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Published in:
Journal of cleaner production

Link to article, DOI:
10.1016/j.jclepro.2021.126439

Publication date:
2021

Document Version
Peer reviewed version

Number of words: 7007 words

The influence of recycling schemes on the composition and generation of municipal solid waste

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Abstract

To ensure the transparency and comparability of life cycle assessment (LCA) studies of waste management systems, a comprehensive waste data is necessary. We sampled and characterised municipal household waste in Denmark to investigate the impact of recycling schemes on the composition and generation of residual household waste (RHW), provide detailed waste data to waste management authorities as well as LCA practitioners. In total, 20 ton of waste, taken from 1,800 households in seven Danish municipalities in 2011 and 2017, was manually sorted. These municipalities had in common the systems for source separation of paper, cardboard, metal and glass, whereas the recycling of food and plastic varied among them. The waste sorting campaigns provided detailed composition of individual recycling scheme including (1) food, (2) plastic, (3) paper, (4) cardboard, (5) metal, and (6) glass as well as (7) RHW. For each of the six recycling schemes, waste was sorted into two different waste catalogues containing 48 and 50 fractions. Such a detailed waste composition enables waste management authorities to design comprehensive guidelines for waste sorting, while providing LCA practitioners with data that can significantly improve the validity and certainty of their results and recommendations. The results show that the highest misplacement rate was found in waste bins dedicated to food, plastic and RHW. The statistical analyses show that source separation of food and plastic waste reduces significantly (11%) the total amount of household waste, suggesting that, in addition to the environmental benefit of diverting food and plastic waste from landfill and incineration, source segregation may as well contribute to waste prevention. Moreover, the source-sorting of food waste, independently of whether plastics were sorted or not, significantly influences the composition of the RHW.

Key words:

Life cycle assessment

Municipal solid waste composition

Recycling scheme

Food and plastic waste

Log-ratio coordinates

1 Introduction

The European Commission has acknowledged the life cycle assessment (LCA) approach as an important decision support tool in waste management (European Commission 2005). This has resulted in a significant increase in the number of LCA studies in all aspects of waste management (Laurent et al. 2013). The importance of LCAs has highlighted the need for high-quality data, to ensure transparent and unbiased results for decision-makers (Henriksen et al. 2017).

Numerous studies have focused on developing practical standards and guidelines as well as a comprehensive interpretation of LCA studies in waste management (Hauschild and Barlaz, 2011). The reliability of these studies depends on the quality of waste composition data, as generally solid waste is subject to local conditions (Edjabou et al., 2015). Clavreul et al. (2012) and Bisinella et al. (2017) have methodically demonstrated that waste composition is a critical parameter in LCA studies. Additionally, Slagstad and Brattebø (2013) established that waste composition was a predominant factor affecting the total environmental impact of solid waste management systems and constituted the principal source of uncertainty for impact categories, including global warming, nutrient enrichment and human toxicity via water.

Waste composition can be subdivided in (i) physico-chemical and (ii) physical composition. Physico-chemical composition refers to energy, ash content and elemental content (Götze et al., 2016), whereas physical composition involves the fractional distribution (on a wet or a dry mass basis) of solid waste materials (Edjabou et al., 2015).

Data for waste composition are usually obtained from waste characterization, albeit this is a costly and time-consuming task. On the other hand, physico-chemical characterization is tedious, more costly and requires advanced and expensive laboratory equipment as well as analytical skills (Götze et al., 2016). Therefore, these studies are rarely conducted despite their importance, which may explain the lack of primary data often highlighted by numerous researchers, local authorities and waste practitioners (Edjabou et al., 2018; Laner et al., 2014). Consequently, most LCAs modelling waste management often employ secondary data. Regardless of a study's aims, the methods used to generate secondary data can be categorized into two approaches: (1) data aggregation and (2) extrapolation of waste composition.

Data aggregation involves historical data-gathering, to generate secondary data. This approach requires holistic knowledge of the data, to assess their reliability, completeness, temporal correlation and geographical correlation (Weidema and Wesnæs 1996). The problem with this approach is that this information is rarely reported (Lebersorger and Beigl 2011); however, only few studies have consistently investigated possible limitations related to the aggregation of waste data. To overcome these limitations, the current study provided two datasets for the physical composition of RHW, using two different waste fraction nomenclature datasets, namely one published by Riber et al. (2009) and the other published by Götze et al. (2016). These two datasets represent a good example of data aggregation hindering comparisons, because the level of detail for some waste fractions is disparate, making it difficult to define transfer coefficients between them.

The second approach implies the extrapolation of waste composition in relation to the current waste generation rate, in order to address future LCA scenarios. Typical examples include modelling the environmental impact of banning single-use plastics or determining the environmental benefit of waste prevention (DEPA 2018, 2017; Møller et al. 2013). These studies require "future" waste composition, which is often calculated by changing the generation rate or the collection efficiency of the target waste fraction. The drawback of these approaches, however, is that they ignore the dynamic correlation between waste fractions (Bisinella et al. 2017), which thus influences the entire waste stream. Although extensive research has been carried out on uncertainties modelling in waste composition datasets (Edjabou et al. 2018), a few published studies have methodically demonstrated the influence of a recycling scheme on the physical composition and generation rate of RHW. To fill this aforementioned knowledge gap, we investigated the influence of introducing the source segregation of food and plastic waste.

The overall goal of this study is to test the hypothesis that the source-sorting of food and plastic waste significantly affects the generation and composition of residual household waste. Thus, this study attempts to (1) analyze the impact of geographical and temporal variation on residual household waste, (2) study the impact of source-sorting food and plastic waste on the generation and composition of residual household waste and (3) provide a detailed fractional composition of household waste, including source-sorted fractions (food, plastic, paper, board, glass, metal) and residual waste.

2 Material and methods

2.1 Waste data and definitions

Data for the generation and composition of household waste were obtained from waste sampling campaigns carried out in 2011 (Edjabou et al. 2016) and 2017. Information about the numbers and types of households was retrieved from the Statistics Denmark database (Statistics Denmark 2020).

Residual household waste (RHW) is "*the remaining mixed waste after source separation of recyclables, hazardous waste and WEEE*" (Edjabou et al., 2015), and it is incinerated in Denmark to generate heat and electricity. Total residual household waste (TRHW) was calculated by following formula (1):

$$TRHW= RHW+ FW+ PW+ OR \quad (1)$$

where *FW* is food waste, *PW* is plastic waste and *OR* is "other recyclable" material fractions, including paper, board, glass and metal. The source-separation of these fractions has been implemented in all municipalities in Denmark for a period of over 15 years (DEPA 2020). Given the high recovery rates of these fractions, it seems the Danish households have been familiar with source-sorting of these fractions regardless of the municipalities (Graasbøll 2017). Therefore, in order to assess the influence of the source-sourcing of food and plastic waste, we focused on RHW, FW, and PW. For this reason, Eq. (1) was simplified, resulting in four (4) waste systems corresponding to Eq. (2-5) and illustrated in Figure 1. This simplification enables to compare consistently the generation rate and composition of RHW, FW and PW among these municipalities

System A: TRHW = RHW (2)

System B: TRHW = RHW + FW (3)

System C: TRHW = RHW + PW (4)

System D: TRHW = RHW + FW + PW (5)

Notably, RHW equates to TRHW when food and plastic waste are not source-sorted (Eq. 2).

2.2 Study area and waste-sorting systems

Although the distribution of dwelling type varied unevenly among these municipalities, the majority of households lived in single-family house areas. The highest proportion of households in the single-family house areas were in the municipalities of Odsherred (90%), Aabenraa (84%) and Viborg (82%). Independently of municipalities, an average household contains more than two people in the single-family house areas (from 2.1 people in Osdherred to 2.7 in Gladsaxe), whereas in the multi-family house areas, the average household size ranged from 1.6 in Viborg to 1.8 people Gladsaxe. In the vast majority of these municipalities, households were evenly distributed in dwelling size, ranging from 50 to over 175 m^2. However, in the municipalities of Gladsaxe (8 %) and Rødovre (5%), few households had a dwelling with a total floor area of over 175 m^2.

Moreover, there was a strong relationship between household size and dwelling size. Here, household size increased with dwelling size (Statistics Denmark 2020).

The waste-sorting systems in the sampling areas are shown in Figure 1. The difference between these municipalities was the waste-sorting scheme. Households source-sorted paper, board, glass and metal in 2011, whereas in 2017, most municipalities implemented additional various sorting schemes, except for Viborg. In 2011 and 2017, the recycling scheme in Viborg remained unchanged. Thus, we estimated the effect of temporal variation on household waste by comparing waste data from Viborg.

