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Smart scale toolset for household food waste estimation

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ABSTRACT

Accurate measurement of household food waste is essential for informed policymaking and effective reduction strategies. Traditional methods – such as questionnaires, food diaries and waste composition analysis – face trade-offs between accuracy, participant burden, scalability and cost. This article presents a novel digital methodology designed to support structured, harmonized and scalable measurement of household food waste in real-life settings. The approach integrates a custom-built smart kitchen scale with a mobile application and a cloud-based portal. The system guides participants through daily waste recording by automatically capturing weight data and allowing users to categorize discarded food by type, avoidability and disposal method. All data is transmitted in real time to a centralized platform, ensuring consistent, high-quality data with minimal user effort. The toolset supports field campaigns involving hundreds of households over a defined period (e.g., one week), improving standardization and reducing reporting errors. The method can be seen as an enhanced form of direct measurement, combining the accuracy of weighing-based approaches with the efficiency of digital tools. A pilot study confirms the system's feasibility, participant acceptance and ability to generate detailed, comparable datasets suitable for food waste reporting at different levels. This work contributes a practical, open-source solution for household food waste monitoring, addressing key limitations of existing methods. It offers a valuable tool for researchers, municipalities and NGOs to conduct reliable, large-scale food waste assessments.

1. Introduction

Food waste has become one of the most pressing global challenges, contributing to environmental degradation, economic losses and social inequality. According to United Nations Environment Programme (UNEP, 2024), 19% of food available to consumers is being wasted at retail, food service and household levels. In households alone, the amount of food waste varies widely across countries, ranging from around 25–40 kg per capita annually in some countries to 70–90 kg or more in others, often reflecting differences in income levels and other socio-economic factors (EUROSTAT, 2024; Sactic and Silva, 2025). These differences reflect not only socio-economic and cultural factors, household size and purchasing behaviour, but also national policies and infrastructure, such as whether bio-waste collection is organized, which can influence awareness and disposal habits. Household waste is driven by multiple causes, including over-purchasing, misinterpretation of date labelling (particularly confusion between “use by” and “best before” dates), poor storage practices and lack of meal planning (Stenmarck et al., 2016; van Herpen et al., 2019). These losses not only represent wasted resources, such as water, land, energy and labour, but also increase food insecurity and food prices. The international community has recognized the urgency of addressing this

issue and, through the United Nations Sustainable Development Goal 12.3 (SGD12.3) (United Nations, 2024), which sets concrete targets to halve global food waste per capita at the retail and consumer levels and to reduce food losses along the supply chain by 2030.

To design effective interventions and to track progress towards reduction targets, it is crucial to understand how much food is wasted. Accurate measurement enables countries to understand the scale of the problem – and therefore the scale of the opportunity – and provides a baseline for evaluating the impact of mitigation strategies over time. However, measuring household food waste remains challenging. Conventional methods, including kitchen diaries, recall surveys and waste composition analysis, often suffer from one or more of the following limitations: high cost, limited frequency, participant bias or underestimation of actual waste (van Herpen et al., 2019). Recent research emphasizes that the measurement problem can be mitigated through digital technologies. Studies such as Bux (2024) demonstrated how digital methods improved food waste monitoring in healthcare food services, while Clark et al. (2025) explored how AI-driven food waste management strategies used in the hospitality sector can support applications in household settings. These examples show that digital solutions – including artificial intelligence, 3D scanners and smart

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scales – can improve the precision of monitoring, enrich contextual data and support sustainability assessments. Yet, their adoption in household settings remains limited, underscoring the need to develop adaptable and user-friendly digital methodologies for large-scale domestic use.

At the global level, the UNEP takes care of the Food Waste Index, whose purpose is to track food waste generated at the retail, food service and household levels worldwide ([United Nations Environment Programme, 2024](#)). All countries are encouraged to regularly measure and report their food loss and waste data. The Food Waste Index provides guidance and a framework for reporting data, with an emphasis on improving the comparability and reliability of food waste statistics across nations.

In the European Union (EU), food waste is also a key policy focus. Under Directive 2008/98/EC on waste ([EU, 2009](#)) and further detailed in the Implementing Decision (EU) 2019/2000 ([EU, 2019b](#)), Member States are required to monitor and report food waste across the entire supply chain—including primary production, processing and manufacturing, retail and distribution, food services and households. These requirements are governed by Commission Delegated Decision (EU) 2019/1597 ([EU, 2019a](#)), which outlines standardized measurement methodologies in Annex III.

The definitions and methodologies mandated by EU regulations are aligned with those of the Food Waste Index, ensuring consistency in reporting from local to global levels. Household food waste is of a particular concern, as studies estimate that it accounts for 54% of all food waste generated in the EU ([EUROSTAT, 2024](#); [Stenmarck et al., 2016](#)).

To address the limitations of traditional and digital methods alike, we developed an integrated digital toolbox comprising of a Bluetooth-connected smart scale, a mobile application for food categorization and photo capture and a cloud-based data storage platform. Compared to kitchen diaries or survey-based approaches, our system minimizes recall bias and participant burden, which are known to lead to systematic underreporting of waste quantities. In contrast to purely weight-based smart bin solutions, it enriches each waste record with relevant contextual data (e.g., food type, avoidability, disposal route), thus overcoming the lack of qualitative insight that limits the explanatory power of existing digital methods. This integration of quantitative and qualitative data enables more accurate behavioural analysis and comparable across households and regions. Data is collected over a fixed period, anonymized and aggregated for extrapolation at the population level, providing both reliable metrics and behavioural insights. Furthermore, the method can serve as a benchmark for validating other measurement techniques, positioning it as a reference methodology that supports progress in household food waste monitoring.

