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A field experiment to assess barriers to accurate household food waste measurements

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ABSTRACT

The United Nations' sustainable development goals call for a 50 % reduction in global household food waste by 2030, but an accurate measurement method to quantify household food waste has yet to be developed. In a field experiment with 359 households, this study compares standard food waste measurement methods (survey, diary, kitchen caddy) and assesses the barriers to accurate measures. Based on our experimental design, we derive a minimal estimate of food waste (ground truth) that allows us to examine and explain the differences in the results of these methods. The results suggest that physical waste measurement is the most accurate measurement method, as it evokes the least behavioral adaptations. However, this method is resource-intensive and not always feasible. We provide guidance on how to measure food waste based on the purpose of the measurement, including specific materials to use and reporting standards to follow.

1. Introduction

The United Nations sustainable development goals (SDGs) (United Nations 2015) call for halving the per capita global food waste at the consumption stage (FAO 2019). Households food waste (HFW) is focal in the SDGs for two reasons. First, HFW is responsible for 61 % of all food waste (corresponding to 11 % of all foods produced for human consumption) (UNEP Food Waste Index Report 2021 2021); thus, the SDGs can only be reached if HFW is at least partially reduced. Second, the environmental and economic costs of food are increasing along the food supply chain (Neff et al., 2015; HLPE 2014). Correspondingly, food waste constitutes roughly 8–10 % of global greenhouse gas emissions (UNEP Food Waste Index Report 2021 2021; Mbow et al., 2019).

Measuring HFW has been recognized as a major obstacle in effectively decreasing food waste at the household level (Withanage et al., 2021; Chaboud, 2017). This obstacle partially arises due to highly heterogeneous definitions and methodologies used in existing HFW studies (Roodhuyzen et al., 2017; Koivupuro et al., 2012; Kirsi et al., 2014; Hoj, 2012). As a result, the comparison between existing food waste estimates is very difficult or even impossible (FAO 2019; Sharp et al., 2010). There have been attempts to overcome this problem by the development of measuring guidelines, but there is an even more fundamental problem, which is also emphasized by these guidelines (Tostivint et al., 2016; Pasos, 2019)'. That is, the most common methods for HFW measurement (surveys, kitchen caddies [KC], and diaries) are affected by various barriers to accurate measurement (e.g., people tend to change their behavior if they participate in food waste diary studies (Quested et al., 2020)) and are therefore biased. These barriers also influence alternative approaches (e.g., modeling and the use of proxy data (HLPE 2019)) that use existing data (e.g., older or foreign data). Many of these barriers to accurate food waste measurement (hereafter referred to as barriers) have been acknowledged as potential explanations for inaccurate measurements (see Table 1) but have not been thoroughly explicated. Only by finding ways to better understand and circumvent these barriers can we accurately quantify food waste, understand the problem (e.g., the specific drivers of food waste), find effective interventions, and measure progress. HFW can only be managed if we can measure it accurately (Quested et al., 2020). This is a major research gap and a pressing issue, considering the SDGs' timeline.

In the present study, we apply three predominant food waste

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Table 1
Barriers to accurate food waste measurement as observed in our study and/or reported in the literature (X denotes the factors that are, based on our study, likely to influence the accuracy of the measurements. The presence of a reference indicates that this has been previously discussed in the literature). [1]Dahlén and Lagerkvist (2008), [2]Elimelech et al. (2018), [3]Giordano et al. (2018), [4]Hebrok and Boks (2017), [5]Hoj (2012), [6]Jörissen et al. (2015), [7]Langley et al. (2010), [8]Quested et al. (2020), [9]'Report on Review of (Food) Waste Reporting Methodology and Practice'(n.d.), [10]Sharp et al. (2010), [11]van Herpen et al. [1](2019), [12]Wenlock et al. (1980).

Type of measurement	**Measurement method**			
	Self-assessment by households		**Physical weighing by researchers**	
Barriers to accurate measurement	**Survey**	**Diaries**	**Kitchen caddy (Aware)**	**Kitchen caddy (Unaware)**
Generalizability: Estimates of food waste are not representative				
Spatial (e.g., urban vs. rural) and temporal (e.g., summer vs. winter or holidays) representativeness of waste	X[1]	X[9]	X[12]	X
Representativeness of participants in terms of characteristics/behaviors		X[8,10]	X[2]	X
Completeness: Estimates are too low as not all food waste that is generated is recorded/collected				
Recall errors: Incomplete estimates owing to recall errors/subconscious disposal	X[4,5]	X[8]		
Misreporting: Misreporting to appear/feel better	X[5]	X[8]	X[3,11]	
Alternative disposal routes: Incomplete estimates as alternative disposal routes are not considered			X[11]	X
Other household members: Incomplete estimates owing to missing data about other household members	X	X[8]		
Collection errors: Incomplete estimates owing to lost bags/wrong labeling			X[2]	X
Response fatigue: Growing tired of participating over time		X[11]		
Validity: Estimates do not reflect reality as households change their behavior				
Social desirability: Reduction of waste to appear/feel better		X[8]	X[2,11]	
Hawthorne effect: Change of behavior owing to participation in the study		X[5,10]	X	
Workload: Less wasting to reduce the workload of reporting/collecting		X[7,11]		
Measurement problems: Estimates contain errors introduced during the measurement process				
Measurement error: Approximations of weights or particles sticking to tools and bowls leading to inaccurate measurements		X[11]	X	X
Translation of units: Inaccuracy introduced through mistakes while translating units to measures		X[11]		
Human errors: Inaccuracy introduced through mistakes in answering questions or recording food waste	X[11]	X[8]	X[12]	X
Misunderstanding: Inaccuracy introduced through unclear instructions or definitions	X[5,11]	X[8]	X	X
Degradation of food items: Change of weight owing to degradation or other chemical reactions			X[2,6,7,12]	X

Note: Aware: Indicates that participants knew that the study was about food waste. Unaware: Indicates that participants did not know that the study was about food waste.

measurement methods (survey, KC, and diaries) and combinations thereof in a single experimental setting (see Fig. 1 for the study design). The study design and the collection of household-level information (e.g., level of social desirability) through questionnaires and interviews enables us to derive an estimate of the ground truth. Although this ground truth is likely quantitatively underestimated (none of the households indicated to have wasted more than usual; liquids that have been removed from the packaging, i.e., poured into a glass and then discarded, are very unlikely to be assessed), the estimate allows us to isolate certain barriers to accurate food waste measurement. Thus, our study design permits insights into the impacts of different measurement methods on food waste estimates, and we discuss how the barriers associated with them (e.g., having to recall or measure food wasting behavior, knowing about the study purpose, and the presence of alternative waste disposal routes) affect outcomes. To conclude, we present a decision aid to help researchers and practitioners find the appropriate measurement method to address their research questions.

