

Characterisation and energy assessment of fats, oils and greases (FOG)

waste at catchment level

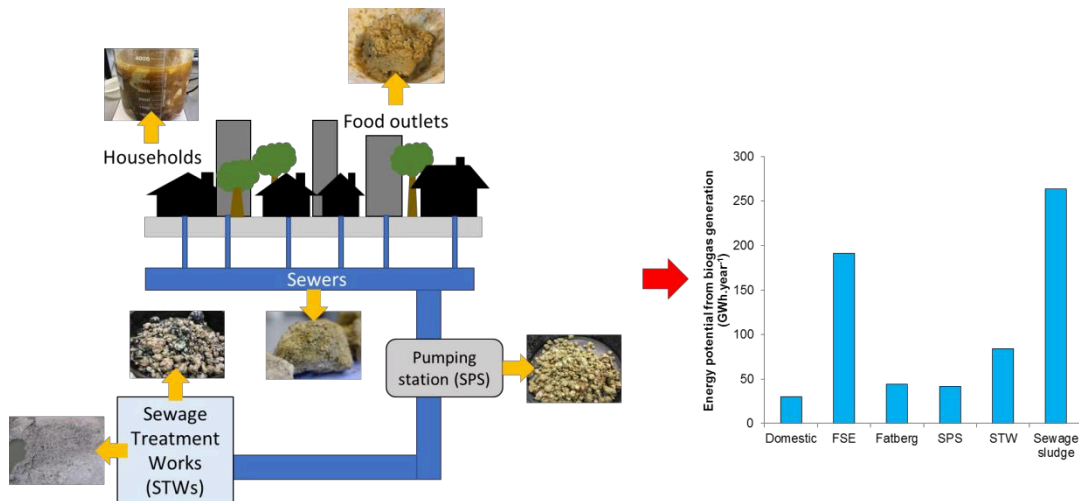
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Graphical abstract



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Highlights

- 240 TWh.year⁻¹ could be generated from food outlets' FOG in the London area.
- FOG collected further away from source were richer in water and other contaminants.
- FOG demonstrated high biomethane potentials.
- Lipids accounted for most of the organic in FOG.
- A shift from unsaturated to saturated fats was noticed from source to end point.

Abstract

Several of the waste materials that have a negative impact on the sewer system are produced by fats, oils and greases (FOG) discharged from commercial and domestic kitchens. These materials accumulate at different points in the sewer catchment, from kitchens to pumping stations, sewers and sewage treatment works (STWs), and comprise oily wastewater, floating agglomerates and hard deposits. Despite their detrimental effects, these waste materials have a high calorific content and are an ideal feedstock for energy recovery processes. So far, the overall volume of each type of waste and their physical-chemical properties in relation to their collection point are unknown. However, from a management point of view, knowledge on each feedstock quality and volumes is necessary to develop an economic viable solution for their collection and for energy recovery purposes. In this study, FOG wastes collected from households, food service establishments (FSEs), sewage pumping stations, sewers and STWs, were compared to sewage sludge in terms of organic contents and energy potentials. As expected, FOG recovered at source (households and FSEs) were 'cleaner' and had a higher energy content. Once mixed with wastewater the materials changed in composition and lost some of their energy per unit mass. Our results showed that around 94,730 tonnes \cdot year $^{-1}$ of these materials could be recovered from the Thames Water Utilities' catchment, one of the most populated in the UK. These materials could produce up to 222 GWh \cdot year $^{-1}$ as biogas, close to double of what is produced with sewage sludge digestion and around 19% of the company energy needs. Finally, even with over six million households in the catchment, the results showed that most of the FOG waste was produced by FSEs (over 48,000 premises) with an estimated average of 79,810 tonnes \cdot year $^{-1}$ compared to 14,920 tonnes \cdot year $^{-1}$ from private households. This is an important outcome as recovery from

FSEs will be cheaper and easier if the company decides to implement a collection system for energy recovery.

Keywords: Anaerobic digestion; energy from waste; fatberg; sewer deposits; sewage sludge

Abbreviations

DS	Dry solids
FSE	Food service establishments
GTW	Grease trap waste
GRU	Grease removal unit
FHRS	Food hygiene rating scheme
FOG	Fats, oils and greases
HHV	Higher heating value
LCFA	Long-chain fatty acids
LHV	Lower heating value
SPS	Sewage pumping station
STW	Sewage treatment works
TFA	Total fatty acid
UCO	Used cooking oil
VS	Volatile solids

56 **1 Introduction**

57

58 Fats, oils and greases (FOG) discharged from households and food service establishments
59 (FSEs) have been identified as one of the major contributors to blockages in sewerage
60 networks and the formation of sewers' fatbergs (Engelhaupt, 2017). Developing effective
61 FOG management strategies has therefore become a priority for many water utilities,
62 including Thames Water, the largest water utility in the UK, which comprises more than
63 six million households in its catchment. These materials accumulate at different points in
64 a sewerage catchment, from kitchens drains to pumping stations, sewers and sewage
65 treatment works (STWs), and they comprise oily wastewater, floating agglomerates and
66 hard deposits. Despite their detrimental effects on the sewer network, FOG-rich wastes
67 have a high calorific content and can be an ideal feedstock for energy recovery processes.
68 An assessment of each material's quality and volume is necessary to evaluate the
69 economic viability of collecting and using FOG waste for energy recovery. Thus far, most
70 of the research has focused on used cooking oil (UCO) harvested from FSEs for biodiesel
71 production (Wallace et al., 2017) or grease trap waste (GTW) for the production of biogas
72 in anaerobic digestion (Long et al., 2012). The potential of GTW FOG waste co-digestion
73 with sewage sludge has been reported by many authors, as summarised by Long et al.
74 (2012). Davidsson et al. (2008) showed that when sewage sludge and GTW (10-30% of
75 total volatile solids load) were co-digested under mesophilic conditions, methane yields
76 increased up to 27%. Similarly, Kabouris et al. (2009) showed that up to 48% of GTW
77 (of the total volatile solids load) could be digested with a mixture of primary sludge and
78 thickened waste activated sludge with no inhibitory effects on the process, with a three-
79 fold increase in methane yields of three. However, little attention has been given to other

80 FOG wastes available in the sewerage catchment, such as fatbergs from sewers, or
81 floating deposits from pumping stations or STWs. The use of these energy-rich materials
82 as co-digestion substrates could offer water utilities a double economic advantage by
83 disposing of unwanted waste and increasing their renewable energy production.
84 Understanding the processing potential of these different FOG-rich materials could help
85 define and drive a more sustainable FOG management at catchment level. For instance,
86 the overall volume of each type of waste and their physical-chemical properties, in
87 relation to their collection point, are still unclear. Furthermore, no attempt has been made
88 to study FOG collected from households, which some authors believe to be one of the
89 major contributors towards FOG discharges in sewerage networks (Foden et al., 2017).
90 Wallace et al. (2017) suggested that grease removal units (GRUs) produce a waste similar
91 to UCOs and with fewer impurities than GTW, but no work to date has intended to
92 characterise this waste. Lastly, most of the research conducted on FOG has focused on
93 explaining the mechanisms of formation of FOG deposits (Keener et al., 2008) and very
94 few have reported their potential for energy recovery. This paper aims to clarify the
95 variation among these substrates in regards to their physicochemical properties and
96 biomethane potential as well as to provide an assessment of their volumes and their
97 energy potential within Thames Water Utilities' catchment.

98 **2 Methods**

99 **2.1 Inoculum and substrates**

100 Digested sludge, used as inoculum in batch tests, was obtained from a full-scale anaerobic
101 digester treating municipal sewage sludge. Six FOG wastes were used in this study: (1)
102 Domestic FOG (Domestic) collected from 30 households (located in different catchment
103 areas). The samples were blended, heated to 35°C and sieved to remove any large food
104 particulates. (2) FOG sample from a FSE grease removal unit (GRU). (3) FOG deposit
105 (Fatberg) was manually excavated during the clean-up of a sewer in London (2-3 kg
106 sample). Fat balls samples were collected from two locations: (4) a sewage pumping
107 station (SPS) and at (5) the inlet of a STW (SPS and STW respectively). The FOG deposit
108 and fat balls samples were grinded to produce finer and more homogeneous samples. (6)
109 Floating scum (Floating scum) accumulating at the inlet of a STW was collected and
110 further analysed. Sewage sludge (Sewage sludge), pre-treated through a thermal
111 hydrolysis process, was used as a comparison material.

112 **2.2 Analytical methods**

113 The physical appearance (i.e. texture and colour) of the different FOG wastes was
114 qualitatively assessed. Dry solids (DS) and volatile solids (VS) were determined
115 according to standard methods (APHA, 2005).

116 A chemical characterisation of the main organic fractions (e.g. lipids, carbohydrates,
117 proteins and fibres) was performed on each material. Fibres were measured as the organic
118 matter remaining after samples were de-fatted and digested successively with acid and
119 alkali under controlled conditions (Horwitz, 2003). Proteins were determined either with

120 the Dumas method using Leco FP528 or as total Kjeldahl nitrogen respectively for solid
121 and semi-solid samples respectively. Lipids were measured using a modified Wiebul acid
122 hydrolysis method (Sciantec Analytical, 2018a). Carbohydrates were estimated as the
123 remaining fraction.

124 Methylated fatty acids profiles were obtained by gas-liquid chromatography using a free
125 fatty acid phase column of dimensions 25m x 0.20mm ID and detection by flame
126 ionisation detector. Fats and oils were trans-esterified to fatty acid methyl esters by
127 heating under reflux for two hours with a mixture of methanol and sulfuric acid in toluene.
128 The resulting methyl esters were extracted using a small volume of n-hexane. The n-
129 hexane solution was dried using anhydrous sodium sulphate and then transferred to a
130 chromatography vial (Sciantec Analytical, 2018b).

131 Theoretical biogas production was calculated from the organic components of the
132 materials (proteins, carbohydrates and lipids) using Buswell's equation (Buswell and
133 Neave, 1930).

134 Calorific values were determined experimentally in terms of the higher heating value
135 (HHV) using a calorimeter (Parr model 6100) equipped with a 1108CL oxygen bomb;
136 solid samples were pelletised whereas semi-solid samples were freeze dried (Sciantec
137 Analytical, 2018c). It is worth noting that the hydrogen content was not measured in this
138 study as such the lower heating values (LHV) were estimated from the measurement of
139 calorific values by subtracting the heat of vaporisation of water in the products as follows:

$$LHV_d = HHV_d \times (1 - M) - H_v \times M \quad (2-1)$$

140 Where M is the moisture content, H_V is the latent heat of vaporisation of water estimated
 141 at 2.447 MJ.kg⁻¹ at 25°C and HHV_d is the gross heating value in MJ.kg⁻¹ on dry basis
 142 determined as follows:

$$HHV_d = \frac{HHV}{1 - M} \quad (2-2)$$

Where HHV is the measured HHV on wet basis.