The remainder of this paper is structured as follows. Section 2 provides a state-of-the-art review of household food waste estimation methods and introduces the rationale behind our proposed smart scale-based approach. Section 3 describes the implementation of the system, including the smart scale, mobile application and cloud-based portal. Section 4 presents validation results from the pilot study. In Section 5, we discuss the main advantages and limitations of the methodology. Finally, Section 6 concludes the paper and outlines directions for future work.

2. Theoretical background and literature review

The design and implementation of food waste measurement approaches are largely shaped by international and national frameworks, which define reporting obligations and methodological guidelines but leave room for diverse implementation strategies. At the operational level, campaign managers – such as public institutions, researchers or NGOs – are responsible for selecting appropriate methods, sampling strategies and instructions for participating households. The quality of the collected data depends not only on methodological accuracy but also on the ability to include households in a manageable way. As such,

there is an ongoing need to develop solutions that reduce the burden on both campaign managers and participants, while ensuring that the data collected are robust, comparable and actionable. This motivates the development of new, digitally enhanced approaches, described in the following section.

To frame the need for such innovations, we first provide an overview of existing food waste measurement methods. In the context of EU reporting obligations (Directive 2008/98/EC; Delegated Decision 2019/1597), which obliges Member States to monitor food waste across the supply chain using harmonized methodologies and the development of the Food Waste Index by UNEP (2021), several methodologies have been proposed and tested. These vary in terms of accuracy, participant burden, cost and potential for scaling. Below, we critically assess the most commonly used methods, relying on methodological reviews and empirical comparative studies to highlight their strengths and limitations. [Amicarelli and Bux \(2021\)](#) emphasize the importance of selecting measurement tools that are aligned with the position in the food chain, resource availability and data comparability needs, recommending a combination of mass balance approaches, food diaries and direct measurements at the consumer level. This analysis forms the basis for the rationale behind our proposed digital methodology.

Questionnaires, surveys and interviews are among the simplest tools commonly used. They rely on participants to self-report food waste-related behaviours through structured forms or guided interviews. These methods are widely used due to their low cost and scalability and are particularly useful for initial screening or observing trends across large populations. However, their reliance on self-reporting often leads to inaccuracies, as respondents may forget specific instances or provide socially desirable answers that misrepresent their actual behaviours. Validated instruments exist to improve data quality—for example, the survey developed by [van Herpen et al. \(2019\)](#) aims to reduce biases and improve comparability across studies. Still, these methods are best suited for exploratory or supplementary use rather than accurate quantification.

Food waste diaries offer improved accuracy over self-reported surveys by requiring participants to actively record their waste as it occurs. Diaries can be paper-based, online or in hybrid formats. This method reduces memory-related inaccuracies and provides more granular insights into waste quantities and types. However, keeping a diary places a relatively large burden on users, which often results in incomplete data entries. Additionally, also in this case participants may consciously or unconsciously change their disposal habits simply due to being observed—a phenomenon known as the Hawthorne effect, which can compromise the validity of the results. [Quested et al. \(2020\)](#) reported an underestimation of 7%–40% when using diaries compared to waste composition analysis. [Ammann et al. \(2021\)](#) found that diaries tend to yield higher estimates than questionnaires, but both methods are strongly correlated. Recent examples of diary-based studies include Switzerland [Ammann et al. \(2021\)](#), Lithuania ([Eičaitė and Baležentis, 2024](#)) and Greece ([Sigala et al., 2024](#)).

Waste composition analysis (WCA) involves the physical sorting and weighing of collected household waste to identify food waste types and quantities. It is considered an objective method as it avoids reliance on participant reporting. It is especially suitable for capturing total waste generation. However, it is also highly resource-intensive, both financially and logistically. Moreover, it offers limited insight into household-level decision processes, alternative disposal routes (e.g. sink disposal, home composting or feeding animals) and item-level contextual information recorded at the time of disposal. [Lebersorger and Schneider \(2011\)](#) highlighted key limitations of WCA, especially its inability to capture food waste that never enters the municipal waste stream. In a study by [Adelodun et al. \(2021\)](#) in South Korea, households placed daily food waste in labelled containers, which were sorted and analysed to obtain detailed food waste profiles. Although innovative, such methods face barriers in multi-unit buildings and sample

Table 1
Overview of common household food waste measurement methods.

Method	Strengths	Limitations
Questionnaires/ surveys	Low cost, scalable; useful for trends	High recall bias; socially desirable answers
Food waste diaries	Granular, time-specific data; less recall bias	High participant burden; Hawthorne effect; incomplete entries
Waste composition analysis	Objective, covers total waste	Costly, labour-intensive; misses food discarded via sink or fed to animals
Direct measurement	Accurate weights; moderate cost	Requires household engagement; limited scalability
Photographic/ app diaries	Rich contextual data; evolving with AI	Manual coding effort; less accurate for mass estimation
Mixed-methods	Mitigates weaknesses; robust for policy	Complex implementation; higher cost

degradation risks. Empirical studies have also combined waste composition analysis with survey-based methods. For example, Parizeau et al. (2021) conducted household-level compositional audits alongside surveys, demonstrating that waste composition analysis can robustly quantify food waste and classify it by food group and avoidability, while survey data provide complementary behavioural insights.

