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Rethinking household food waste quantification: Increasing accuracy and reducing costs through automation

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ABSTRACT

The amount of food waste generated in households constitutes an obstacle to achieving a sustainable food system. To assess food waste quantities and evaluate the effects of waste reduction actions, reliable quantification methodology is needed. This study compares a questionnaire method against a novel automated quantification tool as candidate methodologies. The automated quantification tool was deployed in 18 Swedish households, which also completed a questionnaire for four weeks. The findings revealed that the questionnaire, while less costly in a short-term perspective, captured 46 % of the waste recorded by the automated quantification tool. Thus, questionnaire-based methods appear to be too inaccurate to be used for quantifying food waste in households, especially households with high levels of food waste. However, the results offered promising evidence that technical solutions such as the automated quantification tool used in this study could be useful for providing reliable long-term quantification data which the ambitions of a sustainable food system necessitate.

1. Introduction

While more than 800 million people are suffering from hunger worldwide (FAO et al., 2022), more than a billion ton of food are wasted annually (UNEP, 2024). With regards to these issues, the global food system is faced with multiple challenges that pose a threat to sustainable development if left unaddressed. Implementing strategies to reduce food waste and optimize resource utilization would enhance sustainability within the food system in multiple perspectives. By ensuring more efficient distribution and allocation of resources, such strategies have the potential to improve global food security (Godfray et al., 2010; Foley et al., 2011; Beuving et al., 2024), generate cost savings (FAO, 2014; WRAP, 2015), and mitigate environmental impacts (Springmann et al., 2018; Mbow et al., 2019; Cattaneo et al., 2021; Osei-Owusu et al., 2023; Wu et al., 2024).

When exploring strategies to reduce food waste, one crucial aspect to consider is the quality of primary data used to establish baseline quantities and to track progress over time (Jeswani et al., 2021). Although multiple studies have investigated the quantities of food waste generated in different contexts, and methods for gathering this information, several uncertainties remain, both regarding the real quantities generated and the accuracy of quantification methodologies (Xue et al., 2017; Barco et al., 2019; Baquero et al., 2023). This is especially true for the household level, where a considerable amount of food waste is generated (Caldeira et al., 2019b; UNEP, 2024). Like other stages of the food supply chain, there is currently no single standardized method for quantifying food waste in

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households, resulting in different methods being applied across studies (Hoehn et al., 2023). This creates difficulties in comparing results from different studies, as well as uncertainties in assessments of how much food waste is generated and of whether interventions targeting food waste reduction have had the desired effects (Caldeira et al., 2019a; Reynolds et al., 2019; Fanzo et al., 2021; Withanage et al., 2021; Casonato et al., 2023).

Methods commonly used to obtain primary data on household food waste include waste composition analyses, surveys, and diaries (Hanson et al., 2016; CEC, 2019). Each of these methods can be applied in different ways, and they all have their advantages and disadvantages relating to factors such as cost, reliability, and feasibility (Van Herpen et al., 2016; Quested et al., 2020; Withanage et al., 2021). Whether to deploy one method or the other further depends on a set of other prerequisites, such as study objectives, accessibility to the waste and geographical spread of the study sample (CEC, 2019). For example, waste composition analysis is an expensive and resource-demanding method, but has the potential to provide relatively good estimates of quantities and also information on the composition of the waste (Cicatiello and Giordano, 2018). In waste composition analyses, where curbside waste is collected through the regular scheme of the local authority or by another third party, the households themselves are not part of the actual quantification, which allows for a more objective assessment (Van Der Werf et al., 2020). However, taking this approach restricts the possibilities to derive any information on waste behavioral aspects and reasons why food is wasted, since the insight into individual households is limited (Withanage et al., 2021).

Methods that engage households in the quantification process, such as food waste diaries and questionnaire surveys, allow underlying causes of food waste to be captured. Such methods are also more cost-efficient than waste composition analysis, and can be conducted for large samples with fewer geographical limitations. The main disadvantage with surveys, where households self-assess how much food they are wasting, is that they tend to result in significant underestimations of the food waste quantities generated (Visschers et al., 2016; Delley and Brunner, 2018; van Herpen et al., 2019a; Withanage et al., 2021; Giordano et al., 2023). Diary methods also carry a risk of underestimation, as participants may both intentionally and/or unintentionally under-report the amount of wasted food (Quested et al., 2020; Withanage et al., 2021). Additionally, relying on the active participation of the household often limits the quantification period, as households usually do not have the patience to maintain quantification for longer than a few weeks (Richter and Bokelmann, 2017). Involving households in waste quantification also carries the risk of behavioral changes that lead to an unintentional decrease in food waste during the quantification period, as quantification in itself can act as a type of intervention that makes households more aware of their food waste (Sharp et al., 2010; Merian et al., 2024). Another disadvantage of waste composition analysis, surveys, and diaries, where the quantification period is usually limited to a few weeks, is the difficulty in capturing extreme events and seasonal fluctuations, as well as long-time effects of different interventions.