143 2.3 Batch tests

144 Triplicate batch testing was used to investigate the biomethane content of each material
 145 using an AMPTS II system (Bioprocess Control). These assays were performed at
 146 mesophilic temperatures (37°C) using an inoculum to substrate ratio of 2 g VS_{inoculum}.g
 147 VS_{substrate}. DS and VS were determined before and after the digestion period. The
 148 experiment was terminated when the cumulative biomethane production reached a
 149 plateau phase (at 60 days). The biomethane production was expressed as biomethane
 150 yield, mL CH₄.gVS_{added}⁻¹, and specific biomethane yield, mL CH₄.g VS_{destroyed}⁻¹ and
 151 adjusted to standard temperature and pressure (STP) as follows:

$$V_{STP} = \left(1 - \frac{P_{vap}}{P_{gas}}\right) \times \frac{P_{gas}}{P_{STP}} \times \frac{T_{STP}}{T_{gas}} \times V_{gas} \quad (2-3)$$

152 Where V_{STP} is the volume adjusted to STP, P_{STP} is the standard pressure (101.3 kPa), T_{gas}
 153 is the temperature of the measured gas (311 K), T_{STP} is the standard temperature (273 K)
 154 and V_{gas} is the measured volume of gas. P_{gas} was calculated as the sum of the partial
 155 pressures of methane and carbon dioxide. P_{CO_2} was neglected in the case of the batch
 156 testing as carbon dioxide was removed through the stripping solution. P_{vap} is the water
 157 vapour pressure calculated as follows:

$$P_{vap} = 10^{8.1962 - \frac{1,730.63}{T_{gas} - 39.724}} \quad (2-4)$$

158 **2.4 Volumes and energy appraisal**

159 Quantities of FOG and sewage sludge were estimated for the whole catchment area.
160 Results from the characterisation and batch testing of FOG were further used for the
161 energetic assessment. The calorific value of methane was assumed at 36 MJ.m⁻³ and the
162 efficiency of combined heat and power engines at 30% (Goss et al., 2017).

163 **2.4.1 FOG at source**

164 ArcGIS was used as a support tool for this work to manipulate data with a geographical
165 component. Domestic and commercial properties were respectively extracted from
166 AddressBase® Premium (Ordnance Survey, 2017) and the Food Hygiene Rating Scheme
167 (FHRS) (Food Standards Agency, 2017). A total of 6,543,749 and 68,903 records were
168 obtained for households and FSEs in Thames Water Utilities' catchment. A field survey
169 showed that not all FSEs registered under the FHRS were likely to produce any FOG
170 (Cermakova et al., 2018). For each category, a correction factor was applied reflecting
171 the number of establishments likely to produce FOG over the total number of premises
172 (Table 1). The correction factor was calculated as the number of premises likely to
173 produce FOG over the total number of establishments for each category. FOG from
174 industrial sources (e.g. food and dairy processing plants) were not included in this
175 assessment as their discharges were assumed to be monitored and controlled under the
176 trade effluent consents by the water utility.

177 Volumes collectable from domestic properties were evaluated at 2.3 kg.household⁻¹ per
178 year (Collin et al., 2019b). The data for the estimation of FOG generated from FSEs was
179 calculated based on Doherty (2009) and is reported in Table 1.

180 **2.4.2 FOG in wastewater networks**

181 FOG concentrations were measured monthly at 20 STWs in crude sewage over a period
182 of four years. Briefly, samples were filtered a WhatmanTM GF/C grade filter paper. The
183 filter paper was immersed in boiling hexane using a Gerhardt SOXTHERM® (40 to
184 60°C). Oil and grease were then determined by weight difference and reported in mg.L⁻¹.
185 It should be noted that values below the limit of detection of 8.2 mg.L⁻¹ were replaced
186 with this value. Oil and grease were measured on average at 59.0 mg.L⁻¹ at these STWs
187 (Collin et al., 2019a); this average value was used for the other sites. Quantities of FOG
188 were estimated based on dry weather flow, which is the average daily flow received at
189 STWs, and subtracted from undigested lipids originating from human faeces estimated at
190 4.1 g.capita⁻¹.day⁻¹ with a range of 1.9 to 6.4 g.capita⁻¹.day⁻¹ (Rose et al., 2015). Volumes
191 collected in SPSs were assumed equal to STWs. Sewer deposits were estimated
192 subtracting volumes at STWs from FOG at source (i.e. domestic and FSE).

193 **2.5 Sewage sludge**

194 Data on sewage sludge generation from anaerobic digestion was obtained from Thames
195 Water Utilities. Yearly averages of feeding rates in tonnes dry solids per day were used
196 for each anaerobic digestion sites. The average VS content of sewage sludge was assumed
197 at 75%.

198 **3 Results and discussion**

199 **3.1 Quantification and physicochemical characterisation**

200 The six types of FOG waste collected in the catchment had very different
201 physicochemical characteristics. FOG from households and GRUs, semi-solid at room
202 temperature, had a brown-yellowish colour and looked very similar to UCOs (Figure 1a
203 and 1b, supplementary material). The sewer deposit sample was solid and harder than the
204 other substrates and contained many contaminants such as wipes and plastic waste. Fat
205 balls from STW were darker than those collected from SPS, but both samples had a softer
206 texture than that of the sewer deposit and contained less contaminants. Finally, floating
207 scum had a yellow-greyish colour, with a less structured form (Figure 2a-d,
208 supplementary material). Domestic and GRU FOG presented the lowest moisture content
209 of all the materials, with values around 3% and 15% respectively. FOG collected in
210 sewers and fat balls from SPS and STW, had on average lower moisture contents than
211 floating scum 30%, 46%, 47% and 91% respectively (Table 2). As expected, moisture
212 content of FOG wastes increased further away from the source point. Similar observations
213 were reported by Williams et al. (2012), who reported values of 45%, 52% and 70% for
214 pumping station, sewer deposit and STW respectively. Predictably, the lipid content was
215 inversely proportional to the water content, ranging from 85 to 99% DS for STW, SPS,
216 fatberg, GRU and domestic (Table 2). Surprisingly, the floating scum, generally believed
217 to be FOG, showed a relatively lower lipid content, and had organic concentrations
218 comparable to that of sewage sludge. As a comparison, lipids in sewage sludge were
219 measured at around 11% DS.

220 When examining the availability of FOG wastes, approximately 79,810 tonnes.year⁻¹
221 could be collectable from FSEs, whereas households would only produce around 14,920
222 tonnes.year⁻¹ (Figure 1a). The FOG production rate, calculated from households and
223 FSEs, would be at around 6.4 kg.person⁻¹.year⁻¹. This result is comparable to data
224 available from previous studies with values ranging from 4 up to 10 kg.person⁻¹.year⁻¹
225 (Canakci, 2007).

226 **3.2 Biogas potential**

227 In order to comprehensively assess the energy recovery potential of all the FOG materials,
228 batch digestion system were used to calculated biomethane yields and biomethane
229 specific yields. All FOG samples produced more biogas than sewage sludge alone (Table
230 3). These values were comparable to methane yields for lipid-rich waste reported by other
231 authors, ranging from 606 to 928 mL CH₄.g VS_{added}⁻¹ (Davidsson et al., 2008; Luostarinen
232 et al., 2009; Yalcinkaya and Malina Jr., 2015). Sewer deposit, STW fat balls and floating
233 scum displayed a greater standard deviation than the other wastes tested. This was
234 probably due to the preparation of these highly contaminated materials as producing a
235 homogeneous sample was very challenging (Figures 1 and 2, supplementary material).
236 The much higher biomethane yields (e.g. biomethane per gram of VS destroyed) and
237 therefore bioconversion efficiencies were obtained when digesting FOG compared to
238 sewage sludge (500±31 STP mL CH₄.g VS_{destroyed}⁻¹) or floating scum (367±105 STP mL
239 CH₄.g VS_{destroyed}⁻¹), with yields ranging from 695±98 to 908±145 STP mL CH₄.g
240 VS_{destroyed}⁻¹. The floating scum collected at STW produced less biogas than both FOG and
241 sewage sludge, suggesting a close match to the latter and probably a high content in fibres.

242 Analyses on the lipid fraction showed that FOG triglycerides contained long-chain fatty
243 acids (LCFAs) of 14 or more carbons. LCFAs are associated with inhibition of
244 methanogenesis and toxicity to the anaerobic digestion process (Girault et al., 2012;
245 Luostarinen et al., 2009; Noutsopoulos et al., 2013). This inhibition was found to be
246 dependent on concentrations and types of LCFAs (Dasa et al., 2016). Oleic acid (C18:1)
247 was reported as the most predominant LCFA found in GTW with concentrations ranging
248 from 34 to 48% of total fatty acids (TFA) (Canakci, 2007; Suto et al., 2006). Similar
249 observations were made with domestic and GRU FOG where oleic acids were measured
250 at 47 ± 2 and $47\pm 10\%$ of TFA. Vegetable oils have higher content in mono- and
251 polyunsaturated fatty acids compared to animal fats, and are the most commonly used
252 cooking fat in FSEs in the UK (on average about 14 L every 100 meals) (Envirowise,
253 2008). Accordingly, FOG collected at source shared a relatively comparable fatty acid
254 profile to that of vegetable oils. Despite variations between samples, several authors have
255 reported higher levels of saturation in sewer deposits ranging from 41 to 86% of TFA,
256 with palmitic acid (C16:0) being the most common saturated fatty acid (He et al., 2011;
257 Keener et al., 2008; Nieuwenhuis et al., 2018). Fat balls from SPS presented a slightly
258 lower degree of saturation than sewer deposits, measured at $30\pm 1\%$ of TFA. As a
259 comparison STW fat balls and sewage sludge showed a relatively similar fatty acid
260 profile, with a degree of saturation respectively at 43 ± 1 and $46\pm 1\%$ of TFA. This shift
261 from unsaturated to saturated fatty acids is still unclear (Figure 2). Some authors have
262 suggested that micro-organisms might be involved in that transformation (Williams et al.,
263 2012) while others have hinted at the contribution of soap products (He et al., 2017).

264 Fatty acids composition is very important for anaerobic digestion as the different fatty
265 acids are degraded in different way by the microbial communities in the digester and

266 hence have a different impact on the final biogas production. In addition, unsaturated fatty
267 acids must be first converted in saturated fatty acids before being degraded via the β -
268 oxidation pathway (Salama et al., 2019). For example, oleic acids, found predominantly
269 in FOG collected at source, has been reported by several authors to have greater toxic
270 effects on the anaerobic digestion process than saturated fatty acids, such as palmitic acid
271 (Alves et al., 2009; Dasa et al., 2016; Shin et al., 2003). Davidsson et al. (2008) reported
272 slower digestion time of stearic acid compared to oleic acid.

273 These results confirm that FOG are desirable substrates for anaerobic digestion even
274 when collected from the networks. However, to avoid detrimental impacts, further care is
275 needed to optimise the feeding regime of FOG materials, not only in terms of quantity
276 but also in terms of source and composition.

277 **3.3 Energy recovery potential**

278 Higher organic matter and lipids concentration translated into higher energy content,
279 which was measured as the calorific content of the different materials using a bomb
280 calorimeter (Table 4**Error! Reference source not found.**). FOG collected at source,
281 domestic and GRU, had high calorific values of 36 ± 4 and 33 ± 4 MJ.kg⁻¹ respectively on
282 dry basis. Both values were in the range of those previously reported for GTWs (Al-
283 Shudeifat and Donaldson, 2010) and UCOs at 35 and 39 MJ.kg⁻¹ respectively (Khalisanni
284 et al., 2008). The fatberg sample was measured at 27 MJ.kg⁻¹ DS while SPS and STW
285 had lower values measured at around 25 MJ.kg⁻¹ on dry basis. Floating scum (19 MJ.kg⁻¹
286 DS) and sewage sludge (18 MJ.kg⁻¹ DS) showed similar values, indicating a reduction
287 in calorific value as the location extended away from the source point. Lipids and water
288 concentration showed a linear inverse correlation for all the samples analysed in this study

289 and those reported in literature (Figure 3). Interestingly, oil concentrations in FOG
290 deposits reported by Williams, et al. (2012) were much lower than those measured by this
291 study and Keener et al. (2008) in the US. This suggests that waste collected from the
292 network is likely to be highly variable in terms of quality and contamination as it gets in
293 contact with sewage and other waste materials in the sewers. Critically, the increased
294 moisture content reduced the lipids fraction by mass indicating that not only does FOG
295 collected from the network require more effort but this negative is compounded through
296 a reduction in its resultant energy value. The total energy available (i.e. calorific value
297 measurement) plotted against the energy available from the conversion of biogas showed
298 conversion yields ranging from 20 to 42% for FOG and averaging 30% for sewage sludge
299 (Figure 4). Not all the energy contained in FOG is convertible to biomethane through
300 anaerobic digestion. Particularly, FOG collected at source demonstrated lower energy
301 conversion yields than other wastes collected further downstream. Facilitating the
302 hydrolysis step, which is the rate limiting step, through pre-treatments (e.g. enzymatic)
303 could help improving the efficiency of the digestion of FOG.