Direct measurement approaches involve weighing food waste at the point of disposal, either by households themselves or by researchers, using kitchen scales or standardized containers. When combined with basic categorization (e.g., by food type or avoidability), these methods can provide high-quality data at a moderate cost and participant burden. A study by Elimelech et al. (2018) implemented daily doorstep sampling and sorting in 192 households, yielding an average of 573 g of food waste per capita per day, of which 54% was classified as avoidable. While highly accurate and granular, this method requires strong logistical coordination and consistent participant engagement, which may limit its scalability.

Photographic and app-based food waste diaries involve participants taking photos of discarded food items, which are later analysed to determine waste type, avoidability and approximate quantity. Image analysis can be conducted manually or automated using AI. van Herpen et al. (2019) investigated photographic diaries as a complementary tool to improve measurement richness. These methods are still evolving, particularly as machine learning advances improve food recognition and mass estimation from images. Several practical implementations have been reported recently. For instance, Cropley et al. (2022) introduced the Wastogram method, in which households manually recorded the weight of their food waste and took photographs for later verification and composition analysis. Similarly, Baker et al. (2023) conducted a study in which users reported food waste via photographs sent to researchers through WhatsApp and Roe et al. (2020) developed the FoodImage™ smartphone app, designed for use during food preparation, consumption and disposal. The app transmits users' photographs of food selections and waste, along with tagged information about waste reasons and disposal methods, to researchers.

Mixed-method approaches combine multiple techniques to mitigate individual weaknesses and maximize data quality. For example, diaries can be paired with kitchen scales (direct measurement) or questionnaires can be supplemented with waste composition analysis. Hungarian studies using the FUSIONS methodology (Kasza et al., 2020) exemplify effective integration of diary and direct measurement, using harmonized food waste typologies. Such hybrid approaches are well-suited for national-level baselining under EU reporting guidelines (e.g., Decision 2019/1597).

Table 1 summarizes the main strengths and weaknesses of the commonly used household food waste measurement approaches.

Recent innovations aim to automate data capture and reduce participant effort, motivating the development of digitally enhanced direct measurement methods. These approaches are discussed in the following section.

3. Materials and methods

The proposed methodology aims to enable accurate and consistent measurement of household food waste while minimizing the reporting burden on participants. It combines digital technology with a user-centred approach to streamline data collection, ensure data integrity and support policy-relevant analysis. As illustrated in Fig. 1, the approach is built around a digital toolbox developed specifically for this purpose. It consists of Bluetooth-enabled smart scales, a mobile application and a cloud-based portal that together form a system for data acquisition, analysis and reporting.

The core objective is to systematically capture food waste generation patterns from a representative sample of households using a fully digitalized process. This enables standardized data acquisition and contextual metadata collection, providing a high-resolution dataset suitable for both supporting day-to-day efforts to reduce food waste and for national-level reporting. The system also includes campaign management functionalities, offering tools for configuring campaigns, monitoring participation and generating aggregated reports for stakeholders.

Each participating household receives a Bluetooth-enabled smart scale that can be paired with the mobile application. When food waste is generated, the waste is placed on the scale, which automatically records its weight and transmits it to the app via Bluetooth protocol. The participant then characterizes the waste by entering a short set of context-specific data. First, they classify the item as either avoidable or unavoidable, following the definitions used in the FUSIONS methodology and applied in household studies such as those by Kasza et al. (2020). Based on this classification, the app dynamically presents relevant food category options, allowing the user to assign one or more predefined categories, which are later processed to proportionally estimate waste quantities per category. These categories are aligned with recent EU recommendations on food waste data collection and reporting (De Laurentiis et al., 2023) and are accompanied by illustrative examples, as shown in Fig. 2. The participant then adds further metadata, including the disposal route and food state (e.g., raw, processed, frozen, ready-to-eat), which helps contextualize the type and condition of the discarded food and supports more detailed analysis. An optional comment can also be added. A photograph of the waste is also taken to provide visual verification and support quality control. All entries are timestamped and securely transmitted to a centralized, anonymized database via a cloud API, ensuring harmonized and sufficiently detailed reporting across all households.

To promote consistent reporting, the app guides users through a predefined classification system aligned with international reporting frameworks. In particular, the methodology complies with the Commission Delegated Decision (EU) 2019/1597 (EU, 2019a), ensuring that data collected can be directly integrated into national reporting obligations under the EU Waste Framework Directive. By following these

