circular economy by providing valuable soil amendments and fertilizers, as well as biogas (Chojnacka et al., 2020). In the EU, biowaste is commonly collected via waste collection systems, which is then sorted in waste management facilities or sent directly to landfills or incineration. The sorting facilities of mixed waste have not been successful in separating the different flows of waste, which in turns leads to high rates of waste ending up in landfills or incinerated. Furthermore, biowaste from sorting facilities of mixed waste, that is sent to biologic treatment, results in compost has very poor quality with high heavy metals content and microplastics (EEA, 2020). Therefore, collecting biowaste separately from other municipal waste is of the upmost importance to not only reduce the quantity of waste sent to landfill, but also to obtain biowaste with a level of impurities and contamination low, which in turn allows for cleaner by-products (EC, 2020; Rodrigues et al., 2020). To address the poor management of biowaste, the European Union has set ambitious goals for the waste stream. Directive 2018/851 of the European Parliament and of the Council of May 30, 2018, for example, requires EU Member States to restructure their waste management strategies and systems to prioritize separate collection and treatment of biowaste.

However, this directive recognizes that separate collection may not be feasible due to technical, economic, or environmental factors. To address this, Member States may allow derogations from separate collection of biowaste in accordance with a provision in EU regulations that allows Member States to deviate from certain requirements under specific circumstances. For example, in sparsely populated areas where the ecological benefits of separate collection may not outweigh the negative environmental effects of additional transportation emissions, derogation may be allowed (EC, 2020). A region may apply for exemption to separately collect biowaste if at least one of the following conditions is met: (a) joint collection of certain types of waste does not affect their potential to undergo waste management operations and results in a quality comparable to that achieved by separate collection, (b) separate collection does not lead to the best environmental outcome; (c) separate collection is not technically feasible, taking into account good waste collection practices; or (d) separate collection would entail disproportionate economic costs (EC, 2020).

The decision-making process for waste management planning is a complex task that requires a thorough evaluation of environmental

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impacts, technical considerations, and operational costs (Arena and Di Gregorio, 2014). Successful decision-making in waste management requires a holistic strategy that considers local conditions and clearly defined objectives.

In response to the requirement for territorial coverage, Directive 2018/851 states that an approach focused on methodologies is essential to assess the technical feasibility of implementing a new waste stream collection system. Studies have used life cycle assessment (Pérez et al., 2020; Vinitskaia et al., 2021), multicriteria (Delgado et al., 2020; Vučijak et al., 2016), contingent valuation method (Ferreira and Marques, 2015), optimization for planning service areas and vehicle routes (Hannan et al., 2020; Ramos et al., 2014), quantification of waste streams at different construction stages (Bakshan et al., 2015) and geographical information systems (GIS) for mapping waste (Blanco et al., 2018; Paul and Bussemaker, 2020). These methodologies provide insights into environmental impacts, willingness to pay for sustainable waste collection, optimization of collection routes, and quantification of waste generation rates. Using these quantitative approaches, researchers can assess factors such as carbon footprint, cost effectiveness, and waste generation patterns to develop efficient and sustainable waste collection strategies (Siegfried et al., 2023). However, these studies focused on the operational nature of waste collection systems, such as the definition of routes (Ramos et al., 2014), different containerization systems (Pérez et al., 2020), the assessment of the willingness to pay for a service (Ferreira and Marques, 2015), implementation of waste management solutions (Delgado et al., 2020; Paul and Bussemaker, 2020), and suitable localization of collection infrastructures (Blanco et al., 2018), while this study seeks to address the strategic nature of determining whether or not there is technical viability to develop a new selective waste collection system.

To our knowledge, no research was published or proposed that focuses on the strategic assessment of the viability for implementing selective biowaste collection systems. Nevertheless, methodological approaches were developed related to new waste collection systems in general, focusing on estimating waste generation rates. For example, Bakshan et al. (2015) evaluated the generation rates of construction waste. Their methodology aims to categorize materials by major types and estimate the waste generation rate for each type produced in the construction and/or demolition phases. The authors proposed different indicators to assess such rates, and their methodology extends the study to a larger region, which according to the authors can reach the country level. Also, Cavallin et al. (2020) developed a method for the design of a municipal waste pre-collection network in real scenarios in two neighborhoods of Bahía Blanca, Argentina. The city aimed to improve its waste management system to reduce landfill disposal and promote sustainability. The methodology of the study included estimating waste generation rates, collecting data on population density and waste characteristics, and used a mixed-integer linear programming model to determine the optimal location of waste bins with capacity constraints. Although comprehensive, the proposed approach had clear drawbacks. The most important ones being 1) the lack of available data on waste generation with the required level of granularity (e.g., socioeconomic characteristics of different neighborhoods), which entails extensive fieldwork and estimation; 2) the assumption that the population will consistently separate waste into dry and humid fractions may not be consistent with actual citizen behavior; and 3) the scalability of such an approach to address a larger study area (e.g., nationwide).

In this work, a methodology is presented to quantify biowaste generation rates and assess whether the collection of a waste stream is technically viable. By emphasizing methodologies tailored to assess the technical feasibility of implementing new waste collection systems, this approach aims to improve decision-making processes in waste management planning, ensuring that efficient, sustainable, and environmentally conscious practices are adopted. More specifically, the aim of this study is to find suitable areas within a region for separate biowaste collection, factoring in the amount of waste generated and its geographical distribution. Two key indicators are proposed: “Artificial Urban Area”, closely linked to the concept of "built-up area", defined by the (OECD, 2017) as areas with a significant presence of buildings, and aims to identify the specific zones within each territory where the majority of biowaste is generated; and “Generation”, which estimates the amount of biowaste generated between consecutive collection days, providing information on the frequency and amount of waste generation. Through these two indicators, with predefined thresholds and aggregation methods, the technical suitability of areas for separate biowaste collection can be effectively determined. The proposed method considers a critical issue when dealing with real data: the need to match the geographical scope of the study with the granularity of the available data (Madden et al., 2021). Finally, our approach focuses on finding which regions have technical potential for a selective collection system, rather than assessing which areas may be eligible for a technical exemption. This will provide a basis for a more informed decision of this strategic issue.

