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Comparing diaries and waste compositional analysis for measuring food waste in the home

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ABSTRACT

Diaries have been used to obtain national and subnational estimates of household food waste (HHFW) in several countries. Furthermore, diaries have been proposed as a method for tracking progress towards goals that include HHFW reduction. However, multiple studies have suggested diaries substantially underestimate HHFW. This paper collates and analyses data from five studies in which diary estimates of HHFW can be directly compared to other, more accurate estimates from waste compositional analysis (WCA). This analysis finds that all diary estimates for HHFW were lower than the corresponding WCA estimates, with the degree of underestimation ranging from 7% to 40%. Four main factors are likely to contribute to this underestimation: behavioural reactivity (people wasting less during the diary period), misreporting (not all items discarded being recorded), measurement bias (not all items are weighed) and self-selection bias (those completing a diary being different from the wider population). The study concludes that a) diaries are useful for obtaining *approximate* estimates of HHFW and detailed information on what, why, and where food is discarded, but b) diaries alone are not suitable for tracking HHFW over time or evaluating interventions designed to reduce the amount of HHFW (without substantial further research).

1. Introduction

1.1. Background

Food waste is a globally important issue. Approximately one-third of food produced is either wasted or lost, which wastes resources, generates unnecessary greenhouse gas emissions (GHGs) and reduces the economic value of the food produced (FAO, 2011; FAO, 2015). For example, from 2010 to 2016, global food waste across the supply chain represented 8–10% of all anthropogenic GHG emissions and cost about US$1 trillion per year (Mbow et al., 2019).

As food waste has risen up the social and political agenda, reducing the amount wasted is now an important objective, as reflected in the United Nation's Sustainable Development Goal (SDG) 12.3[1] and other national and regional goals. In medium- and high-income countries, the largest single source of food waste is households (e.g. Stenmarck et al., 2016; Xue et al., 2017; Arcadis, 2019). Therefore, if the SDG target and others are to be met, substantial reductions in the amount of *household* food waste (HHFW) will be required.

Measuring food waste around the world is one of the priorities identified for helping to support and track progress towards such targets (WRI, 2019). This is for a number of reasons, as quantification allows (CEC, 2019):

- the scale of the issue to be quantified, e.g. estimating the amount and impact of the HHFW;
- the nature of food waste to be better understood – e.g. what types of food are being wasted and reasons for this waste – which supports development of solutions (e.g. policies, campaigns, interventions) to reduce the amount of HHFW;
- evaluation of these solutions to understand if they worked and, if so, why; and

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[1] https://sustainabledevelopment.un.org/sdg12.

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- progress against targets to be tracked, many of which require *national* estimates of HHFW to be obtained.

Each reason for quantification places different requirements on the quantification methodology. For instance, understanding the nature of HHFW requires detailed information (e.g. type of food being wasted), but not necessarily a high level of accuracy. In contrast, tracking progress towards targets requires accurate information to compare estimates at different times, but detailed information is not essential. Given the importance and complexity of measurement, there have been many initiatives to improve the quality of measurement of HHFW (e.g. Tostivint et al., 2016; FLW Protocol, 2016a; CEC, 2019).

A range of methods have been developed and used to quantify food waste in the home, including questionnaires (asking people to recall amounts and types of food waste), use of a receptacle to collect HHFW (either weighing or assessing its volume at regular intervals, e.g. Kitchen Canny[2]), photographic methods (e.g. Roe et al., 2018; van Herpen et al., 2019), diaries and waste compositional analysis (both detailed below).

Many studies have demonstrated that questionnaires underestimate HHFW to a high degree making their use problematic (Delley and Brunner, 2018; van Herpen et al., 2019; Giordano et al., 2019). van Herpen et al. (2019) found that diaries, photo records and use of receptacles gave similar estimates of food waste to each other. However, as noted by the authors, it is likely that these three methods also underestimate the amount of food waste, although to a lesser extent than questionnaires. This assertion was based on evidence in the literature (Høj, 2011; WRAP, 2013a; NRDC, 2017a), suggesting that food-waste diaries underestimate HHFW in comparison to waste compositional analysis (WCA). This paper seeks to draw that evidence – alongside newer studies (McDermott et al., 2019) – together and provide new analysis of existing datasets to explore the issue of underestimation in HHFW measurement of diaries compared to waste compositional analysis:

Waste compositional analysis (WCA): at a minimum, sorting food from non-food materials in mixed waste streams and weighing the amount of food present. Further sorting to determine types of food is possible but increases the cost. Has only been applied to solid waste streams leaving the home via collected materials (e.g. kerbside collection) and excludes materials discarded to drain or composted at home. Examples include Parizeau et al. (2015), Edjabou et al. (2016), Elimelech et al. (2018).

Food-waste diaries (sometimes referred to as 'kitchen diaries'): asking household members to record the food that they have discarded, often including the type of food, quantity discarded, the reason why it was thrown away and the discard route (e.g. in the kitchen bin, down the kitchen sink, home composted). Examples include Langley et al., (2010), Silvennoinen et al., (2014), Hübsch and Adlwarth (2017), Richter and Bokelmann (2017). When estimating the quantity of food discarded, some studies provide weighing scales for participants, while others allow the quantity to be recorded by weight, volume, counts, portion sizes, or other estimation such as "handfuls."

Unlike diaries, WCA is not routinely used to establish why food is thrown away, and cannot cover some waste streams (e.g. sewer, home composting). WCA has a reputation for being more expensive (FLW Protocol, 2016a) but may be cheaper than diaries in many circumstances (NZWC, 2018).

A number of reasons for biases in both WCA and diaries have been suggested in the literature as described in the next two sections.

[2] https://www.changeworks.org.uk/projects/kitchen-canny.

1.2. Biases in diaries

It is generally thought that diaries underestimate levels of HHFW, rather than WCA overestimating. This is, in part, based on evidence from diaries used for other purposes, such as dietary intake. Several studies related to food *consumption* have found that people record less food than they actually eat, underestimating consumption by a considerable margin: for example, underestimating by 27% (Lennox et al., no date) and 29% (National Research Institute for Food and Nutrition, 2008).