For further statistical analysis, municipalities were grouped according to their recycling scheme into four categories as follows: (1) RHW from Gladsaxe, Helsingør, Kolding and Viborg (System A); (2) RHW and food waste from Odsherred, (system B); (3) RHW and plastic waste from Aabenraa (system C) and (4) RHW, food and plastic waste from Rødovre (system D). Additionally, source-sorted waste materials such as (i) paper, (ii) board, (iii) glass, and (iv) metal from Rødovre were also sampled, to estimate their composition (see supplementary information (SI)).

Figure 1: Illustration of waste-sorting systems in the municipalities included in this study

2.3 Waste-sampling procedure and fraction classification

In the present study, sampling and characterization errors were reduced by (i) sampling directly from households and (ii) avoiding waste compacting during transportation. Households located on the same waste collection route were selected, thus helping to sample waste following a regular waste collection schedule. This method avoids any changes in waste generation behaviour by households during this sampling period. In each sampling area, the collection route was chosen, based on what was estimated to be representative for the study area, given local experience and knowledge of waste management authorities.

A minimum of 100-200 households (Table 1) were selected in each collection route, as recommended in Edjabou et al. (2016). The number of samples in Rødovre was relatively higher than other municipalities because it is the only municipality that had implemented source sorting of food and plastic waste when the study was conducted. Here, for each household, three waste samples were collected separately, including food, plastic and residual household waste.

For each recycling scheme, waste was sampled once from households in the period April-May in 2011 and 2017. The sampled waste represented one to two weeks household waste, according to the frequency of the waste collection system in these municipalities. To avoid any behavioural changes from households, the waste was collected using the existing collection system (a door-to-door scheme). For each municipality, the sampling and sorting of waste lasted about one week. The difference in mass loss during the period between sampling and final manual sorting was recorded and taken into account (see Edjabou et al., 2015).

The sampled waste (see Section 2.2) was sorted individually by applying the three-level tiered approach described in Edjabou et al. (2015). First, waste was sorted into four fractions: (1) food waste, (2) plastic waste, (3) other recycling materials (e.g. gardening waste, paper, board, metal, glass, etc.) and (4) other (e.g. miscellaneous combustible, inert). These fractions were further sorted into detailed fractions (Table 2).

For this study, waste from institutions, commercial establishments and offices, and construction and demolition waste, was not included in this study. Additionally, waste collected from household recycling centres (Edjabou et al. 2019) was not included.

Table 1: Overview of numbers of households and municipalities involved in the sampling campaigns

Table 2: The waste fraction list based on Riber et al. (2009) (Götze et al., 2016)

2.4 Experimental design

In this study, "household waste" refers to both waste generation and composition, unless specified otherwise. To determine the influence of source-sorting food and plastic waste on household waste, three independent analyses were carried out to address confounding and covariate effects (van den Boogaart et al. 2013; Reimann et al. 2008). First, we investigated the effect of geographical difference, by comparing municipalities with the same waste-sorting system. For this purpose, we compared those municipalities comprising system A, where food and plastic waste were not sorted, namely Gladsaxe, Helsingør, Kolding and Viborg (data collected in 2011). Second, the effect of temporal variation on household waste was investigated, by comparing samples collected in Viborg between 2011 and 2017. Lastly, the study investigated the effect of source-sorting food and plastic waste on RHW and TRHW, by comparing all waste-sorting systems (A, B, C and D).

2.5 Statistical modelling of waste data

The waste data were statistically modelled using both the so-called "classical" method (Crawley 2007) and the "compositional data analysis" technique (Kynčlová et al. 2015). The waste generation rate (kg/person/week) was modelled by applying the classical method. Permutation and bootstrap tests were applied to examine and quantify differences in waste generation rates, whilst the fractional waste composition (percentage distribution of material fractions) was analyzed by means of compositional data techniques (Edjabou et al. 2017; van den Boogaart et al. 2013; Filzmoser et al. 2018). Waste composition as a percentage is a closed dataset, because it always adds up to a constant, i.e. 100 (Edjabou et al. 2018), and this inherent property makes it unsuitable for classical statistics. Therefore, waste composition data were transformed into pivot (log ratio) coordinates (Fišerová and Hron 2011; Egozcue et al. 2003), to "unlock" their structure prior to applying classical statistics. The advantage of using pivot coordinates is that they provide individual interpretations of waste fractions within the defined composition (Filzmoser et al., 2018). Subsequently, compositional regression and analysis of variance (ANOVA) were applied to investigate differences in fractional waste composition (Filzmoser et al. 2018; Martín-Fernández et al. 2015). To quantify these differences, we constructed the bootstrap confidence interval for each waste log-ratio coordinate fraction (Martín-Fernández et al. 2015). Prior to statistical analysis, the normality test, based on the Mahalanobis distance (Martín-Fernández et al. 2015), and the multivariate outlier test (Filzmoser and Gschwandtner 2018) were carried out and are provided in SI.

2.6 Lists of R packages

The "Tidyverse" package (Hadley 2017) was used for data wrangling and data visualization, whilst the packages robComposition (Templ et al. 2016) and composition (van den Boogaart 2008) were used to analyze compositional data. Classical statistics were analyzed by means of the package r companion (Mangiofica 2015). The packages boot (Canty and Ripley 2019) and rsamples (Kuhn et al. 2019) were used to apply bootstrap methods.

3 Results

3.1 Waste generation

3.1.1 Household waste generation rates

Descriptive statistics for waste generation rates are provided in Table 3. For municipalities not source-segregating food and plastic waste, the average generation rates for RHW ranged from 3.74±2.15 to 4.09±2.58 kg/person/week in 2011, and 3.67±2.55 kg/person/week in 2017. These amounts were nearly halved when food waste was source-separated (in Odsherred 2.25±1.72 kg/person/week), albeit they decreased considerably when both food and plastic waste were source-separated (in Rødovre 1.66±1.53 kg/person/week). The waste generation rates for RHW in municipalities where food and plastic waste were not source-sorted (waste-sorting system A) were similar to those seen in Edjabou et al. (2015), who also reported 3-4 kg/person/week. However, the generation rates for RHW in those municipalities where food and plastic waste was source-sorted were considerably lower than those provided by Edjabou et al. (2015).

Table 3: Descriptive statistics for waste generation rates for residual household (RHW), source-sorted food (FW) and plastic (PW) waste (kg/person/week wet mass) in 2011 and 2017

Table 3 summarizes the generation rates for TRHW as a function of recycling schemes, and these amounted to 3.39±2.23 kg/person/week in Rødovre (waste-sorting system D), 3.53±1.99 kg/person/week in Odsherred (waste-sorting system B) and 3.58±1.95 kg/person/week in Aabenraa (waste-sorting system C). Nevertheless, a comparatively high TRHW (3.67±2.55 kg/person/week) was generated in Viborg (waste-sorting system A) in 2011 and 2017.

The depicted trends in waste generation rates associated with the source-sorting systems (Figure 2 and Figure 3) accords with earlier observations in Sweden (Dahlén et al. 2007), which showed that municipalities source-sorting food and plastic had less mass per capita than others.

3.1.2 Factors influencing waste generation rates

The results of the permutation test revealed no significant difference (df=3, p-value=0.652) in RHW rates between Gladsaxe, Helsingør, Kolding and Viborg (Table S1). These results suggest that for similar waste-sorting systems, RHW generation rates were independent of geographical variations in Denmark, most likely due to the relatively homogeneous society in such a welfare state (World Bank 2019). Furthermore, when comparing RHW in Viborg between 2011 and 2017, no significant difference was detected. These findings show that the generation rates for RHW were not affected by temporal variations, at least when operating the waste recycling scheme in the same way.

The results of the bootstrap test displayed in Table 4 highlight that, compared to system A, RHW was significantly reduced by 1.49 kg/person/week in B, 0.60 kg/person/week in C and 1.98 kg/person/week in D. These results lend strong support to the argument that source-sorting food and/or plastic waste reduces significantly the generation of RHW.

Overall, the generation of TRHW was higher in system A than in the other systems (B-D). The results of the permutation show that the difference in TRHW generation rates was statistically significant between waste-sorting systems (df=3, p-values=0.01), as shown in Table 4, which may be attributable to the generation rate in Rødovre (waste-sorting system D), in that it was 11% significantly lower than the municipalities in waste-sorting system A (Figure S1). This suggests that the source-sorting of both food and plastic waste may reduce significantly the generation rate of the total residual household waste. These results are in agreement with those reported by Dahlén et al. (2007), who also found that specific sorting systems may have an effect on the total mass of household waste generated.