In summary, the novelty of this work lies in its use of ready available data to support decision-making at the planning stage, enabling waste management entities to better allocate resources. Unlike most existing literature, which is based on the use of detailed and often resource-intensive data collection, this study demonstrates that strategic waste management planning can be effectively conducted using accessible datasets. This approach addresses a significant barrier identified in prior research, where the requirement for high-detail data has been cited as a major setback for large-scale or strategic studies. Additionally, the proposed methodology is geographical flexible, allowing application at various special scales. This flexibility distinguished this work from previous studies that are often limited to specific regions or require localized data collection efforts. To the best of the authors’ knowledge few studies have proposed methodological approaches that combine both the use of readily available data and geographical adaptability in strategic waste management planning.

The paper is organized as follows. Section 2 presents the two new indicators: Artificial Urban Area and Generation. The methodology is presented step by step in Section 3. The methodology is illustrated by a national case study in Section 4. The final remarks conclude the paper (Section 5).

2. Indicators

The technical potential for implementing a selective waste collection system should be analyzed by integrating two perspectives. On the one hand, one should consider the concentration of waste (in highly urbanized areas versus rural areas); on the other hand, one needs to consider the quantity of biowaste generated. These two perspectives will shed light on the areas with the highest potential for selective waste collection. They will also provide information concerning which areas do not produce enough waste and/or where the generation is high, but where it is so fragmented that it is preferable to implement other waste treatments (e.g., home composting). Therefore, two new indicators are proposed that assess the areas where waste generation is most concentrated and estimate the corresponding generation amounts.

2.1. Artificial Urban Area indicator

The Artificial Urban Area indicator aims to reflect the “concentration” of waste generation. As mentioned above, this indicator is closely related to the concept of “built-up area” which is defined by the Organization for Economic Cooperation and Development (OECD) as the “the presence of buildings” (roofed structures). However, OECD (2017) definition excludes “other parts of urban environments such as paved surfaces (roads, parking lots), commercial and industrial sites (ports, landfills, quarries, runways) and urban green spaces (parks, gardens)”, even though these areas may also contribute to biowaste generation. This methodology allows for the inclusion of such areas when applying it to a real case scenario, if their consideration better fits the specific context under study. This flexibility is important, as waste generation patterns and relevant sources can vary significantly between territories and over time.

The Artificial Urban Area indicator (I_a) is defined as the ratio between the built-up area within the given geographical region and its total area (equation [1]).

$$I_a = \text{built-up area}/\text{total area} \quad [1]$$

High values of this indicator (close to 1) show that the built-up area is close to the total area of the region in analysis. Lower values indicate less urbanized regions. For the latter, the implementation of selective collection will imply traveling greater distances, since the collection points will be more dispersed. This indicator can be read as the percentage of the region that is currently built-up and is associated with biowaste generation.

2.2. Generation indicator

The Generation indicator refers to the amount of biowaste collected per collection day (t/collection day). Since this study addresses the assessment of the technical potential to implement a new selective collection system, there is no precise data available. Thus, assumptions have been made. The first one relates to the behavior of the population, as this is the basis for waste separation (known as the "capture rate"). The study population separates waste appropriately. The second assumption concerns the frequency of collection. This should consider climatic factors and composition of the waste stream. In the case of biowaste, the decomposition of meat and fish waste is the main cause of unpleasant odors, which is accentuated by warmer temperatures. Therefore, the frequency of collection should be higher in areas where the climate registers higher temperatures (Madsen et al., 2021). Finally, the third assumption concerns the characteristics of the collection vehicles. Considering the volume of an average sized mixed waste collection vehicle, implementing a selective collection system has less technical potential in areas where waste generation would not fill the volume of a vehicle on each collection day. Note that mixed waste is already being collected, and the same type of vehicle could be used to collect this new waste stream.

The Generation indicator is defined as follows: let λ be the capture rate, i.e., the waste fraction that is properly separated by the population, and f the collection frequency (occasions per time period). Given W the amount of mixed waste generated per time period, the Generation indicator (I_p) is given in equation [2]:

$$I_p = \lambda \frac{W}{f} \quad [2]$$

This indicator provides an estimate of the amount of selective biowaste collected per region per collection day. Note that the collection frequency should be estimated assuming an average vehicle capacity (e.g., a 5-tonne capacity vehicle). This will be further explored in the methodology section and highlighted when applying such method to a case study.

The Artificial Urban Area and Generation indicators provide complementary and accurate criteria to assess the technical viability of biowaste separation systems. The former identifies spatial suitability by quantifying urbanization density, ensuring logistical feasibility (e.g., minimizing travel distances in dispersed rural areas). The latter evaluates operational viability by estimating biowaste volumes per collection cycle, integrating capture rates, climatic impacts on frequency, and vehicle capacity constraints. Together, they balance geographic concentration (urban vs. rural) and quantitative feasibility (volume vs. infrastructure), enabling an accurate identification of territories where centralized collection is viable versus those where decentralized solutions (e.g., home composting) are preferable.

3. Methodology

The developed methodology comprises six steps, depicted in Fig. 1. As this is a decision support methodology, it is essential that those involved in the implementation of such a selective collection system are aware of all the assumptions made and the results obtained. Therefore, feedback is a fundamental step in this decision-making process.

Step 1 Data collection and defining the geographical area

The first step is to collect the data needed to calculate the indicators. The data to be collected are (i) the amount of mixed waste generated per geographic unit, (ii) the physical characterization of the mixed waste, (iii) the average capacity of vehicles operating in the mixed waste collection system, (iv) the areas of geographical units, (v) the corresponding built-up areas, and (vi) resident population. Additionally, the boundaries of the administrative regions should also be recorded, ideally to be used in Step 4 when visually validating the impact of the thresholds that will be defined for each indicator.