The potential reasons for underestimation with regard to HHFW have been discussed in a number of publications (Høj, 2011; ForMat project, 2016; FLW Protocol, 2016b; NRDC, 2017a). These can largely be grouped into four main (potential) reasons, which are discussed below:

- **Behavioural reactivity:** people wasting less during the diary period.
- **Misreporting**: not all of the food waste that is generated being recorded in the diary.
- **Measurement biases**: biases introduced from the conversion of information about the quantity of an item that is not weight-based (e.g. number of slices of bread, a handful of grapes) to the mass (weight); relevant only for some diaries.
- **Selection biases**: those people completing the diary research not being representative of the wider population with regard to amounts and types of HHFW.

For the **behavioural reactivity**, social desirability bias (also referred to as social acceptability bias) is frequently cited as the main cause (FLW Protocol, 2016b; ForMat project, 2016; NRDC, 2017a). This could occur by the diary raising the salience of food waste as an issue for the participants, meaning that people make more of an effort to 'do the right thing', e.g. reduce the amount of food that they waste or use a more 'socially acceptable' route to dispose of this food waste (for example, via separate food-waste collections). This could involve eating up parts of food that they usually throw away, e.g. bread crusts.

Behavioural reactivity may also occur for other reasons including that people modify their behaviour to minimise the burden of undertaking the diary exercise. For instance, people may delay a clear-out of a fridge or cupboard until after the diary has taken place, in order to avoid having to record all the items they throw out.

If behavioural changes linked to food-waste activities were the only reason for underestimation, this would mean that the diary would be capturing what actually gets wasted in the household during the research period. However, the amount of HHFW generated during that period would *not* be representative of what they typically waste (i.e. outside of the study period), due to the change of behaviour stimulated by the diary. For this reason, the term 'underestimation' is used in this study rather than 'under-reporting', so that it also covers behavioural reactivity.

In contrast, **misreporting** is where the food waste recorded in the diary does not reflect what was actually wasted during the diary period. This difference could relate to the quantity of food waste and/or information about the food waste (e.g. the description of the food wasted, where it was disposed, etc.).

Some of this misreporting could be linked to the diary keeper not being aware of all the food waste generated in the household, i.e. items thrown away by other household members, who aren't fully engaging with the diary research.

As people interact with food on a regular basis, some of their actions may be undertaken subconsciously (or with a low level of consciousness). For example, emptying a cup (of drink) before

putting it in a dishwasher may be done without much thought, and a research participant may forget to enter this item into the diary as a result.

Misreporting could also be influenced by confusion over what should be reported in the diary, either via unclear instructions, or participants not acting upon these instructions fully. For instance, this could result in the diary-keeper not recording items they do not consider 'food waste' (e.g. items being fed to animals, parts considered inedible such as eggshells and meat bones).

Social desirability bias could also be influencing underestimation via misreporting. This would involve people choosing not to record items (or misreporting details about the item) due to how they feel they would be judged.

Some diaries (e.g. GfK Belgium, 2017) only ask participants to record 'wasted food', i.e. items considered edible (e.g. slices of bread) and not to record inedible parts, such as egg shells and meat bones.[3] This introduces an additional issue as it leaves the decision of what is an edible part to the diary participant. For many 'borderline' items, there are different opinions within a single country about what is considered edible (Nicholes et al., 2019).

Misreporting can also occur due to simple mistakes by diary participants or those collating and analysing the data. For example, a participant may use the wrong units, e.g. decilitres instead of litres, cups instead of pints.

Another possible reason for underestimation is due to **measurement biases.** For diaries, this relates to how items entered into the diary are quantified. Some diary research provides participants with weighing scales so that all items in the diary can be weighed (e.g. NRDC, 2017b; McDermott et al., 2019). Other studies allow approximations to be recorded in the diary in addition to weight and volume: e.g. '1 slice of bread', 'two apple cores' (e.g. WRAP, 2013b). These estimates require conversion to a common metric (usually weight). This process will lead to some inaccuracies, as, for instance, not all slices of bread are the same weight. However, asking participants to weigh all items potentially increases the workload of diary keepers, which could increase the degree to which people change behaviour in response to the diary.

Less discussed in the literature to date are **selection biases**. In essence, people who agree to participate and complete the diary may not be representative of the population they have been selected to represent. It is relatively straight-forward to weight the results to account for unrepresentativeness relating to socio-demographic factors (e.g. too many or too few research participants from a particular age or income bracket). However, it is less straightforward to adjust for factors relating to food waste – for example, it could be the case that those who complete the diary are more engaged with food-waste prevention activities or have more time available to complete the diary exercise than the rest of the population. (The amount of time people devote to food-related activities has been found to correlate with food waste in a number of studies, e.g. WRAP, 2014b). Rarely is it practically possible to adjust for such factors.

WRAP (2014a) published the amount of food waste over a 7-day diary period, the findings of which indicate that total food waste recorded was 17% higher on the first day compared to the average of the other 6 days. This could be linked to behavioural reactivity (it may take people a short period of time to react to the diary research) or misreporting (participants might be more accurate in completing their diary early on in the research period: i.e. response fatigue, Thompson and Subar, 2001).

1.3. Biases in waste compositional analysis studies

Waste compositional analysis is not without potential biases. Many studies require participants to provide consent (e.g. WRAP, 2013a). Similar to diaries, this process provides the opportunity for **self-selection bias**. However, the magnitude of any effect has not yet been studied.

Many WCA studies inform the participants of the nature of the study and/or administer a questionnaire prior to waste being collected and analysed. This questionnaire may be relatively brief (e.g. to gather socio-demographic information) or much more involved (e.g. detailed questions on household practices related to HFHW, e.g. WRAP, 2013a). This latter type of questionnaire has the potential to influence the amount and types of food wasted through **behavioural reactivity** (see above). However, given the relative level of involvement between a one-off questionnaire and keeping a diary for a week, it is likely that this behavioural reactivity will be smaller for WCAs than for diaries. Some studies using this type of questionnaire introduce a delay of a few weeks between the questionnaire being administered and households' waste being analysed to minimise behavioural reactivity. However, neither the magnitude of this behavioural reactivity nor its effect over time has been studied with regard to HHFW.

Some WCA studies (NRDC, 2017a,b) intercept the waste to be analysed prior to it being placed in a bin. This involves the participating households doing something differently from their usual routine, often placing waste material in special bags for collection by the research team. This has the potential to influence levels of food waste via behavioural reactivity; participants are likely to be more aware of this type of study (and reduce levels of food waste) than one where waste is intercepted once it is in the bin, often on the day it would usually have been collected.