Figure 2: Overview of RHW waste generation rates in 2011 and 2017 from single-family houses as a function of waste source systems: (A) RHW (residual household waste); (B): source-sorting of food waste; (C) source-sorting of plastic waste; (D) source-sorting of food and plastic waste

Figure 3: Overview of TRHW waste generation rates in 2011 and 2017 from single-family houses as a function of waste source systems: (A) RHW (residual household waste); (B): source-sorting of food waste; (C) source-sorting of plastic waste; (D) source-sorting of food and plastic waste

Table 4: Comparison of residual household waste generation rates, based on bootstrapping regression (1,000 sampling points). Here, waste-sorting systems were compared to system A. As an example, for RHW, B was 1.49 kg/person/week lower than A, whereas for TRHW, B was 0.21 kg/person/week lower than A. A 95% confidence interval containing zero (e.g. -0.45,0.02) means the difference was not significant. Statistically significant differences ($p < 0.05$) are highlighted in bold

Table 5 presents the bootstrap regression for generation rates of individual waste fractions. Here, except for plastic waste, the generation rates in D were higher than in systems B and C. Another important observation was the generation rate for food waste in system D, which was 9% higher than A, corresponding to 0.14 kg/person/week. Moreover, the generation rate for plastic waste in system A was 26% greater than D. These results indicate that source-sorting of a waste fraction affects the generation of other materials differently. Consequently, prediction models that assume a constant generation rate when a new source-sorting system is introduced may be biased and yield erroneous results.

Table 5: Result of a statistical analysis comparing TRHW for individual waste fraction generation rates (kg/person/week) between waste-sorting systems. Statistically significant differences ($p < 0.05$) are highlighted in bold

3.2 Waste composition

3.2.1 Composition of household waste

Table 6 presents the descriptive statistics for the waste composition of both RHW and

TRHW. RHW consisted primarily of food waste (41-45%) in waste-sorting system A. The percentage of food waste in the RHW increased moderately in Aabenraa (waste-sorting system C: PW) between 2011 and 2017. However, it decreased considerably to 26% in Odsherred (waste-sorting system B: FW) and to 25% in Rødovre (waste-sorting system D: FW, PW). While food waste exhibited expected patterns, the percentage of the other waste fractions fluctuated considerably across schemes. The data in Table 6 indicate that the highest percentage of plastic waste in RHW was surprisingly found in the municipality of Rødøvre, which actually source-sorted plastic waste. However, regarding municipalities in system A, there was little variation in the percentage of plastic waste (28 - 32 %).

Table 6: Statistical summary based on “residual household waste” (without source-sorted food and plastic waste) via the classical (mean and coefficient of variance) and compositional data analysis (CoDa) technique (center and percentage distribution of the total variance) for municipalities in 2011 and 2017. (For waste-sorting system A, RHW equated to TRHW)

The proportion of misplaced materials in RHW increased in line with the number of separate fractions included in the recycling scheme. Table 6 shows that RHW consisted of 12-14% for other recyclable materials (system A), 49% for food and other recyclables (system B), 38% for plastic and other recyclables (system C) and 71% for food, plastic and other recyclables (system D). Although these findings may seem obvious, they quantify and document the influence of food and plastic waste-sorting on the composition of RHW. Moreover, these results highlight the participation of citizens in the recycling scheme.

The total variance expressed in percentage terms (%Var-Clr) shows that “other” and food waste contributed principally to total variance in the composition of both RHW and TRHW. Total variance was highest in Rødovre (waste-sorting system D) and Odsherred (waste-sorting system

B), suggesting that the waste composition in these municipalities fluctuated the most. This is also confirmed by greater coefficients of variation (CV) in Table 6 for food waste in Rødovre (72%) and Odsherred (70%). These findings imply that the percentage of misplaced food waste in RHW varied markedly between households, which may be explained by the fact that source-sorting food waste has been only recently (2016) introduced in these municipalities. As a result, the participation of households may require more time, and therefore continuous sensitization campaigns are necessary.

3.2.2 Effect of geographical and temporal variations on waste composition

RHW compositions from municipalities employing waste-sorting system A (2011) were compared, and the results show little variation in waste composition between them (Table S2); for example, food waste was 2% lower than the total average in Viborg. Additionally, the permutation test reveals no significant difference in waste composition in 2011 (Table S3).

Similarly, a small difference in RHW composition was observed between 2011 and 2017 in Viborg (Figure S2 and Table S4). The percentage of food waste increased by 5% in 2017, while the percentages of other recyclables and other waste decreased by 1% and 10%, respectively.

These results suggest that for the same waste-sorting system, geographical and temporal variations do not introduce significant changes in the RHW composition for Denmark, once again most likely due to the country's social homogeneity.

3.2.3 Effect of waste-sorting systems on waste composition

The geometric bar plot shown in Figure 4 and Figure S3 compares the compositions of RHW and TRHW between waste-sorting systems. For each material fraction, the individual waste-sorting systems were compared to the total average of all waste-sorting systems. For RHW, the total average was 32% for food waste, 12% for plastic, 26% for other recyclables and 11% for other waste (Table S5), whereas, for TRHW, it was 40% for food waste, 11% for plastic waste, 24% for other recyclables and 11% for other waste (Table S6).

Considering RHW, food waste exhibited a striking difference. For instance, while food waste was 44% lower than the average in D, it was 32% and 18% above average in C and A, respectively. In addition, plastic waste was 65% higher in system B. In contrast to RHW, TRHW exhibited relatively minor variations. The data from Figure 4 reveal that the percentage of food waste was 19% above average in system D, and 5% below in system A. Although the percentages of other recyclables and plastic waste were respectively 28 % and 24% lower than the average in system D, they appeared to be higher than the total average in system A (13% for other recyclables and 1% for plastic).

The permutation test indicates a significant difference in RHW composition between waste-sorting systems (DF=3, p-value=0.001). The univariate analysis (Table S7) shows that compared to system A, the proportion of food waste in RHW was significantly lower in systems B (-0.88±0.03%) and D (-0.79±0.06%) but significantly higher in system C (0.18±0.06%).

The results of the statistical analysis of TRHW show that a waste-sorting system does indeed influence waste composition, even when adding the mass of source-sorted materials. This result is mainly due to the difference in TRHW composition between systems A and D, as there was no significant difference between systems B and C.

3.2.4 Detailed waste composition and difference between waste datasets

Tables 7 and 8 provide a detailed composition of residual household waste in a system where food, plastic, paper, board, metal and glass waste are source-sorted (see Table 1). These tables indicate the percentage of impurities or misplacement for each fraction. The data from Tables 7 and 8 demonstrate that misplacement and impurity levels were considerable higher in RHW, food waste and plastic waste, whereas metal and glass waste exhibited the lowest impurities. The comparison of waste composition datasets based on 48 (Riber et al. 2009) and 52 (Edjabou et al., 2015; Götze et al., 2016b) fractions is provided in SI.

Figure 4: Bar plot comparing the distribution of the fractional waste composition of RHW and TRHW (bars in black indicate the total average for each individual waste fraction)

Table 7: Detailed composition of source-sorted household waste based on 48 waste fractions (SF) (Riber et al., 2009) from Rødovre municipality

Table 8: Detailed composition of source-sorted household based on 52 waste fractions (SF) (Götze et al., 2016b) from Rødovre municipality

4 Discussion

4.1 Implications of the study

The generation rates of RHW were considerably higher in system A than in other systems where food and/or plastic waste sorting was introduced. The generation rates of RHW and Total Household Waste were considerably lower in the systems, where food and/or plastic waste recycling was introduced (higher decrease when both were introduced). One possible explanation for this observation could be that schemes with an increased number of source-sorted fractions may make citizens more aware of waste generation leading to a reduction in their waste – as suggested by Woodard et al. (2006). By sorting food and plastic waste, households are possibly more aware of the mass and the type of waste that is disposed of. Consequently, households may use this information to develop new behaviours towards reducing waste generation. Other reasons that could have contributed to raising public awareness in those municipalities that implemented food and plastic recycling scheme may include the recent campaigns for food waste reduction, as well as the ongoing discussion on plastic waste in the oceans.

These findings imply that LCA practitioners should account for the possible effect of changing behaviour in household waste generation by including additional scenarios in the sensitivity analysis. While advising that LCA practitioners should account for the possible behaviour-related effects on household waste generation, the present findings also suggest that the previous LCA studies may have underestimated the benefits on the environment induced by waste recycling. This furthers support to ongoing and planned initiatives towards increased source separation of food and plastic waste, both in Denmark and in other countries.