2. Materials and methods

2.1. Participants

In the spring of 2022, we recruited 359 German-speaking households in Switzerland using diverse channels (e.g., blogs, social media, mailing lists, and door-to-door). For easy access to the households' consumption history, they were required to be in the loyalty program of at least one of the two major national retailers and willing to share their purchase logs. Households received a voucher (either ~$20 or ~$50) for a major retailer as an incentive. Sample characteristics are reported in the Appendix (Table A.1).

2.2. Design and procedure

We employed a mixed-subjects design for the field experiment. We assigned households to one of four between-subjects conditions (measurement method: *KC (Unaware)* vs. *KC (Aware)* vs. *Diary (Aware)* vs. *KC+Diary (Aware)*) and collected data over 1–2 weeks (within-subject).

As depicted in Fig. 1, the *KC (Unaware)* group collected the total food waste for one week in the provided bags (one bag for organic waste and another for non-organic waste, including recycling goods). To prevent specific food waste-reducing behaviors, they were told that the purpose of the study was to optimize general waste flows (as opposed to food waste). As we assume that this condition minimizes behavioral adaptations, the *KC (Unaware)* group is our minimal estimate for the ground truth. Note that since we did not tell participants that the study was about food waste (in order to prevent behavioral adaptations), liquid waste that was discarded through the drain was not recorded. The *KC (Aware)* group was explicitly instructed to collect only food waste for two weeks in the provided bags (the same as the *KC (Unaware)* group). Again, although we were able to collect measures on liquid waste (e.g., leftovers in drink containers), alternative food waste disposal routes other than the waste bags were not recorded. The *Diary (Aware)* group reported food waste in a web application-based diary over two weeks. Households were provided with weighing scales and scannable codes (e.g., to stick to the garbage cans) to easily access the app. The *KC+Diary (Aware)* group collected food waste in bags and recorded it in an online diary for one week. The bags were collected by our research team at least once per week.

We also collected covariates such as environmental concerns (Kim-P and H-W, 2017), numerical skills (cognitive reflection test; Frederick, 2005), social desirability (brief social desirability scale; Haghighat, 2007), food waste attitudes (Raghunathan and Chandrasekaran, 2021), intentions to not waste food (Visschers et al., 2016), and perceived barriers to reducing food waste (Quested et al., 2012). Descriptive statistics can be found in the Appendix (Table A.1).

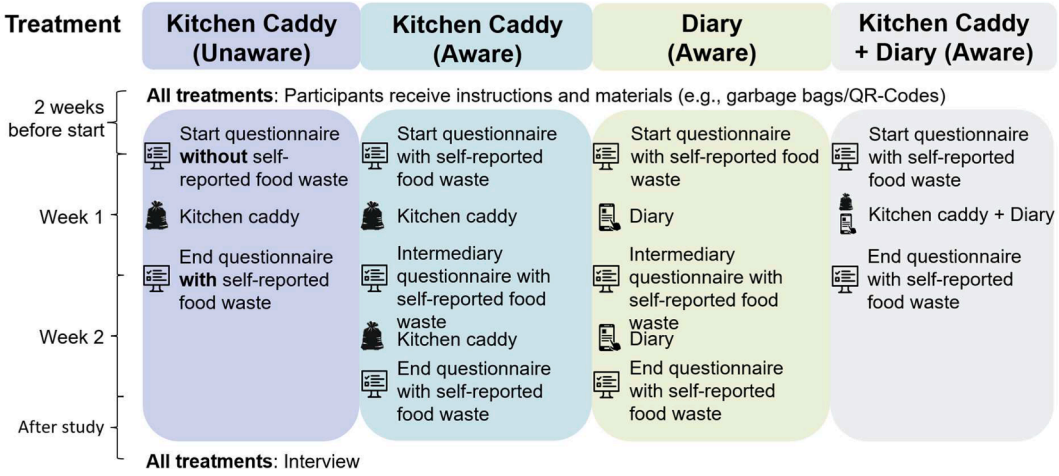

Fig. 1. Study design and procedure. This figure presents an overview of the different experimental conditions (columns) over the different periods (rows). Prior to the start of the study, all participants received the study instructions (e.g., how to share their grocery data) and materials (e.g., garbage bags and weighing scales). Note that "(Aware)" indicates that participants knew the purpose of the study (measuring food waste). "(Unaware)" indicates that the participants were told that the study was about waste flows in general and not food waste in particular.

2.3. Measures

We collected different food waste measures for 16 food categories (e.g., fruits, meat, dairy).

2.3.1. Weekly food waste survey

The survey assessed households' food waste relative to the total weight of purchased food (Elimelech et al., 2018). Apart from the KC (*Unaware*) group, who did not fill in the survey at the start of the experiment, all households filled it in on a weekly basis. Given that recording absolute measures (i.e., grams of food wasted) was difficult for the participants, and asking them to record units introduced uncertainty when measures were transformed to grams or kilograms (van Herpen et al., 2019), we asked households to indicate how much food they wasted as a percentage of what they brought into their homes (for different food categories). Specific instructions can be found in the Appendix (Table A.2).

