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

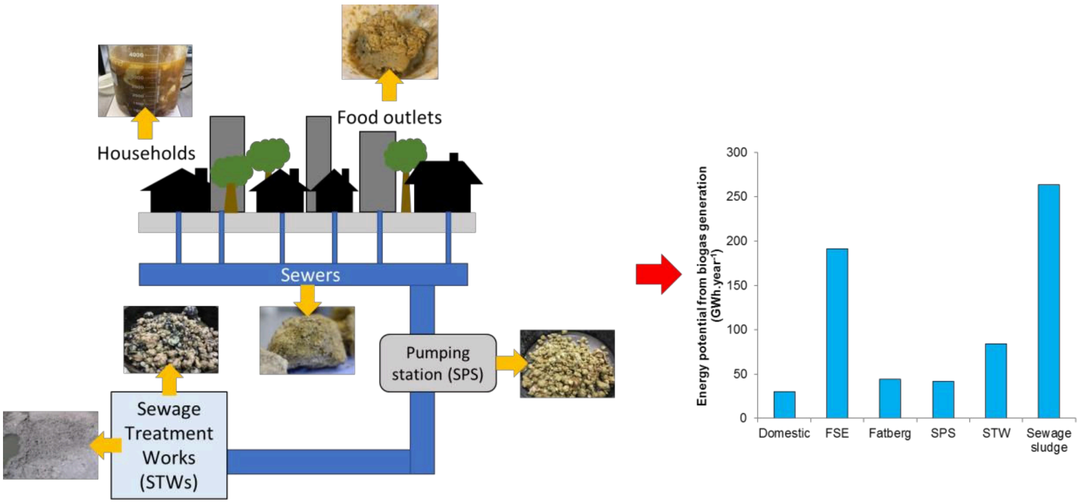
Thomas Collin[1, 2], Rachel Cunningham[2], Bruce Jefferson[1], and Raffaella Villa[1*]

[1] Cranfield University, Cranfield, Bedfordshire, MK43 0AL, United Kingdom

[2] Thames Water Utilities Ltd., Island Road, Reading, Berkshire, RG2 0RP, United Kingdom

*Corresponding author: raffaella.villa@dmu.ac.uk

Graphical abstract



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.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.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.year^{-1} compared to 14,920 tonnes·year^{-1} from private households. This is an important outcome as recovery from

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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

1 Introduction

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

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

2 Methods

2.1 Inoculum and substrates

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

2.2 Analytical methods

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

A chemical characterisation of the main organic fractions (e.g. lipids, carbohydrates, proteins and fibres) was performed on each material. Fibres were measured as the organic matter remaining after samples were de-fatted and digested successively with acid and alkali under controlled conditions (Horwitz, 2003). Proteins were determined either with the Dumas method using Leco FP528 or as total Kjeldahl nitrogen respectively for solid and semi-solid samples respectively. Lipids were measured using a modified Wiebul acid hydrolysis method (Sciantec Analytical, 2018a). Carbohydrates were estimated as the remaining fraction.

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

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

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

$$LHV_d = HHV_d \times (1 - M) - H_V \times M \qquad \textbf{(2-1)}$$

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

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

Where HHV is the measured HHV on wet basis.

2.3 Batch tests

Triplicate batch testing was used to investigate the biomethane content of each material using an AMPTS II system (Bioprocess Control). These assays were performed at mesophilic temperatures (37˚C) using an inoculum to substrate ratio of 2 g $VS_{inoculum}$.g $VS_{substrate}$. DS and VS were determined before and after the digestion period. The experiment was terminated when the cumulative biomethane production reached a plateau phase (at 60 days). The biomethane production was expressed as biomethane yield, mL CH_4.gVS_{added}^{-1}, and specific biomethane yield, mL CH_4.g $VS_{destroyed}^{-1}$ and adjusted to standard temperature and pressure (STP) as follows:

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

Where V_{STP} is the volume adjusted to STP, P_{STP} is the standard pressure (101.3 kPa), T_{gas} is the temperature of the measured gas (311 K), T_{STP} is the standard temperature (273 K) and V_{gas} is the measured volume of gas. P_{gas} was calculated as the sum of the partial pressures of methane and carbon dioxide. P_{CO2} was neglected in the case of the batch testing as carbon dioxide was removed through the stripping solution. P_{vap} is the water vapour pressure calculated as follows:

