

2015

# Quantification of Food Waste Disposal in the United States: A Meta-Analysis

Krista L. Thyberg

*SUNY Stony Brook*, [krista.thyberg@stonybrook.edu](mailto:krista.thyberg@stonybrook.edu)


David J. Tonjes

*SUNY Stony Brook*, [david.tonjes@stonybrook.edu](mailto:david.tonjes@stonybrook.edu)

Jessica Gurevitch

*SUNY Stony Brook*, [jessica.gurevitch@stonybrook.edu](mailto:jessica.gurevitch@stonybrook.edu)

Follow this and additional works at: <https://commons.library.stonybrook.edu/techsoc-articles>

 Part of the [Environmental Engineering Commons](#), [Environmental Indicators and Impact Assessment Commons](#), [Environmental Monitoring Commons](#), [Natural Resources Management and Policy Commons](#), and the [Sustainability Commons](#)

---

## Recommended Citation

Thyberg, Krista L.; Tonjes, David J.; and Gurevitch, Jessica, "Quantification of Food Waste Disposal in the United States: A Meta-Analysis" (2015). *Technology & Society Faculty Publications*. 14.  
<https://commons.library.stonybrook.edu/techsoc-articles/14>

This Article is brought to you for free and open access by the Technology and Society at Academic Commons. It has been accepted for inclusion in Technology & Society Faculty Publications by an authorized administrator of Academic Commons. For more information, please contact [mona.ramonetti@stonybrook.edu](mailto:mona.ramonetti@stonybrook.edu).

1 Quantification of Food Waste Disposal in the United  
2 States: A Meta-Analysis

3 *Krista L. Thyberg*<sup>†</sup> \*

4 *David J. Tonjes*<sup>†</sup>

5 *Jessica Gurevitch*<sup>‡</sup>

6

7 <sup>†</sup>Department of Technology and Society, Stony Brook University, Stony Brook, New York

8 11794-3760, USA

9 <sup>‡</sup> Department of Ecology and Evolution, Stony Brook University, Stony Brook, NY 11794-4245,

10 USA.

11 Food waste; municipal solid waste; meta-analysis; quantification; waste characterization

12

13 Food waste has major consequences for social, nutritional, economic, and environmental issues,

14 and yet the amount of food waste disposed in the U.S. has not been accurately quantified. We

15 introduce the transparent and repeatable methods of meta-analysis and systematic reviewing to

16 determine how much food is discarded in the U.S., and to determine if specific factors drive

17 increased disposal. The aggregate proportion of food waste in U.S. municipal solid waste from  
18 1995 to 2013 was found to be 0.147 (95% CI 0.137-0.157) of total waste, which is lower than that  
19 estimated by USEPA for the same period (0.176). The proportion of food waste increased  
20 significantly with time, with the western U.S. region having consistently and significantly higher  
21 proportions of food waste than other regions. There were no significant differences in food waste  
22 between rural and urban samples, or between commercial/institutional and residential samples.  
23 The aggregate disposal rate for food waste was 0.615 pounds (0.279 kg) (95% CI 0.565-0.664) of  
24 food waste disposed per person per day, which equates to over 35.5 million tons (32.2 million  
25 tonnes) of food waste disposed annually in the U.S.

## 26 **Introduction**

27 Food waste has been identified as a significant social, nutritional, economic, and environmental  
28 problem and interest in preventing food waste and diverting it from disposal has grown rapidly in  
29 the U.S. and abroad, as reflected in federal and state policies.<sup>1 2</sup> Multiple states and cities in the  
30 U.S. have recently enacted legislation banning the disposal of food waste in landfills to encourage  
31 waste prevention and treatment through alternative technologies, such as anaerobic digestion and  
32 composting. However, currently large quantities of food waste, which is biodegradable and some  
33 of which is edible, is still commingled with regular trash and disposed of in landfills or incinerators.  
34 It has been estimated that one quarter of the produced food supply is lost within the food supply  
35 chain; the production of this lost and wasted food globally has been estimated to account for 24%  
36 of total freshwater resources used in food production, 23% of global cropland, and 23% of global  
37 fertilizer use.<sup>3</sup> As the global population continues to quickly grow, urbanize, and become  
38 wealthier, leading to a diversification of dietary patterns and an increase in demand for land,  
39 resources, and greenhouse gas intensive foods, it will be essential that changes be made to food

40 systems to increase sustainability. In addition to reducing the impact of food systems on the  
41 environment, reduced food waste and proper waste management can also save economic resources,  
42 contribute to food security, and minimize negative impacts of food waste on waste management  
43 systems, while obtaining increased benefits, such as energy or compost production.

44 However, because of considerable gaps in both data and methods for analyzing extant data, no  
45 reliable and repeatable information exists on the actual proportion of food lost and wasted  
46 nationally or globally. There is a scarcity of data on food waste all throughout North America<sup>4</sup>,  
47 Europe<sup>5</sup>, and the rest of the world<sup>6</sup>, and available data tend to be incomplete and outdated.<sup>7</sup> Few  
48 peer-reviewed or major studies estimating quantities of food waste have been conducted,<sup>8</sup> and  
49 those that have been done utilize different methodologies,<sup>9 10</sup> making it difficult to compare  
50 findings across studies or aggregate findings. In particular, definitional issues<sup>11</sup>, the absence of  
51 sound quantification methods, and a general lack of political will have led to a deficit of  
52 information with regard to food waste disposal quantities in the U.S.<sup>6</sup> These data gaps have led to  
53 recent calls for further research on wasted and lost food.<sup>5 12 13</sup>

54 Food waste disposal data are essential for the development of effective, well-planned food waste  
55 management policies<sup>11</sup>, and can be used to determine if future food waste recovery and prevention  
56 efforts considerably change the composition of the residual waste stream. Examining the amount  
57 of waste that is currently being disposed shows the amount of waste that has yet to be recovered  
58 from the disposal stream, thus indicating how much waste is available for prevention or alternative  
59 treatments. Recycling programs are well-established and usually mandatory, so it is reasonable to  
60 assume these efforts will continue. Analyzing materials that are still being disposed defines areas  
61 where improvement can be achieved. A better understanding of the municipal solid waste (MSW)  
62 stream (wastes from residential, institutional, and commercial sources)<sup>14</sup> also allows for

63 improvements to key inputs for waste models, such as life cycle assessments (LCA), and better  
64 data-driven policy development and decisions.