There are a number of ways in which **measurement biases** can influence WCA. WCA sometimes involves sieving the waste as part of the sorting process. The mesh size for the sieving is typically 10–40 mm (Lebersorger and Schneider, 2011). Smaller material (called 'fines') passes through the sieve and is usually not sorted further. The use of sieving can introduce a bias to the estimate if there is a disproportionately high or low amount of food in the fines.

There is often a gap of a few days or even weeks between food being placed in a bin by a householder and it being sorted as part of a WCA study. In this time frame, food can degrade (e.g. rot, go mouldy) to such an extent that the material is hard to recognise and/or sort. This can lead to material being excluded or misrepresented in WCA-based estimates of food waste.

Compared to other materials in the household waste streams, food has a relatively high water content. There is the potential for evaporation to occur – especially in hot, dry conditions – reducing the weight of the food being measured. Conversely, in damp condition, dry food may absorb moisture. Both effects could influence the results.

Finally, food is often thrown away in packaging. Some WCAs remove the packaging and weigh the food without it; others do not separate the packaging from the food, weigh both together and include the weight of packaging in the estimate of food waste. Lebersorger and Schneider (2011) found that this added around 8% to the estimate of food waste – a figure that will vary depending on the packaging used within a country and what types of item get wasted.

Whilst not a bias, it is important to note that WCA has only been

[3] In this paper, terminology consistent with the *Food Loss and Waste Accounting and Reporting Standard* (FLW Protocol, 2016a) has been adopted. 'Food waste' is defined as the sum of 'wasted food' (i.e. parts of food intended for human consumption, which the original studies may have referred to as 'avoidable' or 'edible') and 'associated inedible parts' (e.g. egg shells, meat bones, inedible fruit rinds, which may have been originally named 'unavoidable' or 'inedible'). 'Discard route' is used to describe the route by which food waste leaves the kitchen/home.

applied to waste streams collected from households and has not been used for food and drink going down the drain or home composted. Therefore, it usually provides an incomplete picture of HHFW.

1.4. Research questions

This paper brings together findings from previous studies containing comparable data for diaries and WCA. Where possible, the data were further analysed in an attempt to understand *why* there are differences between the two. The research questions investigated are:

1. For each study, what is the difference in estimates of household food waste (HHFW) obtained from WCA and food-waste diaries?
2. Are these differences consistent between studies?
3. What are the reasons for food-waste diaries to underestimate HHFW?
4. Is it feasible to use a correction factor to adjust for underestimation in food-waste diaries, so that their results are more accurate?

Diaries are used to obtain national and subnational estimates of food waste in a number of countries and regions (Hübsch and Adlwarth, 2017; GfK Belgium, 2017). There is the potential for these diary results to be used for future reporting to the UN as part of SDG12.3, the European Commission as part of the EU wide reporting on food waste (European Commission, 2019) and other national and regional goals and policies. Therefore, answering these research questions is not just an academic exercise, but has policy implications: investigation will help us understand the circumstances in which it is appropriate to use results from food-waste diaries and waste compositional analysis.

2. Methodology

This study collates existing comparisons of food-waste diaries and WCA (as described in the introduction) to understand the magnitude of the difference between the two methods. In addition, the datasets available to the authors were further analysed to investigate differences by discard route and household size in addition to the split between wasted food and associated inedible parts. It is worth noting that studies used differing terminology and methods for differentiating between wasted food and associated inedible parts.

For an appropriate comparison, the diary and WCA are required to measure food waste from similar geographies at similar times. Both need to have samples that attempt to be representative of the population in question, although, as discussed in the introduction, there will always be some discrepancies between sample and population.

The comparisons made are for the 'discard routes' common to both methods. In the studies collated in this article, these common routes are waste streams collected from households at the kerbside by or on behalf of the local authority (municipality). Depending on the nature of collections available to households in the study area, this may include:

- Residual waste stream: a mixed waste stream containing unsorted material (Table 1), usually bound for landfill or incineration. Also referred to as trash or garbage.
- Collections targeting food waste: depending on location, this can include separate food waste collections or collections accepting mixed organics (usually garden and food waste). These material streams usually undergo (industrial) composting or anaerobic digestion.

As WCA does not cover food waste going down the sewer, home composted or fed to animals, no comparison is made of these discard routes.

2.1. Studies included in the analysis

Five studies containing information allowing comparison of WCA and diaries were identified for further analysis within this paper. Although searches were performed in the academic and grey literature, four of the five are from the grey literature and one was previously unpublished. These are summarised in Table 2 and discussed below.

WRAP (2009a) undertook extensive research to understand and quantify UK food waste, using information from WCA and two diaries. One diary focused solely on food and drink waste going down the sewer (as described in WRAP, 2009b); given that this study does not have overlapping discard routes with any WCA, it is not considered further in this paper. The other diary – described in Table 2 – was a general food waste diary, covering all five discard routes in Table 1.

This UK study was repeated during the course of 2012/13 (WRAP, 2013a; WRAP, 2013b). Of the five studies compared in this paper, this one has the largest combined sample size. For both years, neither the diary nor the detailed waste compositional analysis is used to estimate the total amount of food waste from UK households in national estimates. National estimates instead rely on estimates derived from a larger number of less-detailed WCAs (WRAP, 2016): differences in results relating to this synthesis are noted in the discussion.

The methodology for the two UK studies was adapted for a study in Jeddah (Saudi Arabia), making changes where circumstance required. Waste for WCA was collected daily to account for differences in climate (hotter and drier) and waste-collection arrangements (residual waste is usually removed from the household daily). The sample sizes for the diary and WCA were much smaller than the UK studies: around 100 participating households for each. At the time of writing, this work is unpublished.

NRDC (2017a,b) estimated the amount and reasons for residential and non-residential food waste in three US cities: Denver, Nashville, and New York City. In the residential part of the study, households completed a one-week food-waste diary and a subset of these households also had a 'bin dig' (WCA) undertaken on their waste (i.e. there was overlap between the diary and WCA samples, in contrast with the other studies). WCA was performed at a similar time to the diary: waste samples compared in this paper were picked up during and/or directly after the diary research period and represented the same time period as the diary. Unlike the aforementioned studies, households were provided with scales to weigh their food waste items.

McDermott et al. (2019) measured wasted food in rural and urban sites in the US state of Oregon using both diaries and WCA. Similar to the NRDC study, diary participants were given weighing scales for the diary exercise. In contrast to the NRDC study, the diaries were undertaken after the WCA; the waste measured in the WCA was not from the same week as the diary record. Diary participants were also given the choice of recording entries online or on paper. Unlike the previous studies, participants were also given a choice of whether to record seven consecutive or non-consecutive days in the diary, with a higher incentive given to households completing consecutive days.