At that stage, it is also necessary to determine the level of geographical detail at which the study will be undertaken. This decision is closely related to the detail level available for the data, as it is often not possible to collect data at the desired level of detail. Furthermore, different countries have distinct administrative organizations with unique waste management responsibilities, and therefore, what makes sense for one study may not make sense for another.

This methodology is generic and can accommodate up to three different levels of geographic detail data. Therefore, it can be applied to different geographic divisions such as countries and regions (level 0), counties and municipalities (level 1), and even smaller subdivisions such as parishes and boroughs (level 2). However, to have the most accurate information to support decision making, data should be collected at the most detailed level available. When data are available at different geographical levels, indicators should be defined at the smallest possible level. The level of detail of the data will be reconciled at a later stage in the methodology, if necessary.

Step 2 Indicators calculation

With the collected data and the geographical levels defined the two indicators, Artificial Urban Area (I_a) and Generation (I_p), can be calculated. As mentioned above, the geographical unit does not have to be the same for each indicator.

For a better understanding of how to deal with the indicators defined for different geographical levels, the remainder of the presentation of the methodology will be done considering that both indicators have different units. Namely, the Artificial Urban Area indicator will be based on a level 2 area and the Generation indicator will be based on a level 1 area.

Step 3 Threshold definition

Once the two indicators have been calculated, criteria must be established to reflect the different levels of potential to implement separate biowaste collection. These criteria are translated into thresholds that identify areas that do or do not have the technical potential to implement a selective collection system.

Let α be the minimum Artificial Urban Area that makes the implementation of a selective collection system viable. Hence, if $I_a \geq \alpha$ then the corresponding territory has a high potential for successful selective waste collection, and if $I_a < \alpha$ then it has less suitability.

Let ρ be the minimum amount of waste that is technically viable to collect per day of collection (e.g., one full vehicle). Therefore, if $I_p \geq \rho$ then the corresponding territory has a high potential for successful selective waste collection, whereas, if $I_p < \rho$ then it has less potential.

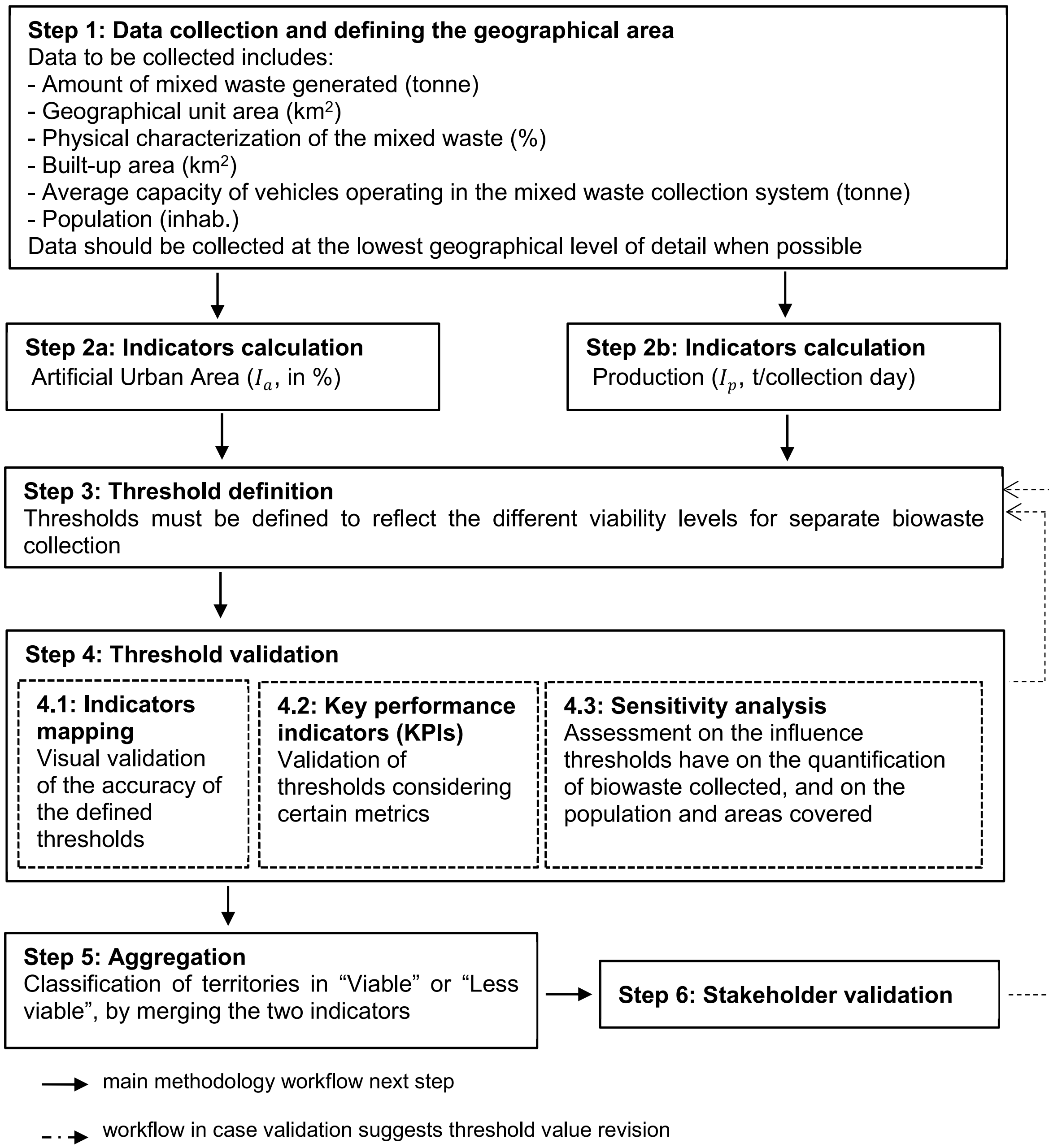

Fig. 1. Overview of the proposed methodological approach.