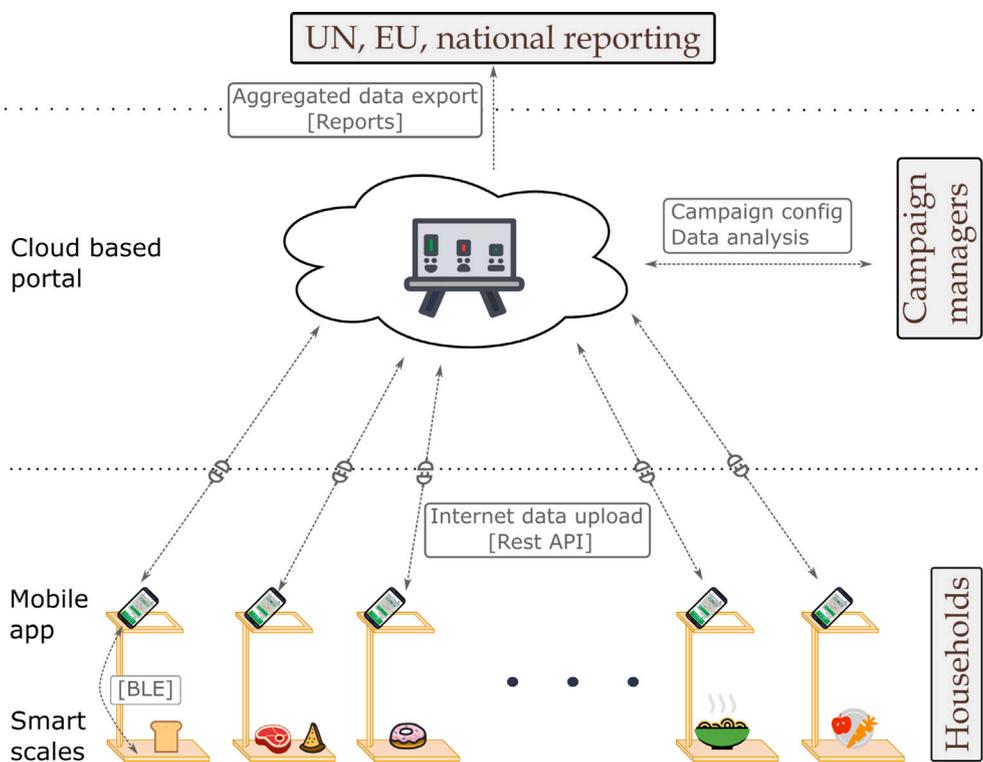


Fig. 1. Overview of the digital methodology for household food waste monitoring, showing the integration of smart scales, mobile application and cloud-based portal.

AVOIDABILITY		AVOIDABILITY	
Avoidable		Unavoidable	
Category	Examples	Category	Examples
	Fruits: Overripe bananas, spoiled apples, rotten oranges		Fruits: Inedible parts (banana peels, orange peels, apple cores)
	Vegetables: Wilted salad, soft tomatoes, sprouted potatoes, edible peels		Vegetables: Potato peels, carrot tops, onion skins
	Dairy & Eggs: Expired milk, moldy cheese, leftover yogurt, dairy substitutes, eggs		Dairy & Eggs: Eggshells, whey, leftover milk solids
	Meat & Fish: Spoiled or leftover meat, fish, and seafood		Meat & Fish: Inedible animal parts (bones, shells)
	Other: Any other food waste not fitting into the categories		Other: Any other food waste not fitting into the categories
	Bakery & Grains: Stale bread, leftover pasta or rice, old pastries, muffins, flour		Bakery & Grains: Rice husks, wheat bran, corn cobs
	Beverages: Leftover mineral water, coffee, tea, alcoholic or non-alcoholic drinks		Beverages: Spent coffee grounds and tea
	Ingredients & Additives: Expired vinegar, old spices, baking mixtures, yeast, condiments		
	Sweets & Snacks: Old candies, chocolate, and other sweets		

Fig. 2. Food categories.

Table 2
Comparison of the proposed digital methodology with traditional approaches.

Method	Accuracy	Cost	Scalability	Participant burden
Surveys	Low	Low	High	Low
Diaries	Medium	Low–medium	High	High
WCA	High (gross mass)	High	Low	None (to household)
Smart bin (weight only)	Medium	High	Medium	Low
Proposed smart scale + app	High – Moderate (weight + context)	Moderate	High	Low – moderate

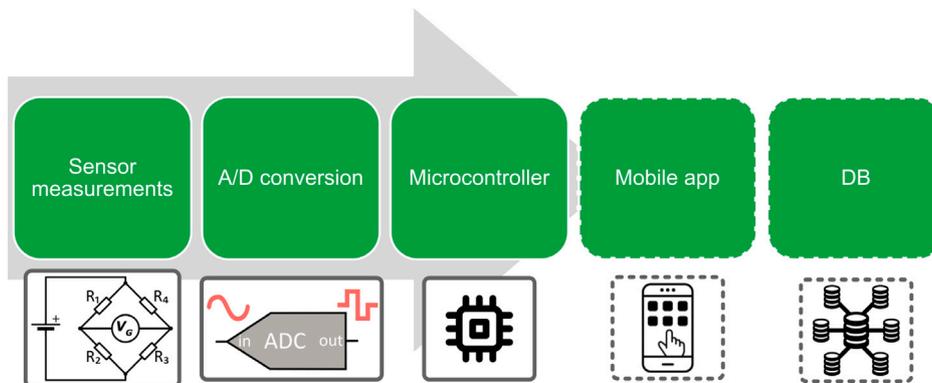


Fig. 3. Conceptual overview of the smart scale data flow.

recommendations directly into the digital workflow, the methodology ensures comparability, reproducibility and regulatory compliance.

In addition to supporting official monitoring, the toolbox enables also behavioural analysis by linking food waste quantities with context-rich data. Moreover, it also provides a reference point for evaluating traditional data collection methods such as surveys and diaries, which are often prone to under-reporting and bias. This capability supports cross-method comparisons and contributes to the development of more effective monitoring strategies.

Table 2 contrasts the proposed smart scale-based methodology with traditional approaches commonly used in food waste measurement in terms of accuracy, cost, scalability and participant burden, highlighting its position in the accuracy–efficiency trade-off. Here, surveys, diaries and WCA are considered traditional approaches, while smart bins and the proposed smart scale + app represent digital measurement methods.

The values in the table reflect general trends; however, their implications differ. For example, although three methods are rated as highly scalable, surveys and diaries achieve this through easy distribution of paper or digital forms, while our approach achieves this through the reusability of the digital toolbox and automated data synchronization.

