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Advanced food waste quantification at municipal level to strengthen the assessment of prevention actions

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Food loss and waste (FLW) demands urgent attention: over 58 million tonnes wasted annually in the EU, while 828 million people face hunger worldwide. SDG 12.3 targets a 50% reduction in FLW by 2030, requiring rigorous quantification. Governments must quantify FLW, especially at the consumption stage, where most of FLW is generated. However, the limited granularity of existing data emphasises the need for improved quantification methods that enable reliable comparisons and set solid basis to measure the impact of future FLW prevention actions. This paper proposes a FLW quantification methodology at municipal and regional scales aligned with the existing urban waste management requirements. The methodology involved experts and stakeholders to define the optimal FLW quantification framework and measurement method. It was validated in 6 Basque municipalities with a common waste characterisation matrix to compare waste fractions, generator types and waste collection systems. A cartographic analysis, from regional to street level, demonstrates how data granularity shapes FLW pattern interpretation. As in the case of Zamudio, where data at container level permits detailed insights. This approach enables improved waste collection and the design of ad-hoc FLW prevention actions (like economic instruments) according to the generator profile and type of FLW.

Keywords Food waste, Food waste quantification, Waste prevention, Waste management, Circular economy, Sustainability

The problem of food loss and waste (FLW) is well-recognised as a global sustainability issue. This food challenge is one of the biggest problems humanity will face in the following decades. Within the European Union (EU), 132 kg of FLW per capita are generated annually, with the household stage accounting for 54% of it[1]. In absolute terms, more than 59 million tonnes of food are being wasted every year only in the EU[1]. This contrasts to the fact that 828 million people suffer from hunger worldwide[2], even as the global population will be about 9.73 billion people by the year 2050[3]. It is estimated that in order to satisfy the food requirements of such a population with the current agricultural area and a rising resource depletion, the production of food will have to be increased by 50% with respect to that of the year 2019[4]. Nevertheless, achieving such an increase presents several challenges. The availability of arable land per capita is steadily declining due to urbanisation and land degradation[5]. By 2050, opportunities for agricultural expansion will be limited, making it necessary to enhance productivity on existing farmland. Additionally, climate change is expected to exacerbate extreme weather events, disrupt rainfall patterns, and increase pest and disease outbreaks, all of which negatively impact crop yields[6]. Addressing these challenges will require agricultural intensification through innovative technologies and practices such as genetically modified crops, precision farming, and soilless cultivation methods like hydroponics and aquaponics[7]. Beyond food production, water scarcity presents another major concern. As of 2019, 25% of the global population faced water shortages[8]. By 2050, this number is expected to rise to 2 billion people across 44 countries, with 95% of those affected living in developing regions[9]. Since agricultural activities account for a significant share of global water consumption, increasing food production will further strain this already scarce resource.

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From an environmental perspective, the food sector is already recognised as a significant contributor to global warming[10], water usage[11] or land exploitation[12]. In particular, the lifecycle of FLW alone, from production to disposal, is responsible for around 186 million tonnes of CO_2 eq in Europe annually[13]. Reducing FLW is therefore essential for improving environmental sustainability and minimising humanity's overall footprint. Agriculture, in particular, is a major contributor, accounting for 86% of the global water footprint[14] and around 13.5% of human-induced greenhouse gas emissions[15]. Economically, the mismanagement of FLW leads to considerable financial losses, ultimately driving up food prices[16], while socially, it worsens food insecurity and deepens existing social disparities[17].

Accordingly, SDG 12.3 aims to achieve by the year 2030 a 50% reduction in FLW. In the European context, the European Commission promotes this objective through the Farm to Fork strategy[18]. To achieve this, FLW quantification is an essential first step to establish the baseline and measure progress. In this regard the publication of the EU Commission Delegated Decision 2019/1597[19] set a milestone for the standardised quantification of FLW across the EU. It obliges Member States to report the annual amount of FLW they generate throughout the whole food supply chain, from primary production to the consumption stage. As a result, EU Member States are now required to measure and report FLW data annually, leading to a rise in research studies and FLW data collection efforts across the region. This quantification of FLW has already provided valuable insights. For instance, a study analysing eight years of FLW data from Sweden's public catering services observed a 15–30% reduction in FLW, demonstrating that achieving the 2030 target is feasible with effective interventions[20]. Similarly, in Germany, a comprehensive study estimated that approximately 11.9 million tonnes of FLW were generated in 2015, highlighting the need for ongoing monitoring and targeted reduction strategies[21].

In addition to large-scale efforts, understanding citizens' behaviour is crucial in addressing FLW, since the household stage is the main contributor to FLW generation[1]. Consumer attitudes, perceived control, and intentions are critical factors influencing FLW. Research has shown that perceived control can lead to a significant reduction in household FLW, emphasising the importance of empowering consumers with the knowledge and tools to manage their food more effectively[22]. Furthermore, cultural and psychological factors, such as materialism and individualism, play a role in shaping ethical norms and behavioural intentions towards FLW[23]. The Theory of Planned Behaviour has been widely applied to study FLW behaviour, demonstrating that attitudes, subjective norms, and perceived behavioural control are strong predictors of FLW tendencies[24,25].

Another key reason for focusing on the consumption stage is that environmental benefits are maximised since end-of-chain waste embodies higher cumulative resource and emission footprint[26]. Moreover, the implementation of FLW prevention at this stage yields higher environmental benefits, even when accounting for rebound effects[27].

So, to quantify this FLW at the consumption level, the EU Commission Delegated Decision 2019/1597[19] permits three methods: waste composition analysis (WCA), surveys and diaries. While surveys and diaries are powerful tools to study consumer behaviour[28], they are not the most adequate methods to measure the actual amount of FLW generation because they lead to underestimations[29,30]. The rationale behind these underestimations lies mainly in: (1) these consumers are voluntary participants who are usually individuals already concerned about the topic and thus not a representative sample of the population, and (2) the bias introduced due to consumers feeling observed leads them to perform better than they normally would. Moreover, in the case of surveys, reliance on memory can introduce inaccuracies[31], while variations in survey techniques and definitions of FLW can lead to incomparable results across studies, complicating efforts to generalise findings or compare data across different regions or populations[28]. Diaries, on the other hand, can lead to a prevention effect, where participants waste less food (even reaching a 20% FLW reduction) simply because they are more aware of their actions[32]. Apart from that, diaries are not usually employed during extended periods and thus fail to capture long-term FLW patterns[33].

That is why WCA is a more objective way to carry out this measurement properly and discern specific attributes such as the proportions of edible and inedible FLW[34]. Its robustness has been validated in studies such as the one conducted by Silvennoinen et al. (2022)[35], which consistently measured FLW across different urban areas, confirming its reliability for both mixed and biowaste flows. Nevertheless, not all municipalities characterise waste in the same way, and the diversity in waste collection methods and types of generators further affects the results. Consequently, these analyses are not always comparable, highlighting the need for standardisation to assess FLW generation reliably, as also pointed out by Withanage et al. (2021)[28]. In addition, this data on FLW generation is mainly presented in the literature at a macro scale, resulting in limited data granularity and increased uncertainties in calculations[36]. To enhance the precision of FLW quantification, it is fundamental to improve the process at lower scales. Smaller-scale quantification allows for the identification of specific waste generation patterns and hotspots. This granularity enables the design of targeted FLW prevention actions that are more likely to be effective[38,39]. Therefore, measuring FLW not only at the municipal level but also at the street level, where feasible, is crucial for setting and subsequently assessing the effectiveness of FLW prevention actions accurately[40]. In this research field, a notable contribution includes the work of Baquero et al. (2022)[37], who propose a methodology employing multiple linear regression analysis to estimate municipal-level biowaste generation. It considers regional characteristics, with particular emphasis on the level of rurality. Yet its robustness could be improved as different types of waste generators seem to be overlooked in the waste characterisation, which entails a significant error.