Both values are challenging to set, so it is important to examine the impact of different thresholds and these on other indicators. This is explored below.

Step 4 Thresholds validation

Validation of the thresholds is done from three different perspectives, as each of them may reveal issues that may not be so clear to others. These are a visual validation (qualitative approach) and two quantitative validations: the impact on other metrics (e.g., total population covered) and the impact of using different threshold values. If either of these analyzes reveal any type of inadequacy, the threshold values set in the previous step should be revised, and the validation steps should be repeated until the results meet the study objectives.

Step 4.1 Indicators mapping – qualitative validation

Using a GIS, the two indicators should be mapped independently, recurring to shapefiles on the level 0 geographic division. As an output, the geographical units above and below the thresholds for each of the indicators should be clearly visible. These two maps allow for visual validation of the accuracy of the classification.

Step 4.2 Key performance indicators

The defined thresholds will have an impact on some metrics that will show how accurately these indicators characterize the territory under study. Therefore, the metrics (hereafter referred to as Key Performance Indicators, KPIs) should be calculated considering only those areas whose indicators are above the thresholds, i.e., those with a higher suitability for selective biowaste collection.

The KPIs are:

- Total amount of waste collected separately at geographical level 0 (t/year),
- Total population covered (at level 0),
- Number and percentage of areas covered at level 1,
- Number and percentage of areas covered at level 2.

Step 4.3 Sensitivity analysis

The last step in analyzing the impact of thresholds is a sensitivity analysis. This analysis assesses the impact of thresholds on the quantification of waste collected, population, and administrative areas where the technical potential for selective biowaste collection has been identified. In addition, the sensitivity analysis should be performed not only for the two thresholds, but also for the capture rate since it plays a fundamental role in the calculation of the Generation Indicator. In summary, three analyzes should then be performed: (i) different capture rates, with both thresholds fixed at the values defined above; (ii) different Generation thresholds (value of ρ), with the capture rate and the Artificial Urban Area threshold fixed at the values defined above; and (iii) different Artificial Urban Area thresholds (value of α), with the capture rate and the Generation threshold fixed at the values defined above.

Step 5 Aggregation

As the thresholds and coverage rate values have been validated in the previous step, they can now be applied in the aggregation step.

The purpose of aggregation is to show which areas have higher technical viability when both indicators are considered simultaneously, so it is necessary that the indicators are in the same geographical unit. Since the smallest possible geographical level is desirable, the Generation indicator values defined at level 1 must be calculated at level 2. Recall that, in step 2, it was assumed that the Artificial Urban Area was calculated with respect to level 2 areas.

Equation [3] estimates the amount of biowaste generated at the level 2 (I_p^2) by proportionally multiplying the amount of biowaste generated at level 1 (I_p) by the population fraction of the level 2 area (P_d) with respect the corresponding level 1 population (P_m):

$$I_p^2 = I_p \times P_d \Big/ P_m \qquad [3]$$

Once both indicators are in the same geographical unit, level 2 areas are ready to be classified as having either higher technical potential (darker color) or lower technical potential (lighter color). Fig. 2 illustrates the classification process.

A level 2 area is identified as having a high technical potential if both indicators are above the thresholds, i.e., the Artificial Urban Area indicator is greater than or equal to α and the Generation indicator is greater or equal than ρ, $\left(I_a \geq \alpha \wedge I_p^2 \geq \rho\right)$. In addition, all level 2 areas with $I_a \geq \alpha$ and $I_p^2 < \rho$ (e.g., having sufficient Artificial Urban Area but low expected generation), if belonging to the same level 1 area where the sum of their generation gives a Generation indicator above the threshold, are also classified as having high technical potential. It should be noted that in the latter case, these are areas that individually do not justify the implementation of a selective collection system, but within their administrative region (all together) they do.

This aggregation step provides the final classification. A map of the geographical area under study, level 0, and the metrics defined in step 4 should be calculated for the level 2 areas, which are classified as having a high potential for implementing such selective waste collection. For the remaining level 2 areas, the technical potential is low, and derogation should be considered.

Step 6 Stakeholder validation

Given the impact of this type of study on waste management, the results should be presented to stakeholders for validation. If any inappropriateness is perceived at this stage, the thresholds should be redefined.

4. Case study

To demonstrate the adequacy of the proposed methodology, the real case of mainland Portugal is presented as a study case.

Mainland Portugal has generation of 1.5 million tonnes of biowaste, per year, associated to a population of 9.8 million people. This waste stream represents for 34 % of the total municipal waste produced. Mainland Portugal has 278 municipalities, usually responsible for the mixed waste collection, and future biowaste selective. These municipalities are divided into 2882 parishes, smaller administrative units, hence why this study will be conducted at the geographical level 2 (parishes). Furthermore, mainland Portugal has 23 Urban Waste Management Systems (SGRU), which are responsible for the selective collection of paper, plastic, and glass packaging, as well as the treatment and disposal of municipal waste. These SGRUs encompass multiple municipalities.

Prior to being made mandatory, biowaste has been collected via a mixed waste system, in Portugal, with some three main notable exceptions of biowaste management schemes: selective biowaste collection of the HORECA sector (hotels, restaurant and catering) in Lisbon and Porto and domestic composting in Leiria Region.