65 Recent interest in implementing policies targeting food waste (e.g., disposal bans, pay-as-you-  
66 throw volume based pricing systems to reduce waste disposal, educational campaigns, regulatory  
67 mandates for diversion) indicate that understanding food waste disposal quantities is particularly  
68 timely.<sup>10</sup> Policies have been recently implemented at the state level in the U.S. to encourage or  
69 mandate diversion of food waste, including food waste disposal bans in Vermont, Rhode Island,  
70 Connecticut, Massachusetts, and California. Some cities have also implemented policies targeting  
71 food waste (e.g., San Francisco, New York, Seattle). BioCycle magazine found 198 communities  
72 in 19 states offered residential food waste collection in 2013 and 2014, an increase from prior  
73 years; in 2005, 24 municipalities offered collection.<sup>15</sup>

#### 74 ***Inadequacies of current data on food waste***

75 The primary source of municipal waste disposal estimates in the U.S. is the U.S. Environmental  
76 Protection Agency's (USEPA) annual Facts and Figures reports which are ubiquitously relied upon  
77 when discussing U.S. MSW (e.g.,<sup>16 17</sup>). The methods used to develop these estimates are flawed,  
78 however. The USEPA estimates are generated using a materials flow model which makes specific  
79 adjustments to industrial production data, such as for imports/exports and product life spans.<sup>18</sup>  
80 However, materials flow concepts are inappropriate for food waste.<sup>19</sup> Food waste is not generated  
81 by industrial processes where the kinds of materials used to create the materials are known and  
82 counted, the outputs are tracked, and product lifespans are understood.<sup>20</sup> So, data on food sales  
83 bear little relation to the generation and disposal of food waste.<sup>21</sup> USEPA has acknowledged this,  
84 stating that 'quantities of MSW components such as food scraps and yard trimmings can only be  
85 estimated through sampling and weighing studies.'<sup>18</sup> It indicates that these wastes are accounted

86 for by compiling data from a variety of waste sampling studies in combination with demographic  
87 and other data (e.g., population, grocery store and restaurant sales). However, there is no detail  
88 provided on exactly which reports and data are included, the criteria for data selection and  
89 inclusion, or specifically how the data are used to generate food waste estimates, so it is impossible  
90 to assess assumptions, sampling error, or accuracy of estimates. Furthermore, results were  
91 routinely revised after they are posted. It is unclear exactly how studies are selected for inclusion  
92 and it cannot be determined if there were any biases involved in the study selection.

93 We propose and implement a more formal, systematic, and transparent analytical approach for  
94 quantifying food waste and use it to estimate U.S. food waste disposal (waste sent to landfills or  
95 incinerators). Specifically, we used meta-analysis and research synthesis, powerful statistical  
96 approaches which employ scientific methodology for data gathering and analysis developed  
97 specifically for generalizing results across studies, to analyze data on food waste from waste  
98 characterization sort studies. Waste characterization sorts involve the representative sampling,  
99 sorting, and weighing of wastes to determine the proportion of waste types in samples of waste.  
100 Numerous waste characterization studies have been completed in the U.S., thus creating an  
101 extensive dataset, and studies have been assessed as consistent, comparable, and reliable,<sup>22</sup> in part  
102 because most follow the widely-cited ASTM method for waste characterization (ASTM D 5231-  
103 08).<sup>23 24</sup> The standard outlines details on: (1) determining the number of samples needed to achieve  
104 reasonably low levels of errors for the mean composition estimates; (2) selecting representative  
105 distribution of incoming trucks containing wastes from the targeted waste shed; (3) obtaining a  
106 representative sample of waste from tipped loads; (4) sorting the samples into individual material  
107 categories and weighing the relative contribution of each constituent to the overall samples; and  
108 (5) calculating the mean, standard deviation, and confidence intervals for the sample data.<sup>24</sup> Waste

109 characterization studies have not previously been collated or statistically analyzed. Most sort data  
110 are available online, although they are not always easily found. Multiple recent waste  
111 characterization studies in the U.S. have indicated large quantities of food waste in the MSW  
112 stream, and results have been found to be different from USEPA estimates.<sup>25 26</sup> The definitive  
113 data generated here can serve as a compelling test of the accuracy and applicability of the heavily  
114 relied upon USEPA dataset and the methods detailed here can be applied in related fields.

115 Two other studies have collated waste characterization studies, although the specific methods,  
116 scales, and overall objectives differ considerably from this study. The U.K.'s Waste and Resources  
117 Action Programme (WRAP)<sup>27</sup> collated and analyzed data from waste composition studies in the  
118 U.K. that focused on disposed food waste. The waste characterization collation findings for  
119 households were averaged and combined with estimated disposal tonnages to generate overall  
120 disposed food waste quantities for 89 local authorities in the U.K. Staley and Barlaz<sup>23</sup> combined  
121 11 state waste sorts using the sample arithmetic mean to create an approximation of the wastes  
122 discarded in landfills. The data were used to estimate landfill gas emissions that would result from  
123 particular organic wastes.

## 124 **Methods**

125 Meta-analysis and research synthesis were used to analyze U.S. waste characterization data. In  
126 meta-analysis, standardized effect sizes are used to compare, on the same scale, the results of  
127 multiple studies in which a common effect of interest has been measured.<sup>27</sup> After an effect size is  
128 calculated for each study, an aggregate (or pooled) effect size across all studies is determined by  
129 weighting the precision of each individual effect value so that studies with greater precision are  
130 given higher weight than those where effect sizes are estimated with lower precision.<sup>28 29</sup>

131 Waste characterization data from state, county, and regional studies were found using the Google  
132 search engine. Primary search terms were ‘waste sort’, ‘waste characterization study’ and ‘waste  
133 composition study’. The search also targeted websites listing waste characterization studies.<sup>30 31</sup>  
134 After an initial selection using search terms and study titles, the methodology and results sections  
135 were carefully reviewed to determine if studies met inclusion criteria.

136 Selection criteria for inclusion were developed prior to choosing or discarding studies. All  
137 studies not meeting all selection criteria were excluded and the reason for exclusion was noted (see  
138 Supporting Information). Inclusion criteria were: (1) followed general principles and methods  
139 outlined by ASTM for waste characterization studies; (2) contained compositional data for food  
140 waste based on weight and enabled percentage (by wet weight) of food waste to be determined;  
141 (3) performed at a municipal scale (e.g., city, county, state); (4) performed post-recovery of  
142 recyclables; (5) involved sampling at the disposal (or transfer) site rather than at the generation  
143 point; (6) examined only MSW (residential, institutional, and commercial waste); (7) involved  
144 primarily manual sorting of samples (not visual); (8) provided confidence intervals and sample  
145 sizes; (9) used a standard, comparable definition of food waste; (10) conducted in the U.S; and  
146 (11) conducted between 1989 and 2013, thus capturing a 25-year span.