Work to date on finding and establishing reliable and standardized quantification methods has resulted in several suggestions on methods in the literature. A specific food waste survey method, the *Household Food Waste Questionnaire* (HFWQ), was developed by van Herpen et al. (2019a), designed to address perceived shortcomings in previous questionnaires used for quantifying food waste in households. By increasing awareness among participating households beforehand, limiting the study period, specifying product categories, and relieving the participant burden, the creators of the HFWQ sought to mitigate the under-reporting otherwise associated with questionnaires (van Herpen et al., 2019a). The HFWQ methodology has been used in various studies (Shu et al., 2021, 2023; Schuster et al., 2022; Cooper et al., 2023; Gimenez et al., 2023; Grant et al., 2023; Van Herpen et al., 2023). In Norway, the HFWQ has also been used to track the country's progress over time, contributing to the nation-wide statistics (NORSUS, 2023). However, while the careful reasoning applied in developing the HFWQ means that it may outperform other questionnaires, the method still remains dependent on the active participation of the household, which is associated with multiple risks such as participant bias, and both intentional and unintentional underreporting. The HFWQ has been validated against other quantification methods, such as diaries and kitchen caddies (a method where food waste is collected in a separate container that is collected and weighed by the researcher), and has been found to record 43 % and 39 % less food waste than those two methods, respectively (van Herpen et al., 2019a). Since quantification accuracy can also be questioned for diaries and kitchen caddies (Høj, 2012; van Herpen et al., 2019b), the accuracy of the HFWQ can therefore still be considered uncertain. Additionally, as acknowledged by van Herpen et al. (2019a), how the HFWQ performs over time when applied to a particular household remains to be determined, especially as regards the reliability of the method in evaluating interventions.

Besides the more traditional methods, there are new emerging technologies that have the potential to mitigate the current uncertainties in household food waste quantification. The core concept of these technologies is that they provide an automated approach to assessing food waste quantities, which can then be directly communicated back to their users. Currently, such technologies are mainly deployed in the food service sector (Leverenz et al., 2021; Malefors et al., 2024), and only a few studies have attempted to use them in households (e.g., Lim et al., 2021; Jones-Garcia et al., 2022). Although able to provide detailed quantification data, the accuracy of automated quantification tools relies on the food waste being properly sorted into the bin attached to the tool. Additionally, the cost of using technical tools is higher than that of e.g. deploying a survey questionnaire. However, compared with other quantification methods, an automated quantification tool reduces the workload for both households and researchers. This allows for longer quantification periods where seasonal fluctuations and normal behavior can be captured, which could ultimately provide more authentic results than other methods where participating households quantify their food waste for a limited period (Silvennoinen et al., 2014; van Herpen et al., 2019b). However, considering the scarcity of studies using an automated approach for quantifying food waste in households, further investigation is needed.

The aim of this study was thus to compare an automated procedure for quantifying food waste in households and a questionnaire based on the HFWQ methodology in terms of their quantification accuracy. An additional aim was to examine how households perform in estimating their food waste over time in both an inter-household and intra-household perspective. Finally, the two methods were compared from an economic perspective to determine the cost of obtaining a more accurate assessment of food waste quantities. The overall goal was to identify strengths and weaknesses of different methods for household food waste quantification, in order to improve quantification practices.

2. Material and methods

The work comprised the following four steps: (i) assessing food waste quantities in households using two different quantification methods; (ii) comparing the capture rate of these two methods; (iii) examining whether quantification discrepancies between the methods vary over time, or are systematic; and (iv) comparing the costs of the two methods and estimating the cost of quantification accuracy. Fig. 1 provides a schematic overview of the study.

The focus area was quantities of solid food waste generated at household level. The system boundaries for the study therefore included food that was wasted inside the homes of the participating households, but not food wasted outside the homes. Thus, if a meal was prepared inside the home but consumed elsewhere, e.g., as a lunch box at the office, and some waste was generated in preparation and some during consumption at the office, the preparation waste was included, but not the parts wasted at the office. Moreover, the study did not distinguish between who wasted the food (member of the household or a guest). Additionally, in order to compare the two methods, only waste discarded in the organic waste bin was included for both methods, while food waste disposed of elsewhere (e.g., liquid foods and drinks poured down the drain or food waste discarded in the general waste bin) was excluded from the study. Finally, to address the possibility of non-organic products being discarded in the organic waste bin due to wrongful sorting, these potential products were also included for both methods. However, to avoid confusion, all waste placed in the organic bin is referred to in this paper as 'food waste'. The term *food waste* was based on the definition presented by Eurostat as "any substance or product, whether processed, partially processed or unprocessed, intended to be, or reasonably expected to be ingested by humans", which includes both edible and inedible parts of food (Eurostat, 2023). This definition also requires food waste to be reported as fresh mass, which complies with the procedure used in the two applied quantification methods.

2.1. Automated quantification tool

To automatically quantify the food waste, an automated quantification tool (AQT) was used. The tool consists of a scale (model KERN PCB 6000–0) with resolution of 1 g, connected to a Raspberry Pi 4 single-board computer, which in turn is connected to a Raspberry Pi Camera module 3. The AQT is installed under the kitchen sink where the household's organic waste bin is placed on the scale, so that every time a food item is placed in the bin, the computer records the weight of the item and the camera is triggered to take a photo. All recorded data, including weight increases, pictures from before and after waste events, and timestamps, are systematically transmitted to a server for central storage and backup. Currently, the AQT is applied in settings where food waste is separated as its own waste fraction in households which facilitates an easier implementation of the methodology. The AQT has previously been described in Jakobsson and Sjölund (2023), and in Eriksson et al. (2023).

A surveillance function that keeps track of the status of each AQT unit allows the researchers to check that the system is online and functioning. With the help of this function, the AQT in each participating household was closely monitored during the quantification period, to ensure that all systems were operating. If a system was detected as non-operational (which happened on five occasions), the household was notified and asked to re-start the system to re-solve the issue. This did not, however, affect the data collection since quantification data is still recorded and stored locally when the AQT goes offline, and then transmitted to the server once the system regains connection to the server.