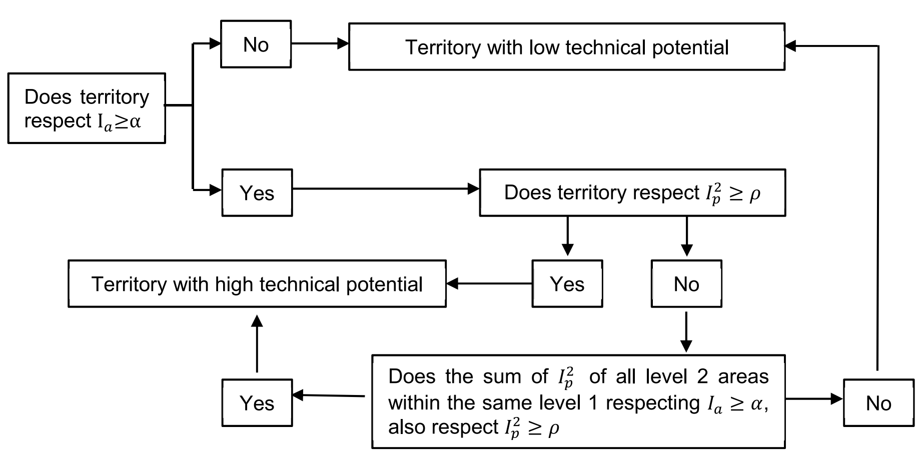

Fig. 2. Aggregation process.

4.1. Data collection and geographical area definition (Step 1)

Given the Portuguese administrative organization and the availability of data, the three levels of geographical areas at which the methodology is applied are: mainland Portugal (level 0), municipality (level 1), and parish (level 2). Note that, in the Portuguese context, these geographical levels represent administrative divisions that can contain cities, villages, or communities.

All data are reported for 2017, as all necessary data were available for that year; namely:

(i) resident population was retrieved from the Portuguese National Statistics Institute (INE), who publishes annually the average of resident population per municipality (INE, 2021a); this estimate is obtained by taking the arithmetic mean of the estimated population at two observation points, usually at the end of two consecutive years;
(ii) physical characterization of the mixed waste, in percentage values, was requested to and provided by the Portuguese Environmental Agency (APA), as it is not public available data; it is measured at the scale of the Urban Waste Management Systems, which are the entities responsible for the collection of household and similar waste whose daily generation does not exceed 1100 L per producer (Amaral et al., 2022; Decreto-Lei n.o 102-D/2020, 2020); since each SGRU aggregates several municipalities, the physical characterization was assumed to be the same among the municipalities within each SGRU;
(iii) amount of mixed waste generated per municipality was obtained from INE (INE, 2021b);
(iv) most common vehicle used in the mixed waste collection system in mainland Portugal is the 5-tonne vehicle
(v) the boundaries of municipalities and their parishes were extracted from the 2017 Official Administrative Charter of Portugal, published by the Portuguese Directorate General of Territory (DGT);
(vi) the built-up area of each parish was calculated using the Portuguese Land Use and Occupancy Map (DGT, 2022b) as a basis; this Portuguese cartography consists of four layers of territorial detail (DGT, 2022a), of which layer 3 was considered to determine the built-up area; this layer 3 is composed of a total of 46 categories, of which seven were considered artificial areas with a significant biowaste generation: “continuous built fabric”, “discontinuous built fabric”, “industry”, “commerce”, “sports facilities”, “leisure facilities and campsites”, “cultural facilities”, “other tourist facilities and installations”; this approach was validated by DGT itself.

4.2. Calculation of the indicators and thresholds definition (steps 2 and 3)

The Artificial Urban Area indicator was calculated with data on the total area and the built-up area of each parish. To better understand the overall distribution of the values of this indicator, I_a, all values are presented on a histogram, in Fig. 3. This figure shows that in mainland Portugal, there are parishes where the percentage of buildings is almost zero (minimum value is 0.1 %), while some parishes are almost entirely covered by buildings (maximum value is 98.9 %).

> “Artificial Urban Area” indicator presents a high asymmetry, which makes the average value (10 %) not representative of the parishes in Mainland Portugal. Therefore, the threshold value (value α) was set to the median level (4 %), due to not being influenced by the presence of very high values.

Given that, to our knowledge, this is the first study on the development of a decision support methodology for the implementation of a selective biowaste collection system, it was necessary to estimate the quantity and collection frequency for such a system regarding the Generation indicator. This was done considering the most common vehicle used in the mixed waste collection system in mainland Portugal (quantity) and international studies whose study regions have similar climatic conditions and composition of the biowaste stream (collection frequency). In mainland Portugal, most common vehicle used in the mixed waste collection is of 5-tonne vehicle and therefore the threshold value (value ρ) was set to 5. This approach comes from considering that vehicles used for mixed waste collection will be use in turns with the biowaste selective collection, since collecting biowaste separately will decrease the quantity of mixed waste collected.

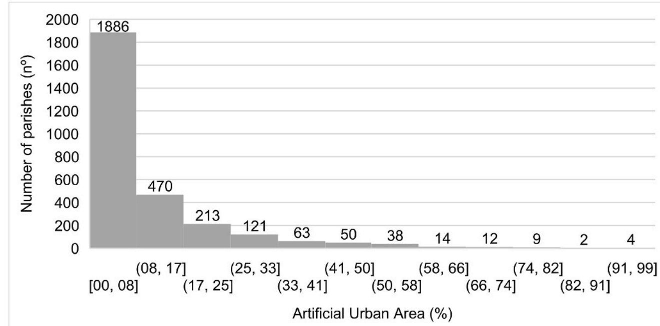

Fig. 3. Values of the indicator "Artificial Urban Area" regarding the parishes of mainland Portugal.

Regarding collection frequency, the separate biowaste collection systems of Catalonia and Milan were taken in consideration. In Catalonia, separate biowaste collection is carried out i) every day in Barcelona (ACR+, 2016), ii) 3–4 days/week in municipalities with a population of less than 20 000 inhabitants (Jofra Sofra and Freire González, 2014), and iii) 3–4 times per week in areas with only a door-to-door collection system (Alvarez et al., 2010). In Milan biowaste is collected twice per week in the domestic sector and daily in the HORECA channel (ACR+, 2016). In Rome, biowaste is collected three times a week (BiPRO/CRI, 2015). Considering these collection frequencies for the present study, the collection should be carried out three times a week. For this purpose, the amount of biowaste collected per collection day calculated based on the collection of the waste stream every two days. Therefore, the collection frequency parameter was set to three ($f = 3$).