Given this context the present research paper aims to answer the following research question: What is the most suitable FLW quantification methodology for assessing FLW generation patterns at regional and municipal levels, ensuring applicability to any municipality and ultimately enabling the measurement of the impact of future FLW prevention actions? With this approach, the study aimed to accomplish the following secondary objectives:

- To select the most adequate FLW quantification method to measure FLW generation patterns at the municipal level.
- To apply such a FLW quantification method to different municipalities in the regions of: Gipuzkoa and Bizkaia.
- To assess FLW generation patterns in both case studies at the highest spatial resolution possible, thereby enabling the identification of local hotspots and supporting the design and evaluation of targeted FLW prevention interventions.
- To benchmark the proposed FLW quantification methodology by comparing its FLW generation pattern results with those obtained in other studies using the other applicable methods outlined in the EU Commission Delegated Decision 2019/1597.

The research activity conducted to achieve the goal of the study was done in collaboration with the Department of Environment and Hydraulic Works of the Provincial Council of Gipuzkoa and the municipality of Zamudio in the Bizkaia province. This close cooperation with public authorities, particularly in the waste management sector is a key strength of this study. This collaboration not only enriched the analysis with first-hand operational data but also allowed for a more practical evaluation of FLW generation patterns, integrating industry-specific challenges and best practices into the assessment, as well as its alignment with other legal requirements in terms of urban waste management.

Methodology

In order to achieve the above-mentioned objectives, the work carried out has been structured in the following 5 key points, which also define the subsections of this section: (2.1) Selection of the FLW quantification method including a common terminology about FLW; (2.2) Validation of the WCA methodology with real case studies; (2.3) Estimation of the FLW generation patterns in each case study from urban waste generation data; (2.4) Geospatial analysis of FLW generation; (2.5) Comparison with other FLW quantification methods.

Detailed descriptions of the waste characterisation protocols (separately for Zamudio and Gipuzkoa) are provided in Annex I.

Selection of the FLW quantification method including a common terminology about FLW

In order to select the most appropriate FLW quantification method a co-creation process was carried out involving professionals specialising in FLW quantification (experts) and municipal or regional representatives directly involved in FLW management (practitioners).

First, a literature review of municipal-level methodologies for quantification including scientific literature, legal framework at the EU level and technical reports was conducted. The aim was twofold:

1. Identify the main discrepancies in terms of terminology to set a common quantification framework.
2. To assess the applicability of the 3 most commonly used methodologies (diaries, surveys and waste composition analysis).

This literature assessment allowed us to identify the main gaps that were organised in the form of the research questions that were later discussed during the workshop. Details about the workshop structure along with the full list of questions and answers is provided in Annex II. The possible answers for the definitions were those derived from the literature. However, references were intentionally omitted during the workshop to prevent biasing the respondents.

The workshop concluded with a plenary session, where representatives from each group summarised their discussions and key findings, highlighting unresolved questions that required further investigation.

All participants provided informed consent prior to the workshop, in accordance with ethical guidelines. The study's experimental protocol was approved by the University of Deusto.

Validation of the WCA methodology with real case studies

As explained in the Results and discussion section, WCA was indeed the selected method for the purpose of the real case study. Consequently, the next step in this study consisted of analysing and comparing two WCA methodologies for assessing FLW generation patterns, leading to the development of a standardised WCA methodology. The application and validation of this protocol using real-world data from municipal case studies further reinforce the robustness and practical applicability of our approach. The original WCA methodologies from the case studies are based on the characterisation of municipal waste generated at regional and municipal levels in the Basque Country (Spain) led by the corresponding public administrations for different approaches to improve the urban waste management systems.

Case studies

The six analysed municipalities (Fig. 1) include Zamudio in Bizkaia and Deba, Mutriku, Mendaro, Beasain, and Donosti in Gipuzkoa (Basque Country, north of Spain). These case studies exhibit quite distinct characteristics that enhance representativeness and provide a heterogeneous sample for the study, thereby enriching the analysis through a broader coverage of varying waste generation patterns and practices. However, this heterogeneity also poses challenges for direct comparability between municipalities. To address this, the key characteristics of each municipality are summarised below and considered in the discussion of the results. Zamudio is a highly industrialised municipality, with a GDP per capita exceeding €450,000. Alongside Zamudio, the municipalities of Deba, Mendaro, and Mutriku are characterised by relatively low populations, all with fewer than 5,500 inhabitants. These three municipalities, along with Beasain, are predominantly rural compared to Zamudio and

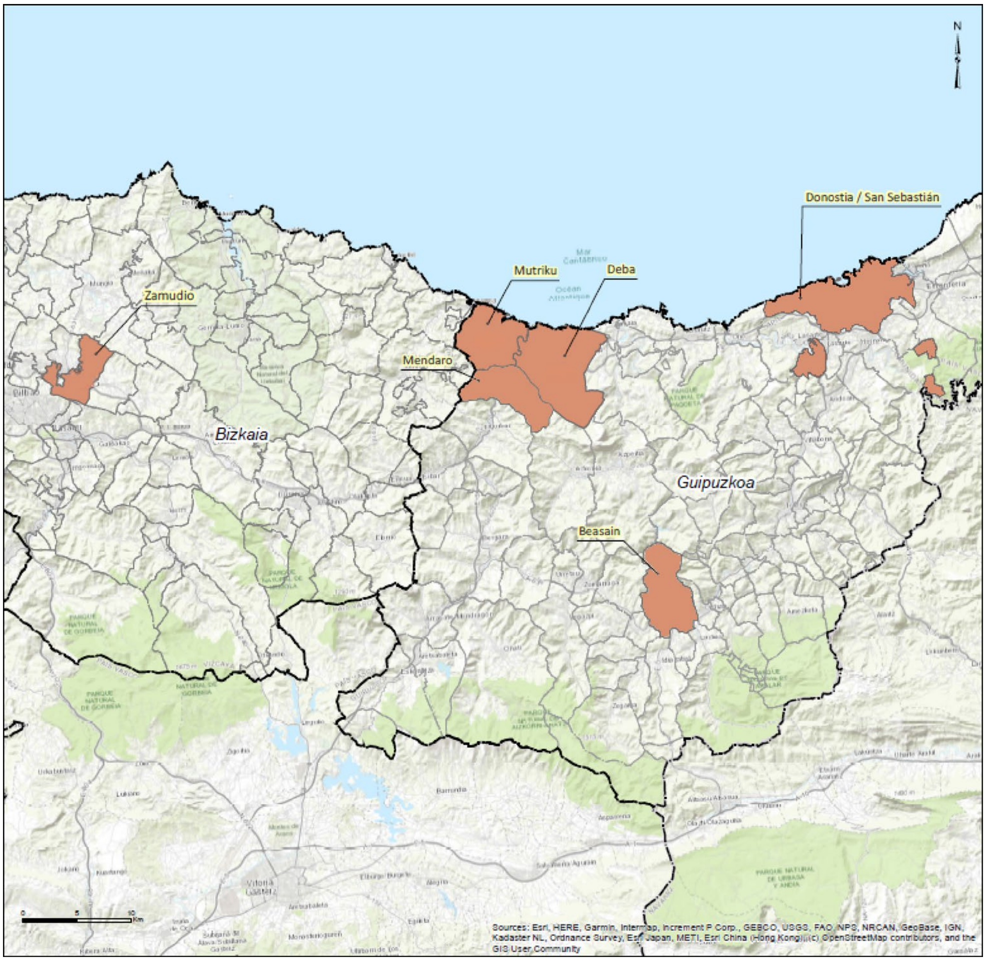

Fig. 1. Municipalities analysed in the case studies (Basque Country).