147 An important selection criterion was that studies focused only on MSW. Some food waste and  
148 loss are not included as MSW food waste (Figure 1). Industrial food loss (agriculture, production  
149 and processing) is not considered MSW, and it is generally not managed with MSW. The industrial  
150 sector faces particular circumstances and regulations making industrial food waste management  
151 different than food waste in MSW. Considerable amounts of industrial food waste are diverted  
152 from disposal; one estimate was 95 percent of food waste from manufacturers did not go to  
153 landfills, with 70 percent used for animal feed.<sup>32</sup> MSW food waste data do not include wastes that



154 escape through pathways other than MSW systems, such as home composting, food disposals, or  
155 food fed to animals. This approach is consistent with how USEPA quantifies U.S. MSW.<sup>18</sup> The  
156 present analysis includes avoidable (food that was edible prior to disposal), possibly avoidable  
157 (food that some people eat and others do not), and unavoidable (food that is not edible under  
158 normal circumstances) food waste.

159 Information coded for each study were: study ID number, name, author(s), year, publication  
160 date, scale (county, state, region), state, region, population of study area, sectors included (all  
161 MSW, residential, commercial/institutional), residential type (single –family, multi-family),  
162 geographical classification (urban, rural), sampling season, number of samples, average sample  
163 weight, and the proportion of food waste as determined from sampling and its 95% confidence  
164 interval. Data on waste shed disposal quantities were recorded as reported in each individual study.  
165 These tonnages allow for the determination of the total food waste disposed annually in the waste  
166 shed and for the calculation of pounds of food waste disposed per person per day.

167 Food waste disposal tonnages and daily disposal rates were determined for each sample (see  
168 Supporting Information). The effect size calculated for each study was a function of the proportion  
169 of food waste in the total waste. The approximation method was used with a variance stabilizing  
170 transformation (arcsine transformation); this transformation is a standard means to minimize  
171 potential bias associated with the approximation method (equations are provided in the Supporting  
172 Information).<sup>33</sup> The aggregate (pooled) mean effect size across studies was determined by  
173 weighting each individual effect size by a term that represents its precision, the inverse variance  
174 weight.<sup>29</sup> Variance stabilizing transformations yielded summary proportions that were back-  
175 transformed to the raw proportion scale using the inverse transformation.

176 In addition to using the proportion as an effect size, the per capita food waste disposal rate was  
177 aggregated for the sample group of studies surveying all MSW, where possible. This rate  
178 represents all food waste disposed in the MSW stream from residential, institutional, and  
179 commercial sectors, consistent with the USEPA's estimates of per capita wastes. Per capita rates  
180 allow comparisons to be made across waste sheds and to rates estimated by USEPA. The sample  
181 mean, which was based on a large sample size, was assumed to be approximately normally  
182 distributed and sample size was used as a proxy for variance. This was based on the assumption  
183 that sampling variances were equal, which is probably not valid because variances are almost never  
184 equal across studies. Therefore the meta-analysis outcomes could be biased to an unknown  
185 extent.<sup>28</sup> However, the statistical technique was used as a tool to assess if disposal rates showed  
186 similar trends across time and region as proportions, and focus was placed on confidence intervals,  
187 rather than point estimates.

188 A continuous random effects model was used to determine aggregate mean effect sizes. An  
189 assessment of overall heterogeneity (variation in study outcomes between studies) was then  
190 performed using Cochran's Q, calculated as the weighted sum of squared differences between  
191 individual study effects and the pooled effect across studies, with the weights being those used in  
192 the pooling method.<sup>34</sup> When a significant level of overall heterogeneity was found, a linear meta-  
193 regression was performed using a mixed effects model to determine if specific moderators  
194 explained any of the heterogeneity. Mixed effects models are random models which allow for the  
195 inclusion of moderators to determine if the moderators account for heterogeneity in the effects.<sup>35</sup>  
196 The specific estimator used in the meta-regression was the restricted maximum likelihood  
197 estimator. Tests for the amount of heterogeneity explained in the model by the moderators and for  
198 the amount of residual heterogeneity were calculated in the meta-regression, along with tests of

199 each coefficient's individual effect on the proportion (or rate). The calculations were performed  
200 using the open-access meta-analysis software Open Mee.<sup>36</sup>

201 Study samples were grouped based on characteristics of the samples (samples of total MSW,  
202 samples differentiating between residential and commercial/institutional sectors, samples  
203 differentiating between rural and urban areas, samples of total MSW that enable per capita rate  
204 calculations) to ensure effect sizes for each group were independent (no more than one effect size  
205 from any subject sample), ensure equitable comparability within a group, facilitate moderator  
206 assessment, and allow for valid statistical modeling. Each group was meta-analyzed separately,  
207 yielding a total of four meta-analyses.

208 Estimates of food waste disposal from the USEPA's 'MSW in the U.S.: Facts and Figures'  
209 quantification reports were collected.<sup>20</sup> Pounds of food waste disposed per person per day were  
210 calculated from these data. The USEPA explicitly states that its waste assessments describe wastes  
211 from residences, businesses, and institutions, and the accounting does not include hazardous  
212 wastes, dedicated construction and demolition debris, sewage sludge, and industrial wastes.<sup>14</sup> This  
213 is consistent with the waste streams analyzed by the waste characterization studies included here  
214 for the total MSW and per capita groups so it is possible to compare the aggregate findings from  
215 the waste characterization studies to USEPA estimates.

## 216 **Results and Discussion**

217 We found and assessed 107 waste characterization studies; 45 of these were eliminated because  
218 they did not meet the pre-defined selection criteria. Sixty-two waste characterization studies were  
219 included in the meta-analyses, representing over 20,000 samples of sorted refuse (waste remaining  
220 after recycling and composting), with a total sample weight of more than four million pounds (1.8  
221 million kg) (see Supporting Information). Food waste was found to make up a considerable