2.2. Questionnaire

The questionnaire sent out to the participating households was based on the validated HFWQ created by van Herpen et al. (2019a). The questionnaire was sent out to each household for a total of four weeks, using an online survey tool. Food waste reporting was done retrospectively by each household on a weekly basis. A pre-announcement (available in Appendix A), as suggested in the original method, was provided three days prior to the first week of quantification, where the households were asked to pay close attention to their food waste generation during the upcoming four weeks. The pre-announcement specified that the households should not weigh or by any other mean record or log their food waste throughout the study period, but only pay attention to what was wasted in the organic waste bin. The pre-announcement also informed the participants that they would be provided with a link by email at the end of each week, asking them to complete the questionnaire as soon as possible, preferably within 48 h, to mitigate the influence of possible memory lapses. If not having responded to the questionnaire after 48 h, the household was sent a reminder. If a household had not

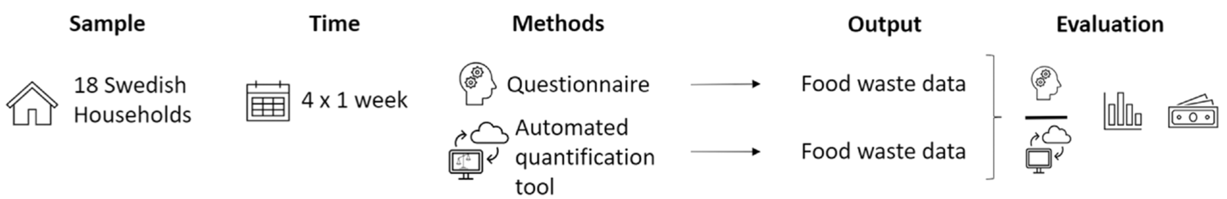

Fig. 1. Schematic overview of the household food waste quantification work conducted in this study.

completed the questionnaire after 72 h, or had not completed the entire questionnaire, that household was excluded from further analysis of that week. After excluding non-valid responses (n = 6), the questionnaire was completed a total of 66 times.

Due to the practicalities of the AQT, some adjustments were made to the original questionnaire in order to meet the research objective of the present study. These adjustments included categories of inedible and possible inedible food waste fractions to be added, such as coffee grounds and tea bags. Categories to capture any possible non-food products and food not listed in other categories were also added, as was an option to select *inedible parts* when asked to specify the state of the discarded food item(s). Including inedible parts of foods in the questionnaire meant that the range in answer options had to be adjusted for some food categories. For instance, in the original questionnaire, the category *eggs* has a response range of 0–5 eggs thrown away in the previous week, but this only refers to the edible part. However, it was considered likely that more than five eggs are wasted per week when including inedible parts (i.e. egg shells), so the response range was adjusted to 0–15 eggs. Additionally, since the AQT is limited to capture only food waste disposed of in the organic waste bin, categories of food waste assumed unlikely to be placed in the organic waste bin, such as beverages, were not included in the questionnaire used (although still possible to get captured under the added *other* category). In the information page, an image illustrating the size of a serving spoon was added to clarify the unit referred to. The questionnaire used is available in Appendix B.

2.3. Participants

As found by van Herpen et al. (2019b), estimates of food waste can vary greatly between households. When comparing different methods, those authors therefore recommend applying the methods to the same sample. Accordingly, since the quantifications in the two methods compared in the present study did not have a direct influence on each other, a within-subject approach was applied where quantification by both methods was performed in parallel and based on the same food waste data.

Using a convenience sampling approach through personal connections from the authors and referrals from individuals within their network, households had since April 2023 been recruited to get an AQT installed in their homes. Since recruitment was done continuously over time, the study was conducted at two separate occasions, one part in September/October 2023 and the other part one year later when additional participants had gotten an AQT installed. From the group of households having gotten the AQT installed, a total of 22 households were invited to participate in the four-week study comparing a questionnaire to the AQT. Of those households, 19 accepted the invitation out of which one was excluded from the study due to completing the questionnaire only once. Each household only took part in one of the quantification occasions. Before the first occasion was initiated, the households of four of the authors of this paper were used as a pilot group to test the questionnaire methodology, and the AQT during its development phase (presented in Jakobsson and Sjölund, 2023). Neither the results from the pilot study nor the households participating in it were included in the present study.

All participating households lived in Sweden and in municipalities where food waste is sorted and collected as a separate waste fraction. Consequently, the participating households did not have to change their behavior or familiarize themselves with any new equipment for sorting out their food waste after having the AQT installed.

Quantification data from the AQT and the questionnaire were recorded from early September to early October on both quantification occasions (a period without holidays or similar deviations to regular weeks). Most households conducted their quantifications during the same weeks, except for three households where the quantification period was delayed by one or two weeks. The details on each household and their participation are presented in Table 1. Children below the age of 1 were not counted as part of the study,

Table 1
Description of members in participating households and date when the automated quantification tool was installed (YYYY-MM-DD), as well as time of participation for the present case study (rightmost column).

Household	Household members (n)	Number of children (below age 18)	Automated quantification tool installed	Quantification period (start; end)
001	3	0	2023–03–30	2023–09–11; 2023–10–08
002	3	0	2023–08–14	2023–09–11; 2023–10–08
003*	2	0	2023–08–14	2023–09–11; 2023–10–08
004	2	0	2023–08–12	2023–09–11; 2023–10–08
005	3	1	2023–08–30	2023–09–11; 2023–10–08
006	2	0	2023–09–26	2023–09–26; 2023–10–23
007*	4	2	2023–06–19	2023–09–11; 2023–10–08
008*	3	1	2023–06–19	2023–09–11; 2023–10–08
009	1	0	2023–11–07	2024–09–09; 2024–10–06
010*	1	0	2023–11–19	2024–09–09; 2024–10–06
011	3	1	2024–08–29	2024–09–09; 2024–10–06
012	2	0	2024–05–05	2024–09–09; 2024–10–06
013*	1	0	2024–03–21	2024–09–09; 2024–10–06
014	1	0	2024–08–27	2024–09–09; 2024–10–06
015*	4	2	2024–02–23	2024–09–09; 2024–10–06
016	2	0	2023–10–13	2024–09–23; 2024–10–20
017	4	2	2023–12–12	2024–09–09; 2024–10–06
018	2	0	2024–02–29	2024–09–16; 2024–10–13

* Did not participate in all four weeks.

since they were assumed not to consume solid food to any great extent and therefore not contribute to solid food waste. The study also only considered the number of residents registered at the household's address, and did not take into account absences by any household member or visits to the household by guests during the study period.