Recent digital innovations such as AI-based image recognition and smart bins are promising but have limitations. Some image-based tools have been developed for specific contexts such as hospitality services, where high-quality cameras and dedicated sensors can be deployed; however, such solutions are not easily transferable to households due to cost, variability and accessibility constraints (Clark et al., 2025). Image-only methods also struggle with overlapping food items, variable lighting and mass estimation errors, while weight-only smart bins provide limited contextual insight beyond gross quantities. In contrast, our approach integrates objective weight measurements with structured contextual input – including avoidability, food category and disposal route – together with photo verification, thereby combining the strengths of both direct measurement and photographic methods. The smart scale combined with manual categorization was chosen over a purely image-based solution to ensure reliable mapping to EU reporting categories, reduce privacy concerns and maintain high data integrity while keeping participant burden low to moderate.

Overall, the digital toolbox offers a scalable, efficient and user-friendly approach for measuring household food waste. By integrating objective weight measurements with structured contextual input, it

generates a comprehensive dataset that supports both statistical reporting and behavioural analysis. In addition to measurements, the system also provides a basis for generating actionable insights to reduce food waste. By combining quantitative data (weight, categories, avoidability) with contextual and temporal information, it enables the identification of critical hotspots—such as frequently discarded avoidable food types, recurring disposal patterns or periods of peak waste. These insights can support targeted interventions, from awareness campaigns and optimized portion planning to estimating the energy or resource loss associated with specific waste streams. Over time, the collected data can also help in evaluating the effectiveness of such measures. The specific technical implementation of the toolbox components is described in the following section.

4. Implementation

This section outlines the technical implementation of each developed tool, focusing on their roles, functionalities and integration within the system.

4.1. Smart scale

To enable accurate and user-friendly measurement of household food waste, a custom-built smart scale was designed and implemented. The design aimed to achieve measurement precision, robustness and usability in real household environments while keeping costs low enough for replication across studies. The system integrates four key functions: weight sensing, signal amplification, microcontroller processing and Bluetooth communication with a mobile application, which together ensure reliable real-time data capture and its transfer to cloud-based database (DB). A simplified concept is illustrated in Fig. 3.

To enable precise weight measurement, the developed smart scale uses four strain gauge load cells arranged in a Wheatstone bridge configuration. The amplified analogue signal is digitized and processed by the ESP32 microcontroller, chosen for its affordability, energy efficiency that supports Bluetooth Low Energy (BLE) communication. The ESP32 was programmed in C, using two main open-source libraries: the HX711 library for load cell signal processing (SparkFun Electronics, 2025) and the official ESP32 BLE Arduino library for Bluetooth communication (Espressif Systems, 2025). This configuration



Fig. 4. A photograph of the assembled scale.

enables continuous weight monitoring, BLE communication and basic command handling (e.g., taring). Each scale was individually calibrated using known reference weights to derive a scale factor that translates the raw digital output into accurate mass values. Each scale broadcasts its unique device ID for secure pairing and data synchronization. This setup ensures high sensitivity and robustness while maintaining low power consumption and cost-effectiveness.

A modular wooden frame was selected due to its sustainability, mechanical stability and ease of fabrication. A photograph of the assembled scale is shown in Fig. 4. A short demonstration video illustrating the assembly and use of the smart scale and mobile application is available online.¹ In total, 45 smart scales were manufactured and distributed to participating households. Each unit was delivered disassembled and could be easily assembled by the user without any special tools. The same units were reused across multiple survey campaigns, ensuring practical implementation and material sustainability. A subset of 25 scales were used in Slovenian validation study to test the usability, reliability and data accuracy of the system in real household conditions.

4.2. Mobile application

To support the structured data collection process described in Section 3, a dedicated mobile application was developed for Android devices. The app guides participants through the entire food waste reporting process—from weight measurement to categorization, metadata entry and photographic documentation. It communicates with the smart scale via BLE and synchronizes data with the cloud portal.

The main goal in designing the application was to minimize user burden while maximizing data quality. Each screen was designed with

¹ Link to the demonstration video: https://youtu.be/uurxM_d9dKU?si=s7WpIm0CFrEryn1T.

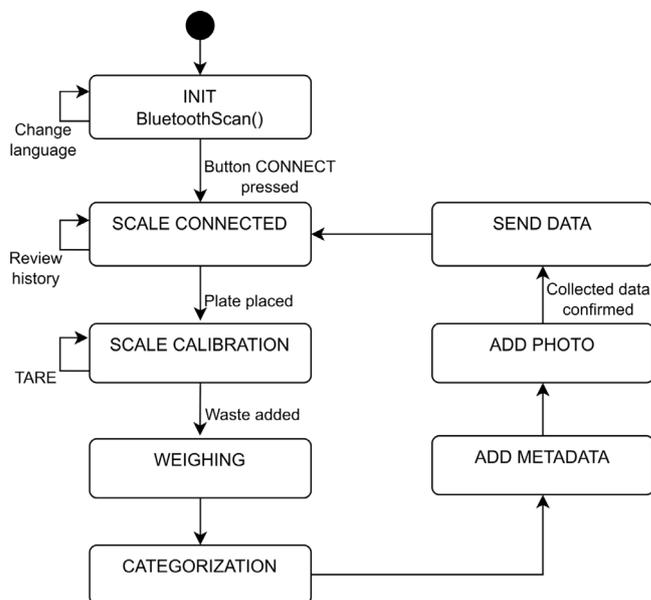


Fig. 5. Finite State Machine representing the food waste measurement workflow implemented in the mobile application.

clear, logically placed controls and concise instructions to ensure intuitive navigation. Fig. 5 illustrates the step-by-step workflow, which is implemented as a finite state machine with conditional transitions between steps, enforcing a structured and error-resistant process for each data entry.