2.3.2. Purchase data

To compare these relative measures with the absolute measures from the different measurement methods, we collected the households' digital grocery receipts from the three months before the study (see the Methods section). Specifically, we divided food waste measures by the averages of the different amounts purchased per week in each category. Here, we assume that we can also obtain representative measures for categories that are typically purchased in larger quantities but less frequently (e.g., pasta, rice). To capture the weight of purchased food, we used each household's historic electronic purchase logs, which they downloaded from one of the two major retailers' web pages. Using the loyalty card or app, purchased items were recorded at the point of sale. Based on our product database (containing approximately 51,300 products), we could append diverse information (e.g., weight, unit, pricing, food category) to households' baskets. For the analysis of the digital receipts, we also asked households how often and what share of the different food categories (in%) they purchased food from the corresponding retailers, how often they used their cards, and the number of individuals for whom the card was used.

2.3.3. Physical food waste

To capture food waste, we conducted a waste compositional analysis of the food waste collected by households (i.e., households in the *KC (Unaware), KC (Aware)*, and *KC+Diary (Aware)* conditions). Note that to prevent weight changes in the waste, households were specifically told to place the bags in front of their door in the morning of the collection. For the analysis, we developed sorting, classification, and weighing guidelines and training material for coders. Based on previous research (Tostivint et al., 2016; Nicholes et al., 2019), food waste was coded as either (a) *avoidable* food waste or (b) *unavoidable* food waste. Coders were provided with scales (1 g accuracy) to weigh the different food waste components and were tasked with entering the weights of all the different food waste components in a table template. Importantly, sorting, classification, and weighing were performed separately for the different food categories (e.g., fruits, meat, dairy). In addition, the state of the products (fresh, processed, heated, processed but raw, dried), their packaging material (glass, plastic, tetra pack, alu/metal, paper, others), package state (unopened, opened full, opened with leftover), and, if applicable, expiry date (best before or use by) were reported. Overall, 23 coders analyzed the content of the KC. All coders needed to pass a performance test (7 out of 10 points). They had to repeat the test until they passed it.

2.3.4. Continuous food waste diary entries

Households in the *Diary* and *KC+Diary (Aware)* conditions reported their food waste on a continuous basis—that is, every time food waste occurred in the household context. Therefore, we developed a web application (the application is available upon request) and provided households with information and prompts (e.g., QR code stickers) that allowed easy access to the web application. Similar to previous research (Quested et al., 2012; Richter and Bokelmann, 2017; Zorpas et al., 2018), we asked respondents to classify, weigh, and describe disposed food as well as provide some insights into the reasons for disposal. Most importantly, the web application asked respondents (a) which food item was discarded (dropdown/text entry), (b) how much it weighed (in grams), (c) the meals related to waste (e.g., breakfast or lunch), (d) the condition of the discarded food (e.g., frozen or packed), (e) where it was discarded (e.g., compost, toilet, or pets), and (f) why it was discarded (e.g., package too big or expired).

2.3.5. Preregistration and data availability

We pre-registered our material, research questions, and analysis plan on 12 April 2022 in the Open Science Framework (OSF). The data were collected and made available on OSF (anonymized pre-registration link; anonymized project link) without identifying information and with consent from the respondents.

2.3.6. Ethics

Ethical approval for this experiment was obtained from the Ethics Committee of a European University on November 02, 2021 (University name and reference number of ethical approval remain blinded for the review process). This research complies with the General Data Protection Regulation requirements.

2.4. Statistical analysis

The measured and self-reported food waste measures were summed for each household and food category. Certain categories were aggregated into combined categories: dairy and dairy alternatives; meat, meat alternatives, and fish; sweets and snacks; oil and fats; and all drinks. We conducted mixed-effects regression analyses with category-specific food waste shares as outcomes and a random structure for food categories and households. The models and their performances (marginal and conditional R2) can be found in the OSF. The models' performances were evaluated using 95 % confidence intervals and the conventional 5 % significance level ($p < 0.05$) for significance testing. All p-values were corrected for multiple testing (Benjamini and Hochberg, 1995).

3. Results

The average shares of food wasted per group, time, and measurement method are shown in Fig. 2.

On average, we measured 0.8 kg of food waste per household member during week 1 in the *KC (Unaware)* group, 0.69 kg per week and household member in the *KC (Aware)* group, and 0.63 kg per week and household member in the *KC+Diary (Aware)* group. In addition, in week 1, households in the *Diary (Aware)* and *KC+Diary (Aware)* groups reported 0.64 kg and 0.76 kg of food waste per member, respectively. In week 2, the households in the *KC (Aware)* group wasted 0.63 kg of food per member, while the *Dairy (Aware)* group reported 0.64 kg of food waste per household member. Note that the average household sizes were not the same under the different conditions.

3.1. Comparing standard measurement methods

The comparison of the experimental conditions of the methods at different times revealed that survey-based measurements generally led to the lowest measures of food waste (Model 1, survey-diary: 0.057, survey-KC: 0.060, $ps < 0.001$, diary-KC: -0.002, $p = 0.542$, whereas no significant differences existed between KC and diaries if the study purpose was known. Additionally, we found that kitchen caddies and diaries performed similarly well in distinguishing between high- and low-wasting households ($r = 0.759$, $p < 0.001$), whereas the correlation between the survey-based rankings of the households with the other two methods was much lower ($r_{survey:kitchencaddy} = 0.152$, $p < 0.05$, $r_{survey:diary} = 0.147$, $p < 0.05$). Regarding how the measurement methods affect the results over time, we found that survey-based food waste shares prior to the study were higher in comparison to the subsequent weeks (weeks 0–1: -0.004, weeks 0–2: -0.005, $ps < 0.001$, weeks 1–2: −0.001, $p = 0.594$.; Model 2.1.1-2). No changes were observed in the measured (*KC (Aware)*: weeks 1–2: 0.010, $p = 0.340$; Model 2.2) or reported (*Diary* week 1–2: 0.006, $p = 0.675$; Model 2.3) food waste. Note that a visualization of week 1 and week 2 measures can be found in the Appendix (Fig. A.1). Knowledge about the study purpose led to a significant reduction in the share of food waste measured (*KC (Aware)* vs. *KC (Unaware)*: -0.061, $p < 0.001$; Model 2.4). As no households indicated having wasted more than usual, and as overweighing was unlikely, we assumed that the *KC* (*Unaware*) group provided the closest estimate to the real amount of food wasted. Thus, we also found evidence that the diary underestimated food waste (-0.050, $p < 0.001$; Model 2.5). Using both a KC and a diary led to significantly higher shares of food waste measured (*KC+Diary (Aware)* vs. *KC (Aware)*: 0.042, $p < 0.001$; Model 2.6) and reported (*KC+Diary (Aware)* vs. *Diary (Aware)*: 0.028, $p = 0.014$; Model 2.7), which were still lower than the ground truth (*KC (Unaware)* vs. *KC+Diary* (*Aware*): -0.016, $p < 0.001$; Model 2.8)