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

2.4 Volumes and energy appraisal

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

2.4.1 FOG at source

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

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

2.4.2 FOG in wastewater networks

FOG concentrations were measured monthly at 20 STWs in crude sewage over a period of four years. Briefly, samples were filtered a Whatman™ GF/C grade filter paper. The filter paper was immersed in boiling hexane using a Gerhardt SOXTHERM® (40 to 60˚C). Oil and grease were then determined by weight difference and reported in $mg.L^{-1}$. It should be noted that values below the limit of detection of 8.2 $mg.L^{-1}$ were replaced with this value. Oil and grease were measured on average at 59.0 $mg.L^{-1}$ at these STWs (Collin et al., 2019a); this average value was used for the other sites. Quantities of FOG were estimated based on dry weather flow, which is the average daily flow received at STWs, and subtracted from undigested lipids originating from human faeces estimated at 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 collected in SPSs were assumed equal to STWs. Sewer deposits were estimated subtracting volumes at STWs from FOG at source (i.e. domestic and FSE).

2.5 Sewage sludge

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

3 Results and discussion

3.1 Quantification and physicochemical characterisation

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

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

3.2 Biogas potential

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

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

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

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

3.3 Energy recovery potential

Higher organic matter and lipids concentration translated into higher energy content, which was measured as the calorific content of the different materials using a bomb calorimeter (Table 4**Error! Reference source not found.**). FOG collected at source, domestic and GRU, had high calorific values of 36±4 and 33±4 $MJ.kg^{-1}$ respectively on dry basis. Both values were in the range of those previously reported for GTWs (Al-Shudeifat and Donaldson, 2010) and UCOs at 35 and 39 $MJ.kg^{-1}$ respectively (Khalisanni et al., 2008). The fatberg sample was measured at 27 $MJ.kg^{-1}$ DS while SPS and STW had lower values measured at around 25 $MJ.kg^{-1}$ on dry basis. Floating scum (19 $MJ.kg^{-1}$ DS) and sewage sludge (18 $MJ.kg^{-1}$ DS) showed similar values, indicating a reduction in calorific value as the location extended away from the source point. Lipids and water concentration showed a linear inverse correlation for all the samples analysed in this study and those reported in literature (Figure 3). Interestingly, oil concentrations in FOG deposits reported by Williams, et al. (2012) were much lower than those measured by this study and Keener et al. (2008) in the US. This suggests that waste collected from the network is likely to be highly variable in terms of quality and contamination as it gets in contact with sewage and other waste materials in the sewers. Critically, the increased moisture content reduced the lipids fraction by mass indicating that not only does FOG collected from the network require more effort but this negative is compounded through a reduction in its resultant energy value. The total energy available (i.e. calorific value measurement) plotted against the energy available from the conversion of biogas showed conversion yields ranging from 20 to 42% for FOG and averaging 30% for sewage sludge (Figure 4). Not all the energy contained in FOG is convertible to biomethane through anaerobic digestion. Particularly, FOG collected at source demonstrated lower energy conversion yields than other wastes collected further downstream. Facilitating the hydrolysis step, which is the rate limiting step, through pre-treatments (e.g. enzymatic) could help improving the efficiency of the digestion of FOG.

This initial characterisation indicated that materials collected at source with high lipid content, such as domestic and GRU, could be easily used as biodiesel feedstock. Whereas other wastes, such as SPS, sewer and STW, with higher water content, would require an initial dewatering step. The water in the feedstock reacts with the catalyst during the transesterification process leading to a more laborious and expensive process, (Sanford et al., 2009). These materials could be better suited for energy recovery through anaerobic digestion. Biogas derived energy from sludge is currently generating 264 GWh.year-1. Biogas from sewer and STW could add an additional 128 GWh.year-1. Whereas FOG from households and FSEs, estimated at 30 and 191 GWh.year-1 of biogas (Table 5), could be converted into approximately 59,340 m3 of biodiesel (at 80% conversion and density of 0.9).

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

4 Conclusion

The characterisation of selected FOG wastes focused on three main aspects: physicochemical composition, organic macromolecules concentrations and LCFA profiles. The main difference was found in the water content: FOG collected from networks (SPS and sewers) and STW had higher moisture content than FOG collected at source (domestic and FSEs). Predictably, FOG were found to be desirable substrate for anaerobic co-digestion as their high organic matter and lipids content resulted in high methane potential (820-1,040 mL CH_4.g VS^{-1}).