Fig. 6 shows an example screenshot of the mobile application interface during the reporting process, illustrating the main user interaction elements.

The app guides users through successive stages including weight measurement, food waste categorization, metadata input and image capture. Logical transitions and validation rules ensure consistency—for example, the scale must be tared before weighing and a photograph is required before submission. These steps, described in Section 3, ensure standardized, high-quality data capture and reduce risk of user error.

All measurement sessions are managed locally on the device until submission, at which point the entries are transmitted to a secure cloud database. This architecture supports intermittent internet connectivity and allows users to review or delete past entries, giving them full control over their data. BLE is used for real-time communication with the smart scale, while cloud synchronization is handled via cloud interface.

The application is multilingual, supporting English, Slovenian, Portuguese, Hungarian and Estonian. Upon initialization, the app dynamically loads the appropriate language strings for all interface elements. Categories are also defined as variables and can be customized to accommodate different study designs or country context.

The app is available through the Google Play Store but it can only be used with a paired smart scale registered as part of an active measurement campaign. This closed system design ensures data authenticity, privacy and traceability while keeping the user experience simple and consistent.

4.3. Cloud based portal for campaign and data management

To complement the physical smart scale and mobile application, a dedicated Cloud based portal was developed, accessible at <http://wasteless.ijs.si/>. The portal serves for: (i) central collection of waste data, (ii) provides user support resources and (iii) enables centralized campaign management across multiple study sites.

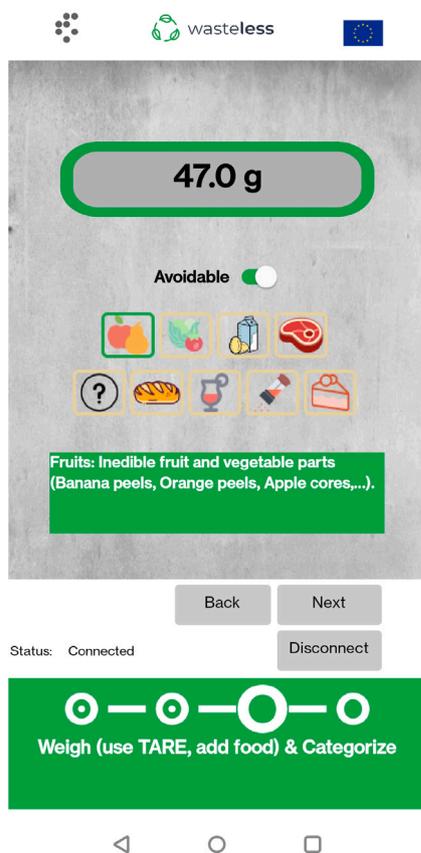


Fig. 6. Screenshot of the mobile application illustrating the food waste reporting interface.

The portal provides the main information entry point for users participating in household food waste surveys. On the portal, users can access instructional content, including setup guides, usage demonstrations and frequently asked questions, all aimed at ensuring correct and consistent use of the toolbox. Supporting materials such as multilingual user manuals, video presentations and survey documentation templates are hosted within the portal to streamline training and participation.

The portal also acts as the central access point that serves as a unified data collection entry point. REST API was developed following the OpenAPI specifications (Linux Foundation, 2025). The API provides two main communication interfaces for mobile applications, one for data upload and the other for remote data access. When data is submitted using user's mobile application, each scale is identified using its own unique key and if the scale is active in a measuring session, sent data is accepted and stored in the central database. The data is structured for easy export to standard formats for further statistical analysis and visualization.

In addition, the portal acts as the primary back-end tool for survey campaign management. As several campaigns can be run in parallel, the cloud portal enables all of the campaigns to be run individually without interfering with each other and within their secured dataspace. Each survey is coordinated by a designated survey manager, responsible for organizing data collection activities in a specific area. Survey managers have possibility to register and manage participants, assign scales to users, set session timeframes, track progress and access data from their specific campaign. The portal can also be used by scale users to review and edit committed data and to access an aggregated statistics about their data collection progress.

Table 3

Descriptive characteristics of participating households in the Slovenian validation study (n = 25)

Characteristic	Category	Households (n)
Household size	1 person	3
	2 persons	7
	3 persons	4
	4 persons	8
	≥5 persons	3
Household type	Single adult	2
	Couple (no children)	6
	Family with children	14
	Elderly couple	3
Housing type	Apartment	10
	House	15
Region	Ljubljana	9
	Eastern Slovenia	9
	Western Slovenia	4
	South-Eastern Slovenia	3

5. Results

To explore the feasibility, usability and robustness of the proposed digital toolbox, a structured pilot study was conducted in real-life conditions. The pilot implementation was carried out in Slovenia, where the research team had full control over participant recruitment, implementation and technical support. This environment enabled in-depth observation of user behaviour, testing of all technical components and collection of direct feedback for iterative refinement.