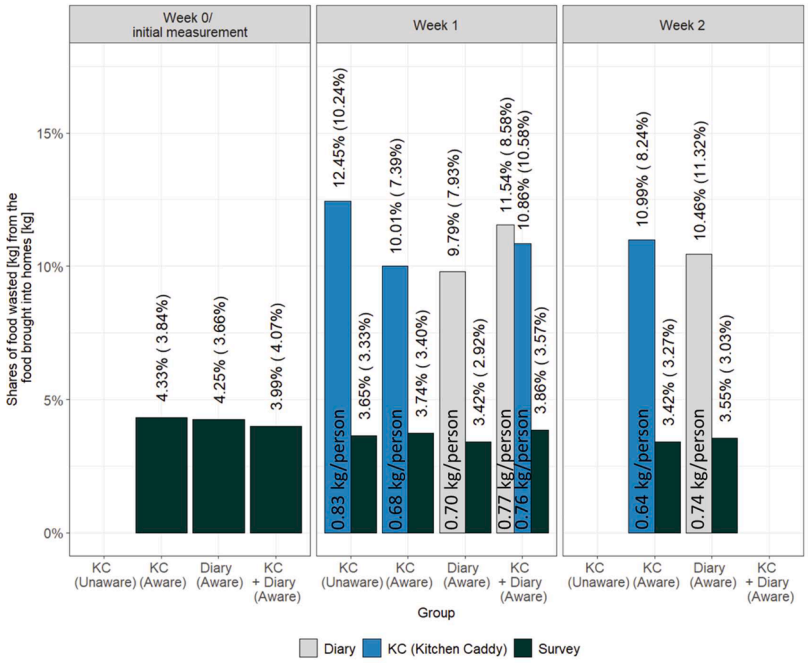

Fig. 2. Group means, standard deviations in brackets, and average weekly food waste amounts measured/reported for different measurement methods over time. The presented means and standard deviations (in brackets) represent the shares of food waste measured (kitchen caddy [KC]) or reported (survey or diary). In the case of diary and KC, the shares were derived by dividing each households' food waste by the total weight of the food purchased. Note that some of the initial 16 categories were combined (e.g., meat substitutes and meat). Survey measures were collected prior to the start of the study (week 0) to assess differences between the groups. KC (Unaware) had no initial measurement (week 0), and KC (Unaware) and KC+Diary (Aware) groups had no measurements in week 2.

3.2. Testing different barriers to accurate survey measures

Based on our model, we found that survey-based underreporting (in comparison with the other methods, Model 1) was relatively pronounced for vegetables and relatively small for fruits, staples, and dairy. Diary and survey measures also showed a significant difference when reporting on ready-to-eat meals (random intercepts were reported in the analysis file stored on OSF). The literature reveals that differences between diaries and surveys or kitchen caddies and surveys can be explained by social desirability and recall errors (Hoj, 2012; Hebrok and Boks, 2017; van Herpen et al., 2019). The initial surveys did not suggest that social desirability affected individual differences in food waste measures (social desirability: -0.005, $p = 0.305$; Model 3.1). To assess the effect of recall error, we compared how reporting accuracy changed over time. We found that the difference between KC, diary, and survey measures increased over time—that is, the individuals reported less accurate estimates (weeks 1–2: 0.015, $p = 0.057$; Model 3.2.1). This decrease in accuracy was further pronounced for individuals with high perceived barriers to reducing food waste (weeks1–2: -0.024, $p = 0.436$, barriers: 0.012, $p = 0.123$, time × barriers: 0.019, $p = 0.015$; Model 3.2.3.4). As a potential explanation for the decrease in accuracy, we asked the interviewees how much attention they paid to the study. On average, the *KC+Diary (Aware)* group had the highest scores of attention (1.59, households' statements were rated from 1 to 3 by our study team), followed by the *Diary (Aware)* and *KC (Unaware)* groups (1.47 and 1.41, respectively). The *KC (Aware)* group had the lowest score (1.25), although only the difference from the *KC+Diary (Aware)* group's score was significant (see OSF, interview data).

3.3. Testing different barriers to accurate KC and diary measures

The consistency of the *KC (Aware)* and *Diary (Aware)* groups indicated that alternative waste disposal routes (e.g., sinks without garbage disposals) did not seem to have a large impact on overall food waste measures. We found that in our study, roughly 3 % of all foods entered in the diary were disposed of through alternative waste disposal routes. In line with the main comparison, we found that the KC and diary measures from the *KC+Diary (Aware)* group (diary: 0.005, $p = 0.692$; Model 4) were not significantly different.

Our results suggested that both the KC and diary methods led to underreported food waste estimates, possibly owing to behavioral adaptations, which can be explained by participants feeling the need to change their behavior (experimenter demand effect) (Hoj, 2012; Sharp et al., 2010), the workload being too high (van Herpen et al., 2019; Langley et al., 2010), or participants getting tired of participation (van Herpen et al., 2019). The direct comparison between the *KC (Aware)* and *KC (Unaware)* groups provided evidence for a Hawthorne effect, as individuals who did not know the purpose of the study reported significantly higher amounts of food waste. This effect was especially pronounced for vegetables, oil and fats, and baked goods but weaker for dairy products. The effect did not vary for households with different degrees of social desirability, environmental concerns, intentions to not waste food, or food waste attitudes (Model 2.4.1-4; see OFS for detailed results).

During the interviews, we asked households whether they changed their behavior during the study in comparison to before the measurement started. The results showed that 20 % of the *KC (Unaware)*, 22 % of the *KC (Aware)*, 46 % of the *Diary (Aware)*, and 40 % of the *KC+Diary (Aware)* groups indicated that they wasted less (differences were significant for the groups with and without diaries).