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

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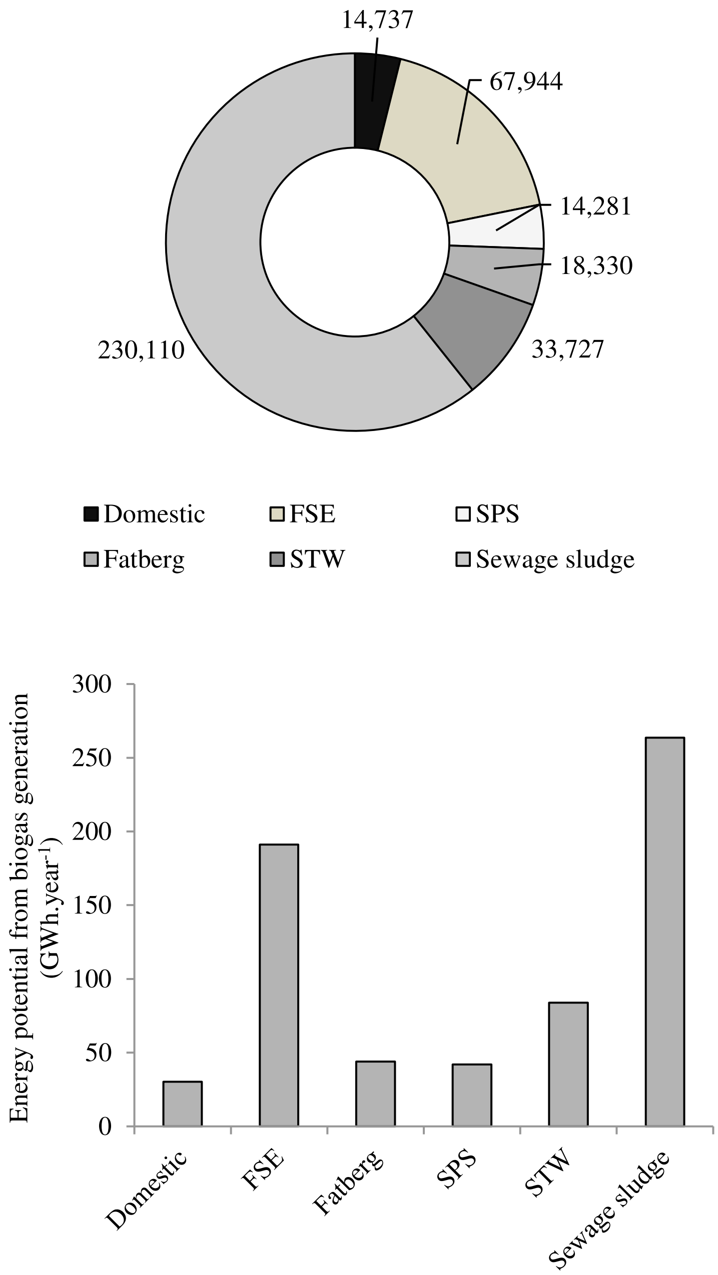

Figure 1 Quantities on a tonnes.year^{-1} dry basis of different types of FOG wastes available in the catchment (a) and their energy potential as biomethane in co-digestion (b)

