# A detailed characterisation of household food waste and the implications of sorting behavior on potentials for anaerobic digestion and nutrient recovery

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**Abstract**

This study investigates household food waste (HH FW) generation in two socio-economically different areas in Lübeck, Germany. The applied waste characterisation protocol provided a detailed insight into the generation and separation behavior of FW collected in the municipal collection system. In total, four characterisation campaigns were conducted in both areas. Results show that about 47% of FW is avoidable. The socio-economic low area generated more FW with a lower source-separation performance. The share of avoidable FW was also higher in this area. The most common fractions found in total FW were *fruit and vegetables*, *leftovers and canned food* and *bread*. In addition to a substantial avoidable fraction, these commodity groups need to be prioritised in management strategies, such as for anaerobic digestion or composting.

**Keywords: Food waste, Waste characterisation, Waste management, Anaerobic digestion, Circular economy**

## 1. Introduction

FW has great potential for minimisation and valorisation. The EU Circular Economy Action Plan, including its Sustainable Development Goals (SDG), addresses the issue of FW. SDG 12.3 aims to reduce FW at the retail and consumption level by 50% by 2030 (EU, 2018). Furthermore, the action plan calls for monitoring of FW and its mandatory separate collection by 2023. Some means of monitoring have already been introduced, e.g. UNEP's food waste index. However, a major uncertainty lies in the lack of data for FW in general but especially unavoidable parts (Caldeira et al., 2019; United Nations Environment Programme, 2021). Caldeira et al. (2017) highlights the need for local studies in bottom-up approaches. At the German level, a study identified a HH FW generation of 61.8 kg $(inh, a)^{-1}$ of which around 44% is avoidable (Schmidt et al., 2019). Hübsch and Adlwarth (2017) estimated that the largest share of FW is fruit and vegetables (50%) followed by beverages (21%) which mainly consist of coffee powder and tea. It was also found that the share of each commodity group is very stable throughout the year. Also at European level, De Laurentiis et al. (2018) found that between 38% and 46% of HH FW consists of fruit and vegetable waste. It is highlighted that especially the unavoidable part needs proper management strategies, while communication activities should focus on the reduction of the avoidable part. Improperly managed bio-waste (BW) is responsible for 3% of the EUs total greenhouse gas emissions (EEA, 2020), indicating the need for proper management strategies of FW.

## 2. Materials and Methods

### *2.1 Goal and Scope*

This study focuses on a detailed characterisation of HH FW found in both source-separated BW and residual waste (RW). The characterisation has four different objectives:

- Insight into inhabitants' food wasting behavior
- Insight into inhabitants' FW separation behaviour
- Identification of potentials for FW avoidance
- Impact of sorting behaviour on biogas potential and nutrient recovery

### *2.2 Case Study*

The areas were identical to those studied in Walk et al. (2019), in the northern German city of Lübeck. Area *A* (37 HH, 1.6 residents per HH) was classified socio-economic low due to the publicly subsidised flats. Area *B* (46 HH, 1.7 residents per HH) was classified socio-economic moderate due to slightly above average rents. Separate collection of BW already existed in both areas before the study. The collection frequency was weekly or biweekly for both, BW and RW.

### *2.3 Sampling and waste characterisation*

Four different characterisation campaigns were carried out. The first two campaigns were described in Walk et al. (2019) and cover the situation before and the time during the test of a new FW collection system. Characterisation campaigns three and four took place six and twelve months after the test to assess long-term impact of the test on FW sorting behaviour.

Sampling followed the procedure described in several German waste sorting guidelines (Intecus GmbH, 2014; Kehres and Günther, 2017). In each campaign, source-separated BW and RW were collected on the regular collection day and, in the case of bi-weekly collection frequency, also in the week in between. In all campaigns, waste was collected at least twice to obtain the quantity for two consecutive weeks. The characterised fractions were adapted from Edjabou et al. (2015) and Lebersorger and Schneider (2011) and consisted of the main fractions avoidable, unavoidable and partly avoidable FW. Partly avoidable FW is a transitional fraction that cannot be clearly assigned to avoidable or unavoidable FW due to habit, culture and preparation. This mainly includes peels and other potentially edible parts of *fruit and vegetable*, e.g. apples, potatoes or carrots.