The waste-sorting scheme significantly affects the composition of RHW and TRHW. Food waste was source-sorted in systems B (FW) and D (FW and PW), and therefore, in percentage terms, it was lowest in these areas. For TRHW composition, the highest percentage of food waste was noted in system D, where food and plastic waste were source-sorted. Another important observation is the fact that in system C, where only plastic waste was source-sorted, the amount of food waste in TRHW was lower than in B. The underlying reason here could be that Aabenraa municipality requires plastic packaging to be emptied prior to disposal (Arwos 2017), and thus citizens probably wash plastic packaging, as recommended by waste management authorities (Arwos 2017), by disposing the contents of plastic packaging (often food waste) directly into the kitchen sink (WRAP 2009). These findings highlight the complexity of household behaviours towards recycling schemes, and they indicate that changes in waste composition when introducing a new recycling scheme may not follow a linear pattern. Therefore, the correlation between waste fractions should be taken into account when predicting the generation and composition of RHW. These findings clearly underline the need to describe literally the waste-sorting system in the study area when RHW is to be analyzed. However, although a waste-sorting system can significantly affect RHW composition, there was no significant difference in TRHW composition between systems A (FW and PW were not source-sorted) and C (PW).

The detailed waste composition for each waste sorting revealed that the generation of RHW could be further reduced if the misplaced material fractions are correctly sorted. On the other hand, the purity of source-separated food and plastic waste could be highly increased by reducing the presence of impurities. Practically, this information strengthens the knowledge of local authorities regarding waste fractions, which is paramount in designing comprehensive and readily waste sorting guidelines. For example, owing to this information, the waste management authorities can provide a list of the most predominant waste fractions that are accepted in the recycling scheme and those that are not accepted. Lastly, this detailed waste composition allows local authorities to follow and understand evolvement of household waste and thereby adjust or update the waste sorting guideline accordingly.

A new political agreement was reached by the Danish parliament in 16 June 2020, to ensure the transition toward circular economy in the Danish waste sector by 2030. It consists of mandatory source separation of 10 different waste fractions including (1) food waste, (2) paper, (3) cardboard, (4) metal, (5) glass, (6) plastic (7) textile, (8) food and drinks packaging, (9) residual waste, (10) hazardous waste in all Danish households (Ministry of Environment and Food of Denmark 2020). The results of this study demonstrated the presence of impurities in all source separated fractions. , which Impurities may influence the quality of the recyclables, which can consequently contaminates the collected materials and thereby affects their recyclability as well as and biases the reported recycling rates in waste statistics (European Commission 2019; Faraca and Astrup 2019). According to the new EU calculation rules for recycling rates, the actual recycled material should be reported and not the collected amounts. Therefore, sampling campaigns that determine the degree of impurities in source-separated waste, such as in this study, can be of high relevance for calculating recycling rates with more precision. Additionally, the waste characterisation can identify the challenges to the recycling of each individual material and the potential improvement opportunities, such as requirements for the design of materials or technologies that are necessary for improving the recycling process.

4.2 Perspective and choice of waste composition datasets

The source-sorting of plastic significantly affected the generation rates of RHW but not its composition. This contradictory result is in line with those of Edjabou et al. (2015), who methodically demonstrated that there was no relationship between waste generation rates and composition, because they belong to different sample spaces (Edjabou et al. 2017). Therefore, for LCA studies, it is recommended to use the detailed RHW composition published by Edjabou et al., (2015) for both system A (food and plastic waste are not source-sorted) and system C (only plastic waste is source-sorted). If food waste (B) or food and plastic waste (D) are source-sorted, it is recommended to use the detailed waste composition in Tables 7 & 8 (Table 9). This waste composition data can be used as default data for LCA studies. Although these data are collected in 2017, they are relatively new compared to those of Riber et al., (2009), which have been extensively used in the last ten years for various LCA studies (Clavreul et al., 2014).

Table 9: Recommended dataset for LCA studies

5 Conclusions

The aim of this study was to investigate the effects of recycling schemes on the generation and composition of residual household waste, and to provide detailed waste composition datasets to waste management authorities, researchers and LCA practitioners. The study revealed that the source segregation of food waste and/or plastic waste appreciably reduces significantly overall household waste. Importantly, while the source-sorting of food waste changes significantly the composition of RHW, it possibly also affects the total waste generation leading to an indirect waste prevention. However, further studies are required to quantify the long-term effects of recycling schemes on the overall waste reduction at home. The relatively higher misplacement rate in RHW indicates that there is a considerable potential for diverting recyclable materials from incineration. On the other hand, there is a need to reduce the presence of impurities in source-sorted food and plastic waste. This could be achieved by utilising the detailed waste composition, which enables a transparent and fair comparison between studies, especially in the waste LCA context, where RHW waste composition can play a crucial role in the ranking of different scenarios. Finally, this study has demonstrated the complex and non-linear changes found in waste composition after a new recycling scheme has been introduced. In an LCA context, this means that the composition of RHW should be differentiated for scenarios with different recycling schemes, and special focus should be given to the food waste collection scheme. Source-sorting of food and plastic waste has been recently introduced in these municipalities. Thus, interpreting and extrapolating these findings in a long-term context should be done carefully. Given the new Danish parliament agreement on circular economy, continuous waste characterisation studies are required to quantify the presence of impurity and investigate the dynamic changes in waste generation rate and composition.

Acknowledgments

The authors acknowledge the Danish Environmental Protection Agency (DEPA) and all the municipalities involved in this project for their diverse contributions to the manuscript.

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Title of paper: The influence of recycling schemes on the composition and generation of municipal solid waste

The core findings of the paper:

- Residual household is significantly affected by recycling scheme
- Recycling of food and plastic reduced by 40% residual household waste
- Recycling of food and plastic reduced by 10% the total household waste
- Residual household waste was not affected by seasonal variation

Maklawe Essonanawe Edjabou: Statistical analysis, R software, writing and editing, visualisation. **Vasiliki, Takou**: Writing, reviewing and editing, discussion in LCA perspective of the findings. **Alessio Boldrin**: Co-supervision, reviewing and editing; experimental design, Discussion and implication of finding for waste management perspective. **Claus Petersen**: Plan and conduct waste sampling and characterization, data-gathering. **Thomas Fruergaard Astrup**: Supervision, planning draft, experimental design, interpretation of the results.

Figure captions

Figure 1: Illustration of waste-sorting systems in the municipalities included in this study

Households waste bins	Waste sorting systems	Municipalities (Year)
RHW, OR	A	Gladsaxe (2011), Helsingør (2011), Kolding (2011), Viborg (2011), Viborg (2017)
RHW, FW, OR	B	Odsherred (2017)
RHW, PW, OR	C	Aabenraa (2017)
RHW, FW, PW, OR	D	Rødovre (2017)

Figure 2: Overview of RHW waste generation rates in 2011 and 2017 from single-family houses as a function of waste source systems: (A) RHW (residual household waste); (B): source-sorting of food waste; (C) source-sorting of plastic waste; (D) source-sorting of food and plastic waste