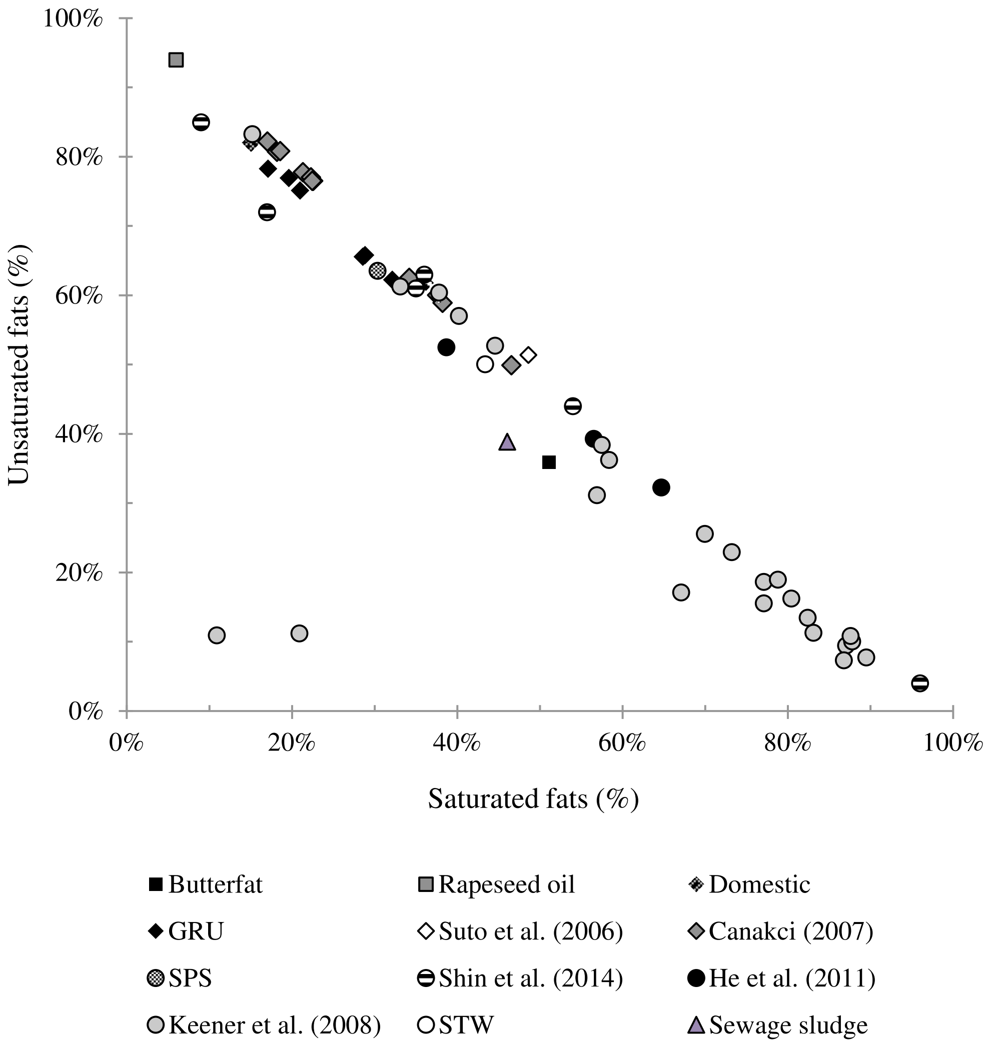

Figure 2 Unsaturated fatty acids reported against saturated fats in FOG wastes as % of total fatty acids. Edible oil and fat are represented with ■ and FOG wastes are categorised as follows: source (◆) and wastewater systems (●).