2.4. Data analysis

This study sought to compare two quantification methodologies based on their ability to capture food waste quantities. Therefore, the composition of the wasted food was not analyzed in the present study, but is planned for future studies utilizing the AQT. For the AQT, a number of measures were taken to avoid registering scale increases that did not correspond to food actually being wasted, most notably when the bin placed on the scale was removed, emptied, and placed back on the scale, which was recognized as a large decrease in weight followed by a large increase (at least 220 g which is the weight of the most commonly used organic waste bin). All recorded quantification data were compiled and verified manually to ensure that no measurement errors had occurred, by comparing wasting events that exceeded 0.2 kg, and weeks where total food waste exceeded 1.0 kg per person, to their corresponding images.

The quantification data from the questionnaire were reported in relative amounts (e.g., serving spoons), and had to be manually translated into absolute amounts (i.e., kg) before the results could be summarized and compared against the AQT data. This was done using the approach suggested in the original HFWQ method, where the same weights were used for each answer option. However, since some adjustments were made to the questionnaire distributed in the present study, some corresponding adjustments had to be made to the calculations. Therefore, the assumed weight for each answer option was adjusted for four food categories (*fresh fruits*, *eggs*, *fish*, and *meat*) where the inclusion of inedible parts could be assumed to significantly influence the results. Hence, if the household reported to having discarded *fresh fruit* where all or some of the pieces were of an inedible character, the share of the fruits reported as inedible was corrected by applying a factor of 0.21, based on an average value of how much inedible material fresh fruits contain suggested by Ruiz-Torralba et al. (2018). For *eggs*, the corresponding factor assumed was 0.1 (Travel et al., 2011), a figure which was also applied for inedible parts in the *fish* category. For the *meat* category, an assumed factor of 0.2 was assigned reported inedible shares.

All quantification data collected were summarized per week, where the recorded food waste quantity for each method was divided by the total number of people living in the households that had responded to the questionnaire for the corresponding week. Based on this, a median value for each method of weekly food waste per person was derived when compiling all four weeks.

To derive the overall capture rate of the questionnaire, the total quantified food waste from both methods was used, where the estimates from the questionnaire were set in relation to the AQT recordings using Eq. 1,

$$Questionnaire\ capture\ rate(\%) = \frac{\sum_{i=1}^{n}\sum_{j=1}^{h}(w_{Questionnaire})_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{h}(w_{AQT})_{ij}} \times 100\# \quad (1)$$

where $w_{Questionnaire}$ and w_{AQT} is the weight registered by questionnaire and AQT, respectively, *i* indicates week, and *j* is household.

The same calculation as described in Eq. 1 was also applied to the quantification data for the individual quantification weeks. When a questionnaire response was missing for a household, the corresponding measurement from the AQT was removed from the calculation.

Spearman's rank correlation was used to estimate the correlation between the estimates in the questionnaire and the recordings of the AQT. To assess the agreement between the questionnaire estimates and the amount of food waste recorded by the AQT, a Bland-Altman plot was created. It was originally developed as a illustrative tool to be used in clinical sciences for analyzing the agreement of two different methods measuring the same parameter (Bland and Altman, 1986). In the present study, it was used to show how well the estimates in the questionnaire compared to the AQT data, and also to assess whether the estimation accuracy varied with the amount of food waste generated, as recorded by the AQT. Finally, to measure the overall spread of quantified food waste in each method, their variances were computed.

2.5. Cost assessment

Cost assessments for both methods were based on the resources required to obtain the quantification data from one household during the study period (i.e. four weeks). The estimated cost for the AQT was considered a one-time investment as acquiring quantification data from the AQT does not require a weekly time input but can be done at one time at the end of the study period. For the questionnaire, a weekly time input was required for manually distributing the questionnaire and compiling the response data. Additionally, an assumption was made regarding full availability of each method, meaning that the costs associated with development of both methods were excluded. To assess the time-related costs for the questionnaire and the AQT, the salary (€42/hour including payroll taxes) of the researcher responsible for installing the AQT was used. The time estimation for creating the questionnaire was based on the total time required for setting up the questionnaire, allocated to one household for a first-time distribution. The estimated response time for the questionnaire time was based on the median time of the 66 responses, multiplied by four. To acknowledge that the respondent's time is also valuable, the monetary cost assigned the participants' response time assumed the same hourly rate used for the other work-time-related tasks, even though the respondents were not paid for participating in the study. The component and time costs for each method are presented and summarized in Table 2.

3. Results

3.1. Food waste quantities and quantification accuracy

Based on the total amount of food waste quantified by both methods, the results showed that the questionnaire had a capture rate of 46 % compared with the quantities recorded by the AQT. The median food waste reported through the questionnaire was 0.44 (min: 0.01, max: 1.10) kg per person per week, while the corresponding median food waste recorded by the AQT was 0.85 (min: 0.10, max: 2.90) kg per person per week. Over all 66 individual household-week observations, the capture rate (i.e., the amount of food waste reported in the questionnaire relative to that recorded by the AQT) of the questionnaire varied from 13 % to 243 %. For each week of the quantification period, the questionnaire recorded a lower total quantity than the AQT computed over all households. However, in some individual cases (8 out of 66), households overestimated the level of food waste they reported in the questionnaire compared with that recorded by the AQT. The quantity of food waste recorded by each method and per week in each of the households is shown in Fig. 2.