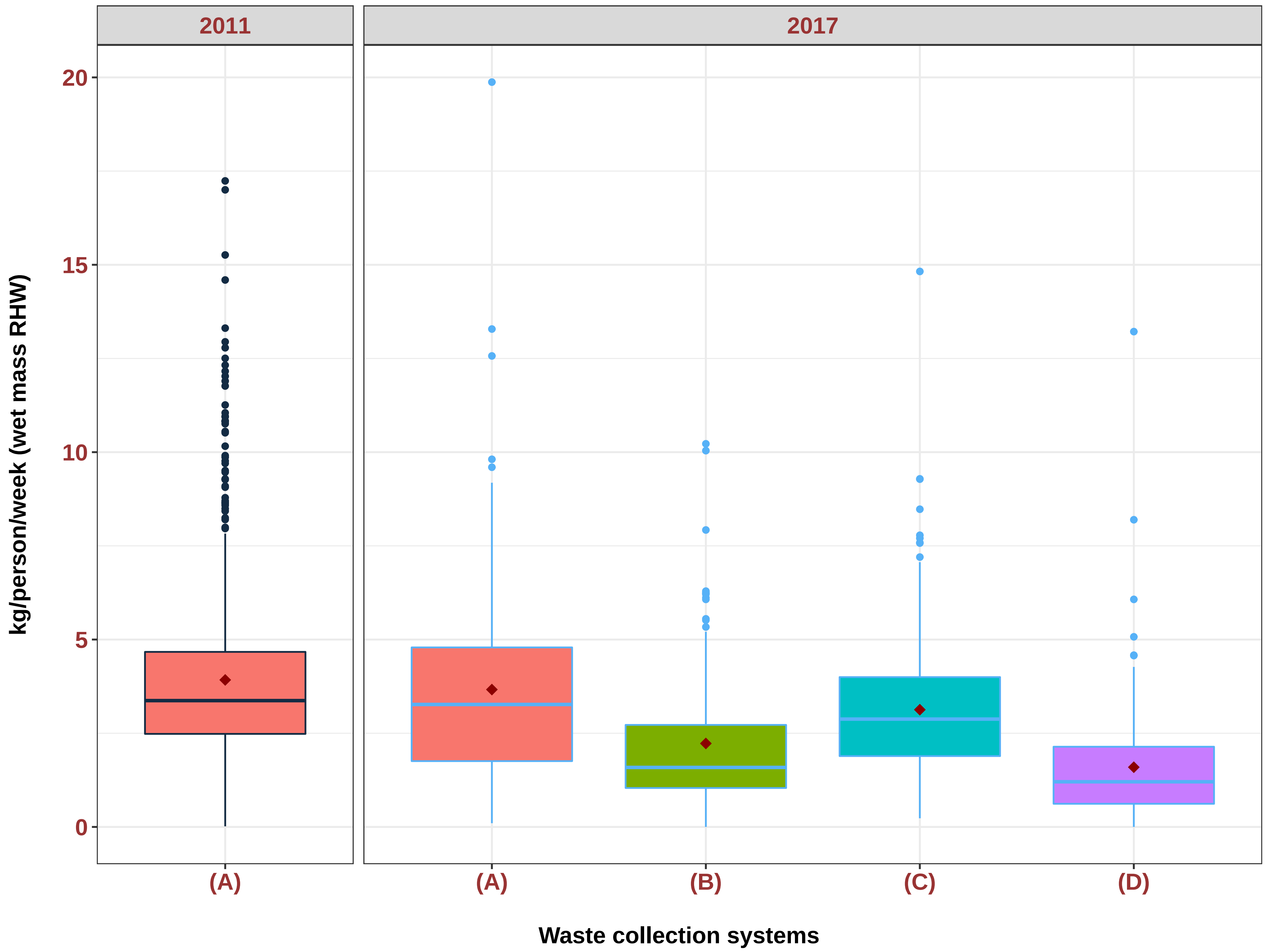

2011
2017
20
15
10
5
0
kg/person/week (wet mass RHW)
(A)
(A)
(B)
(C)
(D)
Waste collection systems

Figure 3: Overview of TRHW waste generation rates in 2011 and 2017 from single-family houses as a function of waste source systems: (A) RHW (residual household waste); (B): source-sorting of food waste; (C) source-sorting of plastic waste; (D) source-sorting of food and plastic waste

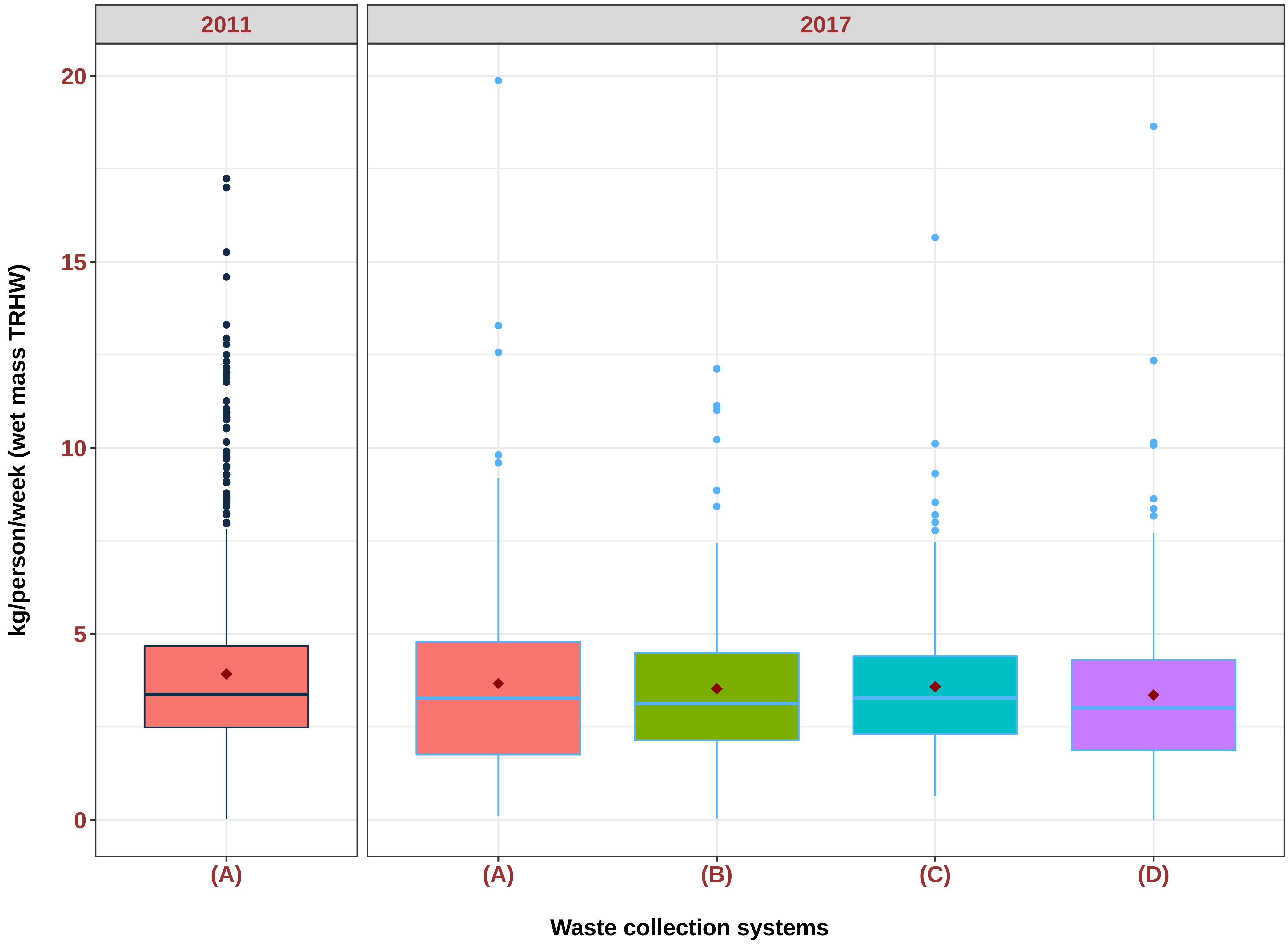
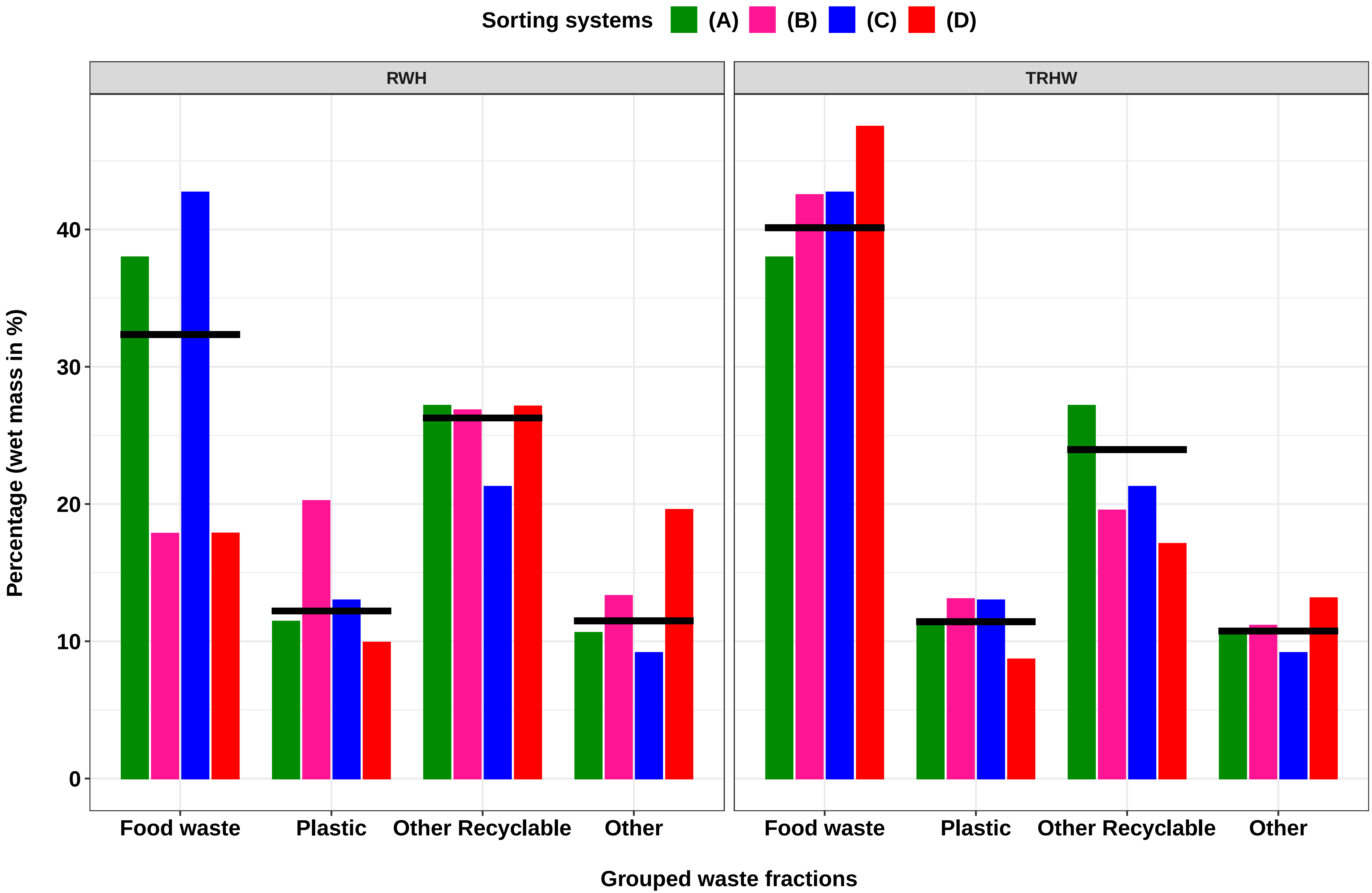