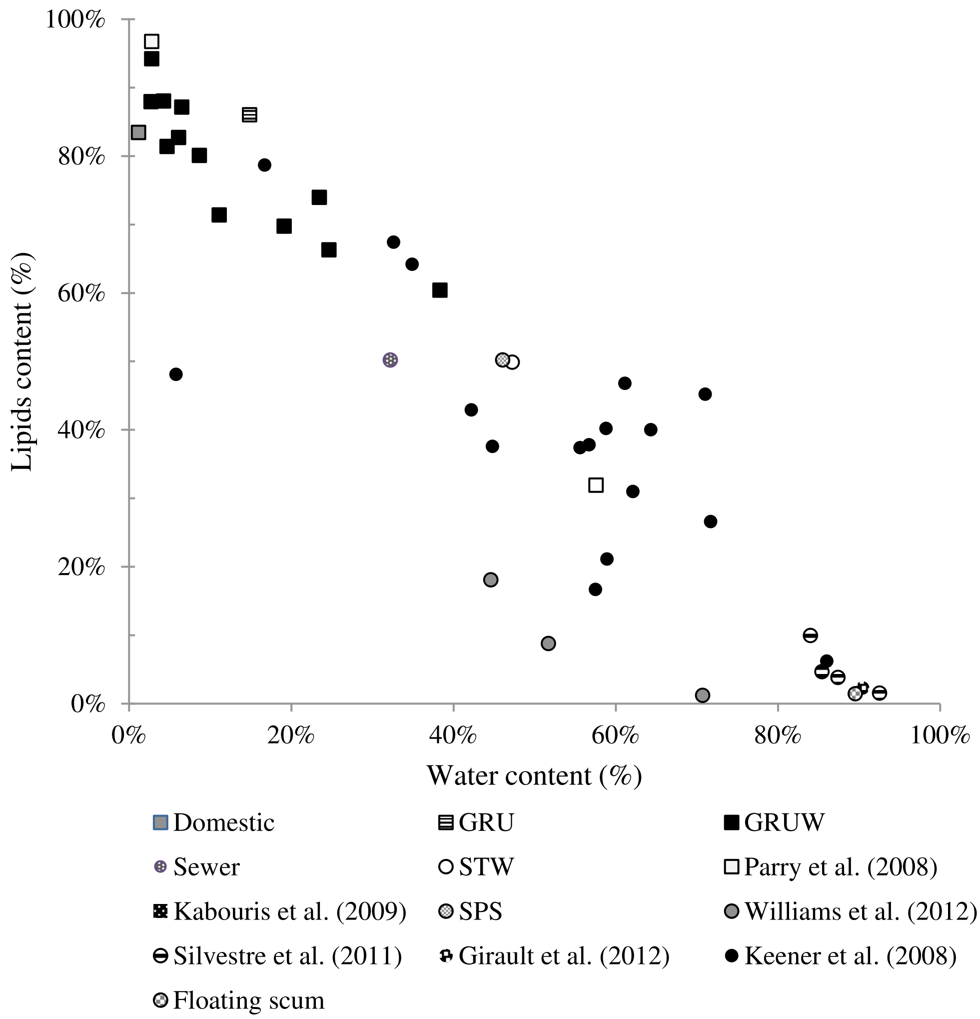

Figure 3 Lipids and water content of FOG wastes (reported as % wet weight). FOG wastes are categorised as follows: source (■) and wastewater systems (●)

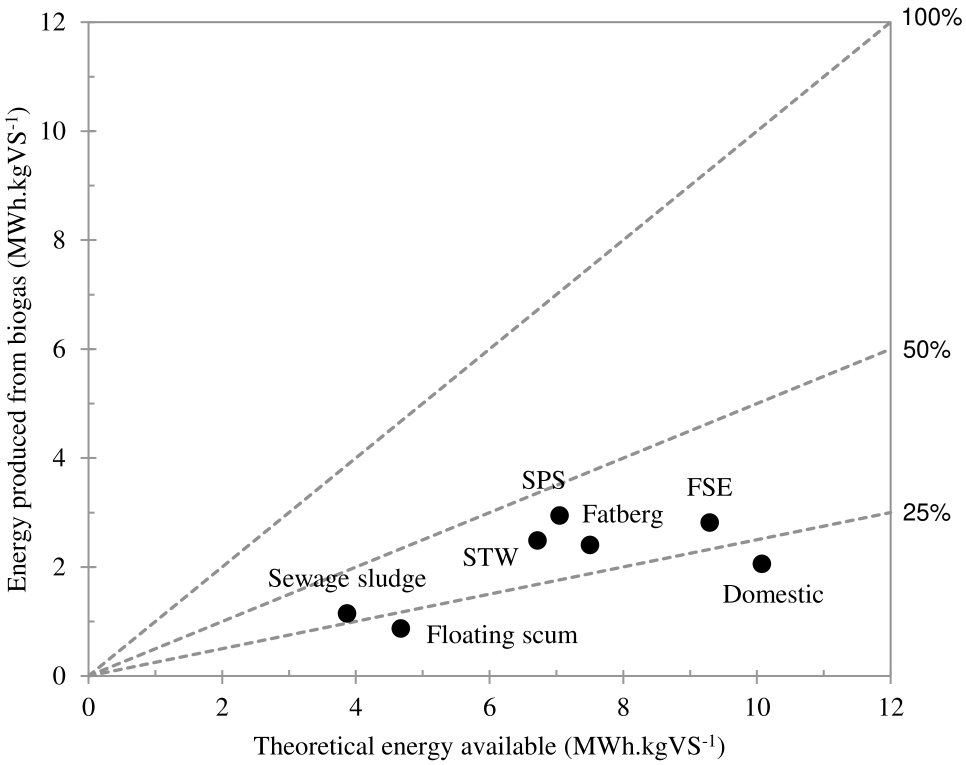

Figure 4 Calorific values of FOG and sewage sludge plotted against biomethane produced for: household FOG (Domestic); FOG from FSEs grease removal units (FSE); FOG/fat balls from pumping station (SPS) and at the sewage treatment works (STW); FOG from sewers deposit (Fatberg); FOG from floating scum at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

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

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

Table 2 Composition in water and organic compounds of different types of FOG wastes 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

[1] Value below the limit of detection

Table 3 Biogas production for FOG and sewage sludge.