Donosti, with less than 5% of their land classified as urban. However, Beasain exhibits a significantly higher population density (460,000 inhabitants/km2). In contrast, Donosti stands out as a larger city, with a population exceeding 180,000 inhabitants and practically no primary sector activities. All data referenced here is sourced from Udalmap[41]. Regarding the waste collection system, in the six municipalities it is based on 5 main fractions: organic, packaging, paper and cardboard, glass, and residual waste.

Data sources
The comparative analysis begins with the utilisation of available data within the case studies regarding urban waste characterisation and waste generation. The details of these available datasets and their respective data sources are provided below:

- Waste characterisation sample data for organic and remainder fractions in Zamudio (Bizkaia) from industrial, residential, and commercial generators in 2022. Source: The FOODRUS project[42].
- Waste characterisation sample data for organic waste bags from households in 5 municipalities of Gipuzkoa (Beasain, Mendaro, Deba, Mutriku, and Donosti) in 2022. Source: Provincial Council of Gipuzkoa.
- Waste characterisation sample data for the remainder fraction from various truck routes from industrial, urban, rural, and commercial generators in Gipuzkoa collected in 2022. Source: Provincial Council of Gipuzkoa.
- Container waste generation data in Bizkaia in 2022. Source: Bizkaia Waste Observatory[43] and the FOODRUS project[42].
- Container waste generation data in Gipuzkoa in 2022. Source: Observatory for the Prevention and Management of Urban Waste in Gipuzkoa[44].

The waste collection routes were organised so that each route serves only one generator category (residential, commercial, or industrial), ensuring clear attribution of waste sources. It is also noteworthy that in both regions biowaste separate collection is in place. Due to the still low separation rates, residual waste fraction has been included in the study.

All this data showcased a considerable heterogeneity since it came from different data sources, which hindered the comparison exercise. For this reason, the definition of a common waste characterisation matrix was deemed essential to enable a comparative data analysis of both provinces. This matrix would allow the subsequent adaptation of the original characterisation matrices from Zamudio and from Gipuzkoa to make them comparable. In order to carry out the study and be able to design a common characterisation matrix, the smallest possible groupings were made in order to keep the waste classification as detailed as possible without losing information. For this purpose, the criterion employed was to use the most restrictive initial characterisation (lowest level of disaggregation) to create the different groups.

After constructing the common waste characterisation matrix, the initial data were adapted for analysis and comparison. To begin with, the characterisation sample data for Zamudio was obtained from 2 different campaigns carried out in different waste containers in the municipality. Each campaign has several samples taken from different containers and, in addition to the kilograms of waste obtained from the characterisation, the samples have the following information:

- Nº characterisation campaign (1st campaign or 2nd campaign).
- Waste characterisation circuit ID (industrial, commercial and residential).
- Acceptance date and time.
- Origin. Classification according to fraction and generator. The following categories are distinguished:
  - Industrial organic, commercial organic, and residential organic.
  - Industrial paper and cardboard, commercial paper and cardboard, and residential paper and cardboard (not included in this analysis).
  - Industrial remainder, commercial remainder, and residential remainder.
- Vehicle license plate.
- Batch ID.
- Amount unloaded (kg).

In Gipuzkoa's case, the separate waste collection circuits used to calculate the generation of residential organic waste were, as follows:

- Total household and community composting.
- Biowaste. Only what is considered household waste:
  - Fermentable organic waste collected door-to-door.
  - Fermentable organic waste collected in the 5th bin.
  - Fermentable organic waste from mixed collection systems.
  - Non-regular fermentable organic waste (e.g., parties and meals).

Data for the remainder fraction in Gipuzkoa was obtained from 71 samples taken from different truck routes in the province. They specify:

- Commonwealth to which the sample belongs.
- Collection system (door-to-door, open containers, closed containers, etc.)
- Generator type (urban, industrial, commercial, rural, mixed…).
- Waste circuit to which the sample belongs.

Estimation of the FLW generation patterns in each case study from urban waste generation data

In order to analyse the information, the aggregated characterisation sample data of the different campaigns was grouped on the basis of the specified generator (industrial, commercial and residential) and the fraction (organic and remainder). To do this, the initial characterisations for Zamudio were reorganised according to the newly established common waste characterisation matrix in order to standardise the data across Zamudio and Gipuzkoa, because Gipuzkoa's characterisations were originally more aggregated (i.e., included fewer waste categories), necessitating the adaptation of Zamudio's data. Subsequently, the percentage of each waste category specified in the characterisation was recalculated. The average characterisation values were then calculated based on the waste generator type and waste fraction. With this data, the percentage of FLW generated (edible and inedible) by waste fraction and generator can be extrapolated to the waste generation data for the organic and remainder fractions of Bizkaia's annual data, specifically for the municipality of Zamudio in the year 2022. This analysis was conducted utilising available information at waste container level. The calculation procedure once Zamudio's characterisation matrix was adapted to the common characterisation matrix is summarised in Eq. (1):

$$FLW_{Municipality} = \sum\nolimits_{g=1}^{G} \sum\nolimits_{f=1}^{F} \left(\frac{\sum\nolimits_{i=1}^{N} FWCP_{g,f,i}}{N_{g,f}} \times WG_{Region,g,f} \right) \quad (1)$$

Where:

- $FLW_{Municipality}$ = Total FLW generated in the municipality (edible and inedible).
- G = Number of generator types (industrial, commercial, residential).
- F = Number of waste fractions (organic, remainder).
- $FWCP_{g, f,i}$ = Food Waste category percentage for generator type *g*, fraction *f*, and characterisation *i*.

- $N_{g,f}$ = Total number of characterisations for generator type *g* and fraction *f*.
- $WG_{Region, g,f}$ = Annual waste generation data for the region, for generator type *g* and fraction *f*.

So, in the case of Zamudio, its FLW generation ($FLW_{Zamudio}$) is calculated with the $WG_{Region, g,f}$ of Bizkaia.