2011
2017
20
15
10
5
0
kg/person/week (wet mass TRHW)
(A)
(A)
(B)
(C)
(D)
Waste collection systems

Figure 4: Bar plot comparing the distribution of the fractional waste composition of RHW and TRHW (bars in black indicate the total average for each individual waste fraction)


Sorting systems
(A)
(B)
(C)
(D)
RWH
TRHW
Percentage (wet mass in %)
0
10
20
30
40
Food waste
Plastic
Other Recyclable
Other
Grouped waste fractions

The influence of recycling schemes on the composition and generation of municipal solid waste

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Table 1: Overview of numbers of households and municipalities involved in the sampling campaigns.

Year	Municipalities	Waste sorting systems (scenario)	Number of households	Mass of waste sampled and sorted (kg)		
				RHW[a]	Food waste	Plastic waste
2011	Gladsaxe	RHW (A)	210	4180	-	-
2011	Helsingør	RHW (A)	190	3900	-	-
2011	Kolding	RHW (A)	200	3950	-	-
2011	Viborg	RHW (A)	200	3920	-	-
2017	Viborg	RHW (A)	200	3210	-	-
2017	Odsherred	RHW and FW[b] (B)	200	1560	950	-
2017	Aabenraa	RHW and PW[c] (C)	200	2840	-	165
2017	Rødovre[d]	RHW, FW[b], and PW[c] (D)	200	1810	1700	140

[a]*Residual household waste;*
[b]*Food waste;*
[c]*Plastic waste*
[d]*Paper, board, metal and glass were sampled from the same households and characterized (see SI)*

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Table 2: The waste fraction list based on Riber et al. (2009) (Götze et al., 2016)

Main fractions	**Grouped fractions**	**Dataset I 48 fractions** (Riber et al., 2009)	**Dataset II 52 fractions** (Edjabou et al., 2015; Götze et al., 2016b)
1-Food waste	Food waste	(1) Animal-derived food waste; (2) Vegetable food waste	(1) Animal-derived food waste; (2) Vegetable food waste
2-Plastic	Plastic	(3) Soft plastic[a]; (4) Plastic bottles; (5) Other hard plastic; (6) Non-recyclable plastic;	(3) Plastic packaging-PET[b]; (4) Plastic packaging-HDPE[c]; (5) Plastic packaging-PP[d]; (6) Plastic packaging-PSf[e]; (7) Plastic packaging-expanded PS[e]; (8) Plastic packaging-no label; (9) Plastic packaging-identification code 7-19; (10) Plastic packaging-foil; (11) Plastic packaging-plastic composite[a]; (12) Non-packaging plastic-identification code 7-19; (13) Non-packaging plastic-PP[f]; (14) Non-packaging plastic-PET[b]; (15) Non-packaging plastic-no label; (16) Non-packaging plastic-LDPE[f]
3-Other recyclabless	Gardening waste	(7) Yard waste, flowers etc.; (8) Animals and excrements; (9) Wood;	(17) Plant material; (18) Woody plant material; (19) Humus, (20) Animal excrements-dog; (21) Animal excrement-cat; (22) Animal bedding
	Paper and board	(10) Newsprints; (11) Magazines; (12) Advertisements; (13) Books and phonebooks; (14) Office paper; (15) Other clean paper; (16) Paper and board packaging; (17) Cardboard; (18) Other cardboard; (19) Milk carton and alike; (20) Juice cartons and other carton with alu-foil; (21) Kitchen tissue; (22) Other dirty paper; (23) Other dirty cardboard[g];	(23) Magazines and advertisement; (24) Newsprint; (25) Office/administrative paper; (26) Books, (27) Tissue paper; (28) Other paper; (29) Cardboard and paperboard; (30) Paper and cardboard composites
	Metal	(24) Aluminum containers; (25) Aluminum –trays and foil, etc.; (26) Metal containers (-Al); (27) Metal foil (Fe); (28) Other metal	(31) Metal packaging-non-ferrous; (32) Metal packaging-ferrous; (33) Metal packaging-aluminum foil; (34) Non-packaging metal-ferrous; (35) Non-packaging metal-non-ferrous
	Glass	(29) Clear glass; (30) Green glass; (31) Brown glass; (32) Other glass[g];	(36) Glass packaging-clear; (37) Glass packaging-green; (38) Glass packaging-brown; (39) Kitchen and table ware glass; (40) Other/special glass[g]
4 Others	Miscellaneous combustibles	(33) Diapers and tampons; (34) Cotton stick, etc.; (35)Textiles; (36) Shoes, leather, etc.; (37) Rubber etc.; (38) Cigarette butts; (39) Vacuum cleaner bags; (40) Other combustibles;(41) Office articles ;	(41) Sanitary products; (42) Textiles, leather, rubber; (43)Vacuum cleaner bags; (44) Other combustibles[g]
	Inert	(42) Soil; (43) Rocks, stones and gravel; (44) Ash; (45) Ceramics; (46) Cat gravel; (47) Batteries; (48) Other non-combustibles[g]	(45) Ceramics/porcelain; (46) Ashes; (47) Cat litter; (48) Gravel, sand, stones; (49) Other non-combustibles; (50) WEEE and other hazardous waste[g]; (51) Batteries ;(52) Residual;

[a]*Soft platic waste was not source-sorted.*
[b]*PET/PETE: Polyethylene terephthalate;*
[c]*HDPE: High density polyethylene;*
[d]*PP: Polypropylene;*
[e]*PS: Polystyrene;*
[f]*LDPE/LLDPE: Low density polyethylene*
[g]*Other: Detailed waste fractions included in other can be found in supplementary information*

Table 3: Descriptive statistics for waste generation rates for residual household (RHW), source-sorted food (FW) and plastic (PW) waste (kg/person/week wet mass) in 2011 and 2017.

Year	Municipalities	Waste sorting systems	Waste type	Mean	SD	Median	Min	Max	Skew	Kurtosis
2011	Gladsaxe	A[a]	RHW	3.74	2.15	3.26	0.45	17.24	2.11	7.95
	Helsingør	A[a]	RHW	3.84	2.19	3.37	0.21	15.26	2.14	7.17
	Kolding	A[a]	RHW	4.03	2.38	3.56	0.02	13.31	1.49	2.59
	Viborg	A[a]	RHW	4.09	2.58	3.36	1.19	17	1.93	4.43
2017	Viborg	A[a]	RHW	3.67	2.55	3.27	0.1	19.87	2.06	8.32
	Odsherred	B[b]	FW	1.65	1.2	1.40	0	6.79	1.29	2.29
			RHW	2.25	1.72	1.62	0.36	10.22	1.92	4.46
			TRHW	3.53	1.99	3.13	0.03	12.12	1.46	3.3
	Aabenraa	C[c]	PW	0.45	0.22	0.42	0.14	0.83	0.76	-0.74
			RHW	3.13	1.92	2.88	0.23	14.82	1.86	6.74
			TRHW	3.58	1.95	3.28	0.65	15.65	1.98	7.49
	Rødovre	D[d]	FW	1.77	1.33	1.46	0.04	10.44	3.06	14.95
			PW	0.3	0.23	0.27	0.02	1.25	1.71	3.85
			RHW	1.66	1.53	1.25	0.06	13.22	3.22	18.31
			TRHW	3.39	2.23	3.01	0.06	18.65	2.55	12.19