222 proportion of the disposed waste stream from 1995 to 2013 (0.147, 95% Confidence Interval [CI]  
223 0.137-0.157) (Table 1), and this proportion has been increasing significantly with time ( $\beta=0.005$ ,  
224  $z=4.112$ ,  $p<0.001$ ). There was significant heterogeneity among studies, with the proportion of food  
225 waste in samples including all MSW ranging from 0.071 to 0.228 ( $Q=144.014$ ,  $p<0.001$ ). The  
226 western U.S. had consistently higher proportions than the eastern or central U.S. (Table 1). A meta-  
227 regression model with year and region as covariates explained a significant amount of the total  
228 heterogeneity ( $R^2=45.69\%$ ,  $Q_M=19.809$ ,  $p<0.001$ ). There also was significant residual  
229 heterogeneity ( $I^2=46.12\%$ ,  $Q_E=77.991$ ,  $p=0.002$ ), indicating that other moderators may also  
230 influence food waste proportion. The mean effect size for the food waste disposal rate in terms of  
231 pounds of food waste disposed per person per day (ppd) from 1995 to 2013 was 0.615 ppd (95%  
232 CI 0.565-0.664) (0.279 kg per person per day) (Table 1). This is equal to 225 pounds (100 kg) per  
233 person per year, and equates to over 35.5 million tons (32.2 million tonnes) of food waste disposed  
234 annually in the U.S. The per capita disposal rate per day had an upward trend with time, although  
235 this was not significant ( $\beta=0.005$ ,  $z=1.089$ ,  $p=0.276$ ). Region, however, was significant, with the  
236 west having higher per capita food waste disposal rates ( $\beta=0.233$ ,  $z=4.549$ ,  $p<0.001$ ) (compared  
237 to eastern and central regions).

238 A meta-analysis of total MSW disposal rates was performed to better understand waste system  
239 dynamics. The aggregate mean total MSW disposal rate from 1995 to 2013 was 4.249 pounds  
240 (1.927 kg) of MSW disposed per person per day (95% CI 3.938-4.561). This equates to over 245.4  
241 million tons (222.6 million tonnes) of MSW disposed in landfills or incinerators each year in the  
242 U.S. There was a decrease in MSW disposal rate with time, but this was not significant. Region,  
243 however, was significant, with the west having higher rates of MSW disposal ( $\beta=0.857$ ,  $z=2.424$ ,  
244  $p<0.05$ ).

245 The aggregate proportion of food waste disposed in the U.S. from 1995 to 2013 as determined  
246 from waste characterization studies (0.147) was four-fifths of that estimated by USEPA for the  
247 same period (0.176) (Table 2). If over 245.4 million tons (222.6 million tonnes) of MSW is  
248 disposed annually in the U.S., this percentage difference represents a difference of over seven  
249 million tons of food waste disposed annually. This substantial difference can have considerable  
250 effects on management approaches for food waste. Both the meta-analysis and USEPA estimates  
251 indicated that the proportion of food waste disposed increased with time, but the correlations with  
252 time were significantly different ( $z=-.2.59$ ,  $p<0.05$ ), with the USEPA's being stronger ( $r=0.96$ ,  
253  $r=0.72$ , respectively) (Figure 2). The aggregate food waste disposal rate as determined from the  
254 meta-analysis of waste characterization studies was 0.615 ppd (0.279 kg) while the average for the  
255 same period as reported by USEPA was 0.548 ppd (0.249 kg). In five out of 13 years, USEPA  
256 estimates for food waste disposal proportion was within the 95 percent confidence bounds for the  
257 meta-analysis estimates. USEPA estimates for the per capita food waste disposal rate was within  
258 the 95 percent confidence bounds for eight out of 13 years. However, the overall USEPA average  
259 for 1995 to 2013 for both proportion and rate was not within the bounds for the aggregate mean as  
260 determined from the meta-analysis (Table 2).

261 Per capita food waste disposal rates increased with time and total MSW disposal rate decreased  
262 with time (albeit neither trend was statistically significant). The increase in food waste proportion  
263 is partially related to waste reduction in other components of MSW, which is supported by the  
264 downward trend of overall MSW disposal rates. The proportion of food waste is consequently  
265 higher relative to these other waste components, even if the amount of food waste disposed remains  
266 constant or only slightly increases. Waste reduction of other materials may be due to consumer  
267 purchasing choices, material light weighting, increased product durability, and waste avoidance.<sup>36</sup>

268 Over the past 25 years there has been an increase in policies aimed at diverting materials away  
269 from disposal, including yard waste disposal bans, bottle bills, more aggressive curbside recycling  
270 program, and volume based waste pricing systems.<sup>37</sup> Increases in food waste proportions with time  
271 may also be partially related to more food being disposed, possibly resulting from more food being  
272 allowed to spoil, increases in over stocking and over preparation of food,<sup>39</sup> confusion over food  
273 labels such as “sell by” dates,<sup>40</sup> misconceptions regarding food safety and desirability<sup>41</sup>, or changes  
274 in household shopping practices, particularly the size of the grocery store and the frequency of  
275 shopping.<sup>42</sup> An extension of the meta-analysis to analyze other materials would provide insight  
276 into specific system dynamics, including significant increases or decreases in other materials  
277 which may be influencing the food waste proportion.

278 Higher proportions of disposed food waste in the western compared to the eastern and central  
279 U.S. was observed for all sample groups; the effect was significant for the sector group (separate  
280 samples from residential and institution/commercial sectors). The higher proportion of disposed  
281 food waste in the western U.S. may be partially due to superior separation of other materials out  
282 of the waste stream in this region, such as removal of traditional recyclables. Robust recycling  
283 programs would lead to a large proportion of food waste being left behind in the disposed waste  
284 stream relative to the other materials in MSW. However, the per capita disposal rate of food waste  
285 was also significantly higher in the west than in east and central regions. It is unclear why the  
286 western U.S. had higher food waste proportions and rates; future work should focus on examining  
287 differentiating factors between the west and the other regions to determine which factors contribute  
288 to increased food waste disposal.

289 The proportion of food waste disposed from residential sectors did not differ significantly from  
290 that disposed by commercial/institutional sectors (residential: 0.182; commercial/institutional:

291 0.178). These proportions were higher than the overall aggregate (0.147) possibly because some  
292 of these sector samples excluded wastes dropped off at management sites directly by generators  
293 (self-haul waste). Self-haul waste has been found to contain lower food waste proportions than  
294 wastes collected from generation points by waste collectors.<sup>42</sup> Since MSW disposal tonnages from  
295 residential versus commercial/institutional sectors are thought to be between a 60:40<sup>21</sup> and a 50:50  
296 proportion,<sup>43</sup> considerable food waste tonnages are disposed by both sectors. This suggests that it  
297 may be equally beneficial to target both sectors with food waste recovery or prevention policies.  
298 However, there are specific industries (e.g., restaurants, supermarkets) that dispose of food waste  
299 at much higher proportions than the overall aggregate for all commercial and institutional  
300 establishments. Targeting large scale generators, such as the approach taken in 2014 by the state  
301 of Massachusetts, may be the easiest way to initiate a food waste management policy.