304 This initial characterisation indicated that materials collected at source with high lipid
305 content, such as domestic and GRU, could be easily used as biodiesel feedstock. Whereas
306 other wastes, such as SPS, sewer and STW, with higher water content, would require an
307 initial dewatering step. The water in the feedstock reacts with the catalyst during the
308 transesterification process leading to a more laborious and expensive process, (Sanford et
309 al., 2009). These materials could be better suited for energy recovery through anaerobic
310 digestion. Biogas derived energy from sludge is currently generating 264 GWh.year⁻¹.
311 Biogas from sewer and STW could add an additional 128 GWh.year⁻¹. Whereas FOG
312 from households and FSEs, estimated at 30 and 191 GWh.year⁻¹ of biogas (Table 5),

313 could be converted into approximately 59,340 m³ of biodiesel (at 80% conversion and
314 density of 0.9).

315 One of the main obstacles to energy generation from some of the FOG wastes studied is
316 collection. Cleaning of sewers and SPSs is either planned or reactive and involves
317 combined vacuum and jetting machines. FOG collected from these tankers would need to
318 be further processed as these systems tend to break them down and mix them with sewage.
319 While equipment seems to be commercially available for FOG collection in SPSs, their
320 efficiency still needs to be demonstrated. In contrast, preliminary treatments are
321 commonly found at STWs to remove FOG from municipal wastewater; the use of these
322 wastes as co-substrates for anaerobic digestion has been reported by several authors
323 (Girault et al., 2012; Harris et al., 2017; Long et al., 2012; Luostarinen et al., 2009;
324 Silvestre et al., 2011). Yet, experience within the water utility with such systems has
325 discouraged further investment. Another alternative at STWs would be to retrofit primary
326 sedimentation tanks with flotation technologies in order to increase FOG removal
327 alongside sewage sludge. Further research is needed to assess the performance of such
328 technologies and the economic viability of collecting FOG from FSEs as a robust logistic
329 management would be require to tailor a sustainable disposal route.

330

331 **4 Conclusion**

332 The characterisation of selected FOG wastes focused on three main aspects:
333 physicochemical composition, organic macromolecules concentrations and LCFA
334 profiles. The main difference was found in the water content: FOG collected from
335 networks (SPS and sewers) and STW had higher moisture content than FOG collected at
336 source (domestic and FSEs). Predictably, FOG were found to be desirable substrate for
337 anaerobic co-digestion as their high organic matter and lipids content resulted in high
338 methane potential (820-1,040 mL CH₄.g VS⁻¹).

339 The assessment of volumes of FOG collectable indicated FSEs to be the main source with
340 around 67,956 tonnes.year⁻¹ (on dry basis) of material relatively easy to collect and
341 potentially available for energy recovery (191 GWh.year⁻¹). The anaerobic digestion of
342 FOG wastes, collected either at source or in the networks, could be almost equivalent to
343 the current energy generated from sewage sludge at Thames Water Utilities' sites. In other
344 words, anaerobic co-digestion could help generating around a third of Thames Water's
345 overall electricity consumption. Although FOG from wastewater networks or STWs still
346 have high values for energy recovery, the practicality and feasibility of collecting these
347 wastes could counterbalance the benefits from biogas generation. This further suggested
348 that collection of FOG before it reaches the sewers is highly desirable. Still, volumes and
349 methods of collection should be analysed in order to assess the economic feasibility of
350 developing sustainable schemes.

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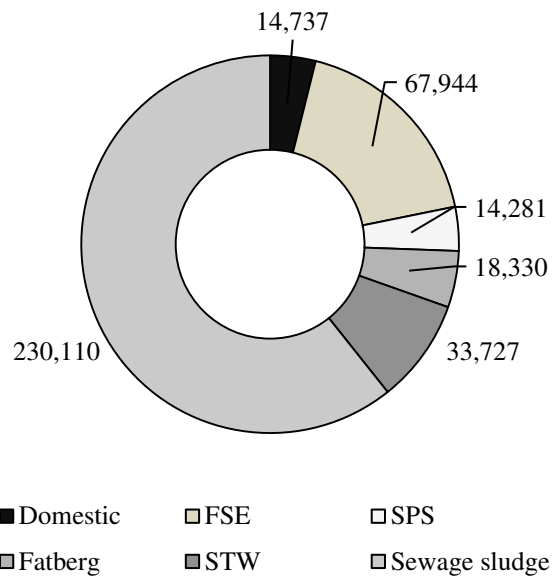
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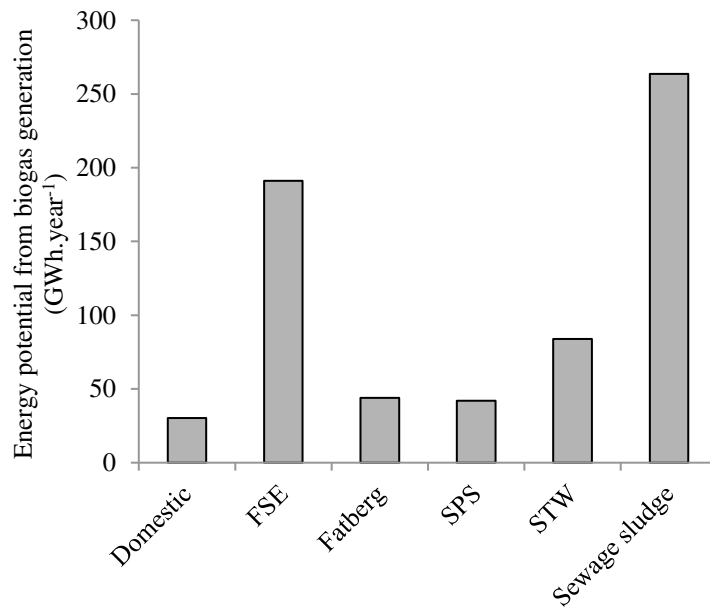
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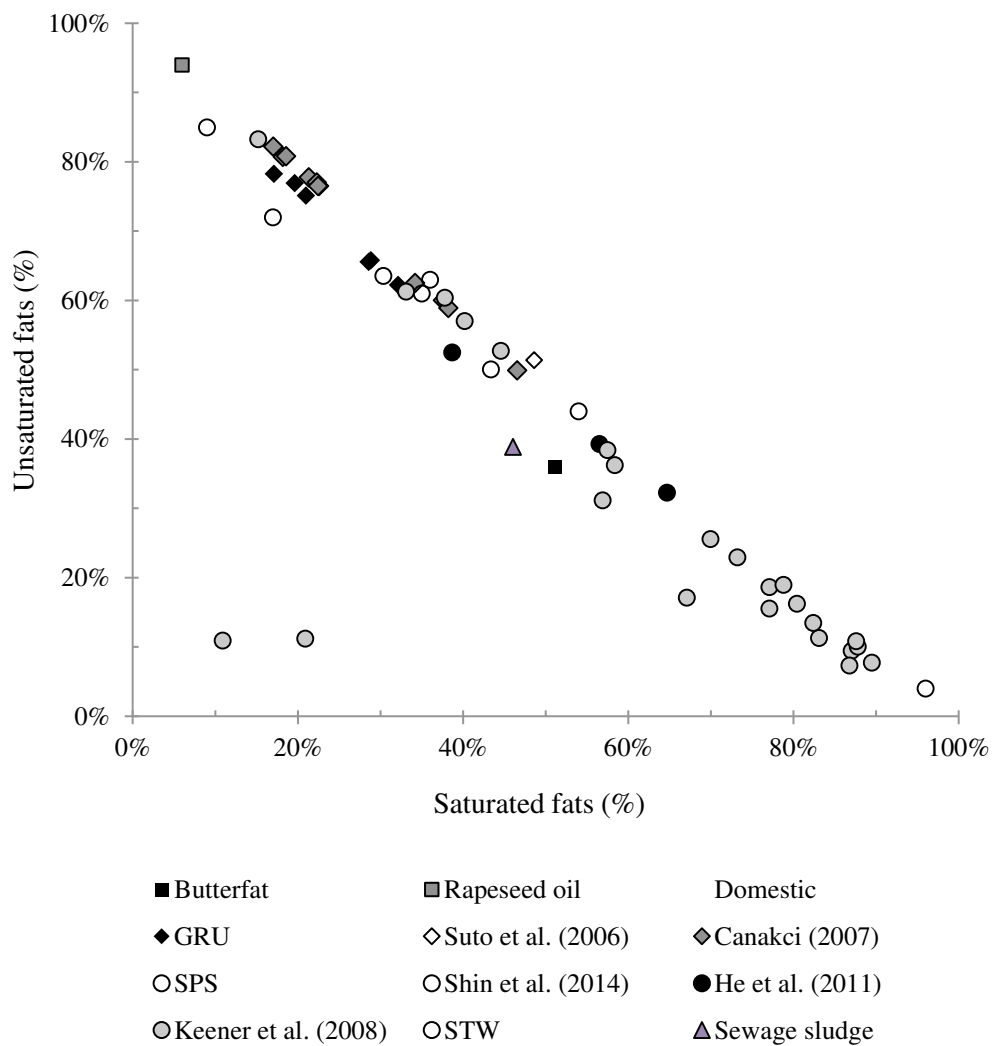


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519

520 **Figure 1** Quantities on a tonnes.year⁻¹ dry basis of different types of FOG wastes
 521 available in the catchment (a) and their energy potential as biomethane in co-digestion
 522 (b)