For the studies included in the analysis, further details of the study, including how the samples were drawn, can be found in the

Table 1
Food-waste discard routes generally included in diaries and waste compositional analysis; the routes compared in this study are indicated.

Discard route	Food-waste diary	WCA	Included in this study?
Residual	Yes	Yes	Yes
Collections targeting food waste	Yes	Yes	
Sewer	Yes	No	No
Home composting, wormery, etc.	Yes	No	
Fed to animals	Yes	No	

Table 2
Methodological details of studies collated and analysed in current paper.

Study/Reference	Geography/year of fieldwork	Method	Households in analysis	Duration of data collection	Are all items weighed in diary?	Form of diary	WCA & diary same sample?
Household food and drink waste in the UK (WRAP, 2009a)	UK, 2007	WCA	2129	1 or 2 weeks, depending on collection cycle			Different sample
		Diary	284	1 week	No, other metrics allowed	Paper-based	
Household food and drink waste in the UK 2012 (WRAP, 2013a,b)	UK, 2012/13	WCA	1799	1 or 2 weeks, depending on collection cycle			Different sample
		Diary	993	1 week	No, other metrics allowed	Paper-based	
Household Food Waste in Jeddah (unpublished analysis by WRAP for Savola)	Jeddah (Saudi Arabia), 2016	WCA	102	4 ¼ days			Different sample
		Diary	100	4 days	No, other metrics allowed	Paper-based	
Estimating quantities and types of food waste at the city level (NRDC, 2017a; NRDC, 2017b)	Denver, Nashville, New York City (USA) 2016/17	WCA	120*	1 week			WCA sample subset of diary sample (WCA before, during or after diary)
		Diary	120*	1 week	Yes, scales provided	Paper-based	
Oregon wasted food study: Residential and commercial sector study (McDermott et al., 2019)	Oregon (USA), 2017/18	WCA	164*	2–4 weeks (adjusted to calculate 1 week)			Diary sample subset of WCA sample (WCA before diary)
		Diary	164*	1 week (within a two-week window)	Yes, scales provided	Paper-based or on-line	

*Sample sizes for the NRDC and Oregon studies were larger; however, the analysis in this paper only compares households who kept a food-waste diary and had their waste analysed by WCA. As a consequence, average amounts of food waste reported in this paper may differ from those in the associated reports.

original publications.

2.2. Other studies considered but not included in the analysis

In addition to the above studies, pairs of studies (diary and WCA) were found for three other countries: Italy (Giordano et al., 2018), Finland (Silvennoinen et al., 2019) and Germany (Hübsch and Adlwarth, 2017; Schmidt et al., 2019). However, these studies were not included in this analysis due small sample size (Giordano et al., 2018), insufficient information to perform the comparison (Silvennoinen et al., 2019) or reported data already adjusted for underestimation (Hübsch and Adlwarth, 2017).

2.3. Analysis methodology

The food waste estimates were calculated as an average mass of food waste per household per week. The calculations were undertaken on a per-household basis, rather than per person, because measurement was taken at the household level.

In this study, *mean* averages have been compared. This is in contrast to previous research investigating this difference (Høj, 2011), which undertook a statistical analysis comparing *median* values for 2007 data from the UK (WRAP, 2009a). For all studies, the sample sizes are large enough to support use of mean averages and parametric tests (Lumley et al., 2002). However, the median is also useful for comparing non-normal distributions, such as those relating to HHFW. Therefore, the discussion includes results from Høj (2011): the results are qualitatively similar irrespective of whether the mean or median was used.

For the two WRAP studies, households have been weighted to adjust for differences between the sample and population with regard to the number of occupants in the household. For the food-waste diaries used in WRAP (2013b), the presence and type of food waste collections was also included for weighting purposes (see WRAP, 2013a for more details). For the Jeddah, NRDC and Oregon studies, no such weighting was undertaken due to a lack of information for the wider population (e.g. distribution of number of people in a household).

The equation used to express the degree of underestimation for diaries in comparison to WCAs was[4]:

$$\text{Degree of difference} = \frac{\mu_{WCA} - \mu_{diary}}{\left(\frac{\mu_{WCA}+\mu_{diary}}{2}\right)}$$

[4] In NRDC 2017a, a different formula was used for reported levels of 'under-reporting', referred to in this article as 'degree of difference'.

Table 3
Comparison of amounts of total food waste for diary and WCA.

Name of study	Diary kg/hh/wk	WCA kg/hh/wk	Under-estimation (%)	Degree of difference (%)
UK, 2007	2.18	3.63	**40%**	50%
UK, 2012/13	1.89	2.69	**30%**	35%
Jeddah, 2016	3.29	5.28	**38%**	46%
NRDC, 2016/17	1.89	2.95	**36%**	44%
Oregon, 2017/18	2.99	3.23	**7%**	8%

$$\text{Degree of underestimation} = \frac{\mu_{WCA} - \mu_{diary}}{\mu_{WCA}}$$

where μ_{WCA} is the mean value for food waste measured by waste compositional analysis and μ_{diary} is the mean value for food waste measured by food-waste diary. The degree of underestimation provided in this paper were calculated *for the relevant sample of households*. An alternative approach would have been to calculate the degree of underestimation for *each household* and then averaging these levels of underestimation. This was not used for two reasons: for some studies, the samples for WCA and diaries comprised different households, so it is not possible to calculate the underestimation by household; in addition, the degree of underestimation in households with no food waste in the WCA is undefined (dividing by zero).

The degree of underestimation has also been used to calculate approximate scaling factors, which, if applied, could correct for diary underestimation. The formula for this is given below. Circumstances in which their use is appropriate are detailed in the discussion.

$$\text{Scaling factor} = \frac{1}{(1 - \text{degree of underestimation})} = \frac{\mu_{WCA}}{\mu_{diary}}$$

3. Results

3.1. Overall estimate of underestimation

In all five studies analysed in this paper, the diaries reported lower levels of food waste compared to waste compositional analysis (WCA) for the discard routes covered by this study (residual and collections targeting food waste). The degree of underestimation varied from 7% (Oregon) to 40% (UK, 2007) (see Table 3 and Fig. 1). This range is moderately large and may reflect cultural differences between countries and methodological differences between studies. Due to the uncertainties for each estimate, it is not possible to state which factors influenced the values found in each study.