In the case of Gipuzkoa, the calculation was performed for each of the five selected municipalities and then aggregated at the regional level, making the procedure slightly different. While different data sources were available for the organic and residual fractions in Gipuzkoa, the same formula was applied for the calculation, as shown in Eq. (2):

$$FLW_{Region,f} = \sum_{m=1}^{M} \sum_{g=1}^{G} \left(\frac{\sum_{i=1}^{N} FWCP_{g,f,m,i}}{N_{g,f,m}} \times WG_{Region,g,f,m} \right) \quad (2)$$

Where:

- $FLW_{Region, f}$ = Total FLW generated in the region (edible and inedible) for the 5 analysed municipalities for waste fraction *f*.
- M = Number of municipalities (Beasain, Mendaro, Deba, Mutriku, Donosti).
- G = Number of generator types (industrial, commercial, residential).
- $FWCP_{g, f,m, i}$ = Food Waste category percentage for generator type *g*, fraction f, municipality *m*, and characterisation *i*.
- $N_{g, f,m}$ = Total number of characterisations for generator type *g*, fraction *f* and municipality *m*.
- $WG_{Municipality, g,f, m}$ = Annual waste generation data for generator type *g*, fraction *f* and municipality *m*.

In the case of the organic fraction in Gipuzkoa, the characterisation sample data (used to calculate $FWCP_{g, f,m, i}$ and $N_{g, f,m}$) were collected from 150 bags of organic waste from households in 5 different municipalities in the province: Beasain, Mendaro, Deba, Mutriku and Donosti. The entire sample corresponds to residential organic waste, so only one generator type would be involved in this case. Then, a similar procedure to that used for Zamudio's data was followed to estimate the residential organic waste generation. First, the initial characterisation defined in Gipuzkoa was adapted to the common waste characterisation matrix. Secondly, the percentage of each waste category ($FWCP_{g, f,m, i}$) was calculated for every bag and then averaged over all the bags corresponding to the same municipality. This method enables the calculation of the average percentage of each waste category in each of the 5 municipalities, which can then be extrapolated to their waste generation data ($WG_{Gipuzkoa, g,f, m}$).

The same process as in Eq. (2) was applied to calculate the FLW coming from the remainder fraction. Initially, the different waste categories were grouped based on the common characterisation matrix. Subsequently, the percentage of each waste category (FWCPg, f,m, i) from the characterisation was calculated for each sample. The samples were then grouped according to the corresponding municipality, collection system, and type of waste generator. Finally, the average weight of each waste category was determined for each group. These data were then extrapolated to the waste generation data for Gipuzkoa in 2022, categorised by municipality and generator type (WGGipuzkoa, g,f, m). In order to match the characterisation sample data with the generation data, the waste collection circuits served as a key reference for matching.

To perform a municipal comparison with respect to the other case study (in Zamudio), the characterisation information of FLW (at the commonwealth level) was extrapolated to the 5 municipalities for which information on the organic fraction was available. This enabled the determination of the FLW proportion attributed to each municipality. By considering the waste characterisation and generation data of each commonwealth alongside the municipalities' population within the commonwealths, municipal-level information was obtained for the 5 municipalities with data on organic waste bags. Consequently, the final figures for FLW (both edible and inedible) from the organic and remainder fractions were derived for 6 municipalities: Zamudio in Bizkaia, and Beasain, Mendaro, Deba, Mutriku, and Donosti in Gipuzkoa.

Geospatial analysis of FLW generation

With the data gathered from the previous stages of the methodology, the final phase involves conducting a spatial and cartographic analysis of the generated data. ArcGIS 10.8.1 software was utilised for this purpose. Prior to this analysis, a preliminary phase was undertaken to adapt the information on FLW generation to the software's visualisation requirements. Maps for Zamudio exhibited higher granularity, given that the availability of data was at the container level. Conversely, data for the Gipuzkoa municipalities could only be detailed at the municipal level due to the lack of more specific information. Due to these limitations in Gipuzkoa's data, the comparative spatial and cartographic analysis across all municipalities (the 5 municipalities of Gipuzkoa alongside Zamudio) was feasible only at the municipal level.

Comparison with other FLW quantification methods

To address the last secondary objective of the study, FLW generation was calculated on a per-household basis to facilitate comparison with the findings of Elika et al. (2023)[46], who assessed FLW across the Basque Country using the other 2 possible FLW quantification methods for the consumption stage: questionnaires and diaries. In their study, Elika et al. (2023)[46] assumed an average of 2.85 people per household, a factor that was applied to the results of this paper to ensure comparability. This comparative analysis was only conducted based on one of the generators (residential) for various reasons. To begin with, there is a lack of data in the characterisation of the commercial sector (HORECA and retail) in Gipuzkoa. Secondly, at the industrial level, the Elika et al. (2023)[46] report only considers the primary sector, the agri-food chain, and the manufacturing industry as sources of FLW generation, whereas the waste characterisations carried out in the present research work encompass the entire industrial sector. So, the comparison of the results from both studies for commercial and industrial generators would not be adequate.

Results and discussion

The results and discussion are outlined below similarly to the methodology, ensuring a clear and logical presentation of findings.

Selection of the FLW quantification method including a common terminology about FLW

A total of 19 individuals from 7 different European countries attended the online workshop on FLW quantification methods at the municipal level.

The majority of participants favoured the FUSIONS definition of food: "Any substance or product, whether processed, partially processed, or unprocessed, intended to be, or reasonably expected to be, ingested by humans"[47]. This definition introduces a subjective component, recognising that cultural influences shape what is "reasonably expected" to be eaten. Similarly, for the definition of edible food, the most selected response was: "Edible food parts are the components associated with food, in its fresh mass status, that are usually consumed by humans in the Member States, either as is (raw consumption) or after processing or cooking"[48]. For inedible food, the chosen definition was the broadest: "Those parts associated with food that are not intended to be consumed (such as bones, eggshells)"[49]. This contrasts with the more specific definitions provided by the FLW protocol and FUSIONS, which emphasise the influence of cultural and technological factors on what is considered inedible. Regarding food loss, the preferred definition was: "Decrease, at all stages of the food chain prior to the consumer level, in mass, of food that was originally intended for human consumption, regardless of the cause"[50]. Responses to the definition of food waste were more evenly distributed among HLPE, FAO, and FUSIONS. Most participants agreed that food waste only occurs at the consumption stage, emphasising the challenge of effectively communicating these definitions to the general public. The discussion on FLW quantification underscored the importance of precise terminology for comparability. In contrast to the EU Commission Delegated Decision 2019/1597, the majority of respondents supported the inclusion of pre-harvest losses in food loss quantification, arguing that these losses should still be considered part of the food supply chain.

When asked about the most appropriate quantification methodology at the municipal level, the majority initially favoured a combination of all three methodologies. This question was later repeated (Question 16) to assess any shift in perspective, but the results remained largely unchanged.

Participants also discussed the challenge of measuring liquid FLW. While they acknowledged its relevance, no clear methodology was proposed for its quantification. Experts unanimously supported the differentiation between edible and inedible food during quantification. Practitioners also recognised its feasibility in practical applications. However, opinions were more divided regarding the distinction between cooked and uncooked food.

Detailed workshop findings on relevant FLW prevention aspects, the ideal survey design, and the ideal diary design are provided in Annex II[58].

Last, the session dealing with WCA started by emphasising the importance of studying a broad range of geographic scales and directly analysing waste from households and HORECA establishments. Key demographic factors identified for sample selection included household size, rural/urban classification, and age. Participants agreed that FLW sources should be distinguished based on origin (e.g., households vs. HORECA establishments), although they were divided on whether edible and inedible food should be separated. Seasonal sampling, conducted four times per year, was deemed essential for representativeness. However, while experts advocated for measuring all waste collection fractions separately, practitioners raised concerns about the associated costs. Most respondents agreed that FLW found in packaging should be extracted and measured separately to improve accuracy. However, there was little support for differentiating FLW by specific categories, as it would add unnecessary complexity. In the final discussion, participants highlighted the importance of establishing standardised characterisation protocols and considering waste homogenisation to improve representativeness. They also noted the potential for integrating waste composition analysis with biowaste separation studies to enhance efficiency and data quality. Overall, the workshop underscored the importance of context-specific methodology selection, balancing data precision with practical feasibility, and fostering greater collaboration between stakeholders to improve FLW measurement and prevention.