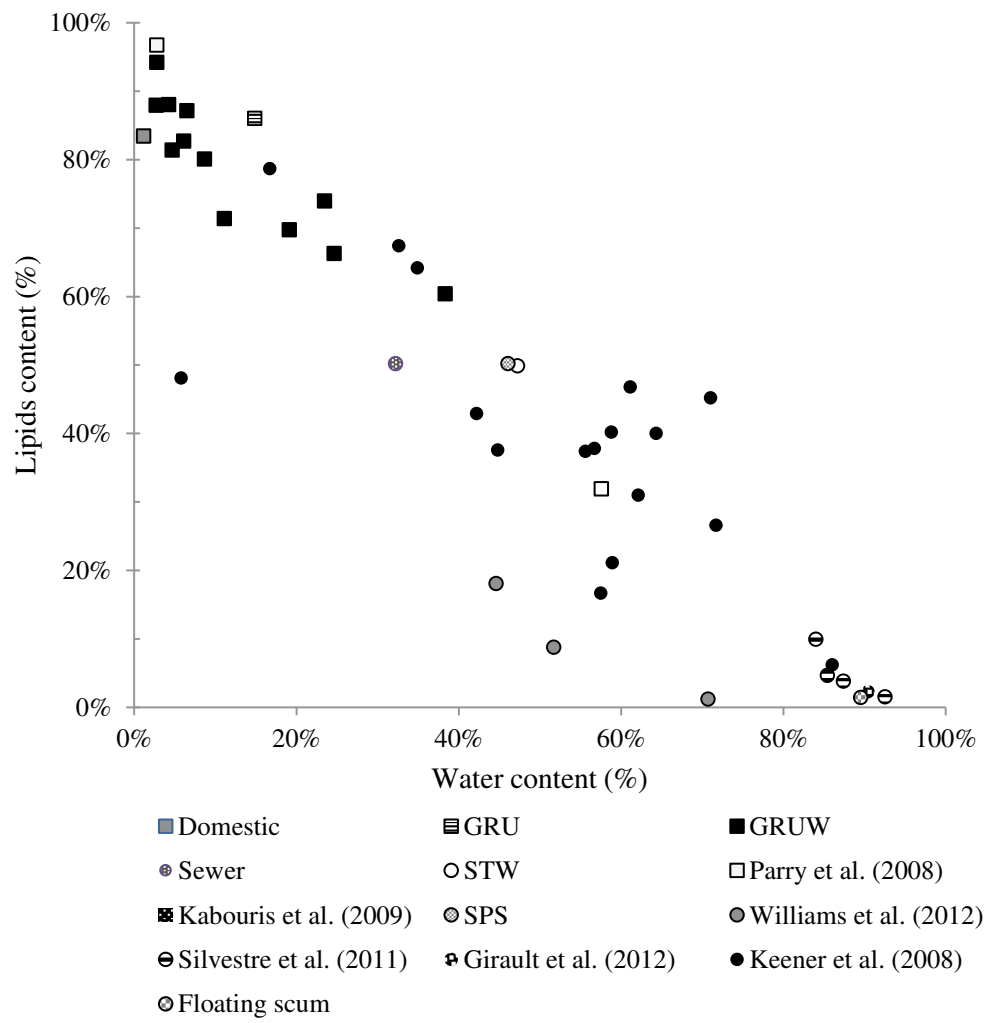


524

525 **Figure 2** Unsaturated fatty acids reported against saturated fats in FOG wastes as % of
 526 total fatty acids. Edible oil and fat are represented with ■ and FOG wastes are categorised
 527 as follows: source (◆) and wastewater systems (●).

528

529

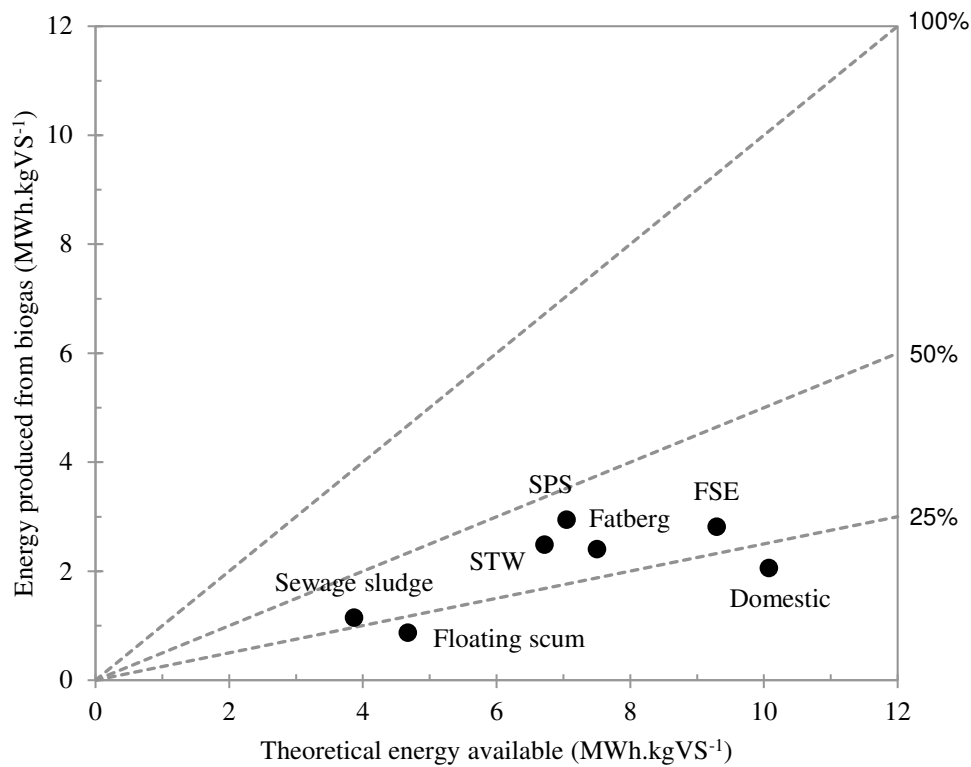


530

531 **Figure 3** Lipids and water content of FOG wastes (reported as % wet weight). FOG
 532 wastes are categorised as follows: source (■) and wastewater systems (●)

533

534



535

536 **Figure 4** Calorific values of FOG and sewage sludge plotted against biomethane
 537 produced for: household FOG (Domestic); FOG from FSEs grease removal units (FSE);
 538 FOG/fat balls from pumping station (SPS) and at the sewage treatment works (STW);
 539 FOG from sewers deposit (Fatberg); FOG from floating scum at the entrance of the
 540 sewage treatment works (Floating scum) and sewage sludge.

541 **Table 1** Assumptions made for FSEs FOG quantification. Volumes of FOG collectable
 542 per premise were based on Doherty (2009). Correction factors were obtained from a
 543 field survey.

544

Business type	FOG collectable (kg.year⁻¹)	FHRS correction factors	Corrected number of premises
Hotel, bed and breakfast and guest house	485	0.8	1,615
Hospital, childcare and caring premise	278	0.6	3,563
Pub, bar and nightclub	997	0.5	4,840
Restaurant, café and canteen	499	0.6	23,668
Supermarket and hypermarket	383	0.9	1,341
School, college and university	9,153	0.5	5,642
Takeaway and sandwich shop	2,527	1.0	4,388
Other catering premises	150	0.5	2,968

545

546

547 **Table 2** Composition in water and organic compounds of different types of FOG wastes
 548 available in the catchment

Waste	Water (%wt.)	Fibres (%DS)	Proteins (%DS)	Lipids (%DS)	Carbohydrates (%DS)	Ash (%DS)
Domestic	1.2±0.1	0.1 ¹	0.8±0.2	84.5±5.3	14.7±5.1	0.0
FSE	14.8±11.7	0.1 ¹	0.7±0.1	101.0±0.4	0.0	0.0
Fatberg	30.0±2.9	0.1 ¹	0.9±0.1	93.1±9.2	5.0±8.7	1.5±0.9
SPS	46.1±2.3	3.1±1.2	3.8±0.6	93.1±4.5	0.4±0.7	3.5±0.1
STW	47.2±10.9	3.3±1.2	3.5±0.3	94.5±3.3	0.0	5.0±0.8
Floating scum	91.1±1.5	28.3±4.8	9.6±1.7	13.7±2.4	43.7±8.8	4.8±3.9
Sewage sludge	90.1±0.03	22.9±3.6	30.7±1.2	11.2±1.3	12.4±5.5	22.7±0.6

549 ¹ Value below the limit of detection

550

551 **Table 3** Biogas production for FOG and sewage sludge.

Samples	Theoretical biogas production (mL CH₄.g VS⁻¹)	Biomethane yield (STP mL CH₄.g VS_{added}⁻¹)	VSd (%)	Biomethane specific yield (STP mL CH₄.g VS_{destroyed}⁻¹)
Domestic	915±31	773±13	93±15	685±98
FSE	931±2	938±39	80±3	890±42
SPS	866±49	981±12	91±6	903±50
Sewer deposit	963±52	801±94	64±11	908±145
STW	839±35	829±285	94±3	795±258
Floating scum	380±6	291±101	75±8	367±105
Sewage sludge	411±16	382±6	69±4	500±31

552

Table 4 Calorific values of FOG wastes in the sewerage catchment and sewage sludge.

Waste	LHV (MJ.kg⁻¹ wet basis)	LHV (MJ.kg⁻¹ dry basis)
Domestic	35±4	36±4
GRU	28±7	33±4
SPS	14±0.2	26±0.3
Fatberg	19±0.3	27±0.4
STW	13±1	25±2
Floating scum	2±0.2	19±2
Sewage sludge	2±0.1	18±1

555 **Table 5** Energy potential from FOG in the Thames Water catchment

	Domestic	FSE	Fatberg	STW	Sewage sludge
Material potential (tonnes.year⁻¹)	14,920	79,809	27,449	67,281	306,800 ¹
Energy potential (GWh.year⁻¹)	150	742	209	476	1,582
Energy produced from biogas (GWh.year⁻¹)	30	191	44	84	264

556

¹ Reported as ton DS per year

1 **Characterisation and energy assessment of fats, oils and greases (FOG)**
2 **waste at catchment level**

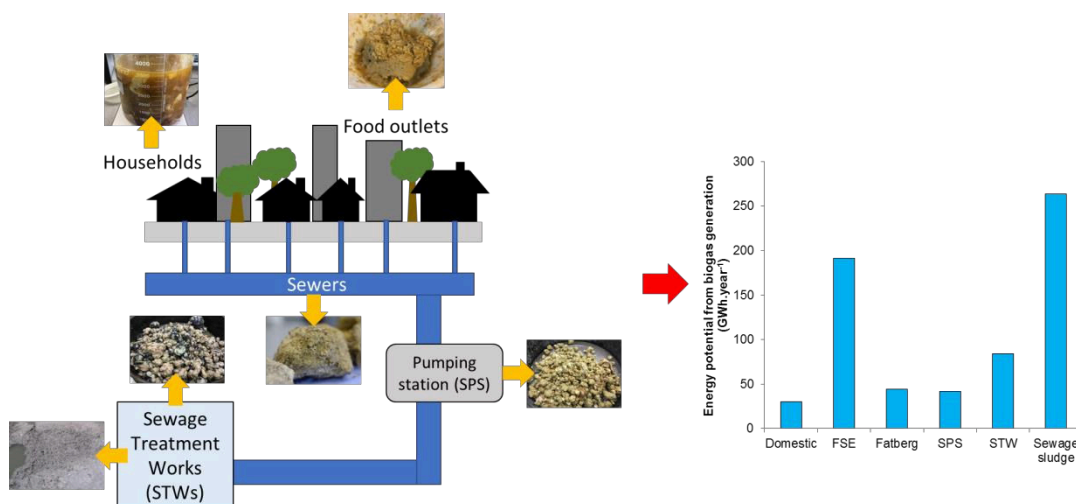
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8 **Graphical abstract**



9

10

11

12 **Abstract**

13 Several of the waste materials that have a negative impact on the sewer system are
14 produced by fats, oils and greases (FOG) discharged from commercial and domestic
15 kitchens. These materials accumulate at different points in the sewer catchment, from
16 kitchens to pumping stations, sewers and sewage treatment works (STWs), and comprise
17 oily wastewater, floating agglomerates and hard deposits. Despite their detrimental
18 effects, these waste materials have a high calorific content and are an ideal feedstock for
19 energy recovery processes. So far, the overall volume of each type of waste and their
20 physical-chemical properties in relation to their collection point are unknown. However,
21 from a management point of view, knowledge on each feedstock quality and volumes is
22 necessary to develop an economic viable solution for their collection and for energy
23 recovery purposes. In this study, FOG wastes collected from households, food service
24 establishments (FSEs), sewage pumping stations, sewers and STWs, were compared to
25 sewage sludge in terms of organic contents and energy potentials. As expected, FOG
26 recovered at source (households and FSEs) were 'cleaner' and had a higher energy
27 content. Once mixed with wastewater the materials changed in composition and lost some
28 of their energy per unit mass. Our results showed that around 94,730 tonnes·year⁻¹ of
29 these materials could be recovered from the Thames Water Utilities' catchment, one of
30 the most populated in the UK. These materials could produce up to 222 GWh·year⁻¹ as
31 biogas, close to double of what is produced with sewage sludge digestion and around 19%
32 of the company energy needs. Finally, even with over six million households in the
33 catchment, the results showed that most of the FOG waste was produced by FSEs (over
34 48,000 premises) with an estimated average of 79,810 tonnes·year⁻¹ compared to 14,920
35 tonnes·year⁻¹ from private households. This is an important outcome as recovery from