Comparing the estimates in the questionnaire responses against the recordings by the AQT, a correlation was found between household estimates and actual waste recorded, where households who estimated that they waste more food were also found to do so ($r = 0.49$). The results also revealed that households with lower levels of food waste performed better in estimating how much food waste they generate than households with higher levels of food waste. Households where the weekly food waste per person exceeded 2 kg were found to underestimate their food waste by 1.5 kg or more. This is evident in the Bland-Altman plot (Fig. 3), where the dotted line indicates where the food waste quantity estimated in the questionnaire would equal the quantity recorded by the AQT.

3.2. Variations of estimation accuracy over time

The overall variance in questionnaire estimates was lower ($s^2 = 0.048$) than the variance in the AQT recordings ($s^2 = 0.427$). The weekly capture rate of the questionnaire was found to decrease slightly over the four weeks, where the highest capture rate (55 %) was obtained in the first quantification week and the lowest (38 %) in the last week. At household level, one household (015) showed an indication to improve its estimates in the questionnaire over time, seen for the entire quantification period. Meanwhile, one household (005) indicated an opposite trend where their estimation accuracy decreased over time. The other households did not indicate a trend in either direction, but instead displayed variation in their estimation accuracy between all weeks.

3.3. Cost estimation

The equipment and working cost for obtaining a result from the AQT in one household for four weeks was estimated to €520. Of this, €21 were required for compilation of quantification data, which constitutes the variable cost for the AQT and only needs to be accounted for once. The corresponding cost for the questionnaire, including both researcher and participant costs, was estimated to be

Table 2
Cost estimations for the automated quantification tool (AQT) and questionnaire based on a 4×1 week study period in one household.

Automated quantification tool (AQT)				
Equipment				
Component	Model		Cost (€)	Fixed/variable
Scale	Kern PCB 6000–0		200	Fixed
USB Serial port adapter	ICUSB232V2		23	Fixed
Computer	Raspberry Pi 4 starter kit		110	Fixed
Camera	Raspberry Pi Camera V3 Video Module		33	Fixed
Camera ribbon cable	Flex cable for Raspberry Pi 1 m		5	Fixed
Light	Anslut LED Strip 90 lm 3000 K 12 V		17	Fixed
Power socket	5 way branch outlet with switch 1.5 m white		5	Fixed
Mounting equipment	Cable ties and tape		1	Fixed
Work				
Task		Time (hours)	Cost (€)	Fixed/variable
Set-up of system		0.5	21	Fixed
Traveling (by bike)		0.5	21	Fixed
Installing*		1	42	Fixed
Removal of system*		0.5	21	Fixed
Compiling and verifying data		0.5	21	Variable
Total cost AQT			**520**	
Questionnaire				
Task		Time (hours)	Cost (€)	Fixed/variable
Creating questionnaire		0.25	11	Fixed
Distributing questionnaire, incl. sending reminders		2	84	Variable
Responding (cost for the household)		0.4	15	Variable
Compiling data		2	84	Variable
Total cost questionnaire			**194**	

* Including time devoted by participants being available when installing/removing the AQT.