In order to achieve the objectives highlighted in section 2.1, a higher level of detail was added to the protocol. Table 1 shows the FW fractions sorted during the characterisation campaigns. Avoidable FW fractions are further divided in unpackaged and packaged items. Packaged items were unpackaged to obtain only the weight of FW. In addition to FW fractions, the waste characterisation protocol included *green waste* and *paper waste* as further biodegradable fractions. Non-biodegradable fractions were grouped together and designated as *macro-impurities* in source-separated BW. Sub-level 2 was only applied during the fourth characterisation campaign, which represents the long-term effects of the tested FW collection system. Sub-level 1 was applied during the previous campaigns.

In order to make an estimate of the annual FW generated, all four characterisation campaigns were included. For the separation efficiency of FW, only the findings of the fourth campaign were assumed in this study, as it varies between the different campaigns due to the influence of the tested collection system. The fourth campaign was therefore assumed representative for long-term impact of the tested collection system.

Characterisation was done by manual sorting and weighing of the individual fractions. The results are given as weighted averages.

### *2.4 Biochemical methane potential*

Each fraction listed in Table 1 was tested for biochemical methane potential (BMP). The tests were performed according to Holliger et al. (2021), in triplicates, a substrate to inoculum ratio of 0.5 and at 37 °C. The detailed experimental procedure can be found in Walk et al. (2021).

**Table 1.** Food fractions of waste characterisation

| Main fraction | Sub-Level 1 | Sub-Level 2 |
|---|---|---|
| Unavoidable FW | Plant-based | Fruit & vegetables |
| | Animal-based | Meat & fish |
| | Mixed | Hardly putrescible |
| Avoidable FW | Plant-based | Raw fruit & vegetables |
| | | Raw cereals & pulses |
| | | Bread |
| | | Other cereal products |
| | | Leftovers & canned food |
| | | Spreads & sauces |
| | | Convenience meals |
| | Animal-based | Raw meat, fish & seafood |
| | | Cold cuts & sausages |
| | | Prepared meat, fish & seafood |
| | | Dairy & Egg |
| | | Convenience meals |
| Partly avoidable FW | Plant-based | Fruit & Vegetables |
| | Animal-based | Skins |

### *2.5 Chemical analysis*

A chemical analysis was carried out for each fraction listed in Table 1. This includes basic elemental analyses such as carbon, hyrdogen, oxygen, nitrogen and sulfur as well as nutritional elements and heavy metals. The methodology used for the analysis of the different elements is described in Walk et al., (2021).

The chemical analysis can be used to determine nutrient recovery potentials, e.g. through composting.

## 3. Results & Discussion

Summarised results of waste data are shown in Table 2. Area B generated less waste, of which the share of total FW as well as of avoidable FW is lower. Absolute figures show that area B generates abound 50% less avoidable FW than area A, 0.5 kg inh.$^{-1}$w$^{-1}$ and 1.0 kg inh.$^{-1}$w$^{-1}$, respectively. Amounts of unavoidable and partly avoidable FW are the same, 0.8 kg inh.$^{-1}$w$^{-1}$. Also, area B has a higher source separation efficiency compared to area A. In both areas, macro-impurities in source-separated BW found in the fourth campaign were below 1%. In area B, a larger share of paper, used to wrap the FW, was found.

Figure 1 shows the distribution of different commodity groups of the fourth campaign summarized for both areas. It includes 44.0% of avoidable FW including *others*, 37.8% of unavoidable FW and 18.2% of partly avoidable FW, which is in the range reported by Schmidt et al. (2019). The proportion of avoidable FW to total FW is lower in source-separated BW than in RW, 28.2% and 55.8%, respectively, while the proportion of unavoidable FW, 46.3% and 31.5%, and the proportion of partly avoidable FW, 25.6% and 12.8%, is higher.

The FW fraction with the highest share in generated FW is *fruit and vegetables* with 66.6%, while 15.9% is avoidable. This is higher compared to the value reported by De Laurentiis et al. (2018). The difference could be due to the inclusion of coffee and tea as part of fruit and vegetables, which was not considered in the aforementioned study. The second and third largest shares are *leftovers and canned food* (7.0%) and *bread* (6.3%).

Figure ***2*** shows the source-separation efficiency of the commodity groups in characterisation campaign 4.