Samples	**Theoretical biogas production (mL CH_4.g VS^{-1})**	**Biomethane yield (STP mL CH_4.g VS_{added}^{-1})**	**VSd (%)**	**Biomethane specific yield (STP mL CH_4.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

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

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

[1] Reported as ton DS per year

*Revised Manuscript (With Track Changes)
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Characterisation and energy assessment of fats, oils and greases (FOG) waste at catchment level

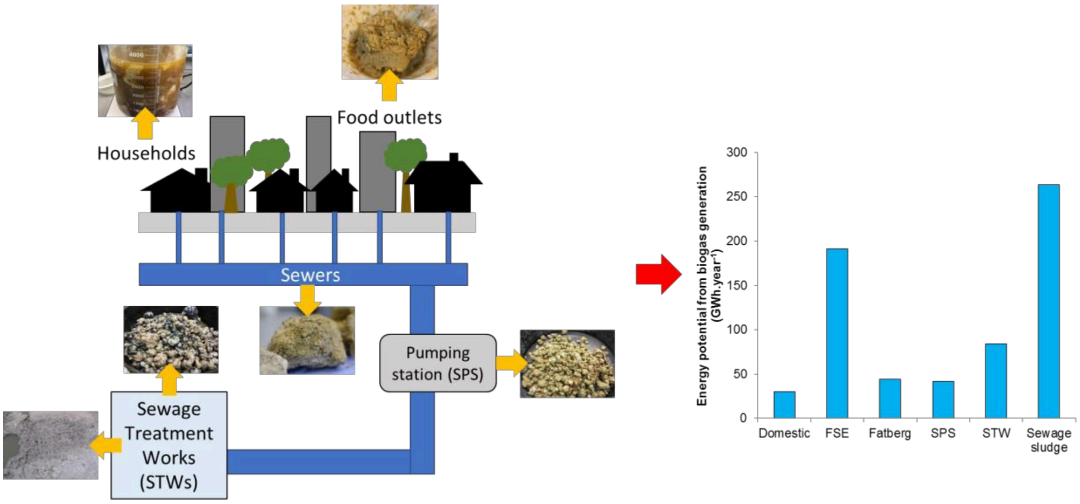
Thomas Collin[1, 2], Rachel Cunningham[2], Bruce Jefferson[1], and Raffaella Villa[1*]

[1] Cranfield University, Cranfield, Bedfordshire, MK43 0AL, United Kingdom

[2] Thames Water Utilities Ltd., Island Road, Reading, Berkshire, RG2 0RP, United Kingdom

*Corresponding author: raffaella.villa@dmu.ac.uk

Graphical abstract



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.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.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.year^{-1} compared to 14,920 tonnes·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

1 Introduction

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

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

2 Methods

2.1 Inoculum and substrates

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

2.2 Analytical methods

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

A chemical characterisation of the main organic fractions (e.g. lipids, carbohydrates, proteins and fibres) was performed on each material. Fibres were measured as the organic matter remaining after samples were de-fatted and digested successively with acid and alkali under controlled conditions (Horwitz, 2003). Proteins were determined either with the Dumas method using Leco FP528 or as total Kjeldahl nitrogen respectively for solid and semi-solid samples respectively. Lipids were measured using a modified Wiebul acid hydrolysis method (Sciantec Analytical, 2018a). Carbohydrates were estimated as the remaining fraction.

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

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

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

$$LHV_d = HHV_d \times (1 - M) - H_V \times M \quad \textbf{(2-1)}$$

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

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

Where HHV is the measured HHV on wet basis.

2.3 Batch tests

Triplicate batch testing was used to investigate the biomethane content of each material using an AMPTS II system (Bioprocess Control). These assays were performed at mesophilic temperatures (37˚C) using an inoculum to substrate ratio of 2 g $VS_{inoculum}$.g $VS_{substrate}$. DS and VS were determined before and after the digestion period. The experiment was terminated when the cumulative biomethane production reached a plateau phase (at 60 days). The biomethane production was expressed as biomethane yield, mL $CH_4.gVS_{added}^{-1}$, and specific biomethane yield, mL CH_4.g $VS_{destroyed}^{-1}$ and adjusted to standard temperature and pressure (STP) as follows:

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

Where V_{STP} is the volume adjusted to STP, P_{STP} is the standard pressure (101.3 kPa), T_{gas} is the temperature of the measured gas (311 K), T_{STP} is the standard temperature (273 K) and V_{gas} is the measured volume of gas. P_{gas} was calculated as the sum of the partial pressures of methane and carbon dioxide. P_{CO2} was neglected in the case of the batch testing as carbon dioxide was removed through the stripping solution. P_{vap} is the water vapour pressure calculated as follows:

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

2.4 Volumes and energy appraisal

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

2.4.1 FOG at source

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

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

2.4.2 FOG in wastewater networks

FOG concentrations were measured monthly at 20 STWs in crude sewage over a period of four years. Briefly, samples were filtered a Whatman™ GF/C grade filter paper. The filter paper was immersed in boiling hexane using a Gerhardt SOXTHERM® (40 to 60˚C). Oil and grease were then determined by weight difference and reported in $mg.L^{-1}$. It should be noted that values below the limit of detection of 8.2 $mg.L^{-1}$ were replaced with this value. Oil and grease were measured on average at 59.0 $mg.L^{-1}$ at these STWs (Collin et al., 2019a); this average value was used for the other sites. Quantities of FOG were estimated based on dry weather flow, which is the average daily flow received at STWs, and subtracted from undigested lipids originating from human faeces estimated at 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 collected in SPSs were assumed equal to STWs. Sewer deposits were estimated subtracting volumes at STWs from FOG at source (i.e. domestic and FSE).