302 There were no significant differences between the proportion of food waste disposed in urban  
303 versus rural areas (urban: 0.155; rural: 0.152). This finding was somewhat surprising, as  
304 urbanization is generally thought to lead to increased food waste generation.<sup>6 22</sup> It may be possible  
305 that it is not urbanization on its own which affects food waste generation; rather urbanization  
306 commingled with other linked factors, such as economic development, globalization, and  
307 industrialization may together lead to increased wastage<sup>10</sup>. Iacovidou et al.<sup>45</sup> point out that  
308 economic condition is a critical factor when assessing food waste generation rates; it acts as an  
309 indicator of a country's wellbeing and food waste disposal weight has been shown to increase from  
310 low to high income countries. Therefore, it is possible that the strong differences between food  
311 waste generation in urban and rural populations may be reduced if overall standards of living are  
312 high within a country, as in the U.S.

313 In summary, this was the first study to formally collate and statistically analyze waste  
314 characterization studies in a transparent, repeatable, and systematic way using the powerful  
315 statistical and conceptual tools of systematic review and meta-analysis. The approach serves as a  
316 strong alternative to the ambiguous methods used to date to estimate food waste and it may be  
317 extended to quantify other materials. The methods used here are systematic, allow for repeatability,  
318 help eliminate biases regarding study inclusion, and enable clarity with regard to how estimates  
319 are determined. The approach is unique in that it focused on food waste disposed in the MSW  
320 stream which makes the findings important for waste management, particularly for planning and  
321 policy making. Furthermore, this approach represented a bottom-up approach which integrated  
322 smaller scale, real-world sampling studies, as opposed to top-down, large scale, modeling  
323 approaches that tend to over-simplify and are rarely validated. It is both essential and urgent that  
324 USEPA adopt a similar scientifically transparent and defensible approach to organic waste  
325 estimations.

### 326 ***Study limitations***

327 Waste characterization studies rely on sampling because it is neither practically feasible nor  
328 desirable to perform waste sorts on all disposed waste. Sampling may lead to random sampling  
329 error and the waste sorting procedure itself may introduce further error. During waste sorting,  
330 food waste components are generally separated out of their packaging but there are some items  
331 which make separation difficult (e.g., mustard packets, sealed cans). The classification of items  
332 which cannot be easily separated from their packaging to the category which proportion by mass  
333 prevails is recommended by the ASTM standard<sup>24</sup>, but discrepancies may occur when packaging  
334 which could have been easily separated is included in the food category or packaging whose  
335 proportion is higher than the food inside is counted in the food category. No estimates are



336 available regarding the dimension of included food packaging within food waste categories from  
337 waste characterization studies. Error also may occur through screening. ASTM recommends that  
338 sorting be continued until the maximum size of remaining waste particles is approximately 12.7  
339 mm.<sup>24</sup> At this point, apportioning of the remaining particles into corresponding waste  
340 components represented in the remaining waste mixture should be done based on a visual  
341 estimate of the mass of the fraction of waste components remaining. This may lead to  
342 underestimations of food in the sample, but the exact scale of this error is difficult to quantify.<sup>46</sup>

343 Agreement does not always exist regarding the definition of MSW and specific waste  
344 categories.<sup>47 10</sup> Most of the waste sorts included in the meta-analysis used fairly consistent MSW  
345 and food waste definitions, but there may have been some differences across studies. There are  
346 some inherent, unavoidable problems with MSW tonnage data, primarily involving the lack of  
347 complete data; quantifying this uncertainty is challenging. Data may be missing due to  
348 systematic or intentional errors in waste reports, unlicensed scavengers collecting materials, or  
349 wastes which are disposed outside of the waste shed.<sup>19</sup> Per capita disposal rates are subject to  
350 error due to the introduction of population statistics. Population data may not accurately reflect  
351 the amount of people living or staying in a municipality at certain times, such as summer  
352 residents or tourists.

353 Although inclusion criteria began with studies performed as early as 1989, only waste  
354 characterization studies from 1995 forward (that fit other inclusion criteria) were located for the  
355 total MSW group. Therefore, only USEPA data from 1995 forward were included in the  
356 comparison to ensure comparability. However, data for years 1996, 1997, 2001, and 2003 were  
357 missing from the waste sort dataset and data for 2013 was missing from the USEPA dataset; these  
358 data gaps may have affected the meta-analytic results.

359 ***Future work***

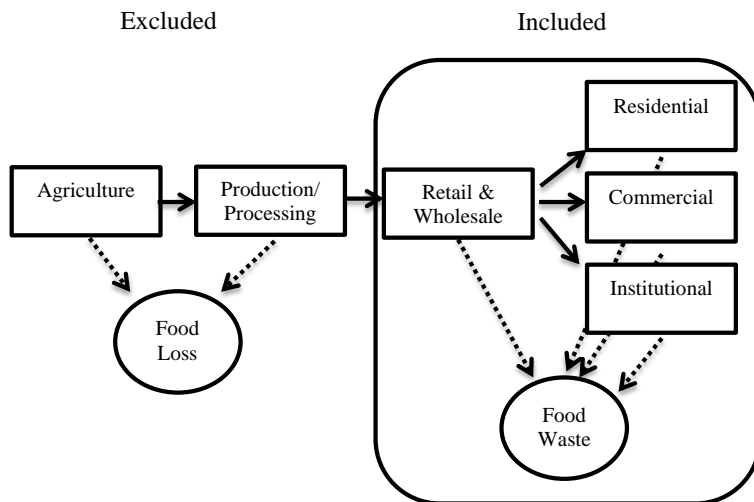
360 Analyses showed that a considerable amount of food waste is disposed on a regular basis  
361 throughout the U.S. These data are important because they indicate how much food waste can  
362 potentially be reduced or diverted from disposal. More research is necessary to evaluate the  
363 impacts and feasibility of food waste prevention and diversion policies. The meta-analyses  
364 indicated that despite the explanatory power of some of the variables (year, region), considerable  
365 heterogeneity remained, suggesting that food waste disposal may be influenced by other factors,  
366 such as education, socio-economic status, or age of residents.<sup>10</sup> Future work should aim to quantify  
367 the effects of other variables.