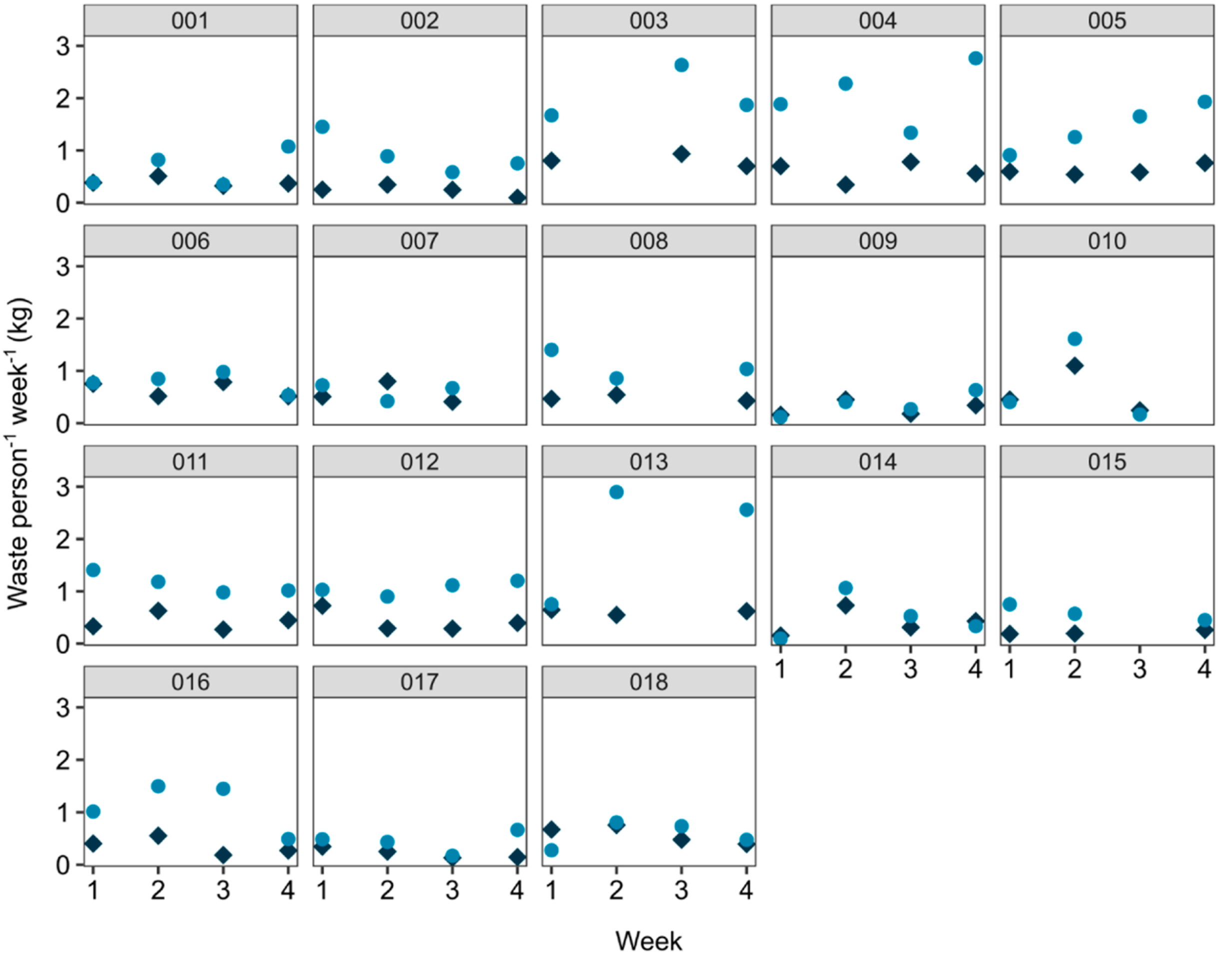

Fig. 2. Weekly food waste (kg per person) estimated in the questionnaire (◆) and recorded by the automated quantification tool (AQT) (●), split by the individual households (001–018).

€194, of which €183 were variable costs associated with distributing the questionnaire, households' response time, and compiling the reported data. This means that the estimated cost of obtaining quantification data from one household over the four weeks was approximately 2.5 times higher using the AQT compared with the questionnaire. However, as the cost for the questionnaire is increases with the number of weeks it is used, while the cost for the AQT remains constant until quantification data are manually downloaded and compiled, the cost difference between the two methods will change over time, with a point of interception at approximately 13 weeks of quantification. Fig. 4 illustrates the cumulative costs over time for each method. Since the cost allocated to creating the questionnaire would decrease with each additional week of use, that cost is not included in the figure. An assumed cost corresponding to one hour of maintenance every five weeks for the AQT is included, relating to e.g. informing the participants of system malfunction and them restarting the system.

4. Discussion

This study showed that using a questionnaire for quantifying household food waste severely underestimates the amount of food waste generated in households, with only 46 % of the food waste recorded by the AQT being captured by the questionnaire. This aligns with previous findings in studies comparing questionnaires with other quantification methods. For instance, van Herpen et al. (2019b) found that on average, 43 % less food waste was reported by households using the HFWQ compared with kitchen diaries. Giordano et al. (2018) found an even greater difference between diaries and another type of questionnaire, where the average food waste amount in questionnaire estimates was 53 % lower than that recorded in diaries. When assessing yet another questionnaire against extrapolations in a study applying waste composition analysis, Delley and Brunner (2018) observed a tenfold difference between the two methods. Although the capture rate of questionnaires may vary across studies and may be dependent on the reference method, as also recognized by Cicatiello and Giordano (2018), there is a clear trend for food waste quantities recorded through questionnaires to be lower than the actual quantities generated, as supported by the findings in the present study.

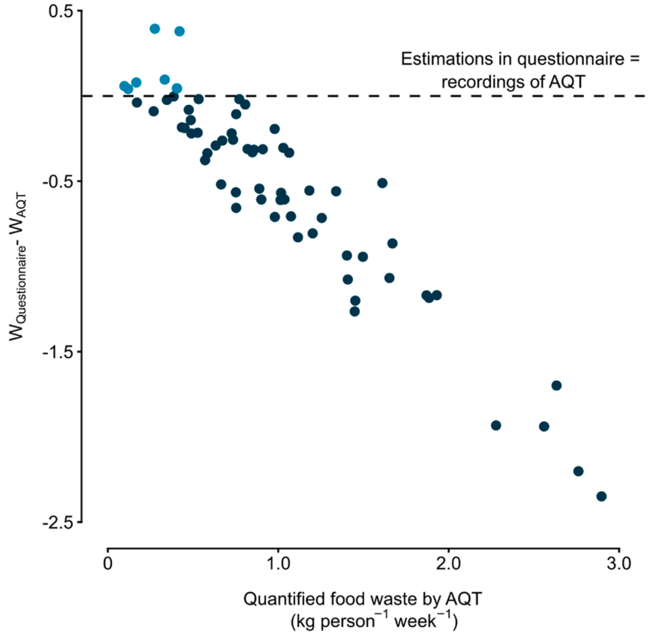

Fig. 3. Bland-Altman plot illustrating the difference in quantified food waste between the questionnaire and the automated quantification tool (AQT) in relation to the quantities recorded by the AQT. Points above the dashed line (●) indicate weeks when households have overestimated their food waste in the questionnaire, whereas points below the dashed line (●) indicate weeks when households have underestimated their food waste.

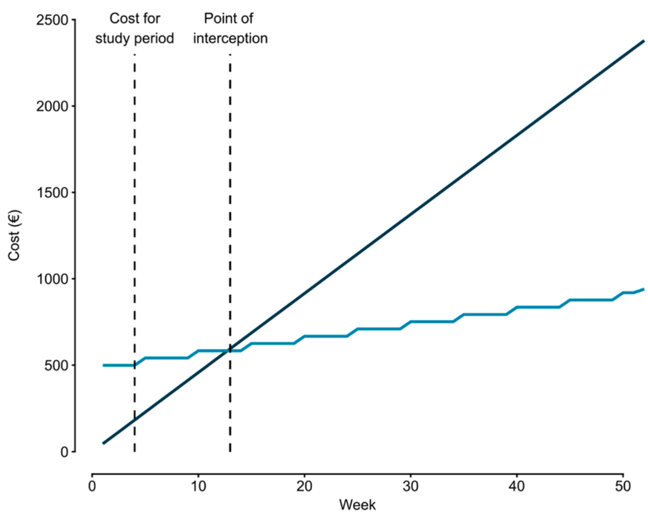

Fig. 4. Cost variations over time for the questionnaire (■) and the automated quantification tool (AQT) (■), based on weekly quantifications in one household.

