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

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

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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.^{1 2} 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.³ 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 America⁴,
47 Europe⁵, and the rest of the world⁶, and available data tend to be incomplete and outdated.⁷ Few
48 peer-reviewed or major studies estimating quantities of food waste have been conducted,⁸ and
49 those that have been done utilize different methodologies,^{9 10} making it difficult to compare
50 findings across studies or aggregate findings. In particular, definitional issues¹¹, 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.⁶ These data gaps have led to
53 recent calls for further research on wasted and lost food.^{5 12 13}

54 Food waste disposal data are essential for the development of effective, well-planned food waste
55 management policies¹¹, 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)¹⁴ 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.¹⁰ 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.¹⁵

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.,^{16 17}). 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.¹⁸
80 However, materials flow concepts are inappropriate for food waste.¹⁹ 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.²⁰ So, data on food sales
83 bear little relation to the generation and disposal of food waste.²¹ 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.'¹⁸ 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,²² in part
102 because most follow the widely-cited ASTM method for waste characterization (ASTM D 5231-
103 08).^{23 24} 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.²⁴ 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.^{25 26} 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)²⁷ 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 Barlaz²³ 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.²⁷ 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.^{28 29}

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.^{30 31}
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.³² 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.¹⁸ 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).³³ 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.²⁹ 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.²⁸ 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.³⁴ 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.³⁵
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.³⁶

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.²⁰ 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.¹⁴ 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.³⁶

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.³⁷ 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,³⁹ confusion over food
273 labels such as “sell by” dates,⁴⁰ misconceptions regarding food safety and desirability⁴¹, or changes
274 in household shopping practices, particularly the size of the grocery store and the frequency of
275 shopping.⁴² 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.⁴² Since MSW disposal tonnages from
295 residential versus commercial/institutional sectors are thought to be between a 60:40²¹ and a 50:50
296 proportion,⁴³ 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.^{6 22} 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 wastage¹⁰. Iacovidou et al.⁴⁵ 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 standard²⁴, 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.²⁴ 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.⁴⁶

343 Agreement does not always exist regarding the definition of MSW and specific waste
344 categories.^{47 10} 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.¹⁹ 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*

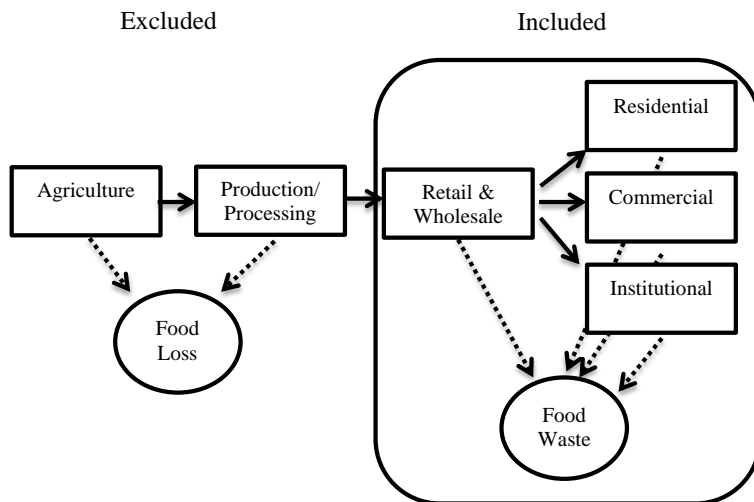
360 Analyses showed that a considerable amount of food waste is disposed on a regular basis
361 throughout the U.S. These data are important because they indicate how much food waste can
362 potentially be reduced or diverted from disposal. More research is necessary to evaluate the
363 impacts and feasibility 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.¹⁰ 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.

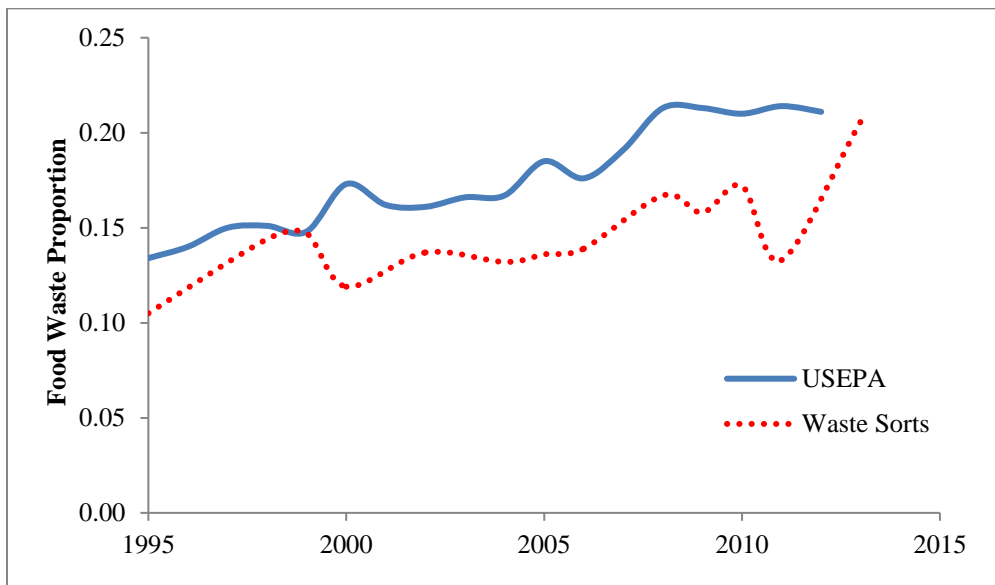
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396 **Figure 1.** Sectors contributing to food loss and food waste. Sectors noted as ‘Included’ were
397 captured in the meta-analysis.

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

409 ^A 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.

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		Proportion Food Waste	Per Capita Food Waste Disposal Rate ^A
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
Overall Aggregate (n=49)	Aggregate Mean Estimate	0.147	0.615
	95% Confidence Interval	0.137, 0.157	0.565, 0.664

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

420 including all MSW.

421 ^A in pounds of food waste disposed per person per day.

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Year ^A	Waste Sort Aggregate		USEPA	
	Proportion ^B	Per-capita Rate ^{B, C}	Proportion	Per-capita Rate ^C
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

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

436 ^A 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 ^B Aggregate mean as determined by meta-analysis; 95% confidence interval indicated.

439 ^C in pounds of food waste disposed per person per day.

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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>.

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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.

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592 Table of Contents Graphic



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