2.5 Sewage sludge

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

3 Results and discussion

3.1 Quantification and physicochemical characterisation

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

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

3.2 Biogas potential

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

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

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

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

3.3 Energy recovery potential

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

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

This initial characterisation indicated that materials collected at source with high lipid content, such as domestic and GRU, could be easily used as biodiesel feedstock. Whereas other wastes, such as SPS, sewer and STW, with higher water content, would require an initial dewatering step. The water in the feedstock reacts with the catalyst during the transesterification process leading to a more laborious and expensive process, (Sanford et al., 2009). These materials could be better suited for energy recovery through anaerobic digestion. Biogas derived energy from sludge is currently generating 264 GWh.year-1. Biogas from sewer and STW could add an additional 128 GWh.year-1. Whereas FOG from households and FSEs, estimated at 30 and 191 GWh.year-1 of biogas (Table 5), could be converted into approximately 59,340 m^3 of biodiesel (at 80% conversion and density of 0.9).

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

4 Conclusion

The characterisation of selected FOG wastes focused on three main aspects: physicochemical composition, organic macromolecules concentrations and LCFA profiles. The main difference was found in the water content: FOG collected from networks (SPS and sewers) and STW had higher moisture content than FOG collected at source (domestic and FSEs). Predictably, FOG were found to be desirable substrate for anaerobic co-digestion as their high organic matter and lipids content resulted in high methane potential (820-1,040 mL CH_4.g VS^{-1}).

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

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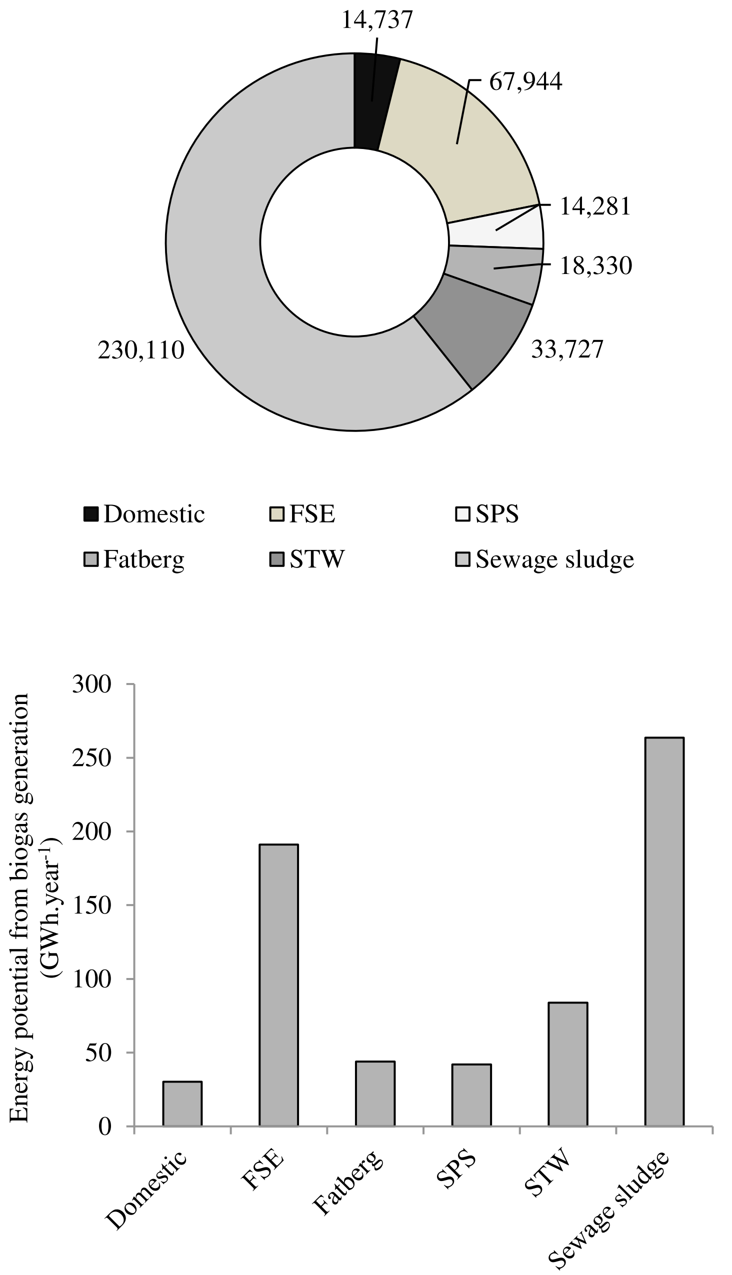