Besides revealing a significant disparity between the methods when comparing the total amounts of food waste quantified, the results also revealed a spread between households. Some households consistently made more accurate estimates of how much food they wasted, while others showed large variation. Additionally, when households wasted a lower amount of food per person, they were generally better able to more accurately estimate their own waste. This suggests that the potential of questionnaires to assess food waste amounts decreases with the amount of waste generated. Similar to the finding of Aitken et al. (2024), the results also showed that households who estimated that they waste more food actually did waste more food. This supports the claim made by van Herpen et al. (2019a) that the HFWQ can be used for distinguishing between households with low and high levels of food waste which can be useful for intervention design where high-profile wasters might be of higher interest to target. However, it should be noted that the type of food waste, whether edible or inedible, was not assessed in this study which focused on total quantities in line with the applied definition suggested by Eurostat (2023). Although it is recognized that the edible fraction of food waste is important to consider due to this being the share that can be reduced, it is highly unlikely that the questionnaire would perform substantially better in estimating the edible quantities than the total. Nonetheless, as the AQT provides indication to provide more reliable estimates, the edible fraction should be considered in future studies applying the methodology, especially if testing and evaluating interventions.

Within participating households, there was a spread in recorded and estimated food waste quantities between the four weeks, which demonstrates the importance of long-term quantifications for obtaining good estimates of food waste quantities. A clear majority of the individual estimates confirmed that the questionnaire was not able to capture the amount of food waste recorded by the AQT. Although the scope and material of the study were not broad enough to draw conclusions on potential trends in whether repeated measures of the questionnaire can increase the estimation accuracy, the results provided some indication that it does not. As the lowest weekly capture rate of the questionnaire (38 %) was obtained from the last week of quantification, the results gave no indication that the households as a group increased their estimation accuracy over the course of the study period. In fact, the weekly capture rate decreased from week to week, which might indicate a saturation effect, that participants get less and less interested in keeping track of their food waste over time. However, at individual level, at least one household tended to improve their estimation accuracy over the four weeks. Nevertheless, the majority of participating households displayed quite large discrepancies between the questionnaire estimates and the AQT recordings across the four weeks. The variation in capture rates found within households could be an indicator of the difficulty in estimating how much food was wasted during the previous week, or may show that completing the questionnaire for multiple weeks does not result in more accurate estimation. Additionally, the overall lower computed variance of the questionnaire estimates (0.047) compared with the variance of the AQT values (0.427) shows that the participants estimated similar quantities from week to week but their actual waste varied. This suggests that households may estimate similar amounts of food waste between weeks because they simply do not have any idea about how much they are actually wasting.

Moreover, considering that the two methods compared were run in parallel and that the participants were aware that their questionnaire estimates would be compared against the waste quantities recorded by the AQT, the low capture rate of the questionnaire can be assumed not to have been a consequence of social desirability (i.e., households not wanting to admit how much food they are wasting). Similarly to findings by Giordano et al. (2023), this suggests that the reason commonly assumed for under-reporting in questionnaires, i.e., participants not wanting to admit that they are wasting food (Withanage et al., 2021), may not be a main cause of under-reporting. Instead, a main influencing factor may be that it is difficult for households to estimate how much food waste they generate, especially if the amount of food waste is high, and that even honest answers may differ significantly from reality. Additionally, if social desirability did not influence the results of the present study, it could be assumed that in a study using a questionnaire without a control measurement like the AQT, social desirability could lead to an even more misleading assessment. However, it cannot be concluded that the questionnaire *and* the AQT together were immune to social desirability. It is possible that recorded quantities may not fully reflect the total amount of (solid) food waste generated during the quantification weeks. Moreover, it is possible that the AQT encountered some undetected technical errors, which means that the total amount of food waste generated within the households during the quantification period cannot be determined with full certainty. It is also possible that some waste may have followed some other disposal route than the organic waste bin, whether deliberately or not. Noteworthy is that this is one of the limitations with the AQT; the methodology is dependent on the food waste being correctly sorted into the organic waste bin. At a larger scale, this might hinder its implementation in settings where source-separation of organic waste is not common practice. However, considering policy implementations such as the EU Waste Framework Directive that aim to increase source-separation of food waste (European Commission, 2018), this might be less of an obstacle in the future.

Irrespective of the method applied in studies investigating household food waste where the households are actively involved, one significant limitation to address is the influence of potential sample bias (Corrado et al., 2019). Households cannot be forced to take part in these kinds of studies, which often results in the participants not being representative of the wider population. In the present study, the 18 participating households constituted a convenience sample and, as such, did not represent the demographic diversity of the wider population. All households can be assumed to have higher awareness on food waste than the general population as they all had been provided an explanation to the rationale behind the AQT. Consequently, the average capture rate of the questionnaire indicated by the results may not reflect how the same questionnaire would perform across a larger and more general sample. Nevertheless, considering the sample of households and their attributes, the difference in self-reported and measured food waste may be even more pronounced in a general population where knowledge and awareness on food waste is more limited.