3.2. Estimates of underestimation for fractions

When considering different fractions of food waste, the range of values for underestimation increases substantially. Underestimation for wasted food (avoidable/edible) varied from 18% to 70% and from −83% to 57% for associated inedible parts (Table 4).

A comparison was made for single- and multi-occupancy households. Diaries in single-occupancy households underestimated food waste by 22%–32%, compared to 35%–44% in multi-occupancy households (Table 5).

The estimates of underestimation for the residual waste stream (i.e. trash) have moderately tight range (27–46%). In contrast, the underestimate estimates for collections targeting food waste vary much more greatly, from −16% to 36% (Table 6). The fraction of

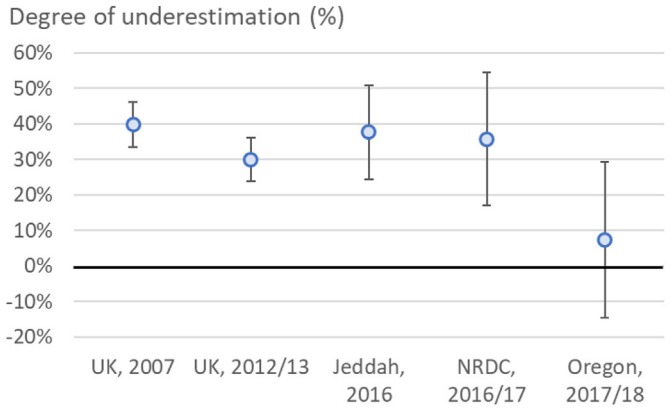

Fig. 1. Degree of underestimation of food-waste diaries compared to WCA, including 95% confidence intervals around the mean.

households in each sample with access to collections targeting food waste was generally low, which exacerbated the scatter between studies.

For these fractions, the level of underestimation has more variation between studies (Tables 4–6) than the variation between the underestimation of total food waste (Table 3). The reasons for this and its implications are discussed in section 4.3.

3.3. Comparison by household

The data presented for the Oregon and NRDC studies only included households that participated in both diaries and WCA phases of the research. Fig. 2 presents a histogram representing the difference in total food waste between the WCA and diaries (WCA minus diary) for each household. For both studies, the majority of the households form an approximately normal distribution centred close to zero (i.e. diaries and waste compositional analysis, on average, giving similar results). However, in both studies, there are a substantial minority of households (10% and 12%) with the WCA estimate of food waste 5 kg or more in excess of that of the diaries (right-hand bar of histogram). It is these households that appear to be influencing the underestimation.

These households and their reported food waste were investigated to see if they could provide any suggestion as to why much more food waste was found in WCA than in the diaries. The following factors were found:

- These households tended to be larger households. A disproportionately high number were multi-occupancy households.
- There were instances where few/no inedible parts were recorded in the diaries, yet substantial amounts were found in the WCA.
- A small number of households indicated that all food waste was fed to pets in the diary, but substantial amounts were found in the WCA.

Table 4
Comparison of diary and WCA for wasted food and associated inedible parts.[5]

Study	Wasted food (or avoidable, edible)			Associated Inedible parts (or unavoidable, inedible)		
	Diary, kg/hh/wk	WCA, kg/hh/wk	Under-estimation (%)	Diary, kg/hh/wk	WCA, kg/hh/wk	Under-estimation (%)
UK, 2007	1.34	2.65	49%	0.84	0.98	14%
UK, 2012/13	1.28	1.77	28%	0.61	0.92	33%
Jeddah, 2016	1.25	4.16	70%	2.04	1.12	−83%
NRDC, 2016/17	1.30	1.58	18%	0.59	1.37	57%

Table 5
Comparison of total amount of food waste for diary and WCA, single-versus multi-occupancy.[6]

Study	Single-occupancy			Multi-occupancy		
	Diary, kg/hh/wk	WCA, kg/hh/wk	Under-estimation (%)	Diary, kg/hh/wk	WCA, kg/hh/wk	Under-estimation (%)
UK, 2007	1.81	2.32	22%	2.33	4.17	44%
UK, 2012/13	1.10	1.61	32%	2.05	3.13	35%

Table 6
Comparison of total amount of food waste for diary and WCA, by discard route.[7]

Study	Residual waste stream			Collection targeting food waste		
	Diary kg/hh/wk	WCA	Underestimation (%)	Diary kg/hh/wk	WCA	Underestimation (%)
UK, 2007	1.74	3.23	46%	0.43[a]	0.40	−10%
UK, 2012/13	1.39	1.92	27%	0.49[a]	0.77	36%
Jeddah 2016	3.29	5.28	38%	n/a	n/a	n/a
NRDC 2016/17	1.47	2.31	36%	2.57[b]	3.96[b]	35%
Oregon 2017/18	1.61	2.36	32%	3.24[b]	2.78[b]	−16%

[a] Average taken across all households.
[b] Average taken of only households with collections targeting food waste.

- Some households appeared to have undertaken a kitchen clear out during the WCA period.

In the Oregon study, there are also 5% of households with diary results 5 kg or more in excess of the WCA result (left-hand bar of histogram). This appears to be linked to households using collections targeting food waste to a high degree. This could account for the lower estimate of underestimation calculated for the Oregon study.

4. Discussion

4.1. Degree of diary underestimation

The results demonstrate that diaries systematically obtain a lower estimate of food waste in comparison to waste compositional analysis (WCA) for food waste found in waste streams collected from households (residual plus collections targeting food waste), Table 3. This aligns with evidence summarised in the introduction, with diaries substantially underestimating levels of food waste, and that the waste compositional analysis is the more accurate of the two methods for *these discard routes*. The degree of underestimation for other disposal routes may be markedly different, as discussed in the limitations section (5.1).

The results further demonstrate that, for total food waste, there is a moderate degree of consistency between the levels of underestimation: the mean values of diaries were 7%–40% lower than their corresponding WCAs and four of the five studies were clustered between 30 and 40%.

This consistency is interesting, as there were some major differences between the studies, in particular, with how the diaries were administered:

- Diaries were of different lengths (4 days–2 weeks).
- Oregon allowed diary information to be recorded on non-consecutive days; all other diaries requested participants to record food waste on consecutive days. This may have reduced 'respondent fatigue' in the Oregon study.
- For three studies, the diary and WCA samples were separate; for Oregon and NRDC, one sample was a subset of the other. When comparing the households that both undertook a diary and had their waste analysed in WCA, the degree of self-selection bias is the same for both methods.
- Two studies (Oregon and NRDC) supplied scales for participants and asked for all food-waste items to be weighed; the other studies allowed approximate amounts to be entered in the diary.
- All but one study used paper-based food-waste diaries while one study had an option to use a digital form to complete the diary or to use paper-based diaries.