368 The technique for quantifying and statistically analyzing the results of waste characterization  
369 studies may be expanded to other waste stream components. It is possible to aggregate findings  
370 from waste characterization studies to determine the overall disposal proportions and rates for  
371 other waste types, as well as to determine if specific moderators are affecting their disposal. It also  
372 would be valuable to perform trend analyses on the proportions of other materials in the disposed  
373 waste stream and per capita disposal rates to determine how other materials are fluctuating with  
374 time. It is necessary to continue performing similar meta-analyses in the future to assess how  
375 moderator effects are changing with time and to determine if food waste proportion continues  
376 increasing. Furthermore, as more food waste prevention and recovery policies are initiated in the  
377 U.S., it will be possible to use the meta-analysis methodology to assess the effectiveness of these  
378 programs and to determine the differences between regions with food waste collections in place  
379 versus those without.

380 The study findings indicate that it is necessary to critically evaluate the impacts of food waste  
381 prevention and alternative treatments for food waste to determine if they can offer environmental,

382 economic, and social benefits. The considerable proportion of food waste in the disposed waste  
383 stream and the substantial tonnages that are annually disposed suggest that food waste prevention  
384 and diversion away from disposal should be a key priority of sustainable waste systems. If the  
385 objective of waste systems is to minimize the amount of materials being disposed in order to  
386 ultimately reduce environmental harm and achieve maximal benefit, then a focus on food waste  
387 should be a key component of this strategy. Quantifying wasted food will help bring national  
388 attention to the issue, which can greatly advance campaigns to minimize and divert it.

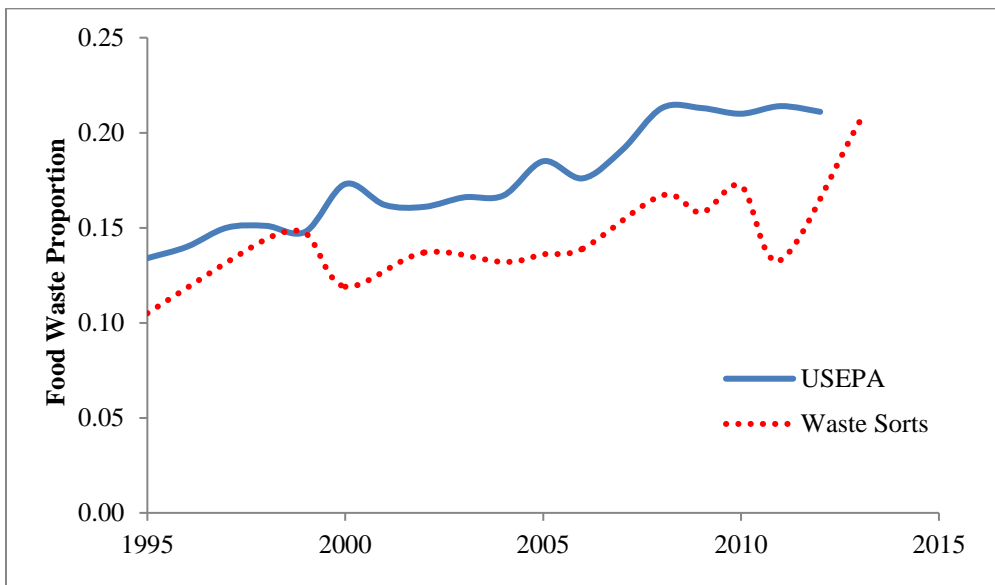
389  
390  
391  
392  
393  
394



395  
396 **Figure 1.** Sectors contributing to food loss and food waste. Sectors noted as ‘Included’ were  
397 captured in the meta-analysis.

398

399  
400  
401  
402  
403  
404  
405



406

407 **Figure 2.** Proportion food waste in disposed stream from USEPA and meta-analysis of waste  
408 characterization studies.

409 <sup>A</sup> There were several years where data were missing (1996, 1997, 2001, and 2003 were missing  
410 from the waste sort data and 2013 was missing the USEPA data). Data were linearly interpolated  
411 in Fig. 2.

412

413

		Proportion Food Waste	Per Capita Food Waste Disposal Rate <sup>A</sup>
Central Region (n=13)	Aggregate Mean Estimate	0.137	0.577
	95% Confidence Interval	0.120, 0.155	0.482, 0.671
West Region (n=17)	Aggregate Mean Estimate	0.153	0.722
	95% Confidence Interval	0.140, 0.167	0.663, 0.781
East Region (n=19)	Aggregate Mean Estimate	0.139	0.503
	95% Confidence Interval	0.117, 0.163	0.436, 0.570
<b>Overall Aggregate (n=49)</b>	Aggregate Mean Estimate	0.147	0.615
	95% Confidence Interval	0.137, 0.157	0.565, 0.664

414

415

416

417

418

419 **Table 1.** Aggregate mean effect sizes (proportions and per capita disposal rates) for samples  
 420 including all MSW.

421 <sup>A</sup> in pounds of food waste disposed per person per day.

422

423

424

425

426

427

428  
 429  
 430  
 431  
 432  
 433

Year <sup>A</sup>	Waste Sort Aggregate		USEPA	
	Proportion <sup>B</sup>	Per-capita Rate <sup>B, C</sup>	Proportion	Per-capita Rate <sup>C</sup>
1995	0.105 (+/- 0.023)	0.647 (+/- 0.046)	0.134	0.441
1996			0.140	0.439
1997			0.150	0.492
1998	0.144 (+/- 0.105)	0.592 (+/- 0.283)	0.151	0.493
1999	0.147 (+/- 0.031)	0.649 (+/- 0.283)	0.148	0.495
2000	0.119 +/- (0.022)	0.701 (+/- 0.043)	0.173	0.583
2001			0.162	0.505
2002	0.137 (+/- 0.051)	0.583 (+/- 0.165)	0.161	0.518
2003			0.166	0.524
2004	0.132 (+/- 0.027)	0.493 (+/- 0.105)	0.167	0.536
2005	0.136	0.558	0.185	0.596

	(+/- 0.058)	(+/- 0.257)		
2006	0.139 (+/- 0.080)	0.803 (+/- 0.203)	0.176	0.546
2007			0.191	0.595
2008	0.167 (+/- 0.028)	0.817 (+/- 0.089)	0.213	0.627
2009	0.158 (+/- 0.032)	0.580 (+/- 0.093)	0.213	0.615
2010	0.172 (+/- 0.025)	0.661 (+/- 0.084)	0.210	0.617
2011	0.133 (+/- 0.046)	0.531 (+/- 0.091)	0.214	0.622
2012			0.211	0.616
2013	0.206 (+/- 0.061)	0.526 (+/- 0.147)		
Mean	0.147 (+/- 0.010)	0.615 (+/- 0.049)	0.176	0.548

434

435 **Table 2.** Annual Waste Sort and USEPA Food Waste Estimates.

436 <sup>A</sup> There were several years where data were missing (1996, 1997, 2001, and 2003 were missing  
437 from the waste sort data and 2013 was missing the USEPA data).