Validation of the WCA methodology with real case studies

As a result of the comparative analysis of waste characterisation data from both Gipuzkoa and Zamudio, a standardised waste characterisation matrix was developed to ensure consistency in FLW assessment across the case studies. This matrix comprised 28 distinct waste categories, which is explained in Annex III.

Estimation of the FLW generation patterns in each case study from urban waste generation data

From a statistical perspective, the datasets collected in Gipuzkoa for waste characterisation (150 organic fraction samples and 71 remainder fraction samples) yield accepTable 97.5% confidence intervals as shown in Table 1, confirming the methodology's reliability under adequate sampling conditions. In the case of Zamudio, only 12 samples were obtained for both the organic and remainder fraction characterisations, for which also reasonable confidence intervals were obtained. It must be highlighted that Gipuzkoa's waste characterisation data derive from public data repositories, whereas Zamudio's characterisation data comes from a study that was designed to measure the impact of a PAYT system in the entire municipality. Its sample therefore covered a much larger set

Region	Fraction	Waste category	Mean (%)	Lower confidence limit (%)	Upper confidence limit (%)
Gipuzkoa	Organic fraction	Fruit, vegetables, legumes, cereals, and others	6.846%	5.374%	7.709%
		Cooked meats, fish, dairy, and eggs	4.737%	4.219%	5.532%
		Uncooked meats, fish, dairy, and eggs	0.777%	0.365%	0.973%
		Other food waste (unavoidable)	74.379%	73.441%	77.160%
	Remainder fraction	Fruit, vegetables, legumes, cereals, and others	1.923%	1.645%	2.187%
		Cooked meats, fish, dairy, and eggs	0.146%	0.138%	0.184%
		Uncooked meats, fish, dairy, and eggs	0.169%	0.086%	0.216%
		Other food waste (unavoidable)	4.859%	4.176%	5.254%
Zamudio	Organic fraction	Fruit, vegetables, legumes, cereals, and others	8.555%	6.151%	9.633%
		Cooked meats, fish, dairy, and eggs	0.402%	0.096%	0.705%
		Uncooked meats, fish, dairy, and eggs	0.347%	0.130%	0.674%
		Other food waste (unavoidable)	51.759%	48.723%	54.529%
	Remainder fraction	Fruit, vegetables, legumes, cereals, and others	6.407%	3.292%	8.504%
		Cooked meats, fish, dairy, and eggs	0.140%	0.036%	0.259%
		Uncooked meats, fish, dairy, and eggs	1.409%	0.703%	2.400%
		Other food waste (unavoidable)	11.231%	5.198%	16.314%

Table 1. Mean and 97.5% confidence intervals for FLW categories characterisations samples.

Province	Gipuzkoa					Bizkaia
Municipality	Deba	Mendaro	Mutriku	Beasain	Donosti	Zamudio
Edible FLW (tons/year)	35.10	8.06	46.90	20.02	1,760.43	80.43
Inedible FLW (tons/year)	444.57	109.79	428.92	71.07	5,944.06	219.55
Total FLW (tons/year)	479.67	117.85	475.82	91.09	7,704.49	299.98
% edible FLW	7.32%	6.84%	9.86%	21.98%	22.85%	26.81%
% inedible FLW	92.68%	93.16%	90.14%	78.02%	77.15%	73.19%
Ratio edible/inedible	0.08	0.07	0.11	0.28	0.3	0.37

Table 2. Edible and inedible FLW generation from domestic generators at municipal scale in 2022 in the 6 studied municipalities.

of 545 waste containers. So, even if there were fewer waste characterisation samples in the case of Zamudio, they remain representative of the local waste stream.

Sampling days were selected to reflect typical municipal waste generation, ensuring that characterised samples meaningfully represent daily flows across fractions and generators. Consequently, sample sizes range from 13.62% of the average daily generation for domestic remainder waste to 78.93% of the average daily generation for commercial organic waste. In the industrial remainder fraction, the sample sizes obtained in the 2 sampling days are close to the maximum daily generation value (7,827 kg). For that reason, the average size of the characterised sample is 378.94% of the average daily industrial remainder generation.

When expressed as a proportion of truck load, the average characterised sample size ranges from 22.22% of the truck's average load for domestic organic waste, to 76.12% for industrial organic waste. For the industrial remainder fraction, the sample size is only 3.93% of the average 6,010 kg truck load, since in Zamudio's case the average characterised sample weighs 201.79 kg. This sample weight follows the characterisation protocol (see Deliverable D1.1, Annex VI of the FOODRUS project[45]), in which details about homogenisation procedures to ensure representativeness can be found.

Additionally, data variability may arise from measurement system adjustments, misidentification of waste fractions at containers, or atypical generation on the selected sampling days.

The FLW generation results, derived from the organic and residual waste fractions in the case studies, are presented at 2 geographical scales: municipal level (aggregated data) and street level (disaggregated data). At the municipal level, the final outputs of the estimated FLW generation from domestic generators in the 6 assessed municipalities are showcased in Table 2. This table focuses on the domestic generators since in Gipuzkoa waste characterisation data was only obtained for this generator type.

Mendaro appears to have the best performance in FLW prevention, with only 6.84% of the FLW generated being edible. However, this interpretation requires careful consideration of the differences in data quality and collection methodologies across municipalities. A key factor influencing FLW percentages is the level of traceability and granularity in data collection. Zamudio, for example, benefits from superior data quality due to its waste traceability system, which differentiates between residential, HORECA, and industrial waste streams. This allows for more precise quantification of FLW sources, reducing the risk of underreporting edible FLW. Conversely, Gipuzkoa's municipalities utilise a door-to-door organic waste collection system, which encourages better waste separation at the source and likely reduces the proportion of edible FLW discarded in mixed waste streams. Thus, when municipalities employ more precise and transparent measurement methods, it may falsely suggest worse performance in FLW prevention simply because their systems capture a more accurate picture of waste generation. Therefore, there is a necessity for policymakers to establish minimum data quality standards required from reporting entities. This is particularly relevant in the context of the FLW quantification task outlined by the EU Commission Delegated Decision 2019/1597[19]. Ensuring standardised waste characterisation prevents underreporting by low-quality data and avoids penalising entities that use more rigorous methods. Moreover, the significant differences in FLW composition between smaller municipalities like Mendaro and larger urban centres like Donosti (where edible FLW accounts for 22.85%) suggest that factors such as population density, waste management infrastructure, and socio-economic conditions also play a crucial role in shaping FLW generation patterns. Overall, these findings underscore the importance of considering data collection methodologies, waste management policies, and local contextual factors when interpreting FLW performance at the municipal level. Without accounting for these differences, direct comparisons of FLW generation between municipalities (which this study does not intend, as its focus is on evaluating quantification methodologies) could lead to misleading conclusions about their effectiveness in FLW prevention.

To conduct a fairer comparison by removing the effect of the population size, the results were normalised based on the population of each municipality obtaining the domestic FLW generated per capita. These results are shown in Fig. 2 for a one-week period.