**Table 2.** General waste quantities and qualities of both areas

| Area | Total waste[a] [kg (inh, week)$^{-1}$] | FW[a] [% of total waste] | Avoidable FW[a] [% of food waste] | BW bin[b] [% of total waste] | Source-separated FW[b] [% of total FW] |
|---|---|---|---|---|---|
| A | 3.8 | 46.2 | 55.3 | 21.4 | 34.9 |
| B | 3.0 | 42.3 | 38.3 | 39.9 | 49.1 |
| Average | 3.3 | 44.2 | 47.0 | 31.4 | 42.8 |

[a]Weighted average of study phases , [b]in study phase 4

With regard to the main fractions, partly avoidable FW had the highest source-separation efficiency, 60.0%, followed by unavoidable FW, 52.3%. Only 27.4% of avoidable FW was sorted correctly. On average, 43.8% of FW were sorted correctly. The majority is therefore still disposed of in the RW bin and is in the range of the findings of Hübsch and Adlwarth (2017) and higher than estimated by Schmidt et al. (2019). This suggests a good long-term effect of the tested collection system. It is noticeable that no packaged FW was found in the source-separated BW.

*Fruit and vegetables* are among the commodity groups with the highest source separation efficiency (53.0%), which is in line with Hübsch and Adlwarth (2017). Animal-based commodity groups showed low source-separation efficiencies at 25.1%, of which 50.7% was *prepared meat, fish & seafood*. Some fractions were found only in RW and only packaged. However, these are the fractions that are difficult to distinguish when unpackaged, such as *spreads and sauces* or *convenience meals*. Overall, 12.8% of the FW found in RW was packaged.

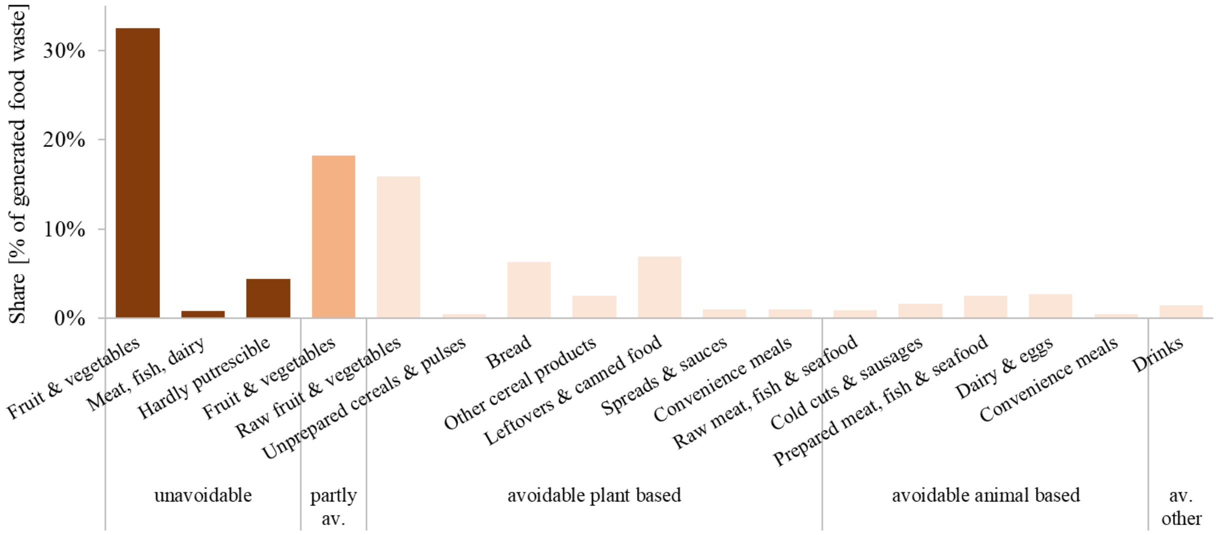


**Figure 1.** Shares of food waste fractions in generated food waste of both areas in the fourth characterisation campaign