36 FSEs will be cheaper and easier if the company decides to implement a collection system
37 for energy recovery.

38 **Keywords:** Anaerobic digestion; energy from waste; fatberg; sewer deposits; sewage
39 sludge

40

41 **Abbreviations**

- 42 DS Dry solids
- 43 FSE Food service establishments
- 44 GTW Grease trap waste
- 45 GRU Grease removal unit
- 46 FHRS Food hygiene rating scheme
- 47 FOG Fats, oils and greases
- 48 HHV Higher heating value
- 49 LCFA Long-chain fatty acids
- 50 LHV Lower heating value
- 51 SPS Sewage pumping station
- 52 STW Sewage treatment works
- 53 TFA Total fatty acid
- 54 UCO Used cooking oil
- 55 VS Volatile solids

56 **1 Introduction**

57

58 Fats, oils and greases (FOG) discharged from households and food service establishments
59 (FSEs) have been identified as one of the major contributors to blockages in sewerage
60 networks and the formation of sewers' fatbergs (Engelhaupt, 2017). Developing effective
61 FOG management strategies has therefore become a priority for many water utilities,
62 including Thames Water, the largest water utility in the UK, which comprises more than
63 six million households in its catchment. These materials accumulate at different points in
64 a sewerage catchment, from kitchens drains to pumping stations, sewers and sewage
65 treatment works (STWs), and they comprise oily wastewater, floating agglomerates and
66 hard deposits. Despite their detrimental effects on the sewer network, FOG-rich wastes
67 have a high calorific content and can be an ideal feedstock for energy recovery processes.
68 An assessment of each material's quality and volume is necessary to evaluate the
69 economic viability of collecting and using FOG waste for energy recovery. Thus far, most
70 of the research has focused on used cooking oil (UCO) harvested from FSEs for biodiesel
71 production (Wallace et al., 2017) or grease trap waste (GTW) for the production of biogas
72 in anaerobic digestion (Long et al., 2012). The potential of GTW FOG waste co-digestion
73 with sewage sludge has been reported by many authors, as summarised by Long et al.
74 (2012). Davidsson et al. (2008) showed that when sewage sludge and GTW (10-30% of
75 total volatile solids load) were co-digested under mesophilic conditions, methane yields
76 increased up to 27%. Similarly, Kabouris et al. (2009) showed that up to 48% of GTW
77 (of the total volatile solids load) could be digested with a mixture of primary sludge and
78 thickened waste activated sludge with no inhibitory effects on the process, with a three-
79 fold increase in methane yields of three. However, little attention has been given to other

80 FOG wastes available in the sewerage catchment, such as fatbergs from sewers, or
81 floating deposits from pumping stations or STWs. The use of these energy-rich materials
82 as co-digestion substrates could offer water utilities a double economic advantage by
83 disposing of unwanted waste and increasing their renewable energy production.
84 Understanding the processing potential of these different FOG-rich materials could help
85 define and drive a more sustainable FOG management at catchment level. For instance,
86 the overall volume of each type of waste and their physical-chemical properties, in
87 relation to their collection point, are still unclear. Furthermore, no attempt has been made
88 to study FOG collected from households, which some authors believe to be one of the
89 major contributors towards FOG discharges in sewerage networks (Foden et al., 2017).
90 Wallace et al. (2017) suggested that grease removal units (GRUs) produce a waste similar
91 to UCOs and with fewer impurities than GTW, but no work to date has intended to
92 characterise this waste. Lastly, most of the research conducted on FOG has focused on
93 explaining the mechanisms of formation of FOG deposits (Keener et al., 2008) and very
94 few have reported their potential for energy recovery. This paper aims to clarify the
95 variation among these substrates in regards to their physicochemical properties and
96 biomethane potential as well as to provide an assessment of their volumes and their
97 energy potential within Thames Water Utilities' catchment.

98 **2 Methods**

99 **2.1 Inoculum and substrates**

100 Digested sludge, used as inoculum in batch tests, was obtained from a full-scale anaerobic
101 digester treating municipal sewage sludge. Six FOG wastes were used in this study: (1)
102 Domestic FOG (Domestic) collected from 30 households (located in different catchment
103 areas). The samples were blended, heated to 35°C and sieved to remove any large food
104 particulates. (2) FOG sample from a FSE grease removal unit (GRU). (3) FOG deposit
105 (Fatberg) was manually excavated during the clean-up of a sewer in London (2-3 kg
106 sample). Fat balls samples were collected from two locations: (4) a sewage pumping
107 station (SPS) and at (5) the inlet of a STW (SPS and STW respectively). The FOG deposit
108 and fat balls samples were grinded to produce finer and more homogeneous samples. (6)
109 Floating scum (Floating scum) accumulating at the inlet of a STW was collected and
110 further analysed. Sewage sludge (Sewage sludge), pre-treated through a thermal
111 hydrolysis process, was used as a comparison material.

112 **2.2 Analytical methods**

113 The physical appearance (i.e. texture and colour) of the different FOG wastes was
114 qualitatively assessed. Dry solids (DS) and volatile solids (VS) were determined
115 according to standard methods (APHA, 2005).

116 A chemical characterisation of the main organic fractions (e.g. lipids, carbohydrates,
117 proteins and fibres) was performed on each material. Fibres were measured as the organic
118 matter remaining after samples were de-fatted and digested successively with acid and
119 alkali under controlled conditions (Horwitz, 2003). Proteins were determined either with

120 the Dumas method using Leco FP528 or as total Kjeldahl nitrogen respectively for solid
121 and semi-solid samples respectively. Lipids were measured using a modified Wiebul acid
122 hydrolysis method (Sciantec Analytical, 2018a). Carbohydrates were estimated as the
123 remaining fraction.

124 Methylated fatty acids profiles were obtained by gas-liquid chromatography using a free
125 fatty acid phase column of dimensions 25m x 0.20mm ID and detection by flame
126 ionisation detector. Fats and oils were trans-esterified to fatty acid methyl esters by
127 heating under reflux for two hours with a mixture of methanol and sulfuric acid in toluene.
128 The resulting methyl esters were extracted using a small volume of n-hexane. The n-
129 hexane solution was dried using anhydrous sodium sulphate and then transferred to a
130 chromatography vial (Sciantec Analytical, 2018b).

131 Theoretical biogas production was calculated from the organic components of the
132 materials (proteins, carbohydrates and lipids) using Buswell's equation (Buswell and
133 Neave, 1930).

134 Calorific values were determined experimentally in terms of the higher heating value
135 (HHV) using a calorimeter (Parr model 6100) equipped with a 1108CL oxygen bomb;
136 solid samples were pelletised whereas semi-solid samples were freeze dried (Sciantec
137 Analytical, 2018c). It is worth noting that the hydrogen content was not measured in this
138 study as such the lower heating values (LHV) were estimated from the measurement of
139 calorific values by subtracting the heat of vaporisation of water in the products as follows:

$$LHV_d = HHV_d \times (1 - M) - H_v \times M \quad (2-1)$$

140 Where M is the moisture content, H_V is the latent heat of vaporisation of water estimated
141 at 2.447 MJ.kg^{-1} at 25°C and HHV_d is the gross heating value in MJ.kg^{-1} on dry basis
142 determined as follows:

$$HHV_d = \frac{HHV}{1 - M} \quad (2-2)$$

Where HHV is the measured HHV on wet basis.

143 2.3 Batch tests

144 Triplicate batch testing was used to investigate the biomethane content of each material
145 using an AMPTS II system (Bioprocess Control). These assays were performed at
146 mesophilic temperatures (37°C) using an inoculum to substrate ratio of $2 \text{ g VS}_{\text{inoculum.g}}$
147 $\text{VS}_{\text{substrate}}$. DS and VS were determined before and after the digestion period. The
148 experiment was terminated when the cumulative biomethane production reached a
149 plateau phase (at 60 days). The biomethane production was expressed as biomethane
150 yield, $\text{mL CH}_4.\text{gVS}_{\text{added}}^{-1}$, and specific biomethane yield, $\text{mL CH}_4.\text{g VS}_{\text{destroyed}}^{-1}$ and
151 adjusted to standard temperature and pressure (STP) as follows:

$$V_{STP} = \left(1 - \frac{P_{vap}}{P_{gas}}\right) \times \frac{P_{gas}}{P_{STP}} \times \frac{T_{STP}}{T_{gas}} \times V_{gas} \quad (2-3)$$

152 Where V_{STP} is the volume adjusted to STP, P_{STP} is the standard pressure (101.3 kPa), T_{gas}
153 is the temperature of the measured gas (311 K), T_{STP} is the standard temperature (273 K)
154 and V_{gas} is the measured volume of gas. P_{gas} was calculated as the sum of the partial
155 pressures of methane and carbon dioxide. P_{CO_2} was neglected in the case of the batch
156 testing as carbon dioxide was removed through the stripping solution. P_{vap} is the water
157 vapour pressure calculated as follows:

$$P_{vap} = 10^{8.1962 - \frac{1,730.63}{T_{gas} - 39.724}} \quad (2-4)$$

158 **2.4 Volumes and energy appraisal**

159 Quantities of FOG and sewage sludge were estimated for the whole catchment area.
160 Results from the characterisation and batch testing of FOG were further used for the
161 energetic assessment. The calorific value of methane was assumed at 36 MJ.m⁻³ and the
162 efficiency of combined heat and power engines at 30% (Goss et al., 2017).

163 **2.4.1 FOG at source**

164 ArcGIS was used as a support tool for this work to manipulate data with a geographical
165 component. Domestic and commercial properties were respectively extracted from
166 AddressBase® Premium (Ordnance Survey, 2017) and the Food Hygiene Rating Scheme
167 (FHRS) (Food Standards Agency, 2017). A total of 6,543,749 and 68,903 records were
168 obtained for households and FSEs in Thames Water Utilities' catchment. A field survey
169 showed that not all FSEs registered under the FHRS were likely to produce any FOG
170 (Cermakova et al., 2018). For each category, a correction factor was applied reflecting
171 the number of establishments likely to produce FOG over the total number of premises
172 (Table 1). The correction factor was calculated as the number of premises likely to
173 produce FOG over the total number of establishments for each category. FOG from
174 industrial sources (e.g. food and dairy processing plants) were not included in this
175 assessment as their discharges were assumed to be monitored and controlled under the
176 trade effluent consents by the water utility.

177 Volumes collectable from domestic properties were evaluated at 2.3 kg.household⁻¹ per
178 year (Collin et al., 2019b). The data for the estimation of FOG generated from FSEs was
179 calculated based on Doherty (2009) and is reported in Table 1.

180 **2.4.2 FOG in wastewater networks**

181 FOG concentrations were measured monthly at 20 STWs in crude sewage over a period
182 of four years. Briefly, samples were filtered a WhatmanTM GF/C grade filter paper. The
183 filter paper was immersed in boiling hexane using a Gerhardt SOXTHERM® (40 to
184 60°C). Oil and grease were then determined by weight difference and reported in mg.L⁻¹.
185 It should be noted that values below the limit of detection of 8.2 mg.L⁻¹ were replaced
186 with this value. Oil and grease were measured on average at 59.0 mg.L⁻¹ at these STWs
187 (Collin et al., 2019a); this average value was used for the other sites. Quantities of FOG
188 were estimated based on dry weather flow, which is the average daily flow received at
189 STWs, and subtracted from undigested lipids originating from human faeces estimated at
190 4.1 g.capita⁻¹.day⁻¹ with a range of 1.9 to 6.4 g.capita⁻¹.day⁻¹ (Rose et al., 2015). Volumes
191 collected in SPSs were assumed equal to STWs. Sewer deposits were estimated
192 subtracting volumes at STWs from FOG at source (i.e. domestic and FSE).