As shown in the figure, again Zamudio appears to be the municipality with the highest waste generation when expressed in mass per capita. On the other hand, Donosti, which is the largest municipality in the sample, demonstrates a significantly better performance. However, it is still notably outperformed by Beasain, which stands out for a remarkably lower value than the average. This municipality has the lowest proportion of HORECA establishments with respect to its population among the six studied[41], which may partially explain these results.

Extrapolating the weekly FLW generation data to a yearly per capita basis and comparing it with the EU average of 132 kg/person·year[1] reveals that even the highest measured value among the evaluated municipalities (Zamudio, at 92.04 kg/person·year) falls well below the EU benchmark. The weekly FLW values per person are 1.71 kg in Deba, 1.15 kg in Mendaro, 1.73 kg in Mutriku, 0.13 kg in Beasain, 0.79 kg in Donosti, and 1.77 kg in Zamudio. These discrepancies can be partly attributed to the fact that not all stages of the food supply chain are captured by municipal waste collection systems. For instance, in a highly industrialised municipality like Zamudio, FLW generated during primary production, particularly on farms that supply the local population, is often not collected by the municipality and thus remains unquantified. Consequently, while these municipal figures provide valuable insights into urban FLW patterns, they likely underestimate total FLW generation per capita if the FLW generated outside the municipality or region outreach is considered. Additionally, variations in local waste management practices and collection efficiencies further contribute to these lower municipal figures, leading to underestimations when compared with the broader EU context.

Similarly, when examining FLW generation in Asian countries, the average FLW generation is also above the results of the case studies. Saiphet and Kunta (2023)[51] report that the FLW in Thailand amounts to 0.4 kg FLW/person·day, which equals approximately 146 kg FLW/person·year. This higher figure can be attributed both to socioeconomic and methodological differences. The Thai study follows the FLW Standard[52] and incorporates

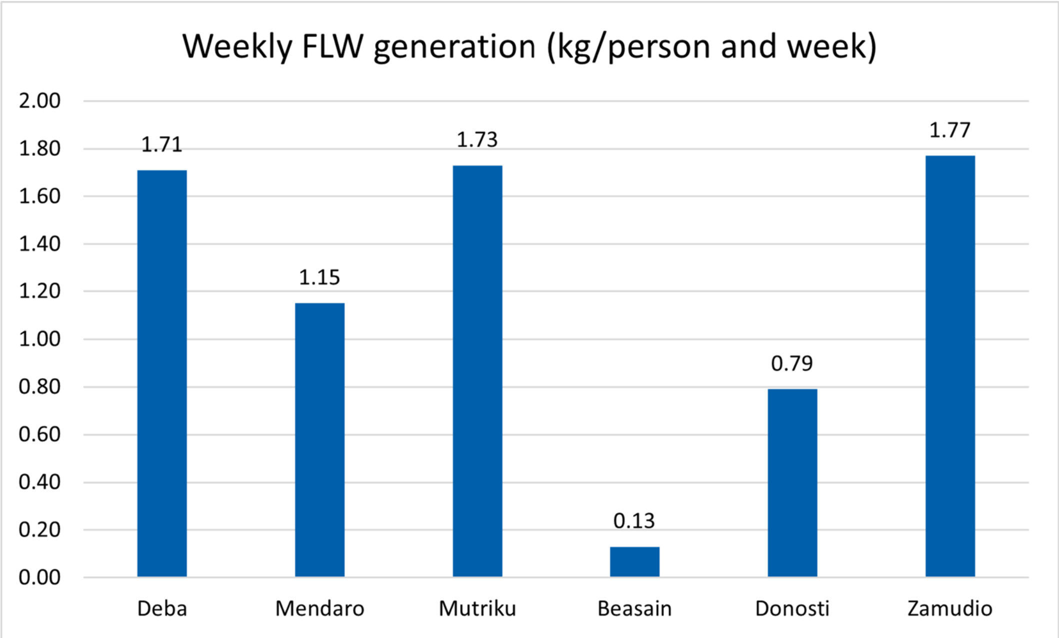

Fig. 2. Weekly FLW generation per capita (kg/person and week).

comprehensive waste characterisation data from 18 government agencies as well as a local solid waste database. Thus, while our study focuses on developing a robust FLW quantification method for municipalities (intended primarily to measure FLW at the municipal level) it is important to consider these methodological differences and the broader context when comparing results across regions.

Geospatial analysis of FLW generation

Moving to a more granular level, in the case of Zamudio, it was possible to assess the results at a more disaggregated scale and reach the street level (container level), thanks to its high data quality in this respect. Using the ArcGIS software, the spatial and cartographic analysis produced the images depicted in Figs. 3 and 4. These figures illustrate the FLW generated within the municipality, with each bubble representing the quantity of FLW in the respective container.

These maps provide a clear overview of the distribution of FLW across the municipality, where even the residential and industrial areas can be distinguished at a glance in Fig. 3. It can be observed that residential FLW contributes the most to the total, being mainly concentrated along the main avenue of the municipality, as well as in more isolated areas on the outskirts, specifically to the north and also to the west of the municipality. These quantities often exceed 2 tons/year for a container, which may be influenced by higher population density, frequent waste disposal habits, or differences in household consumption patterns. Additionally, the presence of multi-family housing units and residential complexes in these areas could contribute to a greater volume of FLW per container. On the other hand, the industrial areas, located to the southeast and west of Zamudio, generate smaller quantities of FLW and in a more distributed manner in the containers. This lower concentration can be attributed to several factors, including the nature of industrial activities, which often involve more controlled food handling processes with lower waste generation, as well as the presence of internal waste management systems or private collection services that prevent large quantities of FLW from entering municipal waste streams. In Fig. 4, it is depicted that the FLW collected in the organic fraction is mainly accumulated in the centre of the municipality, with 3 containers surpassing the threshold of 2 tons/year. This pattern suggests that areas with a higher concentration of commercial establishments, such as restaurants, supermarkets, and food vendors, might significantly contribute to organic FLW. The high accumulation in these containers could also be a result of increased participation in organic waste separation programs or the availability of a more efficient collection infrastructure. At the same time, remainder fraction containers gather FLW from all areas of the municipality in a more dispersed manner, most of which coming from industrial generators. This distribution may indicate that certain types of FLW, particularly from industrial sources, are less systematically sorted into organic collection streams. Additionally, the presence of improper waste disposal practices or insufficient incentives for strict FLW separation could result in FLW being mixed with the general waste fraction.