Even though the characteristics of the households may not have contributed to favoring the AQT, the participant sample consisted of households that were aware of the study objectives, which could have led to potential bias in the responses to the questionnaire, with participants responding in ways they believed were desired. On the other hand, all participants were provided with the same instructions, following the original methodology of the HFWQ, where they were asked to make as fair estimates as possible without the aid of other tools. It can only be assumed that the households followed these instructions. Looking at the spread in responses over the weeks, it can also be noted that if a household actually did try to deviate from the instructions, it was not successful, as there was no indication a systematic error for one household compared with the others. Moreover, an indication of the validity of the results can be derived from findings in previous studies, where the discrepancy between the capture rate of questionnaires and that of other more reliable methods was of similar magnitude to that found in the present study.

One of the main advantages often attributed to questionnaire-based studies is that they can be carried out at a low cost (van Herpen et al., 2019b; Withanage et al., 2021). An additional aim of the present study was therefore to compare the costs of the two quantification methods. The results indicated that the cost of obtaining quantification data from one household during the four weeks was about 2.5 times higher when using the AQT compared with the questionnaire. Using the difference in quantified food waste between the two methods, saving approximately €320 in costs over a four-week period would give an estimated value for food waste generation that is around half the actual amount. Whether this cost-saving can be justified or not is of course debatable, especially considering that there are other methods, such as food waste diaries, which can perform better in assessing food waste amounts than questionnaires, while (potentially) being less costly than technical solutions such as the AQT. However, it should be borne in mind that the cost of the AQT is almost exclusively associated with its equipment cost and the time required for installing it, while once it is installed it has the potential to provide reliable quantification data for a long period, up to several years, with very little extra cost, as demonstrated by some of the households participating in the present study. To obtain the same amount of long-term quantification data from questionnaires, the cost would increase over time as each questionnaire requires additional work, and eventually match the cost of the AQT. According to the cost estimates, this point of interception would be reached after approximately three months, based on the assumption that each questionnaire has an associated cost of about €46 for work time required to distribute and respond to the questionnaire, and compile the reported data. To set the cost differences in a hypothetical perspective, the cost of using the questionnaire instead of the AQT for the household that used the AQT for the longest period (approximately 80 weeks, see Table 1) would be almost €3600. This is considerably more than the cost of using the AQT during the same period, which would be approximately €1200 if including an assumed cost of one hour of maintenance every five weeks, which, however, is likely to be more time than what is actually needed. It should also be noted that the hypothetical perspective of using a weekly questionnaire for a year is unlikely to be successful due to respondent fatigue and dropouts (Ghafourifard, 2024).

Although the cost estimates may speak in favor for the AQT in a long-term perspective, it should be noted that these estimates are based on the approximated costs for obtaining data for the purpose of this study. In reality, the questionnaire would not be applied alongside a tool like the AQT as this would serve little purpose for assessing food waste quantities. It is therefore likely that distributing unique links to each household and each week are not necessary, which it was in this study to be able to trace the responses back to each individual household. Instead, to distinguish between household characteristics, such as the number of household members, some additional questions could be embedded into the questionnaire. Moreover, what added to the cost of the questionnaire was the manual compilation of responses, which mainly related to the inclusion of inedible food waste fractions. For the four food categories where this inclusion was assumed to result in misleading quantities if not corrected for their inedible fractions (e.g., if not corrected, an apple core would be equal to a whole apple since the unit in the questionnaire is "pieces of fruit"), each response had to be manually adjusted based on the answer given. If excluding the inedible fraction, compiling the questionnaire data would have been more time efficient, and, thus, less costly. Also, it is probable that this compilation is possible to automate, which would serve beneficial if distributing the questionnaire to a larger sample. Considering these remarks, it is possible that using the questionnaire can be done at a lower cost than estimated in this study, giving that the point of interception would be pushed further. Still, regardless the time of when the cost of two methods breaks even, the questionnaire would not provide reliable estimates.

Besides the lower short-term costs, another benefit of questionnaires, especially the HFWQ according to its creators (van Herpen et al., 2019a), is that it can be used for distinguishing between high and low profile waste generators. The result obtained in the present study supports this claim. However, if used for other purposes, such as tracking food waste over time as done in e.g. Norway (NORSUS, 2023), or determine the impact level of interventions (see e.g. (Cooper et al., 2023; Gimenez et al., 2023; Van Herpen et al., 2023)), the questionnaire approach is limited due to its high level of uncertainty. Given the week-to-week variation in food waste generation demonstrated in this study, it is clearly necessary to use long-term quantification methods with a high capture rate when quantifying food waste in households for any purpose. In this regard the results of the AQT provide an indication that such tools could help in evaluating, with high precision, long-term effects of interventions, and in understanding how food waste levels vary over time, while also being cost-effective when applied in a long-term perspective. These elements are crucial for understanding household food waste in greater detail, ultimately aiding the development of effective interventions to reduce food waste and foster a more sustainable food system.

5. Conclusions

Reducing food waste in households is an essential step towards achieving a sustainable food system. To succeed in this, food waste reduction measures need to be implemented, which requires the use of reliable quantification methodology that provides evidence on the effectiveness of these measures. The results in this study revealed that a questionnaire-based approach, while less costly in a short-term perspective, was able to capture only 46 % of the household food waste recorded by the AQT employed in parallel. Thus, self-assessment methods such as questionnaires do not provide reliable food waste estimates, limiting their use for quantification purposes. By instead leveraging the AQT technology, it may be possible to evaluate the effectiveness of interventions, prioritize actions, and gain a deeper understanding of the circumstances under which different actions are most successful, which are crucial elements in achieving a sustainable food system.

CRediT authorship contribution statement

Mattias Eriksson: Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Claudia von Brömssen:** Writing – review & editing, Methodology. **Christopher Malefors:** Writing – review & editing, Software, Methodology, Funding acquisition, Conceptualization. **Erik Svensson:** Writing – review & editing, Software. **Amanda Sjölund:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, 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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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eti.2024.103993.

Data availability

The authors do not have permission to share data.

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