193 **2.5 Sewage sludge**

194 Data on sewage sludge generation from anaerobic digestion was obtained from Thames
195 Water Utilities. Yearly averages of feeding rates in tonnes dry solids per day were used
196 for each anaerobic digestion sites. The average VS content of sewage sludge was assumed
197 at 75%.

198 **3 Results and discussion**

199 **3.1 Quantification and physicochemical characterisation**

200 The six types of FOG waste collected in the catchment had very different
201 physicochemical characteristics. FOG from households and GRUs, semi-solid at room
202 temperature, had a brown-yellowish colour and looked very similar to UCOs (Figure 1a
203 and 1b, supplementary material). The sewer deposit sample was solid and harder than the
204 other substrates and contained many contaminants such as wipes and plastic waste. Fat
205 balls from STW were darker than those collected from SPS, but both samples had a softer
206 texture than that of the sewer deposit and contained less contaminants. Finally, floating
207 scum had a yellow-greyish colour, with a less structured form (Figure 2a-d,
208 supplementary material). Domestic and GRU FOG presented the lowest moisture content
209 of all the materials, with values around 3% and 15% respectively. FOG collected in
210 sewers and fat balls from SPS and STW, had on average lower moisture contents than
211 floating scum 30%, 46%, 47% and 91% respectively (Table 2). As expected, moisture
212 content of FOG wastes increased further away from the source point. Similar observations
213 were reported by Williams et al. (2012), who reported values of 45%, 52% and 70% for
214 pumping station, sewer deposit and STW respectively. Predictably, the lipid content was
215 inversely proportional to the water content, ranging from 85 to 99% DS for STW, SPS,
216 fatberg, GRU and domestic (Table 2). Surprisingly, the floating scum, generally believed
217 to be FOG, showed a relatively lower lipid content, and had organic concentrations
218 comparable to that of sewage sludge. As a comparison, lipids in sewage sludge were
219 measured at around 11% DS.

220 When examining the availability of FOG wastes, approximately 79,810 tonnes.year⁻¹
221 could be collectable from FSEs, whereas households would only produce around 14,920
222 tonnes.year⁻¹ (Figure 1a). The FOG production rate, calculated from households and
223 FSEs, would be at around 6.4 kg.person⁻¹.year⁻¹. This result is comparable to data
224 available from previous studies with values ranging from 4 up to 10 kg.person⁻¹.year⁻¹
225 (Canakci, 2007).

226 **3.2 Biogas potential**

227 In order to comprehensively assess the energy recovery potential of all the FOG materials,
228 batch digestion system were used to calculated biomethane yields and biomethane
229 specific yields. All FOG samples produced more biogas than sewage sludge alone (Table
230 3). These values were comparable to methane yields for lipid-rich waste reported by other
231 authors, ranging from 606 to 928 mL CH₄.g VS_{added}⁻¹ (Davidsson et al., 2008; Luostarinen
232 et al., 2009; Yalcinkaya and Malina Jr., 2015). Sewer deposit, STW fat balls and floating
233 scum displayed a greater standard deviation than the other wastes tested. This was
234 probably due to the preparation of these highly contaminated materials as producing a
235 homogeneous sample was very challenging (Figures 1 and 2, supplementary material).
236 The much higher biomethane yields (e.g. biomethane per gram of VS destroyed) and
237 therefore bioconversion efficiencies were obtained when digesting FOG compared to
238 sewage sludge (500±31 STP mL CH₄.g VS_{destroyed}⁻¹) or floating scum (367±105 STP mL
239 CH₄.g VS_{destroyed}⁻¹), with yields ranging from 695±98 to 908±145 STP mL CH₄.g
240 VS_{destroyed}⁻¹. The floating scum collected at STW produced less biogas than both FOG and
241 sewage sludge, suggesting a close match to the latter and probably a high content in fibres.

242 Analyses on the lipid fraction showed that FOG triglycerides contained long-chain fatty
243 acids (LCFAs) of 14 or more carbons. LCFAs are associated with inhibition of
244 methanogenesis and toxicity to the anaerobic digestion process (Girault et al., 2012;
245 Luostarinen et al., 2009; Noutsopoulos et al., 2013). This inhibition was found to be
246 dependent on concentrations and types of LCFAs (Dasa et al., 2016). Oleic acid (C18:1)
247 was reported as the most predominant LCFA found in GTW with concentrations ranging
248 from 34 to 48% of total fatty acids (TFA) (Canakci, 2007; Suto et al., 2006). Similar
249 observations were made with domestic and GRU FOG where oleic acids were measured
250 at 47 ± 2 and $47\pm 10\%$ of TFA. Vegetable oils have higher content in mono- and
251 polyunsaturated fatty acids compared to animal fats, and are the most commonly used
252 cooking fat in FSEs in the UK (on average about 14 L every 100 meals) (Envirowise,
253 2008). Accordingly, FOG collected at source shared a relatively comparable fatty acid
254 profile to that of vegetable oils. Despite variations between samples, several authors have
255 reported higher levels of saturation in sewer deposits ranging from 41 to 86% of TFA,
256 with palmitic acid (C16:0) being the most common saturated fatty acid (He et al., 2011;
257 Keener et al., 2008; Nieuwenhuis et al., 2018). Fat balls from SPS presented a slightly
258 lower degree of saturation than sewer deposits, measured at $30\pm 1\%$ of TFA. As a
259 comparison STW fat balls and sewage sludge showed a relatively similar fatty acid
260 profile, with a degree of saturation respectively at 43 ± 1 and $46\pm 1\%$ of TFA. This shift
261 from unsaturated to saturated fatty acids is still unclear (Figure 2). Some authors have
262 suggested that micro-organisms might be involved in that transformation (Williams et al.,
263 2012) while others have hinted at the contribution of soap products (He et al., 2017).

264 Fatty acids composition is very important for anaerobic digestion as the different fatty
265 acids are degraded in different way by the microbial communities in the digester and

266 hence have a different impact on the final biogas production. In addition, unsaturated fatty
267 acids must be first converted in saturated fatty acids before being degraded via the β -
268 oxidation pathway (Salama et al., 2019). For example, oleic acids, found predominantly
269 in FOG collected at source, has been reported by several authors to have greater toxic
270 effects on the anaerobic digestion process than saturated fatty acids, such as palmitic acid
271 (Alves et al., 2009; Dasa et al., 2016; Shin et al., 2003). Davidsson et al. (2008) reported
272 slower digestion time of stearic acid compared to oleic acid.

273 These results confirm that FOG are desirable substrates for anaerobic digestion even
274 when collected from the networks. However, to avoid detrimental impacts, further care is
275 needed to optimise the feeding regime of FOG materials, not only in terms of quantity
276 but also in terms of source and composition.

277 **3.3 Energy recovery potential**

278 Higher organic matter and lipids concentration translated into higher energy content
279 which was measured as the calorific content of the different materials using a bomb
280 calorimeter (Table 4). FOG collected at source, domestic and GRU, had high calorific
281 values of 36 ± 4 and 33 ± 4 MJ.kg⁻¹ respectively on dry basis. Both values were in the range
282 of those previously reported for GTWs (Al-Shudeifat and Donaldson, 2010) and UCOs
283 at 35 and 39 MJ.kg⁻¹ respectively (Khalisanni et al., 2008). The fatberg sample was
284 measured at 27 MJ.kg⁻¹ DS while SPS and STW had lower values measured at around 25
285 MJ.kg⁻¹ on dry basis. Floating scum (19 MJ.kg⁻¹ DS) and sewage sludge (18 MJ.kg⁻¹ DS)
286 showed similar values, indicating a reduction in calorific value as the location extended
287 away from the source point. Lipids and water concentration showed a linear inverse
288 correlation for all the samples analysed in this study and those reported in literature

289 (Figure 3). Interestingly, oil concentrations in FOG deposits reported by Williams, et al.
290 (2012) were much lower than those measured by this study and Keener et al. (2008) in
291 the US. This suggests that waste collected from the network is likely to be highly variable
292 in terms of quality and contamination as it gets in contact with sewage and other waste
293 materials in the sewers. Critically, the increased moisture content reduced the lipids
294 fraction by mass indicating that not only does FOG collected from the network require
295 more effort but this negative is compounded through a reduction in its resultant energy
296 value. The total energy available (i.e. calorific value measurement) plotted against the
297 energy available from the conversion of biogas showed conversion yields ranging from
298 20 to 42% for FOG and averaging 30% for sewage sludge (Figure 4). Not all the energy
299 contained in FOG is convertible to biomethane through anaerobic digestion. Particularly,
300 FOG collected at source demonstrated lower energy conversion yields than other wastes
301 collected further downstream. Facilitating the hydrolysis step, which is the rate limiting
302 step, through pre-treatments (e.g. enzymatic) could help improving the efficiency of the
303 digestion of FOG.

304 This initial characterisation indicated that materials collected at source with high lipid
305 content, such as domestic and GRU, could be easily used as biodiesel feedstock. Whereas
306 other wastes, such as SPS, sewer and STW, with higher water content, would require an
307 initial dewatering step. The water in the feedstock reacts with the catalyst during the
308 transesterification process leading to a more laborious and expensive process, (Sanford et
309 al., 2009). These materials could be better suited for energy recovery through anaerobic
310 digestion. Biogas derived energy from sludge is currently generating 264 GWh.year⁻¹.
311 Biogas from sewer and STW could add an additional 128 GWh.year⁻¹. Whereas FOG
312 from households and FSEs, estimated at 30 and 191 GWh.year⁻¹ of biogas (Table 5),

313 could be converted into approximately 59,340 m³ of biodiesel (at 80% conversion and
314 density of 0.9).

315 One of the main obstacles to energy generation from some of the FOG wastes studied is
316 collection. Cleaning of sewers and SPSs is either planned or reactive and involves
317 combined vacuum and jetting machines. FOG collected from these tankers would need to
318 be further processed as these systems tend to break them down and mix them with sewage.
319 While equipment seems to be commercially available for FOG collection in SPSs, their
320 efficiency still needs to be demonstrated. In contrast, preliminary treatments are
321 commonly found at STWs to remove FOG from municipal wastewater; the use of these
322 wastes as co-substrates for anaerobic digestion has been reported by several authors
323 (Girault et al., 2012; Harris et al., 2017; Long et al., 2012; Luostarinen et al., 2009;
324 Silvestre et al., 2011). Yet, experience within the water utility with such systems has
325 discouraged further investment. Another alternative at STWs would be to retrofit primary
326 sedimentation tanks with flotation technologies in order to increase FOG removal
327 alongside sewage sludge. Further research is needed to assess the performance of such
328 technologies and the economic viability of collecting FOG from FSEs as a robust logistic
329 management would be require to tailor a sustainable disposal route.

330

331 **4 Conclusion**

332 The characterisation of selected FOG wastes focused on three main aspects:
333 physicochemical composition, organic macromolecules concentrations and LCFA
334 profiles. The main difference was found in the water content: FOG collected from
335 networks (SPS and sewers) and STW had higher moisture content than FOG collected at
336 source (domestic and FSEs). Predictably, FOG were found to be desirable substrate for
337 anaerobic co-digestion as their high organic matter and lipids content resulted in high
338 methane potential (820-1,040 mL CH₄.g VS⁻¹).