4. Discussion

Developing high-accuracy HFW measurement methods is a major global challenge for practitioners, governments, and academics. The problem of food waste has received increasing attention, and a key barrier to reducing food waste is the lack of accurate and scalable measurement methods. Therefore, gaining a solid understanding of all barriers is important to achieving accurate food waste measurements. Our analysis—a field experiment with 365 households to investigate potential barriers—shows that we are still in the early stages of meeting this objective, despite the urgent need to mitigate food waste. Synthesizing our results and putting them into the context of existing research allows us to provide a decision aid, that is, a guideline that informs the optimal choice of measurement method for the needs of a study. Further, Table 2 provides some insights into aspects to consider in the design of studies and areas that need to be researched.

4.1. Survey-based measures lead to underreporting

Our analysis of the different measurement methods in a single setting confirms that survey-based measures lead to substantial underreporting in comparison with KC and diaries (Hoj, 2012; Giordano et al., 2018; Visschers et al., 2016; Delley and Brunner, 2018; Ammann et al., 2020) and that the degree of underreporting depends on product categories. Thus, to better understand underreporting and find interventions, analyses on a general level are not sufficient. In contrast to the common assumption that social desirability drives underreporting, we do not find such an association. Researchers have acknowledged that social norms possess the capacity not only to elicit socially desirable responses (Steenkamp et al., 2010) but also to shape behaviors (Otterbring and Folwarczny, 2024; Otterbring, 2021). Consequently, the absence of significant findings regarding the moderating role of social desirability may be attributable to the social desirability biases inherent in KC and diary measures. This is plausible, considering that all participant groups were aware that their waste would undergo sorting and analysis. The lack of good alternative measures for comparison has been recognized as a primary reason for not detecting socially desirable responses (Vesely and Klöckner, 2020). Further, our results support the findings of Giordano et al. (2018), who suggested that individuals' skills in estimating their food waste do not improve despite having observed their food waste over the course of the study. This indicates that the recall error is either not as predominant as previously thought (Hebrok and Boks, 2017; Giordano et al., 2018) or does not decrease despite participation in the study. The exact underlying mechanism is unknown, but potential reasons could be decreasing attention toward the study over time, fatigue effects, or other household members' behaviors, which are not always known or considered. In addition, many participants indicated that the food waste estimates were very difficult to obtain. Given that we sought shares of food wasted from what was brought into the households, the survey-based underreporting could be attributed to an overestimation of the initial purchases. Consequently, future research aiming to gather self-reported data on the fraction of food wasted should assess this in further detail.

The problem of biases in self-reports is well-known, not just in the domain of food waste (Rathje, 1984) but also for more general environmentally friendly behaviors (Warriner et al., 1984; Corral-Verdugo, 1997; Kormos and Gifford, 2014). Although researchers and social marketers are often constrained by resources, the urgent need for action and accurate food waste measurement underscores the importance of exercising caution in the use of purely survey-based measures. As the costs of using sensors (e.g., cameras and scales) to measure waste behavior (Likotiko et al., 2021) are decreasing, this seems to be a promising path not only for obtaining measures of food waste behaviors but also for reducing the predominance of self-reports in consumer research and psychological science (Otterbring, 2021; Baumeister et al., 2007).

4.2. Diaries lead to behavioral adaptations

Diaries seem to be a good option for overcoming some of the weaknesses of surveys, as households are repeatedly reminded (e.g., in

Table 2
Decision aid for measuring HFW, including typical study purposes, strengths, weaknesses, opportunities, risks, and other aspects to consider.

	Survey	Kitchen caddy/waste compositional analysis	Diary
Study purpose	- If **classifications** of households (e.g., high vs. low-wasting) need to be done - Exploratory research for a limited set of items (as it is based on recall)	- For monitoring **interventions** or food waste tracking (representative studies by governments)	- **Exploratory research**: To recognize relations (e.g., reasons for wasting, time of disposal, and meal) - To assess (single) **alternative waste** routes
Strengths	Is relatively cheap and hence can be used for large samples.	Can provide the most accurate measures of solid food waste.	Allows to gather very detailed information on every item wasted.
Weaknesses	- Leads to underreporting - Based on recall. There is evidence that pre-announcing a survey that includes relative amounts of food wasted correlates comparably more with other food waste measurements (van Herpen et al., 2019). - Households rely on their own definitions of food waste. - Potentially very difficult for households, given the nature of the question and the fact that the behavior of other household members is not always known.	- Resource intensive - Likely behavioral adaptations if households know that their waste is collected - Missing alternative food waste disposal routes (e.g., sink)/liquid waste in waste compositional analysis (very extensive as a part of KC studies) - In the case of a waste compositional analysis, it is difficult to link waste data with household characteristics, especially for multi-home buildings. - Food degrades between wasting and analysis - Prone to errors (e.g., wrong labeling) due to complexity of study	- Can be resource intensive - Leads to underreporting - Small amounts are less likely to be reported (Quested et al., 2012), which is supported by our interviews. - Constant reminding reduces the likelihood of incomplete measures but increases behavioral adaptations. - Households rely on their own definitions (including what is edible and non-edible food waste). - If no scales are used, researchers must optimally transform the measures.
Opportunities	- Can be repeatedly used for representative samples - Can easily use and analyze online surveys	- Combining method with diary does not seem to increase underreporting - Using smart technologies (e.g., smart bins or cameras, sensors)	- Diary measures potentially improve if only single-waste streams are assessed (Quested et al., 2012). - Can be used to collect pictures - Online diaries are easy to use and analyze.
Risks	Little is known about - How the type of measurement (absolute, relative, approximate) is related to underreporting. - Underreporting, its drivers, and how it changes over time. - How well survey measures reflect changes/ interventions.	Little is known about - How underreporting changes over time (e.g., participants forget about the study). - Drivers of underreporting (social desirability, Hawthorne effect, response fatigue). - How well liquid waste can be assessed.	Little is known about… - …how the accuracy of the reporting changes over time (reporting fatigue). - … the drivers of underreporting (e.g., social desirability). - …how well diaries on alternative food waste disposal routes (composting, pets) perform (Quested et al., 2012).
Aspects to consider			
Ethical issues	As it is generally recommended to collect household information (Gustavsson et al., 2014), ethical approval is required and recommended otherwise.		
Pre-announcement	There is no clear evidence whether pre-announcing the study improves estimates (e.g., our study vs. (van Herpen et al., 2019)).	Leads to underreporting results according to our study.	
Reminders		Our study shows that individuals forget about the study over time. Therefore, reminders should be minimized.	There is a trade-off between having complete estimates vs. biased estimates.
Measurement	If units are used instead of weights or percentages, the translation of units into weights should be done by researchers.	Optimally, food should be sorted and unshredded prior to the analysis.	Provide information about households' scales. If no scales are used, the translation of units should be done by researchers and reported.
Food waste definition	Use standard definitions (Tostivint et al., 2016; Pasos, 2019). Provide concrete definitions, including specific examples of what is considered edible or not.	Use standard definitions (Tostivint et al., 2016; Pasos, 2019). Information on the measurement process needs to be reported (weighting with packaging or not, classification of food, etc.).	Use standard definitions (Tostivint et al., 2016; Pasos, 2019). Provide a concrete definition, including what is considered edible or not. Instruct households on how to handle packaging and how to measure liquid waste.
Waste sources*	Households need to be very precisely informed about specific waste streams that need to be considered.	Combine KC with a diary for alternative waste routes. This should not increase underreporting.	Diary measures depend greatly on whether one or more waste sources have to be recorded (Quested et al., 2012)
Sample selection	Surveys allow for the collection of large-scale data sets. The samples should be representative, and random sampling should be applied.	Due to the extensive nature of the measurement method, representative samples are not always possible.	Online diaries allow for the collection of large-scale data sets. Report characteristics of dropouts.
What to report	Food waste definition applied, materials provided to the households, sampling mechanism (description of areas, type of households etc.), sample characteristics (location, household size, income, children etc.), characteristics of drop-outs, timing of collection, and whether there were holidays or not, average temperature (Quested et al., 2012), confidence interval of estimates		
Grocery purchases	There is great value in collecting grocery data as it can be used to adjust for seasonality (Quested et al., 2012), to get absolute food waste totals (Elimelech et al., 2018), as well as to explore potential food waste drivers (Merian et al., 2022)		
Repeated measures	It is important to keep the methodology constant (Quested et al., 2012).		