In total, 25 households participated in the Slovenian validation study, using 25 of the 45 manufactured smart scales. Households were selected through voluntary recruitment from existing research networks and local communities, ensuring geographical coverage of all major Slovenian regions and diverse household compositions (from single-person to five-member households). No participants dropped out during the study period. To acknowledge their time and effort, participating households received a small non-monetary incentive in the form of grocery store vouchers of symbolic value. The sample included diverse household types – from single individuals to families with children and elderly couples – to reflect varying consumption and food management patterns. Although the sample was relatively small, it included households differing in size, composition, housing type and region, as summarized in Table 3. The study aimed to verify the usability, technical reliability and data quality of the proposed method rather than to generate nationally representative food waste estimates. For this exploratory validation, only Android users were included due to the absence of an iOS version at the time of testing. Although the dataset was not statistically representative, the recorded average weekly waste per household (38.11 kg/year) was within the range reported in national waste statistics for Slovenia (EUROSTAT, 2025) – approximately 34 kg/year in 2023 – indicating that the collected quantities were broadly consistent with existing estimates. We could see also that fruits, vegetables and meat were the most wasted food categories, which corresponds to findings reported in national statistics (Vidic, 2023).

Each participating households used the smart scale and mobile application to log their daily food waste for one week. Participants were asked to record each waste event by weighing the item, selecting its characteristics and taking a photo. These entries were then transmitted to the cloud portal for centralized review and quality control.

Feedback was collected at the end of the campaign using structured questionnaires and informal reports. The main observations can be summarized as follows:

- **Usability.** Participants reported a positive user experience, finding the smart scale and app intuitive and easy to use while appreciating the overall concept and design. This tool led to

raised awareness of food waste habits for many users, which encouraged more careful meal planning and waste reduction. Almost 90% of respondents to the post-study questionnaire (22 out of 25 responses) reported that the system was “easy” or “very easy” to use, with difficulties particularly experienced by older people who are not as familiar with mobile phones. These observations suggest that digital literacy may influence engagement and data completeness, potentially introducing bias in voluntary studies relying on digital measurement tools. To mitigate this bias, it would be advisable to provide to this group of users an additional training prior to the use of the smart scale and app. Although over two-thirds of participants expressed willingness to participate again, a subset did not. While the pilot did not include a structured assessment of reasons, informal feedback suggested that reluctance was more often related to perceived time commitment than to technical difficulties.

- **Technical performance.** The initial deployment revealed minor issues related to Bluetooth connectivity, understanding of certain app features and the scale’s tare function. These were resolved through algorithmic improvements in load cell signal filtering and BLE communication stability, as well as by simplifying the user interface. The hardware and software operated reliably throughout the rest of the campaign.
- **Data quality.** Most users followed the prescribed protocol; however, a small number of entries requiring post-processing due to misclassification—mainly confusion between avoidable and unavoidable waste or food reused as animal feed or omission of small waste events. These errors were infrequent and had negligible impact on total waste estimates. All entries were reviewed during and after the campaign. Approximately 3% of entries ($n = 482$) required minor post-processing, primarily due to misclassification between avoidable and unavoidable waste or missing metadata. Quality control required approximately 4 min per household per week. The combination of automatic weight capture and mandatory photo logging substantially minimized the likelihood of entry errors compared to conventional diary-based reporting. To decrease the need for postprocessing future versions of the app could integrate automatic detection of food categories.
- **Suggestions for improvement.** Participants expressed interest in a battery-powered version of the scale, iOS app support and access to personalized waste statistics after the study. These suggestions have been incorporated into the roadmap for future development.

Overall, the validation conducted in Slovenia confirmed that the digital toolbox can be effectively used in household environments by non-expert participants with minimal training. The insights gained helped refine the system in terms of technical stability, user interface design and instruction materials. Although the presented validation was limited to a single region and a modest sample size, the results demonstrate the practical feasibility, usability and reliability of the methodology and the associated toolbox and provides the foundation for broader deployment and comparison with traditional waste composition analyses.

6. Discussion

The digital methodology presented in this study was designed to enable structured, harmonized and scalable measurement of household food waste at the population level. By combining a smart scale, a mobile application and a cloud-based portal, the approach offers a comprehensive toolbox for collecting high-quality data in real-life settings.

The toolbox was designed to be customizable. Campaign managers can modify food categories, disposal routes and instructions within the app to align with regional waste management practices or nutritional norms. For example, locations without meat consumption or without

bio-waste bins can adjust options accordingly. This flexibility supports both localization and cross-country comparability in international campaigns.

Compared to conventional food waste measurement methods, such as waste diaries or self-reporting surveys, this toolbox reduces the possibility of measurement errors and increases the informativeness of the data through the inclusion of photos and contextual metadata. Traditional diaries and surveys often suffer from recall bias, selective reporting and incomplete entries, while waste composition analyses provide accurate quantities and can classify food waste by food group and avoidability (Parizeau et al., 2021), but often lack item-level information recorded at the point of disposal, such as disposal route, photographic documentation and user-provided classification of avoidability. The proposed digital approach combines the strengths of both—direct measurement accuracy with behavioural and contextual insight. However, it introduces new trade-offs: it requires user interaction and dedicated hardware, which may limit scalability or cause underreporting of very small waste events. Despite these limitations, the Slovenian validation showed that the resulting waste quantities and category distribution were consistent with national waste statistics (Vidic, 2023), supporting the internal validity of the collected data while substantially improving data richness.