339 The assessment of volumes of FOG collectable indicated FSEs to be the main source with
340 around 67,956 tonnes.year⁻¹ (on dry basis) of material relatively easy to collect and
341 potentially available for energy recovery (191 GWh.year⁻¹). The anaerobic digestion of
342 FOG wastes, collected either at source or in the networks, could be almost equivalent to
343 the current energy generated from sewage sludge at Thames Water Utilities' sites. In other
344 words, anaerobic co-digestion could help generating around a third of Thames Water's
345 overall electricity consumption. Although FOG from wastewater networks or STWs still
346 have high values for energy recovery, the practicality and feasibility of collecting these
347 wastes could counterbalance the benefits from biogas generation. This further suggested
348 that collection of FOG before it reaches the sewers is highly desirable. Still, volumes and
349 methods of collection should be analysed in order to assess the economic feasibility of
350 developing sustainable schemes.

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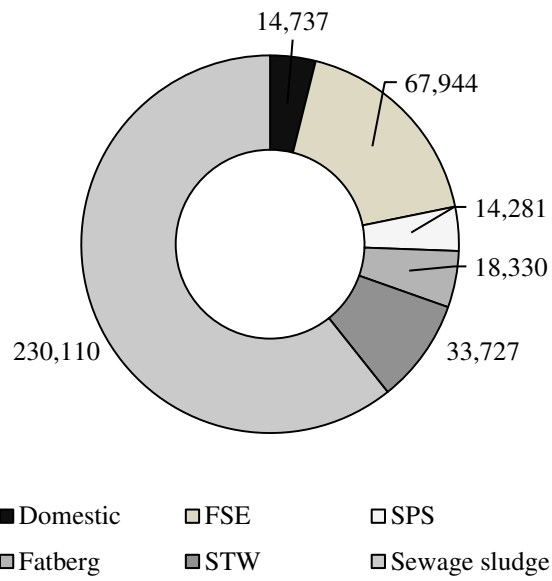
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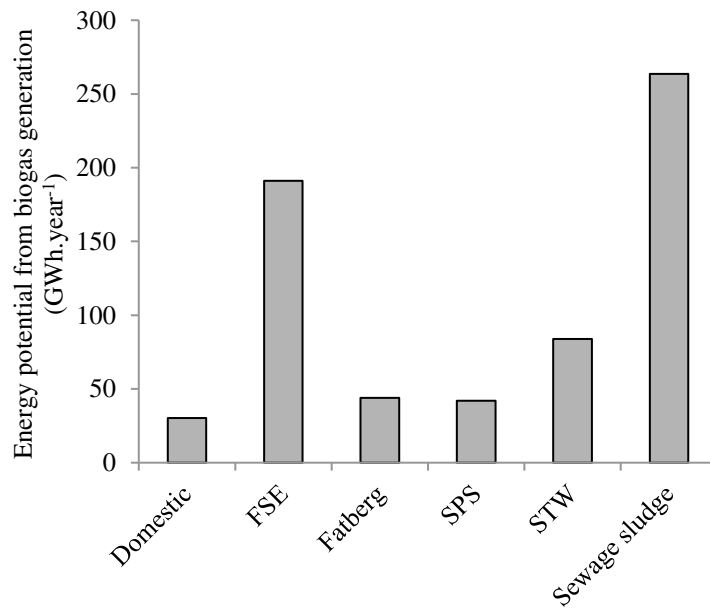
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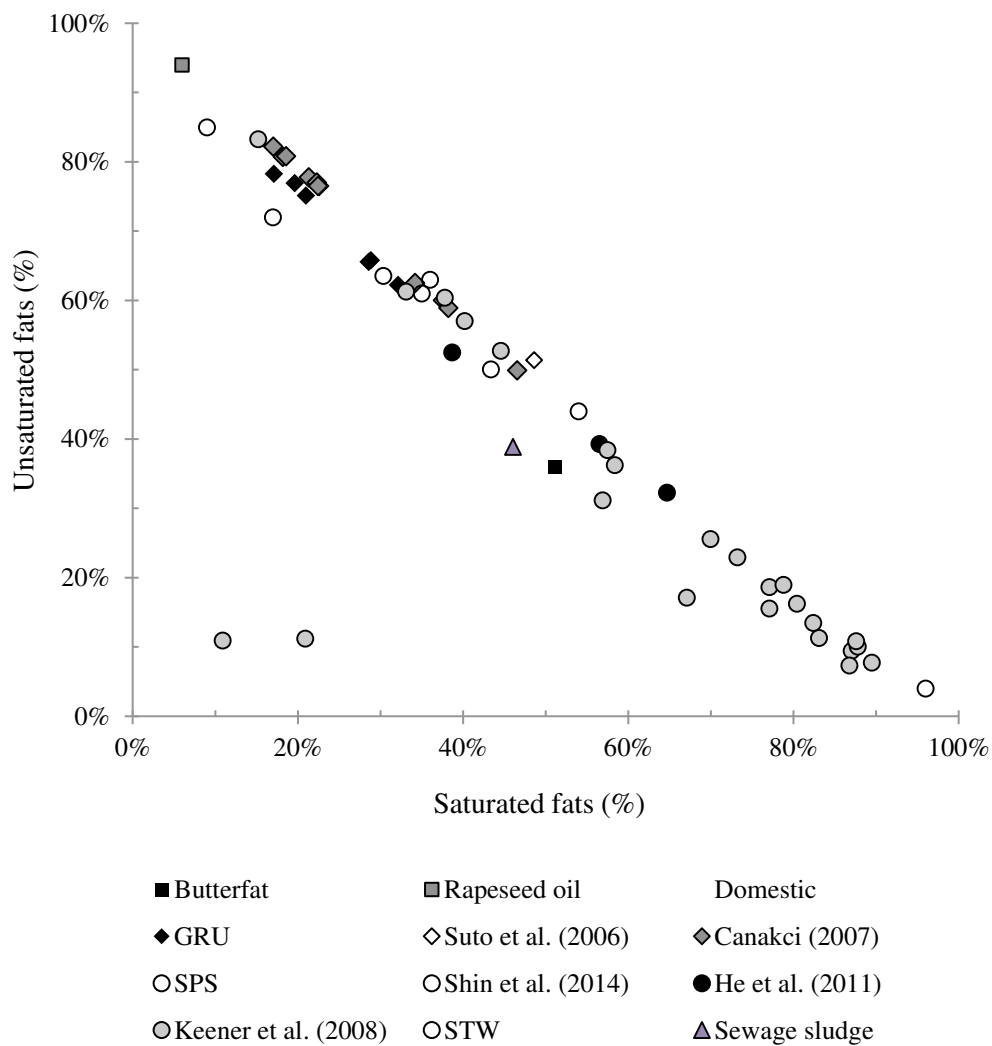


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520 **Figure 1** Quantities on a tonnes.year⁻¹ dry basis of different types of FOG wastes
 521 available in the catchment (a) and their energy potential as biomethane in co-digestion
 522 (b)

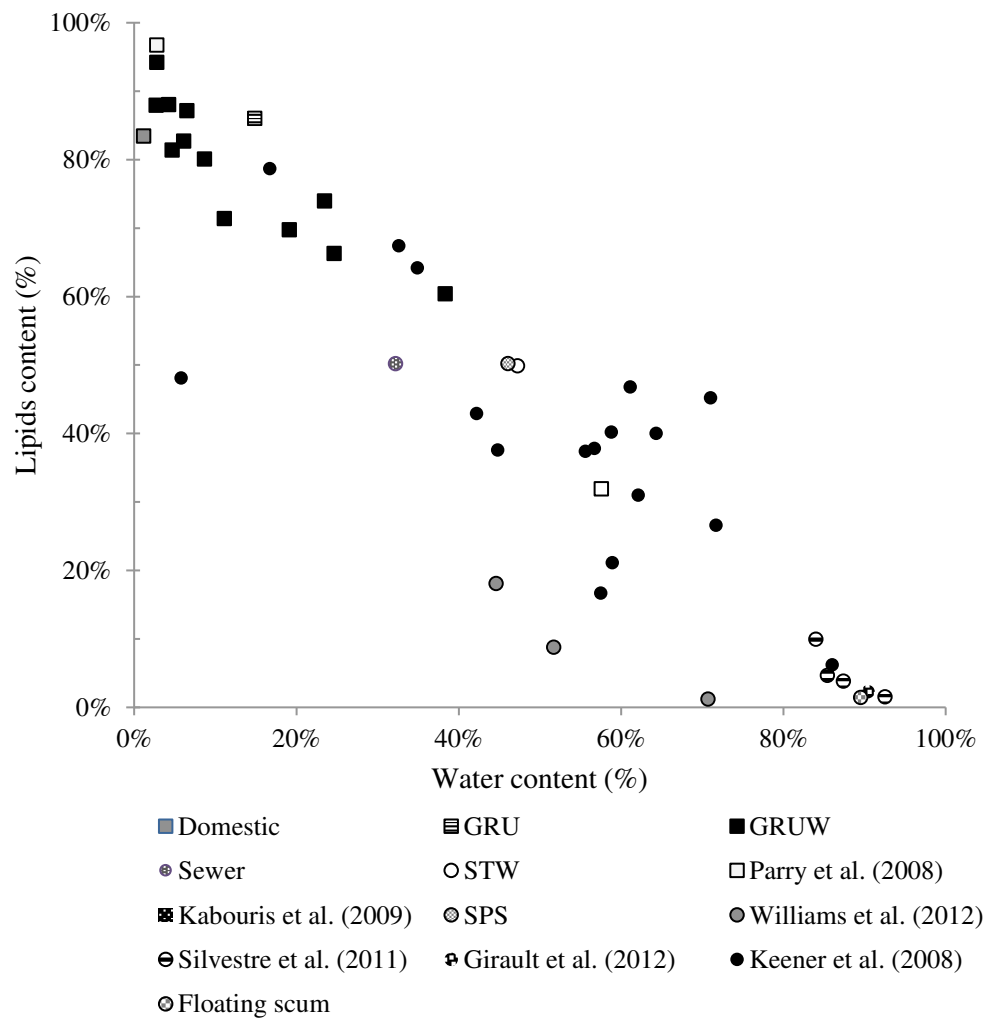


524

525 **Figure 2** Unsaturated fatty acids reported against saturated fats in FOG wastes as % of
 526 total fatty acids. Edible oil and fat are represented with ■ and FOG wastes are categorised
 527 as follows: source (◆) and wastewater systems (●).