Note: *Alternative waste streams have been shown to only represent a minority of the food waste (Timmermans, 2015), which is also supported by our findings. Given that the amount of food waste associated with these streams and the barriers to receiving an accurate measurement as well as the costs of collection, their inclusion needs to be evaluated thoroughly.

our study, through scales or QR codes) to think about their waste. Further, diaries offer the possibility of assessing a broad set of data that cannot be collected otherwise (e.g., disposal state, location) (Hoj, 2012). However, constantly being reminded has an intervention character, and if participants pay more attention to the problem (Hoj, 2012; Sharp et al., 2010), they are likely to change their behavior (i.e., one potential channel through which a Hawthorne effect might arise (Schwartz et al., 2013; Levitt and List, 2011)). In the case of our study, the interviews revealed that the diary groups were significantly more likely to self-report a change in their behavior than the remaining groups. Further, because the task of filling in a diary was very demanding, households admitted to increasingly (based on the length of the study) estimating the amounts. Although the participants' food waste estimation skills might have improved, uncertainty remains. The inaccuracy of

diaries compared to physical waste measurements is supported by Quested et al. (2020), who concluded (and explicitly called for measures that account for the uncertainty of these estimates) that diaries lead to 7–40 % lower reported food waste than traditional waste compositional analyses, in which participants do not necessarily know that their waste is analyzed.

4.3. Liquids are especially prone to underreporting

The comparison of our results with existing studies reveals that the share of liquids was comparably much smaller (e.g., 3% vs. 22 % (Quested et al., 2012)). According to our interviews, this comparably low share could be explained by households not considering liquids as food waste but also due to more practical reasons, such as not knowing how to measure liquids (e.g., the remaining sauce in a pan). Therefore, liquid food waste remains a particularly underresearched area and should be assessed in future studies.

4.4. Households ideally should not know that their food waste is analyzed

Lastly, we found evidence of a Hawthorne effect in the case of KC. Therefore, it is important to mention that there are different channels through which such an effect can occur. In this study, potential contributors to the Hawthorne effect include the influence of participating in the study, the influence of being reminded about the issue, and the influence of participants' feeling that they must adjust (i.e., experimenter demand effect (Levitt and List, 2007)). We did not find significant differences between the *KC (Aware)* and *Diary (Aware)* groups, although diaries would be expected to have a much stronger interventional effect. Thus, participation in the study is likely to have biased both results but does not explain the difference between the *KC (Aware)* and *(Unaware)* groups. Therefore, our effect is potentially the result of households being reminded about food waste and wanting to look good in front of the experimenter (Levitt and List, 2011). In terms of accurate measurement methods, this highlights the benefits of measurement methods in which participants do not know that they are part of a study (i.e., traditional waste compositional analysis). However, because household-level information can be crucial for the analysis of food waste drivers, classic waste compositional analysis without households' consent was no alternative. When evaluating hybrid forms that are ethically sound, such as obtaining consent from the households without setting a specific collection date (i.e., informing households of the random collection of their bags) or allowing an elapsed time between the announcement and collection, the question about the durability of the phenomenon arises. Based on the evidence thus far, we can only speculate about the robustness of this phenomenon over time (i.e., whether it is short- or long-run (Levitt and List, 2011)). An experimentally induced sensitivity toward food waste leading to long-run reductions in food waste as well as households converging back to their old behaviors over time are plausible. Although we found evidence that the phenomenon was short-termed (i.e., we saw a directional increase in the shares of food wasted in the second half of the study, and many households in the *KC (Aware)* condition reported in the interview that they forgot about the study over time), consistent with evidence from the energy-saving domain (Tiefenbeck, 2016), future research should assess how this phenomenon changes over time.