Capture rate values vary depending on different factors, such as the population’s awareness of selective waste collection, the collection model (door-to-door or curbside collection), economic incentives and the quality of the collection service, among others.

For example, among the ten European capitals with selective collection biowaste systems, the values vary between 22 % and 73 % (BiPRO/CRI, 2015), where commonly values closer or above 50 % capture rate are associated with door-to-door collection systems and capture rates below 50 % are associated with curbside collection systems. Assuming that Portugal will have different selective collection models, and considering that Directive (EU) 2018/851, has a target of 55 %, for 2025, for preparing for re-use and recycling for municipal waste, the present study considers a capture rate of 50 % for mainland Portugal, which is also approximate to the rate seen in Catalonia (ACR+, 2016). The parameter λ is then equal to 0.5.

4.3. Qualitative validation and KPIs (steps 4.1 and 4.2)

4.3.1. Artificial Urban Area indicator

Fig. 4 highlights the set of parishes whose Artificial Urban Area is greater than the threshold, i.e., $\alpha = 4$ % (darker color). The geographical contours of the municipalities allow us to observe the parishes of each municipality that meet this criterion. The Portuguese population lives mainly in the coastal area, with the highest concentration in the

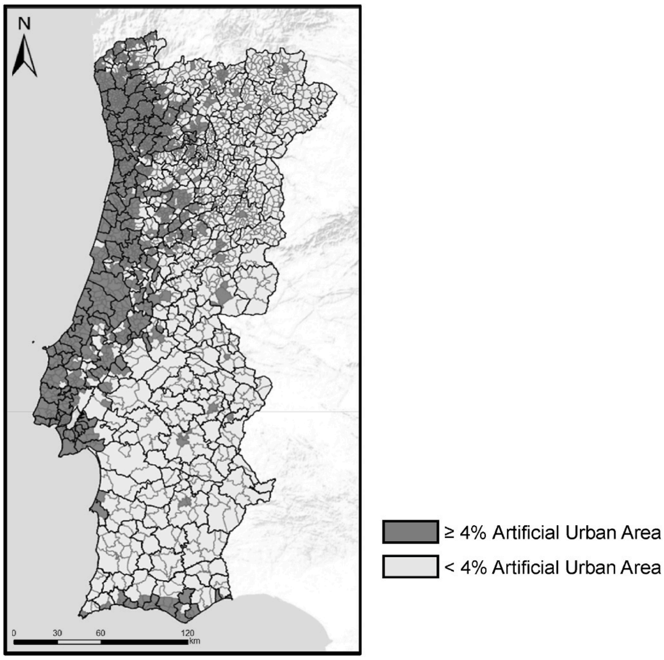

Fig. 4. Parishes in mainland Portugal (gray line), within each municipality (black line) whose Artificial Urban Area indicator is above the threshold (darker color) or below (lighter color) the threshold.

metropolitan areas of Lisbon and Porto. The interior of the country is mostly rural except for some parishes in the main cities. These characteristics visually confirm the choice of the threshold for the Artificial Urban Area indicator.

With this threshold value, an estimated amount of about 699 million tonnes of biowaste would have been collected in 2017, which corresponds to about 1,500 parishes (more than 50 % of the total parishes in mainland Portugal). These are part of 204 municipalities (about 73 % of the total municipalities) and cover 87 % of the population of mainland Portugal.

4.3.2. Generation indicator

Fig. 5 shows the municipalities that would collect at least 5 t/collection day of separated biowaste if collection were implemented. Municipalities that meet this criterion are mainly located in the coastal area of mainland Portugal. This is due to a higher population density, and consequently, a higher generation of biowaste compared to more sparsely populated municipalities found further inland.

The municipalities with Generation indicator values above 5 t/collection day correspond to 55 % of the total municipalities in mainland Portugal, which represent around 91 % of the total population of the mainland. Assuming a capture rate of 50 %, it is estimated that 731 million tonnes of biowaste could have been collected in the year under study.

4.4. Sensitivity analysis (step 4.3)

To analyze the impact of the thresholds used and some of the assumptions made on the KPIs, a sensitivity analysis is performed. This analysis shows how different values affect the quantification of the estimated biowaste collected, the number of municipalities and parishes qualified as having the technical potential to have a selective collection system for biowaste, and the resident population covered by such a collection system.

First, the different values of the Artificial Urban Area threshold were evaluated assuming an unchanged capture rate (50 %). Table 1 shows the KPIs for the base case ($\alpha = 4$ %) and the corresponding values when

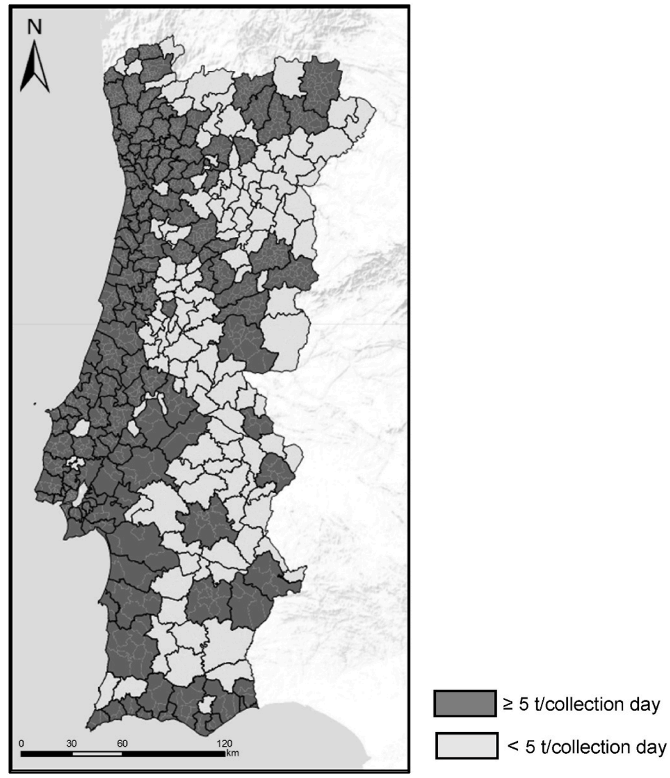

Fig. 5. Municipalities in mainland Portugal whose Generation indicator is above the threshold (darker color) or below the threshold (lighter color).