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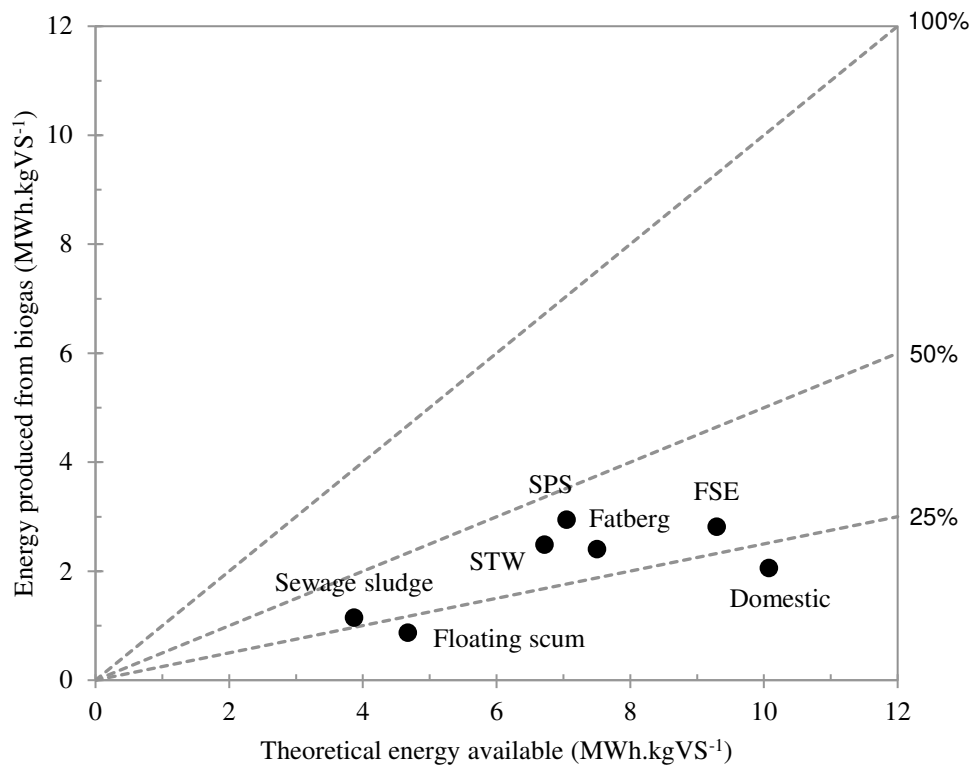


530

531 **Figure 3** Lipids and water content of FOG wastes (reported as % wet weight). FOG
 532 wastes are categorised as follows: source (■) and wastewater systems (●)

533

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536 **Figure 4** Calorific values of FOG and sewage sludge plotted against biomethane
 537 produced for: household FOG (Domestic); FOG from FSEs grease removal units (FSE);
 538 FOG/fat balls from pumping station (SPS) and at the sewage treatment works (STW);
 539 FOG from sewers deposit (Fatberg); FOG from floating scum at the entrance of the
 540 sewage treatment works (Floating scum) and sewage sludge.

541 **Table 1** Assumptions made for FSEs FOG quantification. Volumes of FOG collectable
 542 per premise were based on Doherty (2009). Correction factors were obtained from a
 543 field survey.

544

Business type	FOG collectable (kg.year⁻¹)	FHRS correction factors	Corrected number of premises
Hotel, bed and breakfast and guest house	485	0.8	1,615
Hospital, childcare and caring premise	278	0.6	3,563
Pub, bar and nightclub	997	0.5	4,840
Restaurant, café and canteen	499	0.6	23,668
Supermarket and hypermarket	383	0.9	1,341
School, college and university	9,153	0.5	5,642
Takeaway and sandwich shop	2,527	1.0	4,388
Other catering premises	150	0.5	2,968

545

546

547 **Table 2** Composition in water and organic compounds of different types of FOG wastes
 548 available in the catchment

Waste	Water (%wt.)	Fibres (%DS)	Proteins (%DS)	Lipids (%DS)	Carbohydrates (%DS)	Ash (%DS)
Domestic	1.2±0.1	0.1 ¹	0.8±0.2	84.5±5.3	14.7±5.1	0.0
FSE	14.8±11.7	0.1 ¹	0.7±0.1	101.0±0.4	0.0	0.0
Fatberg	30.0±2.9	0.1 ¹	0.9±0.1	93.1±9.2	5.0±8.7	1.5±0.9
SPS	46.1±2.3	3.1±1.2	3.8±0.6	93.1±4.5	0.4±0.7	3.5±0.1
STW	47.2±10.9	3.3±1.2	3.5±0.3	94.5±3.3	0.0	5.0±0.8
Floating scum	91.1±1.5	28.3±4.8	9.6±1.7	13.7±2.4	43.7±8.8	4.8±3.9
Sewage sludge	90.1±0.03	22.9±3.6	30.7±1.2	11.2±1.3	12.4±5.5	22.7±0.6

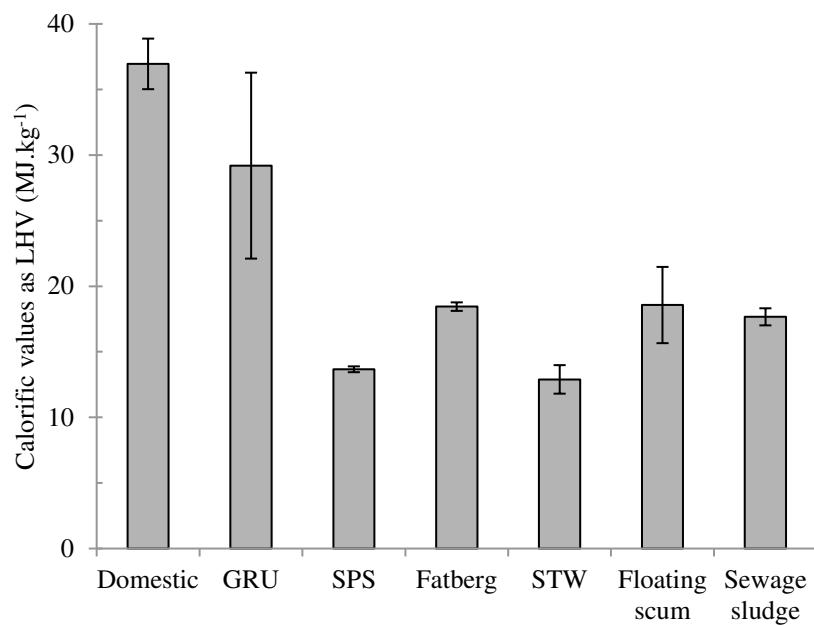
549 ¹ Value below the limit of detection

550

551 **Table 3** Biogas production for FOG and sewage sludge.

Samples	Theoretical biogas production (mL CH₄.g VS⁻¹)	Biomethane yield (STP mL CH₄.g VS_{added}⁻¹)	VSd (%)	Biomethane specific yield (STP mL CH₄.g VS_{destroyed}⁻¹)
Domestic	915±31	773±13	93±15	685±98
FSE	931±2	938±39	80±3	890±42
SPS	866±49	981±12	91±6	903±50
Sewer deposit	963±52	801±94	64±11	908±145
STW	839±35	829±285	94±3	795±258
Floating scum	380±6	291±101	75±8	367±105
Sewage sludge	411±16	382±6	69±4	500±31

552



553

554 **Figure 3** Calorific values of FOG wastes in the sewerage catchment and sewage sludge.

555 **Table 4** Calorific values of FOG wastes in the sewerage catchment and sewage sludge.

<u>Waste</u>	<u>LHV (MJ.kg⁻¹ wet basis)</u>	<u>LHV (MJ.kg⁻¹ dry basis)</u>
<u>Domestic</u>	<u>35±4</u>	<u>36±4</u>
<u>GRU</u>	<u>28±7</u>	<u>33±4</u>
<u>SPS</u>	<u>14±0.2</u>	<u>26±0.3</u>
<u>Fatberg</u>	<u>19±0.3</u>	<u>27±0.4</u>
<u>STW</u>	<u>13±1</u>	<u>25±2</u>
<u>Floating scum</u>	<u>2±0.2</u>	<u>19±2</u>
<u>Sewage sludge</u>	<u>2±0.1</u>	<u>18±1</u>

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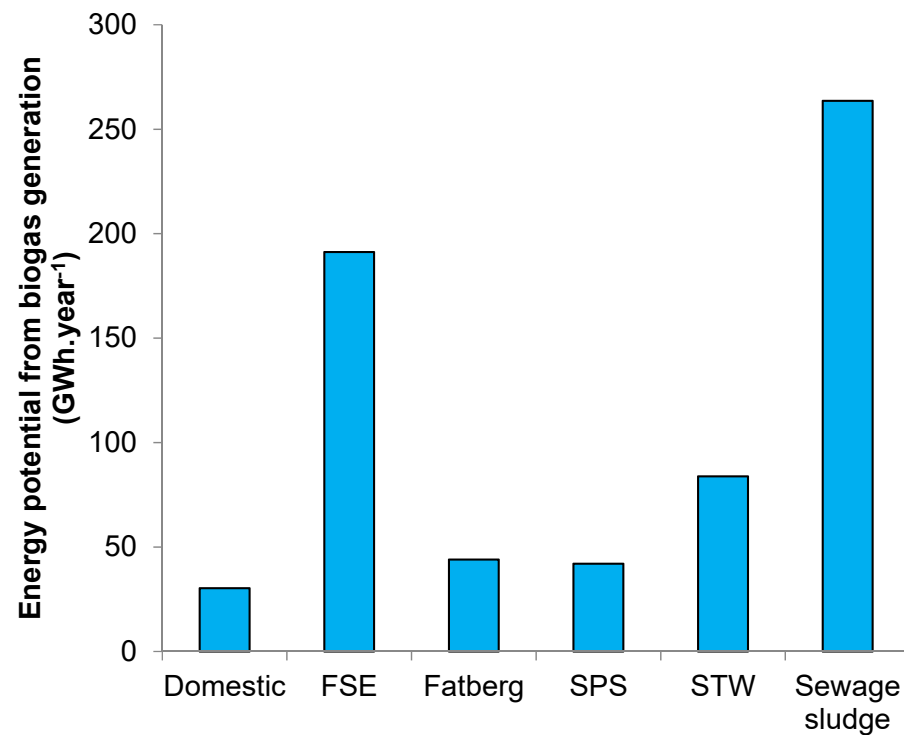
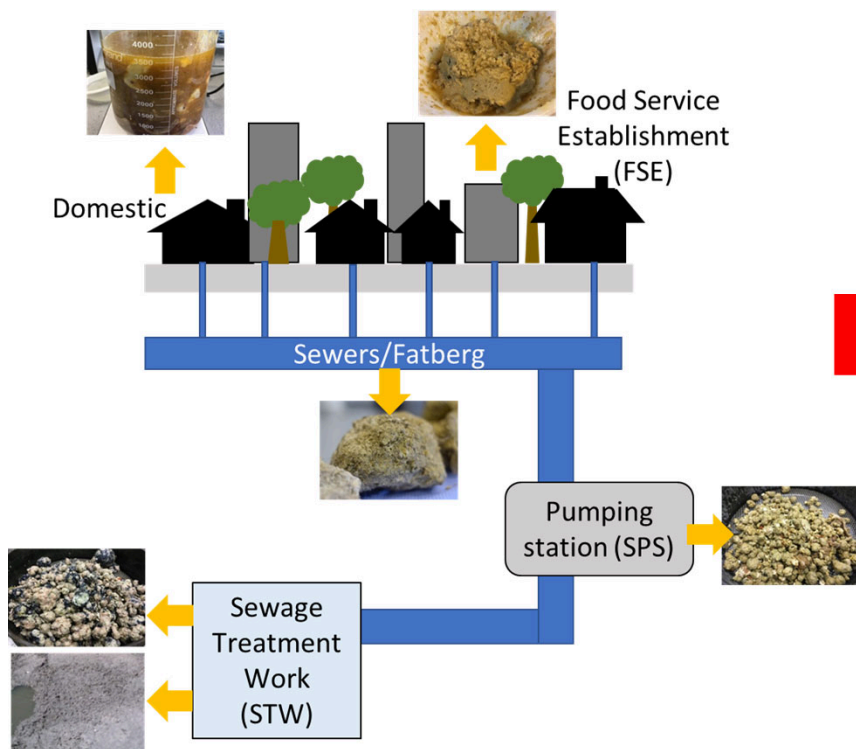
557 **Table 5** Energy potential from FOG in the Thames Water catchment

	Domestic	FSE	Fatberg	STW	Sewage sludge
Material potential (tonnes.year⁻¹)	14,920	79,809	27,449	67,281	306,800 ¹
Energy potential (GWh.year⁻¹)	150	742	209	476	1,582
Energy produced from biogas (GWh.year⁻¹)	30	191	44	84	264

558

¹ Reported as ton DS per year

Graphical Abstract



E-Component

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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