Another option for improving KC and diary measures seems to be a combination of methods. We found that both the KC and diary measures were significantly higher in the *KC+Diary (Aware)* group. Given that both measures of this group were not significantly different, a potential explanation for this pattern could be that households wanted to look very conscientious and thus put great emphasis on recording everything from the KC in the diary and vice versa. This is supported by the fact that on a product level, 75 % of all waste incidents were reported in both the KC and the diary. However, given that this is only one of many potential explanations for the higher reporting in the *KC+Diary (Aware)* group, this finding should be replicated and assessed in future studies.

Overall, despite the advantages of waste collection and analysis, two main disadvantages remain. First, assessing liquids through a traditional waste compositional analysis (without households' knowledge) is impossible, and collecting liquids as a part of KC studies is complex (containers need to be provided for all sorts of liquids). A comparison of the *KC+Diary (Aware)* group measures revealed that only 30 % of the liquids reported in the diary were also found in the KC. Thus, for waste analyses whose focal interest is liquids, KC may not be an effective measurement method. Second, waste collection and analysis are generally very expensive and resource-intensive (Elimelech et al., 2019) and therefore often not feasible for academic researchers and social marketers. This is likely to remain an issue for waste collection because a holistic picture of liquids at least partially relies on self-reports (Dahlén and Lagerkvist, 2008; Gray, 2009) or an extensive collection procedure. Regarding the challenge with analysis, we address this issue by combining our findings and previous literature to develop a decision aid for the design of food waste studies (see Table 2). Within this decision aid, researchers and social marketers can, depending on the purpose of their study, gain valuable insights into the strengths, weaknesses, opportunities, and risks of the different measurement methods and gain valuable insights into design aspects. For example, for the evaluation of interventions targeted at reducing solid food waste, we suggest the use of physical waste management and discuss aspects that should be considered. Furthermore, to enhance the applicability of physical waste measurements, we call for the formation of alliances of resources (money, data), skills (e.g., data analysis (Hoj, 2012)), and stakeholders (e.g., governments, academics, marketers, and parties along the food supply chain, such as Great Britain's Waste and Resources Action Programme [WRAP]). Such efforts could focus on conducting studies that are specifically designed to reduce barriers, find accurate measurement methods, reduce uncertainty, and eventually test interventions for reducing food waste. Despite the costs associated with such an endeavor, experiences from WRAP show that reducing food waste offers a huge financial return on investments. In fact, on a national level, every £1 invested resulted in savings of £250 (HLPE 2017). Our work emphasizes that some of this return may be worth sacrificing to find better measurement methods, especially because a reduction in uncertainty will help to increase the efficiency of the methods and therefore increase returns even further. From a practical standpoint, our derived estimates are highly relevant. Observing a difference of 6 % between survey measures and kitchen caddy measures and assuming that individuals consume roughly 785 kg (Federal Statistical Office, 2024) of food a year, such a difference would, on a yearly-base, indicate measures that differ by roughly 47 kg of food waste per individual and 413.4 tons of food waste on a national level (Switzerland had 8.8 million inhabitants in 2022 (Federal Statistical Office)).

Finally, we call our fellow food waste researchers to publish all materials (e.g., sample characteristics, instructions, statistical analysis plans, and data, including confidence intervals) such that uncertainty can be quantified, results can be reproduced, and best practices in planning and designing studies can be established. Although our study has several limitations (e.g., we had data only from spring, purchase logs might be incomplete, the sample size was determined based on resource constraints (Bulus and Dong, 2021; Lakens, 2022), our sample was not fully representative owing to a likely selection bias, other barriers were not fully controlled for, and we did not assess the intercoder reliability), sharing all relevant data has the potential to accelerate food waste research and prevention.

CRediT authorship contribution statement

Sybilla Merian: Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Kevin O'Sullivan:** Writing – review & editing, Software, Resources, Methodology,

Investigation, Data curation. **Sabrina Stöckli:** . **Claudio Beretta:** Writing – review & editing, Resources, Methodology, Investigation, Funding acquisition. **Nadina Müller:** Writing – review & editing, Supervision, Funding acquisition. **Verena Tiefenbeck:** Writing – review & editing, Supervision. **Elgar Fleisch:** Writing – review & editing, Funding acquisition. **Martin Natter:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sybilla Merian reports financial support was provided by Swiss National Science Foundation. Kevin O'Sullivan reports financial support was provided by Swiss National Science Foundation. Sabrina Stoeckli reports financial support was provided by Swiss National Science Foundation. Claudio Beretta reports financial support was provided by Swiss National Science Foundation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data is made available through OSF.

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Appendix

Analyzing whether the groups were significantly different in terms of their characteristics, we found that, on average, *KC (Aware)* households were bigger than others. Therefore, we controlled for households in the subsequent analysis. Tables A.1, A.2 and Fig. A.1

Table A.1
Sample characteristics.

Characteristics	KC (Unaware)	KC (Aware)	Diary (Aware)	KC+Diary (Aware)
N	92	94	84	89
Household size	2.65	$2.95^{3,4}$	2.25^{2}	2.33^{2}
Gender (share of females)	0.69	0.71	0.77	0.72
Age	35.80	37.47	32.66	37.44
Food waste reduction intention	18.32	17.98	17.99	18.34
Cognitive reflection	1.77	1.88	2.06	1.99
Social desirability	4.01	4.05	4.00	4.02
Environmental concerns	4.08	4.00	4.11	4.09
Barriers	2.19	2.11	2.24	2.15
	Overall sample			
N	359			
Gender	Female: 496 (54 %)			
	Male: 415 (45 %)			
	Other: 1 (<1 %)			
Education (including children)	No formal education: 88 (9.83 %)			
	Mandatory school: 173 (19.32 %)			
	Apprenticeship: 153 (15.53 %)			
	General qualification for university: 108 (12.07 %)			
	Technical high school: 143 (15.98 %)			
	Bachelor: 150 (16.76 %)			
	Master: 72 (8.04 %)			
	PhD or higher: (0.89 %)			

Note: KC: Kitchen caddy; Superscripts indicate that significant differences exist between the groups; the groups are numbered from 1 to 4 (1: *KC (Unaware)*, 2: *KC (Aware)*, 3: *Diary (Aware)*, 4: *KC+Diary (Aware)*). A value of $2.95^{3,4}$ indicates that the group mean is significantly different from the means of the *Diary (Aware)* and *KC+Diary (Aware)* groups.