438 <sup>B</sup> Aggregate mean as determined by meta-analysis; 95% confidence interval indicated.

439 <sup>C</sup> in pounds of food waste disposed per person per day.

440

441

442

443

444

445

446

447

448

449 **Supporting Information.**

450 Detailed description of methods, study limitations, and additional tables. This material is

451 available free of charge via the Internet at <http://pubs.acs.org>.

452 **Corresponding Author**

453 \* Corresponding author: Krista L. Thyberg

454 Department of Technology and Society

455 Stony Brook University

456 Stony Brook, NY 11794-3760

457 [KLThyberg@gmail.com](mailto:KLThyberg@gmail.com)

458 P: 631-632-8770

459 **Author Contributions**

460 The manuscript was written through contributions of all authors. All authors have given approval

461 to the final version of the manuscript. All contributed equally.

462 **Funding Sources**

463 Krista L. Thyberg was supported by the Town of Brookhaven under a Professional Services

464 Agreement; David J. Tonjes received some support from the Town similarly. Although the Town



465 of Brookhaven supported this research, it does not necessarily reflect the view of the Town and no  
466 official endorsement should be inferred.

#### 467 **ABBREVIATIONS**

468 CI confidence interval; LCA life cycle assessment; MSW municipal solid waste; PPD pounds of  
469 waste disposed per person per day; USEPA United States Environmental Protection Agency.

#### 470 **REFERENCES**

471 1. USEPA. Reducing Wasted Food and Packaging: A Guide for Food Services and  
472 Restaurants. USEPA: Washington, DC, USA, 2014; [http://www2.epa.gov/sites/production](http://www2.epa.gov/sites/production/files/201508/documents/reducing_wasted_food_pkg_tool.pdf)  
473 [/files/201508/documents/reducing\\_wasted\\_food\\_pkg\\_tool.pdf](http://www2.epa.gov/sites/production/files/201508/documents/reducing_wasted_food_pkg_tool.pdf).

474 2. Platt, B.; Goldstein, N.; Brown, S. State of Composting in the U.S.. Institute for Local Self  
475 Reliance, Washington, DC, USA, 2014; [http://ilsr.org/wp-content/uploads/2014/07/state-of-](http://ilsr.org/wp-content/uploads/2014/07/state-of-composting-in-us.pdf)  
476 [composting-in-us.pdf](http://ilsr.org/wp-content/uploads/2014/07/state-of-composting-in-us.pdf).

477 3. Kummu, M.; de Moel, H.; Porkka, M.; Siebert, S.; Varis, O.; Ward, P. J. Lost food, wasted  
478 resources: Global food supply chain losses and their impacts on freshwater, cropland, and fertiliser  
479 use. *Science of the Total Environment*. **2012**, 438, 477-489.

480 4. Kelleher, M.; Robins, J. What is Waste Food? *BioCycle*. **2013**, 54 (8), 36-39.

481 5. Brautigam, K. R.; Jorissen, J.; Priefer, C. The extent of food waste generation across EU-  
482 27: Different calculation methods and the reliability of their results. *Waste Management &*  
483 *Research*. **2014**, 32 (8), 683-694.

- 484 6. Parfitt, J.; Barthel, M.; Macnaughton, S. Food waste within food supply chains:  
485 Quantification and potential for change to 2050. *Philosophical Transactions of the Royal Society*  
486 *B-Biological Sciences*. **2010**, 365 (1554), 3065-3081.
- 487 7. Cuellar, A. D.; Webber, M. E. Wasted food, wasted energy: The embedded energy in food  
488 waste in the United States. *Environmental Science & Technology*. **2010**, 44 (16), 6464-6469.
- 489 8. Buzby, J. C.; Hyman, J. Total and per capita value of food loss in the United States. *Food*  
490 *Policy*. **2012**, 37 (5), 561-570.
- 491 9. Gjerris, M.; Gaiani, S. Household food waste in Nordic countries: Estimations and ethical  
492 implications. *Nordic Journal of Applied Ethics*. **2013**, 7 (1), 6-23.
- 493 10. Thyberg, K. L.; Tonjes, D. J. Drivers of Food Wastage and their Implications for Sustainable  
494 Policy Development. *Resources Conservation and Recycling*. **2015**, In press.
- 495 11. Thyberg, K. L.; Tonjes, D. J. A Management Framework for Municipal Solid Waste  
496 Systems and Its Application to Food Waste Prevention. *Systems*. **2015**, 3, 133-151.
- 497 12. Gustavsson, J.; Cederberg, C.; Sonesson, U.; Otterdijk, R.; Meybeck, A. *Global Food*  
498 *Losses and Food Waste*; Food and Agriculture Organization: Rome, Italy, **2011**;  
499 <http://www.fao.org/docrep/014/mb060e/mb060e.pdf>.
- 500 13. Oelofse, S. H. H.; Nahman, A. Estimating the magnitude of food waste generated in South  
501 Africa. *Waste Management & Research*. **2013**, 31 (1), 80-86.
- 502 14. USEPA Municipal Solid Waste; <http://www.epa.gov/osw/nonhaz/municipal/index.htm>.

- 503 15. Yepsen, R. Residential Food Waste Collection in the US- BioCycle Nationwide Survey.  
504 *BioCycle*. **2013**, 56 (1): 53.
- 505 16. Zhang, R. H.; El-Mashad, H. M.; Hartman, K.; Wang, F. Y.; Liu, G. Q.; Choate, C.;  
506 Gamble, P. Characterization of food waste as feedstock for anaerobic digestion. *Bioresource*  
507 *Technology*. **2007**, 98 (4), 929-935.
- 508 17. Saer, A.; Lansing, S.; Davitt, N. H.; Graves, R. E. Life cycle assessment of a food waste  
509 composting system: Environmental impact hotspots. *Journal of Cleaner Production*. **2013**, 52 (1),  
510 234-244.
- 511 18. USEPA *MSW in the United States: 2011 Facts and Figures- Full Report*; USEPA:  
512 Washington D.C., USA. **2013**; <http://www3.epa.gov/epawaste/nonhaz/municipal/msw99.htm>.
- 513 19. Tonjes, D. J.; Greene, K. L. A review of national municipal solid waste generation  
514 assessments in the USA. *Waste Management and Research*. **2012**, 30 (8), 758-771.
- 515 20. Nakamura, S.; Kondo, Y. *Waste Input-Output Analysis: Concepts and Application to*  
516 *Industrial Ecology Vol. 26*; Springer Publishing: New York, NY, USA, 2009.
- 517 21. Bailie, R. C.; Everett, J. W.; Liptak, B. G.; Liu, D. H. F.; Rugg, F. M.; Switsenbaum, M.  
518 S. Solid Waste. In *Environmental Engineer's Handbook*; LLC, C. P., Ed; CRC Press LLC: Boca  
519 Raton 1999.
- 520 22. Lebersorger, S.; Schneider, F. Discussion on the methodology for determining food waste  
521 in household waste composition studies. *Waste Management*. **2011**, 31 (9-10), 1924-1933.