Table 1
KPIs absolute and relative variation considering different Artificial Urban Area threshold values (α).

Artificial Urban Area (%)	3		4(*)	5	
	absolute	%		absolute	%
Quantity of biowaste selectively collected biowaste (t/year)	+23 224	+3.3	695 949	−21 744	−3.1
Municipalities covered (no.)	+19	+9.3	204	−13	−6.4
Parishes covered (no.)	+191	+12.8	1490	−134	−9.0
Total population covered	+287 151	+3.4	8 565 026	−282 295	−3.3

(*) The base case.

a 1 % variation was made. It also shows the variation with respect to the baseline case. The results show that in terms of the expected amount of biowaste collected, the variation would be approximately 3 % higher if the threshold was one percentage point lower ($\alpha = 3$ %), and a 3 % increase if it were one percent higher ($\alpha = 5$ %). The biggest impact of changing the threshold is on the number of parishes considered to have higher technical potential. Increasing the threshold would reduce the number of parishes by 9 %, lowering it would lower the number by about 13 %. In terms of the total number of parishes in mainland Portugal, thresholds of 3 % and 5 % would change the number of parishes by 58 % and 47 %, respectively. In terms of population, a minimum coverage of 5 % of the built-up area would result in 85 % of the population being served by the biowaste collection system, while a minimum coverage of 3 % would increase this percentage to 90 % (not shown in the table).

A similar analysis was conducted for the threshold value of the Generation indicator (value ρ). Assuming a capture rate of 50 %, the collection quantity varied between 4 and 6 t/collection day. Table 2

Table 2
KPIs absolute and relative variation considering different Generation threshold values (ρ).

Generation (t/ collection day)	4		5 (*)	6	
	absolute	%		absolute	%
Quantity of biowaste selectively collected (t/year)	+21 200	+2.9	731 653	−12 218	−1.7
Municipalities covered (no.)	+26	+16.9	154	−12	−7.8
Parishes covered (no.)	+254	+13.3	1914	−143	−7.5
Total population covered	+287 185	+3.2	8 917 147	−143 200	−1.6

(*) The base case.

shows the KPIs for the base case, $\rho = 5$ t/collection day, and their values when a variation of 1 t/collection day variations was made. The results show that in terms of the expected amounts of biowaste collected, the variation would be an increase of about 3 % if the threshold were lowered, and an increase of approximately 1.7 % if it were higher by one tonne. The biggest impact of changing this threshold value is on the number of municipalities that are considered to have a higher technical potential. Raising the threshold would reduce the number of municipalities by about 8 %. Lowering the threshold would increase the number of municipalities by about 17 %. In relation to the total number of municipalities in mainland Portugal (not shown in the table), the thresholds of 4 and 6 t/collection day would change the number of parishes by 67 % and 51 %, respectively. In relation to the total population of mainland Portugal, a 6 t/collection day would result in 90 % of the population being served by the biowaste collection system, while a 4 t/collection day would increase this percentage to 94 % (not shown in the table). In short, a reduction of the generation threshold of 1 t/ collection day reaches only about 287 000 more people (i.e., 21 tonnes more biowaste selectively collected).

The impact of the capture rate on the KPIs was assessed assuming a Generation threshold of 5 t/collection day. Two different scenarios were studied: population unwilling to participate (capture rate of 30 %) and population willing to participate (capture rate of 70 %). Table 3 shows the absolute and relative variation of the KPIs for the Generation indicator considering the different capture rates. It is interesting to observe the impact of a variation of 20 percentage points. In terms of the quantities of biowaste collected selectively, the variation was almost 50 % for the year under study. It should be noted that only municipalities that produce at least 5 t/collection day were considered. Regarding the number of municipalities, the relative variation is of the same order of magnitude. In relative terms, the total population covered decreases more than it increases when the capture rate varies. This suggests that municipalities that are no longer considered to have technical potential when the capture rate is reduced to 30 % are more populated than those that become eligible when the capture rate is increased to 70 %. Finally, in terms of the total population of mainland Portugal, a capture rate of 30 % would result in 85 % of the population being covered by such a selective collection system (not shown in the table). This value increases to 95 % if the capture rate is 70 %. Note that in terms of the population covered if the entire mainland population is considered, a 40 percentage point increase in the capture rate results in a 20 percentage point increase in the population covered. This analysis was not performed when addressing the Artificial Urban Area indicator, since this indicator only evaluates the concentration of the biowaste generation. The KPIs related to the number of municipalities, parishes and population covered will not be affected by these changes. Only the amount of biowaste will increase in the same proportion as the capture rate.

Table 3
KPIs absolute and relative variation for Generation indicator considering different capture rates (λ).

Capture rate (%)	30		50(*)	70	
	absolute	%		absolute	%
Quantity of biowaste selectively collected (t/year)	−319 174	−43.6	731 653	+333 851	+45.6
Municipalities covered (no.)	−37	−24.0	154	+38	+24.7
Parishes covered (no.)	−425	−22.2	1914	+374	+19.5
Total population covered	−575 445	−6.5	8 917 147	+406 430	+4.6

(*) The base case.