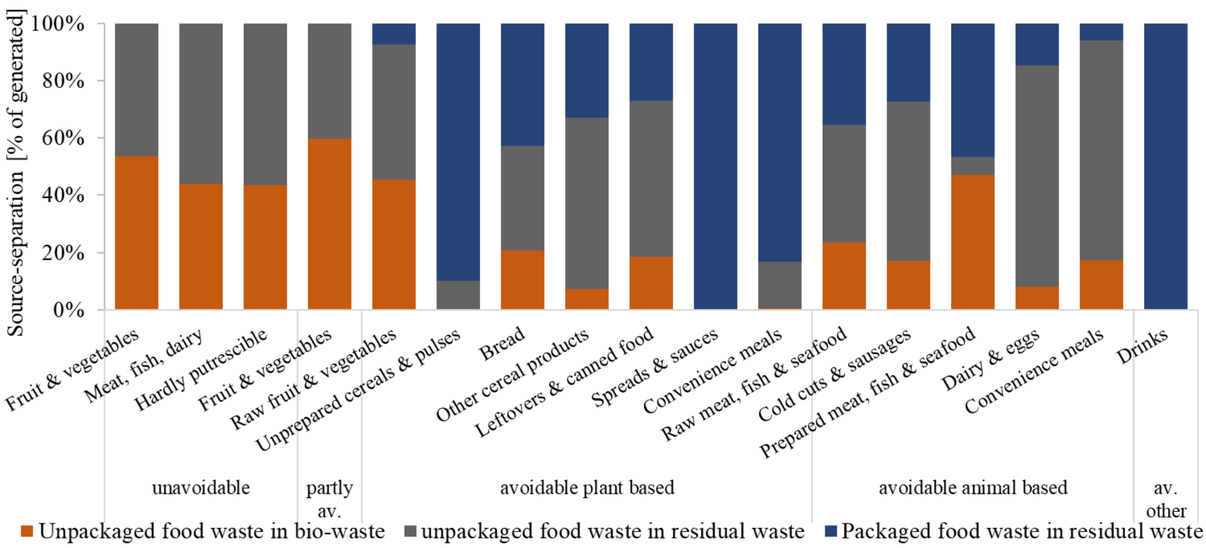


**Figure 2.** Source-separation efficiencies of food waste fractions of both areas in the fourth characterisation campaign

Unavoidable, avoidable and partly avoidable *fruit and vegetables* showed a BMP of 532, 627, and 398 $NmL(CH_4)$ $gVS^{-1}$, respectively. *Leftovers and canned food* have a potential of 466 $NmL(CH_4)$ $gVS^{-1}$ and *bread* 463 $NmL(CH_4)$ $gVS^{-1}$. Animal-based fractions of FW range between 700 and 800 $NmL(CH_4)$ $gVS^{-1}$, but have rather small shares in generated FW. The chemical composition of the aforementioned fractions supports estimates on nutrient recovery when used as digestate or compost. A summary of the chemical composition of these fractions is presented in Table 3. In addition, the average composition of generated FW with the composition shown in Figure 1 is highlighted. It shows that TS is higher, but elements are in mostly in-line compared to the findings of Fisgativa et al. (2016).

## 4. Conclusion

The detailed characterisation showed, that only a few fractions, among others *fruit and vegetables*, account for the majority of generated FW. This fraction also has the greatest potential for reduction and already shows good source-separation efficiency. These results suggest that planning FW management initiatives should focus on these fractions, including strategies on reducing avoidable FW. On the other hand, animal FW contains a much higher energy content compared to plant-based waste, which can be beneficial for anaerobic treatment.

**Table 3.** Chemical characteristics of the most abundant food waste fractions

| **Food waste fraction** | Unavoidable fruit & vegetables | Avoidable fruit & vegetables | Partly avoidable fruit & vegetables | Leftovers & canned food | Bread | Average total FW |
|---|---|---|---|---|---|---|
| TS [%FM] | 22.8 | 16.8 | 17.4 | 32.9 | 59.3 | 29.3 |
| VS [%TS] | 93.6 | 94.2 | 90.3 | 91.0 | 96.3 | 91.1 |
| TC [%TS] | 45.00 | 43.00 | 39.00 | 44.00 | 44.00 | 43.78 |
| TOC [%TS] | 41.80 | 37.70 | 35.60 | 40.50 | 41.70 | 39.74 |
| TN [%TS] | 1.91 | 1.34 | 1.55 | 2.01 | 2.17 | 2.14 |
| H [%TS] | 7.35 | 7.70 | 3.70 | 9.00 | 8.87 | 7.11 |
| O [%TS] | 39.05 | 42.00 | 45.91 | 35.63 | 41.10 | 37.82 |
| S [%TS] | 0.26 | 0.19 | 0.18 | 0.31 | 0.19 | 0.24 |
| P [%TS] | 0.17 | 0.22 | 0.24 | 0.21 | 0.22 | 0.26 |
| K [%TS] | 1.37 | 1.67 | 2.22 | 0.96 | 0.33 | 1.31 |


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