[a]*A:Food and plastic were not source-sorted;*
[b]*B: Only food waste was source-sorted:*
[c]*C: Only plastic waste was source-sorted;*
[d]*D: Both food and plastic waste were source-sorted*

Table 4: Comparison of residual household waste generation rates, based on bootstrapping regression (1,000 sampling points). Here, waste-sorting systems were compared to system A. As an example, for RHW, B was 1.49 kg/person/week lower than A, whereas for TRHW, B was 0.21 kg/person/week lower than A. A 95% confidence interval containing zero (e.g. -0.45,0.02) means the difference was not significant. Statistically significant differences ($p < 0.05$) are highlighted in bold

Dataset[e]	Waste sorting systems	Estimates[f]	bootSE[g]	95% Confidence intervals	
				Lower	Upper
RHW	Intercept A[a]	3.51	0.06	3.71	3.90
	B[c]	-1.49	0.13	**-1.7**	**-1.27**
	C[b]	-0.6	0.13	**-0.81**	**-0.39**
	D[d]	-1.98	0.13	**-2.2**	**-1.77**
TRHW	Intercept A[a]	3.53	0.06	3.73	3.93
	B[c]	-0.21	0.14	-0.45	0.02
	C[b]	-0.17	0.14	-0.39	0.05
	D[d]	-0.40	0.14	**-0.64**	**-0.17**

[a]*Residual household waste (food and plastic waste were not sorted)*
[b]*Residual household waste with source segregation of plastic waste*
[c]*Residual household waste with source segregation of food waste*
[d]*Residual household waste with source segregation of both plastic and food waste;*
[e]*Residual household waste (RHW) and calculated total residual household;*
[f]*Estimate of average difference between intercept (waste sorting system A) in kg/person/week between and other systems;*
[g]*Standard error of estimates*

Table 5: Result of a statistical analysis comparing TRHW for individual waste fraction generation rates (kg/person/week) between waste-sorting systems. Statistically significant differences ($p < 0.05$) are highlighted in bold.

Fractions	Parameters	Estimates	Std.error	P-value	95% Confidence intervals	
					Lower	Upper
Food waste	Intercept (A)	1.63	0.04	0.00	1.56	1.7
	B	-0.79	0.09	0.00	**-0.97**	**-0.61**
	C	-0.88	0.09	0.00	**-1.06**	**-0.71**
	D	0.14	0.09	0.13	**-0.04**	**0.31**
Plastic	Intercept (A)	0.45	0.01	0.00	0.43	0.47
	B	-0.21	0.03	0.00	**-0.26**	**-0.16**
	C	-0.03	0.03	0.29	-0.08	0.02
	D	-0.12	0.03	0.00	**-0.18**	**-0.07**
Other recyclables	Intercept (A)	1.19	0.03	0.00	1.13	1.25
	B	-0.83	0.08	0.00	**-0.99**	**-0.68**
	C	-0.83	0.08	0.00	**-0.98**	**-0.68**
	D	-0.54	0.08	0.00	**-0.69**	**-0.39**
Other	Intercept (A)	0.57	0.02	0.00	0.52	0.61
	B	-0.25	0.06	0.00	**-0.36**	**-0.13**
	C	-0.3	0.06	0.00	**-0.41**	**-0.2**
	D	0.05	0.06	0.42	-0.07	0.16

Intercept is waste system A. Other waste sorting systems (B, C, D) were compared to A. Negative estimates mean less waste compared to system A, whereas a positive estimates indicate higher waste than system A. For example, a person in system B generated 0.76 kg/person/week less food waste than in system A, whereas a person in system A disposed 0.12kg/week more waste than in system

Table 6: Statistical summary based on “residual household waste” (without source-sorted food and plastic waste) via the classical (mean and coefficient of variance) and compositional data analysis (CoDa) technique (center and percentage distribution of the total variance) for municipalities in 2011 and 2017. (For waste-sorting system A, RHW equated to TRHW)

			Statistical descriptive							
Year	Municipalities	Grouped fractions	Classical (RHW)		Classical (TRHW)		CoDa (RHW)		CoDa (TRHW)	
			Mean	CV (%)	Mean	CV (%)	Mean-ilr	%Var-clr	Mean-ilr	%Var-clr
2011		Food waste	43	40			44	30		
		Plastic	28	46			12	12		
	Gladsaxe (A)	Other recyclables	12	50			30	17		
		Other	17	81			14	40		
			100				100	100		
		Food waste	42	35			42	29		
		Plastic	30	41			13	14		
	Helsingør (A)	Other recyclables	14	54			32	17		
		Other	15	81			13	39		
			100				100	100		
		Food waste	41	37			42	23		
		Plastic	32	47			13	11		
	Kolding (A)	Other recyclables	13	42			33	23		
		Other	14	88			12	43		
			100				100	100		
		Food waste	41	40			42	26		
		Plastic	31	47			13	11		
	Viborg (A)	Other recyclables	12	42			32	19		
		Other	15	87			13	44		
			100				100	100		
2017		Food waste	45	34			47	25		
		Plastic	29	44			13	13		
	Viborg (A)	Other recyclables	13	48			30	17		
		Other	13	99			10	45		
			100				100	100		
		Food waste	26	70	47	36	23	37	49	24
		Plastic	30	43	14	47	26	10	15	10
	Odsherred (B)	Other recyclables	23	47	22	46	34	13	23	13
		Other	21	90	17	91	17	40	13	52
			100		100		100	100	100	100
		Food waste	47	34	47	34	50	19	50	19
		Plastic	24	47	14	46	15	11	15	11
	Aabenraa (C)	Other recyclables	14	46	24	47	25	15	25	15
		Other	15	97	15	97	11	55	11	55
			100		100		100	100	100	100
		Food waste	25	72	51	34	24	26	55	25
		Plastic	33	55	10	53	13	14	10	13
	Rødovre (D)	Other recyclables	13	68	21	54	36	19	20	21
		Other	29	77	19	77	26	41	15	41
			100		100		100	100	100	100

Table 7: Detailed composition of source-sorted household waste based on 48 waste fractions (SF) (Riber et al., 2009) from Rødovre municipality.