The results of the sensitivity analysis show that a variation in the thresholds set for each indicator does not lead to significant variations in the amounts of biowaste collected in the number of municipalities, parishes, and population covered. On the other hand, a variation in the capture rate (30 %, 50 %, and 70 %) leads to significant differences in the quantification of these KPIs, especially for biowaste collected. In view of these results, it is possible to validate the thresholds previously established while assuming a capture rate of 50 %.

4.5. Aggregation (step 5)

To assess which geographical area has technical potential for the implementation of selective biowaste collection both indicators were combined. Since these were determined on a different scale, the total expected generation of biowaste was distributed among the parishes of each municipality according to the corresponding population. In this way, the Generation indicator was brought to the same scale as the Artificial Urban Area indicator. Thereafter, the first step was to identify, among the parishes with an Artificial Urban Area greater than or equal to 4 %, those with a Generation indicator greater than 5 t/collection day. In a second step, those parishes with an Artificial Urban Area above the threshold but with a Generation indicator below the threshold were analyzed within their municipal boundaries. In other words, within each municipality, the estimated generation (the Generation indicator values), of the parishes with a sufficient proportion of built-up area, was added together. If the global value was above the 5 t/collection day, the parishes were also considered to have technical potential.

Fig. 6 shows the mainland Portuguese parishes that are classified as having higher and lower potential for the implementation of a selective collection system. As expected, once again the distribution of areas identified as having higher potential is found in the coastal zone of the country. It is also possible to verify that for several municipalities this potential is limited to some parishes. These cases are mainly observed in parishes that contain cities or parish councils. In those municipalities and parishes that have lower technical potential for implementing selective biowaste collection, solutions such as domestic and community composting should be considered.

4.6. Stakeholder validation (step 6)

The final step was to present the results to stakeholders, who were invited to a public meeting. These included technical personnel responsible for waste collection systems.

A presentation was given explaining the methodology, the results and how KPI's vary according to different thresholds and capture rates. The participants voted on the thresholds they agreed with using a mobile website. The grand majority agreed with the thresholds already set for Mainland Portugal. The only specific change made to the final results was related to a parish, part of the Lisbon metropolitan area, whose territory consists largely of submerged lands of the Tejo River, but the urban area is very concentrated with a high population density. Thus, this parish was considered suitable for the implementation of a biowaste selective system.

Overall, and according to the results presented, 44 % of the parishes covering 84 % of the population in mainland Portugal have technical

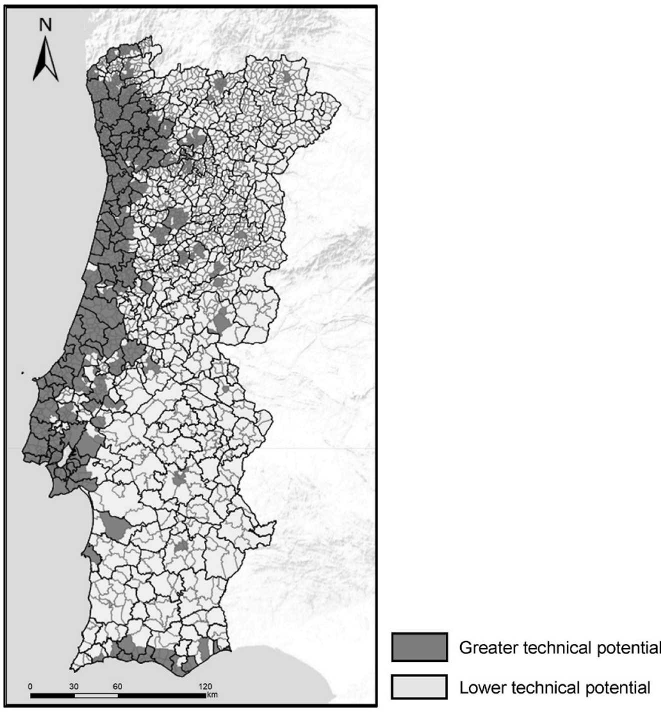

Fig. 6. Parishes on the Portuguese mainland (gray line), within municipalities (black line), classified as having higher potential for implementing a selective collection system (darker color) and lower potential (lighter color).

potential to implement a selective biowaste collection system. This results in an expected annual collection amount of 672 000 tonnes for this waste stream, assuming a capture rate of 50 %. The remaining parishes may consider derogation supported by the quantitative analysis of the proposed methodology.

5. Conclusions

This work responds to EU Directive 2018/851, which mandated separate biowaste collection, allowing territorial derogation where unsustainable. The methodology evaluates the technical feasibility of implementing separate biowaste collection systems using commonly available data. Applied to mainland Portugal, this study identified parishes suitable for separate biowaste collection by combining two indicators: "Artificial Urban Area" and "Generation". By considering built-up areas associated with potential biowaste collection per day, the analysis showed 1274 out of 2881 parishes are suitable for separate collection, representing 85 % of total biowaste generation. Results align with expectations: areas with the greatest technical potential are primarily in the coastal zone.

This methodology is designed to be applicable at any geographical scale and incorporates both qualitative and quantitative analyses to validate key assumptions, with stakeholder engagement playing a central role. In the case study, stakeholders input clarified the suitability of a municipality for biowaste selective collection that was initially considered unsuitable.

It should be noted that the methodology relies on certain assumptions, such as a capture rate of 50 %. If these are not met or if waste management entities' policies differ (especially, regarding circular economy and environmental sustainability) suitability assessment may be affected and the proposed decision-making process must be redone.

While this study focus on technical factors, future work will address these limitations by incorporating economic and environmental assessment to provide more comprehensive support for decision-making.

CRediT authorship contribution statement

João Brito Ana: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rodrigo Moreno:** Resources, Methodology, Investigation, Conceptualization. **Maria Isabel Gomes:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Ana Silveira:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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