In addition, the studies were undertaken in different countries (although all are high-income countries) and over the course of 11 years.

For the two UK studies, the difference between the two levels of underestimation (40% and 30%) appears to be statistically significant: a reduction of 10 percentage points (95% confidence interval: 1 to 19 percentage points). It should also be noted that the level of food waste reduced substantially (19% per household, WRAP, 2013b), at a similar time to rising public awareness of the issue

[5] Data on wasted food and inedible parts was available for four of the studies examined for this paper.
[6] Data for Jeddah, NRDC and Oregon has been omitted as the sample size for single-occupancy households is too small.
[7] In the Jeddah 2016 study, there were no collections targeting food waste in the participating households.

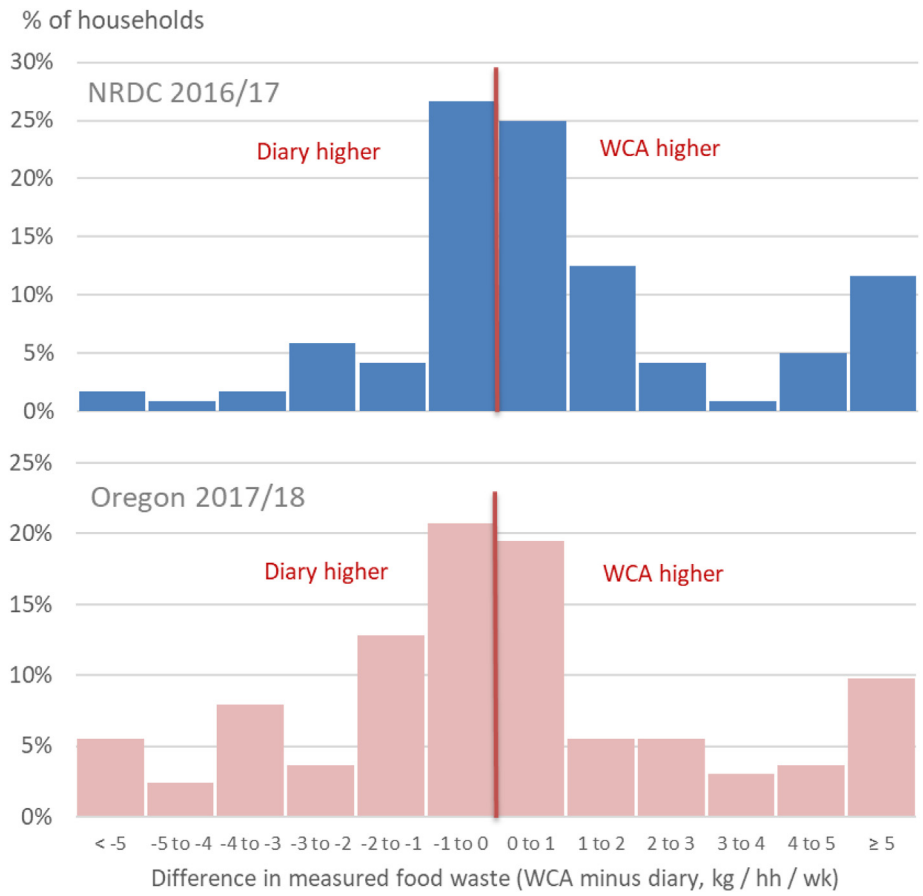

Fig. 2. Histogram of household-by-household comparison: amount of food waste measured by waste compositional analysis minus amount measured by food-waste diary.

and a large-scale campaign related to food waste prevention in the home (*Love Food Hate Waste*). This substantive change in the UK *may* have raised the salience of food-waste as an issue between the two studies, which might have influenced the degree of underestimation. However, caution should be exercised in overinterpreting these findings: given the number of differences between the studies and the uncertainties around the underestimation estimates, it is not possible to determine what factors influenced the differences between studies (see limitations section, 5.1).

This study can also be used to shed light on the underestimation of other methods for measuring HHFW. In van Herpen et al. (2019), the estimates were similar for the following methods: food-waste diaries, use of caddies to collect and weight HHFW, and photographic records. As the current study demonstrates that diaries underestimate food waste, it follows that these other two methods (use of caddies and photographic records) as used in the van Herpen et al. (2019) study also underestimate HHFW substantially (and to a similar extent).

4.2. Reasons for underestimation

It is important to understand the causes of diary underestimation of food waste. These are summarised in Fig. 3, presented as a hierarchy. Four categories of underestimation are presented (behavioural reactivity, misreporting, measurement biases, sample-selection bias) each with multiple contributing reasons. Social desirability – cited by a number of studies as an important factor – contributes to two of these reasons, potentially influencing how much people throw away during the study period and how they record information within the diary.

In theory, it is possible to understand the relative importance of some of these reasons by comparing the degree of underestimation between different types of household, different fractions of food waste, or different studies. Although this was attempted for this study, the results were largely inconclusive.

Underestimation due to the **diary keeper not being aware of all the food waste** generated in their household can be assessed by comparing underestimation rates for single-and multiple-occupancy households. Only two studies had sufficient single-occupancy households to undertake meaningful comparisons. For the 2007 UK study, there was a clear difference between the two (shown to be statistically significant by Høj, 2011). However, for the 2012/13 UK study, the underestimation for these two types of household was similar (Table 5). Therefore, the comparison of averages provides inconclusive results as to the importance of the number of people in the household. However, the analysis of the outliers in the NRDC and Oregon studies with much higher levels of food waste in the WCA compared to diaries showed that a disproportionately high number of these households were multi-occupancy (section 3.3). Whilst not conclusive proof that this effect occurs, it does provide some evidence.