Table A.2
Measures and covariates.

Variable	Construct	Statistics
Weekly food waste survey	Please indicate a percentage estimate of how much food you dispose of during a typical week. Ask yourself what percentage of the food you buy you dispose of in a typical week. Include all food, meals, and beverages that you dispose of in your garbage, organic waste collection or compost, feed to animals, or empty into your garbage disposal. Edible parts of food, such as bread crusts, apple peels, or fish skin, are also included, along with any spoiled, rotten, or expired food." (see Fusion Definitional Framework; Gustavsson et al., 2014). Note that we provided households with a list of 16 food categories (e.g., fruits, meat, bread, dairy products, and eggs) and asked them to indicate a percent estimate for all of these food categories separately on an 11-point scale from 0 % to 100 % (0 %, 1–5 %, 6–10 %, 11–15 %, 16–20 %, 21–25 %, 26–30 %, 21–25 %, 26–30 %, 31–40 %, 41–60 %, 61–80 %, 81–100 %; Merian et al., 2022)	
Food waste reduction intention	Four items evaluated on a 5-point Likert scale (disagree-agree) I intend to waste no food at all. I intend to eat all purchased food. I intend to produce only a little food waste. I intend to reuse all leftovers.	Mean inter-item correlation= 0.56 Cronbach's alpha= 0.83

(*continued on next page*)

Table A.2 (*continued*)

Variable	Construct	Statistics
Cognitive Reflection	Three questions assessing the cognitive reflection: A bat and a ball cost $1.10 in total. The bat costs a dollar more than the ball. How much does the ball cost? ___ cents If it takes 5 machines 5 min to make 5 widgets, how long would it take 100 machines to make 100 widgets? ___ min In a lake, there is a patch of lily pads. Every day, the patch doubles in size. If it takes 48 days for the patch to cover the entire lake, how long would it take for the patch to cover half of the lake? ___ days	Mean inter-item correlation= 0.41 Cronbach's alpha= 0.68
Social desirability	Four items evaluated on a 5-point Likert Scale (disagree-agree): I always practice what I preach. If I say to people that I will do something, I always keep up my promise, no matter how inconvenient it might be. I would never lie to people. I smile at people every time I meet them.	Mean inter-item correlation= 0.29 Cronbach's alpha= 0.61
Environmental concerns	One item evaluated on a 5-point Likert Scale (not concerned – very concerned): How concerned are you, in general, regarding environmental issues?	
Collective-efficacy	Three items evaluated on a 5-point Likert Scale (disagree-agree): In difficult situations, we can rely on our skills. We can deal with most problems using our own resources. Difficult and complicated tasks can be successfully resolved by us.	Mean inter-item correlation= 0.84 Cronbach's alpha= 0.94
Food Waste Barriers	Eleven items evaluated on a 5-point Likert Scale (disagree-agree): We do not have enough time. There are more important things that we care about. I don't believe that my food waste costs me a lot of money. We compost our food waste. We don't want to restrict the choice of fresh food. We have to purchase a great variety of foods to ensure that we have enough healthy foods. Children do not always eat up their food. We don't know how to reduce our food waste. Package sizes are too big, such that we cannot consume everything in time. Products are often of bad quality, such that we have to waste them. We are cautious, as we don't want to get ill.	Mean inter-item correlation= 0.186 Cronbach's alpha= 0.70

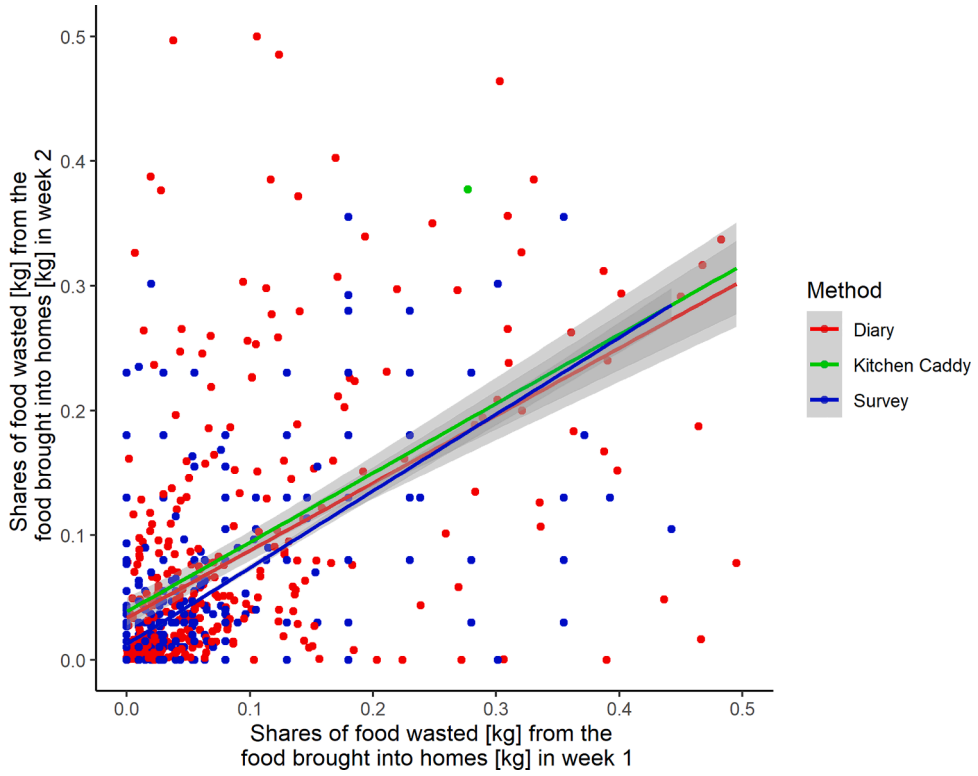

Fig. A.1. Visualization of food waste measures based on different methods over time (measures collected in the first week of the study are on the x-axis and measures collected in the second week of the study are on the y-axis).

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