Previous studies have already demonstrated some potential of digital and AI-supported systems for monitoring food waste in controlled or institutional environments, such as hospitals or hospitality sectors (Bux, 2024; Clark et al., 2025; Sigala et al., 2025). However, as highlighted by Clark et al. (2025), key obstacles to transfer such technologies to households remain, particularly due to the high variability in food consumption patterns and the limited economic viability of specialized devices for individual users. Based on these findings, our study shows that a simplified, low-cost digital system can be effectively implemented in real-world household environments. Unlike systems that rely only on image recognition or manual diary entries, the presented toolbox combines direct weight measurement with photographic and contextual metadata, providing objective quantification and improved interpretation. This hybrid data structure combines quantitative accuracy and behavioural insights, thereby addressing both technical and social dimensions of food waste measurement. From a theoretical perspective, the methodology contributes to the advancement of data-driven approaches to household waste monitoring, while from a management (domestic) viewpoint, it provides a scalable and user-centred framework that can contribute to targeted waste prevention interventions at household and community levels.

The main advantage of this approach is in the integrated and user-driven workflow that combines weight measurement, categorization, metadata entry and image capture into a single, simplified process. The mobile application implements a standardized procedure using a finite state machine with logical transitions and validation rules, which helps to ensure consistency across households and studies.

The system enables data collection aligned with international reporting frameworks, such as the Commission Delegated Decision (EU) 2019/1597. The inclusion of photos and other metadata, such as timestamps, increases the reliability and verifiability of each entry.

Furthermore, multilingual support and dynamic configuration allow for use in different linguistic and national contexts. Category definitions and interface labels can be easily adapted to specific study requirements. All collected data is anonymized and securely transmitted to a central database, ensuring participant privacy and compliance with data protection regulations.

In addition to its primary use, this toolbox could also be used to validate conventional food waste measurement methods by providing a digital benchmark for cross-comparison. As such, it can also serve as a basis for improving existing practices and improving methodological consistency in future research and policy development.

Despite its advantages, several limitations were observed and specific strategies for their mitigation are planned:

- **Participant burden.** Although the process is simplified, it still requires multiple actions per data entry. This may lead to fatigue or underreporting, particularly for small or frequent waste events. The pilot study design did not allow direct quantification of under-reporting; future studies could address this through parallel waste composition analyses, passive sensing or short-term audit periods. Additionally, participants could be asked to provide a simple self-assessment at the end of the measurement period to report their perceived completeness and commitment, enabling more accurate interpretation of the data. Future work will focus on automatic detection of food category and food type using AI-based image recognition to reduce user effort, especially for frequent or small waste items.
- **Smart scale logistics.** The methodology relies on a custom-built smart scale, introducing logistical constraints for large-scale or long-term deployments. Alternatives with weighing devices or smartphone-based assessment methods should be explored, which could make the system more flexible.
- **Mobile app compatibility.** The current mobile application supports a wide range of Android devices. An iOS version is planned to expand accessibility and inclusion.

Overall, the digital toolbox performed reliably across different field settings and user groups. Its effectiveness in supporting data collection, while maintaining user autonomy and privacy, demonstrates its value as a methodological framework for future food waste studies.

The digital toolbox can play an important role in supporting both policy and behavioural interventions at the household level. By generating reliable and comparable data on what, when and why food is wasted, the system can contribute to national and municipal waste reduction strategies, help identify waste “hotspots”, i.e. food categories or time periods associated with the highest waste generation and guide targeted education or prevention campaigns. The data collection procedure was designed in line with the categories and principles defined in Commission Delegated Decision (EU) 2019/1597, enabling potential integration with official reporting frameworks and use as supporting evidence for policy development and evaluation. In managerial or domestic contexts, aggregated feedback could be provided to households to stimulate reflection on waste generation patterns and more sustainable consumption habits.

7. Conclusion

This article presents a novel digital toolbox designed to support structured, harmonized and scalable measurement of household food waste. By combining a custom-built smart scale, a mobile application and a cloud-based portal, the system enables objective weight-based data collection while reducing several limitations of conventional self-reported methods.

The pilot validation conducted in Slovenia demonstrated the practical usability and technical feasibility of the proposed toolbox in real-life household conditions. Most participants were able to complete the measurement protocol with minimal training. After initial development refinements addressing connectivity and user interface issues, the system operated reliably throughout the study. The collected waste quantities and category distributions were broadly consistent with available national statistics, supporting the internal plausibility of the recorded data. At the same time, the pilot revealed some limitations, including usability challenges for less digitally experienced users, potential participant burden and logistical constraints related to the use of dedicated hardware.

Rather than representing a full validation of a population-level measurement instrument, the results should be interpreted as a methodological feasibility study. The findings highlight both the strengths of the approach – objective weight measurement combined with rich contextual information – as well as the uncertainties that remain regarding

long-term engagement, inclusiveness across socio-demographic groups and potential biases in reporting small or frequent waste generation events. Based on its design, the method has the potential to support repeated and objective monitoring of food waste in households over longer periods of time and across larger groups. This makes it suitable for identifying waste patterns, evaluating the effects of awareness campaigns or supporting policy development and evaluation, subject to further validation in larger and more diverse samples. Compared to traditional methods such as questionnaires or food diaries, the approach aims to offer a more reliable and user-friendly alternative by combining direct weight measurement with standardized categorization, disposal route information, timestamps and photographic documentation. Future work will focus on further reducing user input by integrating automated food image recognition for classifying waste types and potentially estimating quantities directly from images what could enable broader use of the system across diverse user groups and contexts.

CRedit authorship contribution statement

Dejan Gradišar: Writing – review & editing, Writing – original draft, Validation, Software, Resources, Methodology, Funding acquisition, Conceptualization. **Viktor Govže:** Validation, Resources. **Miha Glavan:** Writing – review & editing, Validation, Software, Resources, Methodology, 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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