Previous studies have suggested that, for reasons linked to **social desirability** (e.g. behavioural reactivity and misreporting), there should be greater levels of underestimation in diaries for wasted food compared to the associated inedible parts (e.g. caused by greater levels of guilt associated with the former). However, evidence to support this from the analysis is not clear cut: two studies had higher estimates of underestimation for wasted food,

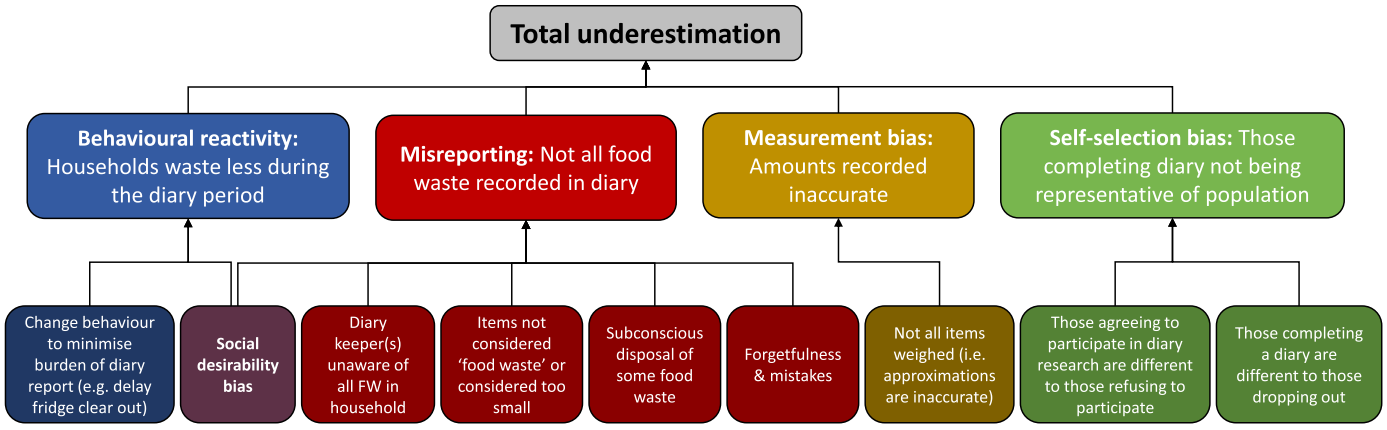

Fig. 3. A hierarchy of reasons for underestimation of diaries when measuring food waste.

two had lower estimates (Table 4). Again, the analysis of outliers from NRDC and Oregon suggested that, in contrast to the hypothesis above, some households may not be properly recording their inedible waste in the diary. If this is contributing to underestimation in diaries, it highlights the need for clear instructions to diary participants as to what material should be recorded in those diaries. Additionally, the Oregon study sample that had both kerbside trash and compost collection available to them underestimated the amount of food waste going to the trash stream and overestimated the amount going to the compost stream. This could be due to a social desirability bias, where disposing to the compost stream is viewed more positively than disposing to the trash stream (Qi and Roe, 2017; NRDC, 2017b).

There is evidence from these studies regarding the influence of **self-selection bias**. In the UK 2012/13 study, those households that had agreed to undertake the diary but did not complete the exercise ($n = 244$) gave measurably different questionnaire responses compared to those that did complete the diary exercise ($n = 948$). In particular, the questionnaire that both groups completed (pre-diary) included questions to measure the level of engagement with activities that have the potential to reduce HHFW (e.g. making shopping lists, planning meals, using up leftovers). Those that did *not* complete the diary were, on average, significantly less engaged with these activities than those who did complete the diary. This suggests that, for this study, self-selection bias was contributing to diary underestimation.

In contrast, two of the studies (NRDC and Oregon) contained analyses on samples of households who undertook both WCA and diaries. Therefore, there will be the same degree of self-selection bias for both diaries and WCA (as they are the same households). Given that both studies showed underestimation (Table 3), this suggests that self-selection bias is not the only factor contributing to diary underestimation. However, the above analysis of the UK 2012/13 data indicates it does contribute to underestimation in some circumstances.

Other potential causes of underestimation, as listed in Fig. 3, were much harder to assess with the data available to this study, e.g. the impact of allowing approximate values to be recorded in the diary. Overall, the evidence available does not allow the magnitude of the various causes of underestimation to be determined. Potentially all are important depending on the methodology used and where it is deployed.

4.3. A scaling factor for food-waste diaries?

Given that there is a degree of consistency between WCA and diaries (Table 3), one practical question that arises is: can a scaling factor be applied to amounts of food waste calculated in food-waste diaries so that they are comparable with waste compositional analyses?

As with many questions about quantification of food waste, the answer depends on what the data is being used for (CEC, 2019). For some purposes, *approximate estimates* of food waste may suffice, e.g. in order to make the case for acting to reduce food waste. In such cases, if a diary similar to those described above has been used, then scaling the diary-based estimate would provide an estimate that is sufficiently accurate for this particular purpose.

However, if accurate tracking of food waste is required, e.g. to monitor the change in food waste within a nation for specific targets such as SDG12.3 or for the EU delegated act, then scaling up diary estimates will probably introduce sufficient uncertainty to make interpretation of trends over time unfeasible. Taking a specific example, had the diaries from the UK been used to assess the national trend between 2007 and 2012, these would have estimated a 13% reduction (assuming the same scaling factor had been applied for both years). However, had the two detailed WCAs been used, a 26% reduction would have been estimated. Therefore, the estimate of change estimated from diaries is half that from waste compositional analysis.[8] Similarly, comparison of diary data from different countries could also lead to erroneous conclusions being drawn.

There appears to be less consistency between studies when more detailed analyses are performed (Tables 4–6), e.g. wasted food has underestimation levels of between 28 and 70%. In addition, previous studies (not analysed in this paper) have shown large changes in estimates for some discard routes when the methodology of the diary was altered. For sewer waste in UK households, a change from a diary focusing only on food and drink waste going down the sewer (WRAP, 2009b) to an estimate of sewer waste from a diary covering five discard routes (WRAP, 2013a) was accompanied by change in amount of food and drink waste recorded going down the sewer of 75%. After extensive investigation, the authors of WRAP (2013a) concluded the most likely explanation was the change in scope of the diary instrument had caused a measurement artefact, rather than a drastic reduction in sewer waste occurring over this time period. The fact that a change in methodology led to such a dramatic change in estimate illustrates the potential issues

[8] Of note, these two estimated reductions compare to a value of 21% for the same time period from a synthesis (meta-analysis) of existing WCAs and waste data (WRAP, 2016).

with diaries and the difficulties in comparing diary-based estimates.

Given the above, the authors recommend that scaling up diary-based estimates (to allow comparison with estimates based on waste compositional analysis, WCA) should be undertaken with caution.