This geospatial analysis can support a fairer distribution of waste management costs when services are shared across municipalities. Moreover, container-level data makes it possible to identify waste generation patterns at the level of neighbourhoods, streets, or even individual collection points. Such insights facilitate the optimisation of residual and organic waste collection systems by adjusting container volumes and collection frequencies based on actual waste generation. In addition, this approach provides the necessary framework for implementing Pay-as-You-Throw (PAYT) schemes that incorporate waste prevention incentives, as demonstrated

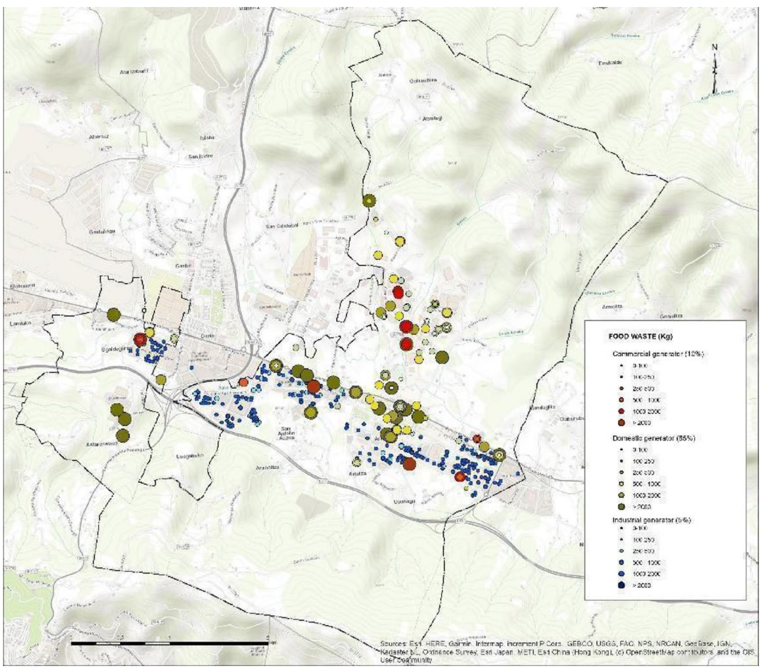

Fig. 3. FLW generation at container level in Zamudio by generator type.

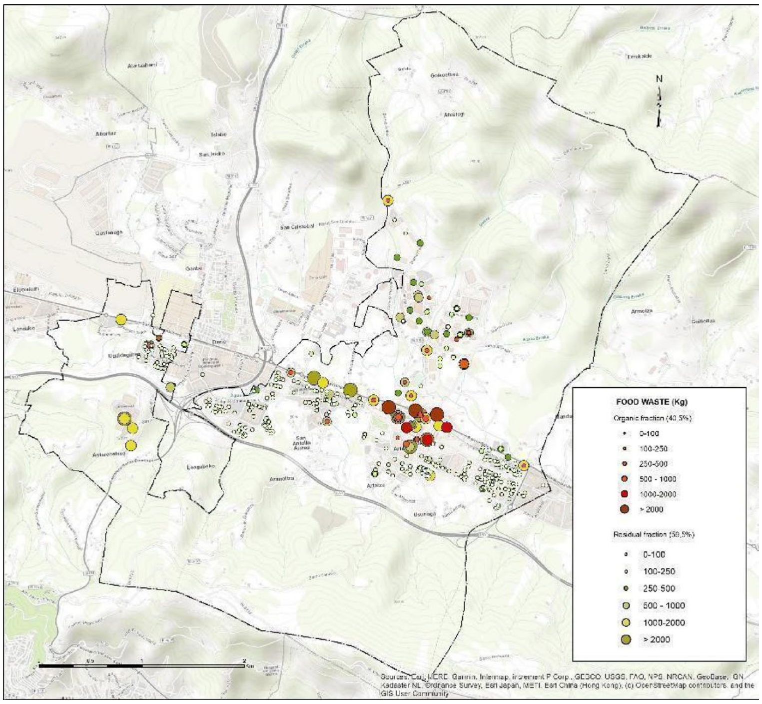

Fig. 4. FLW generation at container level in Zamudio by fraction.

in the case of Zamudio within the FOODRUS project. By integrating PAYT systems with the detailed spatial data, municipalities can tailor FLW prevention actions more effectively to the specific waste profiles of different generator groups. Also, an integrated analysis that includes other waste fractions, such as packaging, should also be considered. The level of non-recyclable materials in this fraction remains high, and a significant portion of packaging waste originates from food products. Examining FLW alongside packaging waste would allow for a more comprehensive assessment of its impact on overall waste generation and provide valuable insights for the development of more effective FLW preventionstrategies.

Building on granular container-level data, municipalities could partner with local food banks and donation centres to target neighbourhoods where edible FLW is most prevalent, optimising collection routes to redistribute food surplus before disposal[53]. This is especially critical given that most edible surplus is not redistributed despite its potential value[54]. Furthermore, this could serve to introduce an edible FLW avoided indicator that quantifies the amount of edible FLW successfully prevented. Such an indicator would provide a more holistic framework for evaluating the sustainability of municipal FLW prevention actions[55].

The robustness of our methodology is supported by its comprehensive evaluation across various waste collection systems and diverse data sources. By incorporating data from multiple municipalities with different waste management practices, our approach has been tested under varied real-world conditions. This validation exercise confirms that our standardised WCA protocol is not only adaptable to different municipal contexts but also provides trustworthy measurements of FLW.

Comparison with other FLW quantification methods

The analysis comparing FLW quantification methods with the findings of Elika et al. (2023)[46] yields several key outcomes. According to the results from Elika et al. (2023)[46], 65.5% of the FLW generated in households is inedible, 24.2% is edible, and around 10.3% corresponds to a mixed group including both edible and inedible. This leads to an edible/inedible ratio of 0.42 ± 0.1, which exceeds the values obtained in the current study with WCA. This is in line with other studies, as the proportion of edible FLW seems to be higher when measured with diaries (52-71%)[56] and surveys (40%)[33] in comparison to WCA (37.7%)[57]. The higher ratio in the referenced report represents the average for the entire Basque Country, where different waste collection systems, along with other factors, influence waste generation and separation. In contrast, the ratio observed in the selected municipalities of Gipuzkoa is significantly lower, largely due to the reduced generation of edible FLW, which is primarily driven by the predominance of the door-to-door collection system in the analysed municipalities. This system not only facilitates more accurate waste sorting but also raises awareness among residents, potentially leading to more conscious food consumption behaviours. Conversely, in Zamudio's case, waste collection is not conducted through the door-to-door system but rather employing the traditional truck collection method. Nevertheless, although Zamudio's results are closer to the ranges established by Elika et al. (2023)[46], a difference remains, with Zamudio reporting 5.05 kg FLW/household·week compared to the 2.89 kg/household·week for Bizkaia. Again, this discrepancy may be partially attributed to the different FLW quantification methodologies employed in each study: Elika et al. (2023)[46] used surveys and diaries while the present study relies on WCA, which tends to capture a more comprehensive and direct measurement of actual waste disposal. Since WCA involves the physical sorting and weighing of waste, it eliminates the bias inherent in self-reported data and ensures a more precise estimation of FLW. However, it also requires more resources and logistical effort, making it less feasible for large-scale continuous monitoring. Additionally, it is important to consider the socio-economic context of the studied areas. Zamudio, as a highly industrialised municipality, has a unique socio-economic profile that may not be fully representative of the average household in Bizkaia. Such a profile influences its food consumption patterns and waste generation behaviours. For instance, the presence of a significant workforce commuting daily to industrial zones might lead to increased FLW from commercial food establishments, rather than from households.