Fractions	RHW	Food waste	Plastic	Paper	Board	Glass	Metal
Animal food waste	5.3179	10.8920	0.0160	0.0000	0.0000	0.4950	0.4975
Vegetable food waste	17.7991	78.3151	1.0933	0.0000	0.0000	0.4950	0.0000
Newsprints	0.4925	0.0108	0.0557	20.0000	0.0000	0.0000	0.0000
Magazines	0.2864	0.0063	0.0324	10.1000	0.0000	0.0000	0.0000
Advertisements	0.8234	0.0181	0.0931	63.8000	0.0000	0.0000	0.0000
Books and phonebooks	0.1254	0.0028	0.0142	0.4000	0.0000	0.0000	0.0000
Office paper	0.6501	0.0143	0.0735	4.2000	0.0000	0.0000	0.0000
Other clean paper	0.4264	0.0094	0.0482	0.5000	0.0000	0.0000	0.0000
Paper and carton containers	1.0271	0.4031	0.0556	0.0000	3.6000	0.0000	0.0000
Cardboard	5.3928	0.0615	1.1094	0.0000	96.4000	0.0000	0.0000
Milk cartons and alike	2.1069	0.8268	0.1141	0.0000	0.0000	0.0000	0.0000
Juice cartons and other carton with alum-foil	0.7727	0.3032	0.0418	1.0000	0.0000	0.0000	0.0000
Kitchen tissue	6.1601	2.4173	0.3336	0.0000	0.0000	0.0000	0.0000
Other dirty paper	3.2776	1.2862	0.1775	0.0000	0.0000	0.0000	0.0000
Other dirty cardboard	1.2880	0.5055	0.0698	0.0000	0.0000	0.0000	0.0000
Soft plastic	6.2197	0.3076	30.2694	0.0000	0.0000	0.0000	0.0000
Plastic bottles	4.3502	0.1025	53.7242	0.0000	0.0000	0.0000	0.0000
Other hard plastic	0.2229	0.0079	0.5469	0.0000	0.0000	0.0000	0.0000
Non-recyclable plastic	1.5208	0.0537	3.7320	0.0000	0.0000	0.0000	0.0000
Yard waste, flowers etc.	2.5724	2.6549	0.0000	0.0000	0.0000	0.0000	0.0000
Animals and excrements	0.2858	0.8373	0.0000	0.0000	0.0000	0.0000	0.0000
Diapers and tampons	15.0979	0.5125	1.1054	0.0000	0.0000	0.0000	0.0000
Cotton stick etc.	0.9435	0.0320	0.0691	0.0000	0.0000	0.0000	0.0000
Other cotton etc.	0.6283	0.0213	0.0460	0.0000	0.0000	0.0000	0.0000
Wood	1.2890	0.0438	0.0944	0.0000	0.0000	0.0000	0.0000
Textiles	3.2539	0.0160	0.0000	0.0000	0.0000	0.0000	0.0000
Shoes, leather	0.7127	0.0035	0.0000	0.0000	0.0000	0.0000	0.0000
Rubber etc.	0.2038	0.0010	0.0000	0.0000	0.0000	0.0000	0.0000
Office articles	0.4188	0.0142	0.0307	0.0000	0.0000	0.0000	0.0000
Cigarette buts	0.8349	0.0283	0.0611	0.0000	0.0000	0.0000	0.0000
Other combustibles	4.1366	0.1404	0.3029	0.0000	0.0000	0.0000	0.0000
Vacuum cleaner bags	2.6262	0.0892	0.1923	0.0000	0.0000	0.0000	0.0000
Clear glass	0.0006	0.0000	0.0002	0.0000	0.0000	79.2079	0.0000
Green glass	0.0001	0.0000	0.0000	0.0000	0.0000	11.8812	0.0000
Brown glass	0.8941	0.0000	0.2766	0.0000	0.0000	7.9208	0.0000
Other glass	0.1298	0.0000	0.0402	0.0000	0.0000	0.0000	0.0000
Aluminum containers	0.4411	0.0112	0.0864	0.0000	0.0000	0.0000	19.9005
Alum-trays, alum-foil	0.3678	0.0093	0.0721	0.0000	0.0000	0.0000	14.9254
Metal containers (-Al))	0.2394	0.0000	0.0000	0.0000	0.0000	0.0000	29.8507
Metal foil (-Al))	0.0899	0.0000	0.0000	0.0000	0.0000	0.0000	4.9751
Other of metal	0.1561	0.0000	0.0000	0.0000	0.0000	0.0000	29.8507
Soil	0.3029	0.0026	0.0100	0.0000	0.0000	0.0000	0.0000
Rocks, stones and gravel	0.7070	0.0060	0.0233	0.0000	0.0000	0.0000	0.0000
Ash	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ceramics	0.7934	0.0068	0.0261	0.0000	0.0000	0.0000	0.0000
cat gravel	3.0142	0.0257	0.0992	0.0000	0.0000	0.0000	0.0000
Batteries	0.4134	0.0000	1.5848	0.0000	0.0000	0.0000	0.0000
Other non-combustibles	1.1864	0.0000	4.2789	0.0000	0.0000	0.0000	0.0000
Total	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000

Table 8: Detailed composition of source-sorted household based on 52 waste fractions (SF) (Götze et al., 2016b) from Rødovre municipality.

Fractions	RHW	Food waste	Plastic	Paper	Board	Glass	Metal
Animal-derived food waste	5.1888	10.6894	0.0163	0.0000	0.0000	0.5000	0.4926
Vegetable food waste	17.3669	76.8580	1.1121	0.0000	0.0000	0.5000	0.0000
Plant material	1.8047	3.4253	0.0000	0.0000	0.0000	0.0000	0.0000
Woody plant material	0.2745	0.5210	0.0000	0.0000	0.0000	0.0000	0.0000
Humus	0.4307	0.8174	0.0000	0.0000	0.0000	0.0000	0.0000
Animal excrements-dog	0.1859	0.3529	0.0000	0.0000	0.0000	0.0000	0.0000
Animal excrements-cat	0.0930	0.1764	0.0000	0.0000	0.0000	0.0000	0.0000
Animal bedding	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Magazines and advertisement	1.0828	0.0239	0.1276	40.4193	0.0000	0.0000	0.0000
Newsprint	0.4806	0.0106	0.0566	22.1910	0.0000	0.0000	0.0000
Office/administrative paper	0.6343	0.0140	0.0747	25.7574	0.0000	0.0000	0.0000
Books	0.1224	0.0027	0.0144	0.7925	0.0000	0.0000	0.0000
Tissue paper	6.0105	2.3724	0.3393	0.8238	0.0000	0.0000	0.0000
Other paper	0.4161	0.0092	0.0490	7.4978	32.6906	0.0000	0.0000
Cardboard and paperboard	6.2640	0.4559	1.1850	0.0000	62.3133	0.0000	0.0000
Paper and cardboard composites	7.2644	2.8673	0.4101	0.0000	2.4780	0.0000	0.0000
Plastic packaging-PET	0.8064	0.0191	16.7554	0.0355	0.0355	0.0000	0.0000
Plastic packaging-HDPE	0.6149	0.0146	20.7258	0.0439	0.0439	0.0000	0.0000
Plastic packaging-PP	0.9697	0.0230	7.0711	0.0150	0.0150	0.0000	0.0000
Plastic packaging-PS	0.1539	0.0036	1.1287	0.0024	0.0024	0.0000	0.0000
Plastic packaging-expanded PS	0.1082	0.0026	0.5907	0.0013	0.0013	0.0000	0.0000
Plastic packaging-no label	0.9956	0.0236	0.0000	0.0000	0.0000	0.0000	0.0000
Plastic packaging-identification code 7-19	0.0000	0.0000	8.3755	0.0177	0.0177	0.0000	0.0000
Plastic packaging-foil	6.0686	0.3019	28.1793	0.6781	0.6781	0.0000	0.0000
Plastic packaging-plastic composite	0.5958	0.0141	2.6101	0.0628	0.0628	0.0000	0.0000
Non-packaging plastic-identification code 7-19	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Non-packaging plastic-PP	0.3212	0.0114	1.7185	0.0000	0.0000	0.0000	0.0000
Non-packaging plastic-PET	0.0285	0.0010	0.0000	0.0000	0.0000	0.0000	0.0000
Non-packaging plastic-no label	1.3516	0.0480	2.3948	0.0000	0.0000	0.0000	0.0000
Non-packaging plastic-LDPE	0.0000	0.0000	0.2391	0.0000	0.0000	0.0000	0.0000
Sanitary products	16.2649	0.5554	1.2414	0.5470	0.5470	0.0000	0.0000
Textiles, leather, rubber	4.0691	0.0201	0.0000	0.0000	0.0000	0.0000	0.0000
Vacuum cleaner bags	2.5624	0.0875	0.1956	0.0000	0.0000	0.0000	0.0000
Other combustibles	5.2594	0.1796	0.4014	0.9117	0.9117	0.0000	0.0000
Metal packaging-non-ferrous	0.2846	0.0000	0.0000	0.0280	0.0280	0.0000	36.4532
Metal packaging-ferrous	0.3443	0.0000	0.0000	0.0588	0.0588	0.0000	52.2167
Metal packaging-aluminum foil	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9852
Non-packaging metal-ferrous	0.1292	0.0000	0.0000	0.0000	0.0000	0.0000	3.9409
Non-packaging metal-non-ferrous	0.1890	0.0000	0.0000	0.0000	0.0000	0.0000	5.9113
Glass packaging-clear	0.0006	0.0000	0.0002	0.0264	0.0264	80.0000	0.0000
Glass packaging-green	0.0001	0.0000	0.0000	0.0406	0.0406	12.0000	0.0000
Glass packaging-brown	0.8724	0.0000	0.2813	0.0487	0.0487	5.0000	0.0000
Kitchen and table ware glass	0.0806	0.0000	0.0260	0.0000	0.0000	2.0000	0.0000
Other/special glass	0.0461	0.0000	0.0149	0.0000	0.0000	0.0000	0.0000
Ceramics/porcelain	0.7741	0.0066	0.0265	0.0000	0.0000	0.0000	0.0000
Ashes	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Cat litter	2.9411	0.0252	0.1009	0.0000	0.0000	0.0000	0.0000
Gravel, sand, stones	0.6898	0.0059	0.0237	0.0000	0.0000	0.0000	0.0000
Other non-combustibles	4.0084	0.0343	0.1375	0.0000	0.0000	0.0000	0.0000
Residual	0.6921	0.0059	0.0237	0.0000	0.0000	0.0000	0.0000
WEEE and other hazardous waste	1.1576	0.0000	4.3524	0.0000	0.0000	0.0000	0.0000
Batteries	0.0000	0.0201	0.0000	0.0000	0.0000	0.0000	0.0000

Table 9: Recommended dataset for LCA studies

Waste recycling systems	Recycling system include		Recommended waste composition datasets
	Food waste	Plastic waste	
A	No	No	Edjabou et al. (2015)
B	Yes	No	Table 7 & 8
C	No	Yes	Edjabou et al. (2015)
D	Yes	Yes	Table 7 & 8