- 522 23. Staley, B. F.; Barlaz, M. A. Composition of Municipal Solid Waste in the United States  
523 and Implications for Carbon Sequestration and Methane Yield. *Journal of Environmental*  
524 *Engineering-ASCE*. **2009**, *135* (10), 901-909.
- 525 24. ASTM. Standard D5231(08)- Standard Test Method for Determination of the  
526 Composition of Unprocessed Municipal Solid Waste. ASTM International: West Conshohocken,  
527 PA, USA, 2008.
- 528 25. Abramowitz, H.; Sun, Y. *Municipal Solid Waste Characterization Study for Indiana*;  
529 Purdue University: West Lafayette, IN, 2012.
- 530 26. R.W. Beck *Georgia Statewide Waste Characterization Study*; Georgia Department of  
531 Community Affairs, Waycross, GA, 2005.
- 532 27. WRAP *Synthesis of Food Waste Compositional Data 2010*; WRAP (Waste Resources and  
533 Action Programme), Banbury, U.K., 2011.
- 534 28. Koricheva, J.; Gurevitch, J.; Mengersen, K. *Handbook of Meta-Analysis in Ecology and*  
535 *Evolution*; Princeton University Press: NJ, USA, 2013.
- 536 29. Lipsey, M. W.; Wilson, D. B. *Practical Meta-Analysis Vol. 49*; SAGE Publications:  
537 Thousand Oaks, CA, USA, 2001.
- 538 30. USEPA List of MSW Characterization Studies.  
539 [http://www.epa.gov/epawaste/conserves/tools/recmeas/msw\\_st\\_rpt.htm](http://www.epa.gov/epawaste/conserves/tools/recmeas/msw_st_rpt.htm).
- 540 31. Minnesota Pollution Control Agency- Other MSW Composition Studies;  
541 <http://www.pca.state.mn.us/index.php/waste/waste-and-cleanup/waste-management/solid->

542 waste/integrated-solid-waste-management/minnesota-msw-composition-study/other-msw-  
543 composition-studies.html?nav=0.

544 32. BSR, *Analysis of U.S. Food Waste Among Food Manufacturers, Retailers, and*  
545 *Wholesalers*; Food Waste Reduction Alliance: Washington, D.C., USA, 2013.

546 33. Trikalinos, T. A.; Trow, P.; Schmid, C. *Simulation-Based Comparison of Methods for*  
547 *Meta-Analysis of Proportions and Rates*; US Department of Health and Human Services: New  
548 York, NY, USA, 2013.

549 34. Hedges, L. V.; Olkin, I. *Statistical Methods for Meta-Analysis*; Academic Press: FL, USA,  
550 1985.

551 35. Viechtbauer, W. Conducting Meta-Analyses in R with the Metafor Package. *Journal of*  
552 *Statistical Software*. **2010**, *36* (3), 1-48.

553 36. *Open Mee Software* Website; [http://www.cebm.brown.edu/open\\_mee](http://www.cebm.brown.edu/open_mee).

554 37. Tonjes, D.J.; Swanson, L. How do we measure them? Lessons from Long Island on  
555 Computing Recycling Rates. *Journal of Urban Technology*. **2000**, *7* (3), 63-79.

556 38. Greene, K.L.; Aphale, O.; Ntshalintshali, G.; Nayak, P.; Swanson, L.; Tonjes, D.J.  
557 Recycling on Long Island 2009. Waste Reduction and Management Institute, Stony Brook  
558 University Stony Brook, NY, USA, 2010;  
559 [http://www.stonybrook.edu/est/research/FINAL%20Recycling%20Report%20\(4-16-](http://www.stonybrook.edu/est/research/FINAL%20Recycling%20Report%20(4-16-11)%20PDF.pdf)  
560 [11\)%20PDF.pdf](http://www.stonybrook.edu/est/research/FINAL%20Recycling%20Report%20(4-16-11)%20PDF.pdf).

561 39. Quested, T.; Johnson, H. *Household Food and Drink Waste in the UK*; WRAP: Banbury,  
562 UK, 2009.

- 563 40. Kosa, K. M.; Cates, S. C.; Karns, S.; Godwin, S. L.; Chambers, D. Consumer knowledge  
564 and use of open dates: Results of a web-based survey. *Journal of Food Protection*. **2007**, *70* (5),  
565 1213-1219.
- 566 41. Pearson, D.; Minehan, M.; Wakefield-Rann, R. Food Waste in Australian Households:  
567 Why does it occur? *The Australasian-Pacific Journal of Regional Food Studies*. **2013**, *3*  
568 (November), 118-132.
- 569 42. Washington Department of Ecology. 2009 Washington Statewide Waste Characterization  
570 Study. Washington Department of Ecology: Seattle, WA, USA, 2010;  
571 <https://fortress.wa.gov/ecy/publications/documents/1007023.pdf>
- 572 43. Jorissen, J.; Priefer, C.; Brautigam, K.R. Food Waste Generation at Household Level:  
573 Results of a Survey among Employees of Two European Research Centers in Italy and Germany.  
574 *Sustainability*. **2015**, *7*, 2695-2715.
- 575 44. R.W. Beck *Minnesota MSW Composition Study 1999-2000*, Minnesota Pollution Control  
576 Agency: MN,2000.
- 577 45. Iacovidou, E.; Ohandja, D. G.; Gronow, J.; Voulvoulis, N. The household use of food waste  
578 disposal units as a waste management option: A Review. *Critical Reviews in Environmental*  
579 *Science and Technology*. **2012**, *42* (14), 1485-1508.
- 580 46. Dahlen, L.; Lagerkvist, A. Methods for household waste composition studies *Waste*  
581 *Management*. **2008**, *28* (7), 1100-1112.

582 47. Greene, K. L.; Tonjes, D.J. Quantitative assessments of municipal waste management  
583 systems: Using different indicators to compare and rank programs in New York State. *Waste*  
584 *Management*. **2013**, *34* (4), 825-836.

585

586

587

588

589

590

591

592 Table of Contents Graphic



593

594

595

596