Of course there are limitations that must be considered when interpreting the results. Differences in sample sizes and potential variations in waste circuits across municipalities make it challenging to express results in absolute mass units, affecting the comparability of quantitative data. However, if waste generation data are comprehensive, the proposed methodology can be applied to compare proportions regardless of the initial waste characterisation matrix and data collection method. It should also be noted that anomalies were identified when correlating the collection system and generator type in the characterisation and generation of the residual fraction in certain municipalities of Gipuzkoa (San Markos, Debagoiena, Sasieta, Tolosaldea, and Txingudi). In the waste generation data of these municipalities, some waste categories reported zero kilograms of waste. Nonetheless, the samples collected for waste characterisation, which were deemed most similar to these waste categories based on collection system and generator type, reported having collected waste. These anomalies arise from limitations in the waste generation data, as there are insufficient resources to conduct the exhaustive waste separation and differentiation performed in the waste characterisation. Consequently, in some cases, different types of waste collection systems from each generator were grouped together in the same category. A further general limitation is that achieving full coverage (across multiple municipalities, waste generators, fractions, and collection systems) requires a large number of detailed waste characterisations, which are typically costly and logistically demanding. Case studies with limited resources may therefore need to streamline the characterisation matrix, focusing on the most critical waste categories to reduce costs without sacrificing the data necessary to estimate FLW generation. Furthermore, the inclusion of the plastic packaging fraction in the analysis would be beneficial since elevated quantities of FLW end up in those containers. Moreover, analysing plastic packaging waste disposal habits could help verify whether FLW prevention efforts are indeed working effectively, since a reduction in FLW should also lead, as a result, to a decrease in purchased food. In this article it was not accounted for because of a lack of updated waste characterisation sample data for such a fraction in the studied area. Finally, the comparison between WCA and other FLW quantification methods highlights the strengths and limitations of each approach. WCA provides a direct and objective measurement of actual waste disposal, minimising biases common in self-reported methods such as surveys and diaries. This often results in higher FLW estimates, as seen in Zamudio, where WCA captured more comprehensive data compared to the survey-based results from Elika et al. (2023)[46]. However, while WCA ensures greater accuracy in quantification, self-reported methods offer valuable insights into consumer behaviours and motivations behind waste generation. The choice of method should therefore consider the balance between data precision and the broader contextual understanding of FLW patterns.

Applying this methodology to other geographical or structural contexts would require adjustments based on local waste management practices and data availability. In regions with limited resources, where WCAs may involve fewer waste categories and lower precision, practitioners can focus on the most critical waste fractions related to FLW. For example, simplifying the characterisation matrix to key categories and implementing representative sampling protocols over extended periods could help mitigate issues arising from reduced data granularity. Additionally, integrating complementary data sources (such as local waste collection records or targeted surveys) can further enhance the accuracy of the analysis. Similarly, when geolocation data for waste containers is unavailable, alternative strategies must be employed to approximate spatial distribution. One option is to collaborate with local authorities to obtain existing records or maps of container placements, even if they are not as detailed as those used in this study. Researchers might also consider employing manual mapping techniques, community-based surveys, or leveraging mobile applications to gather approximate container locations. These approaches can provide a viable spatial framework for analysis in contexts where high-resolution geospatial data is lacking. By adopting these adaptive strategies, the proposed FLW quantification methodology can be effectively tailored to various contexts. This flexibility is necessary in such non-optimal cases to enhance the methodology's replicability. Even if the accuracy would not be the same in such cases, it still ensures meaningful insights into FLW generation patterns and represents a science-based starting point to measure the impact of future FLW prevention actions in the municipality.

Conclusion

In conclusion, the results of this study not only have significant implications for the management of FLW in the provinces of Gipuzkoa and Bizkaia, but also provide valuable insights that could be of interest to populations in other regions with similar characteristics. The utilised methodology proves to be capable of measuring FLW generation at regional, municipal and even at container level. Therefore, it allows for comparison of results between municipalities. To implement this successfully, information on FLW definitions utilised, description of the waste fractions considered, and identification of the waste generators and the waste collection systems become necessary.

More specifically, ensuring agreement on definitions is crucial to enable comparability of FLW data across regions. Additionally, food loss occurring at the preharvest phase must be explicitly accounted for, while the quantification of non-solid food remains a significant challenge, with no definitive methodology yet identified. It is also necessary to differentiate between edible and inedible FLW, as well as between food that is technically eatable and food that is practically uneatable. Although distinguishing between cooked and non-cooked food can be useful, it is not a priority for FLW quantification. Regarding the three assessed FLW quantification methods, surveys should ideally cover a one-week period, requiring participants to estimate the amount of food wasted by category, provide reasons for waste from a predefined list, and report their purchasing habits and prevention practices. Diaries, in contrast, should span a two-week period, asking participants to record every instance of FLW, classify it according to predefined categories, and document any prevention actions or waste management strategies used. WCA, as the most objective method, should involve direct measurement of FLW from households and food establishments through different collection circuits to ensure reliable and representative quantification.

Several key aspects were identified as essential for a comprehensive FLW quantification methodology at the consumption stage. A combination of methodologies is recommended to achieve a more complete and in-depth understanding of FLW. However, WCA emerges as the most objective and reliable approach for direct measurement at the consumption stage, as it minimises the biases associated with self-reported methods such as surveys and diaries.

Although different characterisation matrices were used in the two case studies, similar conclusions can be drawn when sufficient information about the origin of the data is available. This includes a clear understanding of the definitions applied, the description of the waste fractions considered, and the identification of waste generators. Establishing a system that allows for accurate identification of waste generation is essential, whether through differentiated waste collection by trucks, as in the case of Gipuzkoa, or through the identification of containers and their users via smart containers, as implemented in Zamudio.

The incorporation of container specific data proves to be advantageous to quantify FLW. Although this equipment implies an additional cost, this approach allows for a more realistic allocation of waste generation, fostering equitable management expenses in services shared in the commonwealth. Moreover, it enables a more comprehensive spatial analysis, identifying patterns at neighbourhood or even street level. This provides potential benefits to improve urban waste management: flexibility to adjust the container volume and collection frequency, the implementation of Pay-As-You-Throw systems (including specific incentives to prevent FLW) as well as planning appropriate FLW prevention campaigns.

Lastly, this research work emphasises the need for a common standard WCA methodology to ensure reliable and comparable data across regions. Establishing a common framework for waste characterisation and measurement is critical for accurately tracking progress towards SDG 12.3 and enhancing FLW mitigation efforts at the municipal level.

Data availability

The authors declare that the data supporting the findings of this study have been properly cited within the paper. Publicly available data include: the socioeconomic indicators of the Basque municipalities extracted from Udalmap (https://www.euskadi.eus/web01-apudalma/es/t64amVisorWar/mapaGeo? lan=0); Bizkaia's total waste generation data extracted from the Bizkaia Waste Data Observatory (https://bizkaikohirihondakinenbehatokia.com/es/observatorio-de-residuos/); Gipuzkoa's total waste generation data extracted from the Provincial Council of Gipuzkoa (https://www.gipuzkoa.eus/es/web/ingurumena/residuos-urbanos/observatorio/datos-gestion); Basque Country's food waste generation data extracted from Elika's reports (https://zerodespilfarro.elika.eus/es/diagnostico-de-despilfarro-en-euskadi/).

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Author contributions
All authors contributed to the study conception and design. Data collection and analysis were performed by Begoña Untzizu Olano Oteiza, Virginia Vargas Viedma and Manuel Amador Cervera. Supervision was performed by Ainhoa Alonso Vicario. The first draft of the manuscript was written by Manuel Amador Cervera and all authors commented on previous versions of the manuscript. The final version was written by Begoña Untzizu Olano Oteiza and Manuel Amador Cervera. All authors read and approved the final manuscript.

Declarations

Competing interests
The authors declare no competing interests.

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