Firstly, it is suggested that scaling-up is only undertaken where an *approximate* estimate of the total amount of food waste is required. In contrast, where there is a need to compare two or more estimates (e.g. to track over time), the diary underestimation is not sufficiently well understood to be used. With the current state of knowledge, this makes diaries unsuitable for quantitatively evaluating interventions (i.e. activities and policies designed to prevent food waste in the home) or tracking levels of food waste over time. However, improvements to diaries using technology to reduce the burden of reporting (e.g. Roe et al., 2018) have the potential to increase accuracy and usability for quantitative comparisons (but further research to assess this potential is required).

Secondly, scaling up should only be done for aggregate measures (e.g. the mean of a sample of households) and not used to adjust data for individual households. Fig. 2 illustrates that there is considerable scatter for individual households between estimates of food waste derived from WCA and from diaries.

Thirdly, scaling-up using information from this article should only be applied to the relevant discard routes (i.e. waste streams collected by local authorities); the degree of difference between diaries and WCA for other discard routes (e.g. home composting, sewer) may be very different.

Fourthly, to minimise bias in diary estimates, the following should be incorporated into the design of the diaries:

- Diaries used to estimate the amount of HHFW should be designed with quantification in mind, rather than designed to stimulate a reduction of HHFW.
- Sampling strategies for the diary should be robust and attempt to minimise the degree of self-selection bias.
- The diary methodology should seek to involve all household members in the diary exercise, to minimise underreporting due to the diary keeper being unaware of all food waste.
- The diary methodology should encourage participation, e.g. through the use of incentives.
- Researcher should consider the balance between minimising the burden of participating (e.g. through allowing approximate quantities of food waste to be entered into the diary) and accurate reporting of items by households (e.g. by using scales).

Finally, in circumstances where it is appropriate to scale up, the authors recommend using both ends of the range of estimates for underestimation (7% underestimation leading to a scaling factor of 1.08 and 40% underestimation leading to 1.66). This will lead to a range in the final estimate which will reflect the underlying uncertainty in the scaling up factor. Future research may alter the values of the scaling factor to use.

5. Conclusions and recommendations

There are three conclusions that can be drawn from this study. First, food waste diaries are an important tool for understanding the types of food that get discarded in the home, why they get thrown away and the discard routes by which they leave the home. However, there is strong evidence presented in this paper that they underestimate the amount of household food waste (HHFW), with the degree of underestimation ranging from 7% to 40%.

Second, the study results suggest that four main factors contribute to this underestimation: behavioural reactivity (people wasting less during the diary period), misreporting (not all items discarded being recorded), measurement bias (not all items are weighed in some studies) and self-selection bias (those completing a diary being different from the wider population). This study has been unable to determine the relative importance of the different. This is partly due to an insufficient number of studies and too small sample sizes. However, the reasons for underestimation may well differ over time and between countries, e.g. due to cultural differences between the countries or differences in methodology. More research is required to understand this better.

Third, diaries alone are not sufficient for tracking HHFW over time or evaluating interventions. Diaries can be used for assessing the amount HHFW (via a scaling factor) under a limited set of circumstances:

- an approximate estimate of household food waste is sufficient (i.e. not for tracking purposes),
- the scaling factor is only applied to aggregate measures (e.g. the average of a sample of households), not to individual households,
- the scaling factor in this paper is only applied to the same discard routes investigated in this paper (i.e. the combined total of residual plus any collections targeting food waste)
- the diary instrument is well-designed for measurement purposes and applied within a robust methodology, and
- scaling is undertaken with low and high scaling factors (1.08 and 1.66) to incorporate the uncertainty of applying this approach.

Some countries have adopted methods that combine the use of diaries, WCA and other methods in an integrated measurement and evidence-gathering programme (e.g. WRAP, 2013b in the UK, van Dooren et al., 2019 in the Netherlands, Schmidt et al., 2019 in Germany). This article provides support for this 'hybrid' approach – it allows total amounts of food waste to be tracked relatively accurately (e.g. via WCA), while also providing useful information (e.g. on reasons for food waste) from diaries.

5.1. Limitations

Despite the conclusions that this study has been able to draw, it does have limitations:

Firstly, it only compares the use of these two methods *in the home*. Other settings for the use of these methods (e.g. in a commercial kitchen) have not been considered. Secondly, the two discard routes considered in this study (residual and collections targeting food waste) represent only some of the discard routes available to homes. This report gives no estimate of the underestimation of diaries for these other routes – indeed, diaries may not underestimate some of these other discard routes (e.g. ones seen as sociably desirable, such as home composting).

The analysis relied on existing datasets, due to the cost of obtaining data explicitly for this purpose. Although the primary role of the original studies was not to compare these two measurement methods, the data did allow this comparison. However, some assumptions had to be made: for instance, in some circumstances there was a short gap in time between the WCA and diary. In situations where levels of food waste are susceptible to greater fluctuations (either a seasonal effect, or a long-term trend), this could add to the uncertainty within the estimates. Previous research suggests that seasonality in levels of household food waste is relatively small (e.g. WRAP, 2016, appendix 1.2) and that long-term trends are rarely strong enough to influence the overall conclusions of this paper (WRAP, 2016, Fig. 2).

For some of the studies, the sample sizes were relatively small, which will mean there are relatively wide confidence intervals

around the estimates of food waste for each method and underestimation. With larger sample sizes, it may be possible to state which types of food are more likely to be underestimated by diaries; this was not possible with the current datasets. Finally, the studies were undertaken in only three countries, which are not representative of the world (e.g. no low-income country was included).

Analysis of underestimation was not possible for factors such as age, income and population density due to the size of the samples and differences in how participating households were classified in the five studies.

5.2. Suggested further research

There are several areas of further research that would help answer practical questions relating to quantifying HHFW, especially if diaries continue to be used:

- Extending the research to low-income countries, which were not covered by any of the studies in this report
- Investigation of the accuracy of diaries for other discard routes (e.g. home composting, sewer).
- Increase understanding of the reasons for diary underestimation, to understand the relative importance of the reasons, with a view to designing diaries with lower levels (or more stable levels) of underestimation. This could include lowering the burden of diary participants to record information and engaging all household members.
- Testing whether the degree of underestimation in diaries changes over the course of an HHFW-prevention intervention.

Contributions to the paper

TQ conceived the paper. All authors undertook analysis on their respective datasets. TQ and GP led on drafting the manuscript with contributions and review from all other authors.

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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