Figure 1 Quantities on a tonnes.year^{-1} dry basis of different types of FOG wastes available in the catchment (a) and their energy potential as biomethane in co-digestion (b)

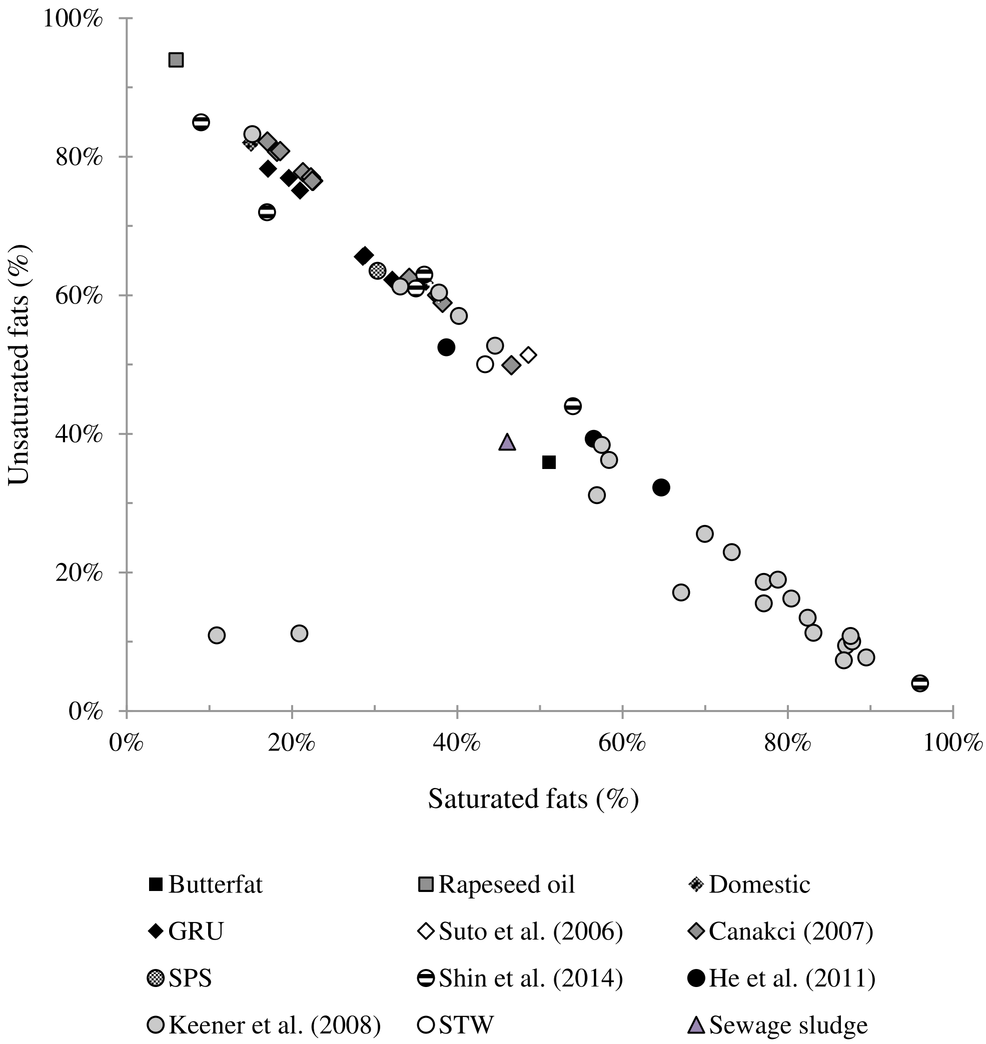


Figure 2 Unsaturated fatty acids reported against saturated fats in FOG wastes as % of total fatty acids. Edible oil and fat are represented with ■ and FOG wastes are categorised as follows: source (◆) and wastewater systems (●).

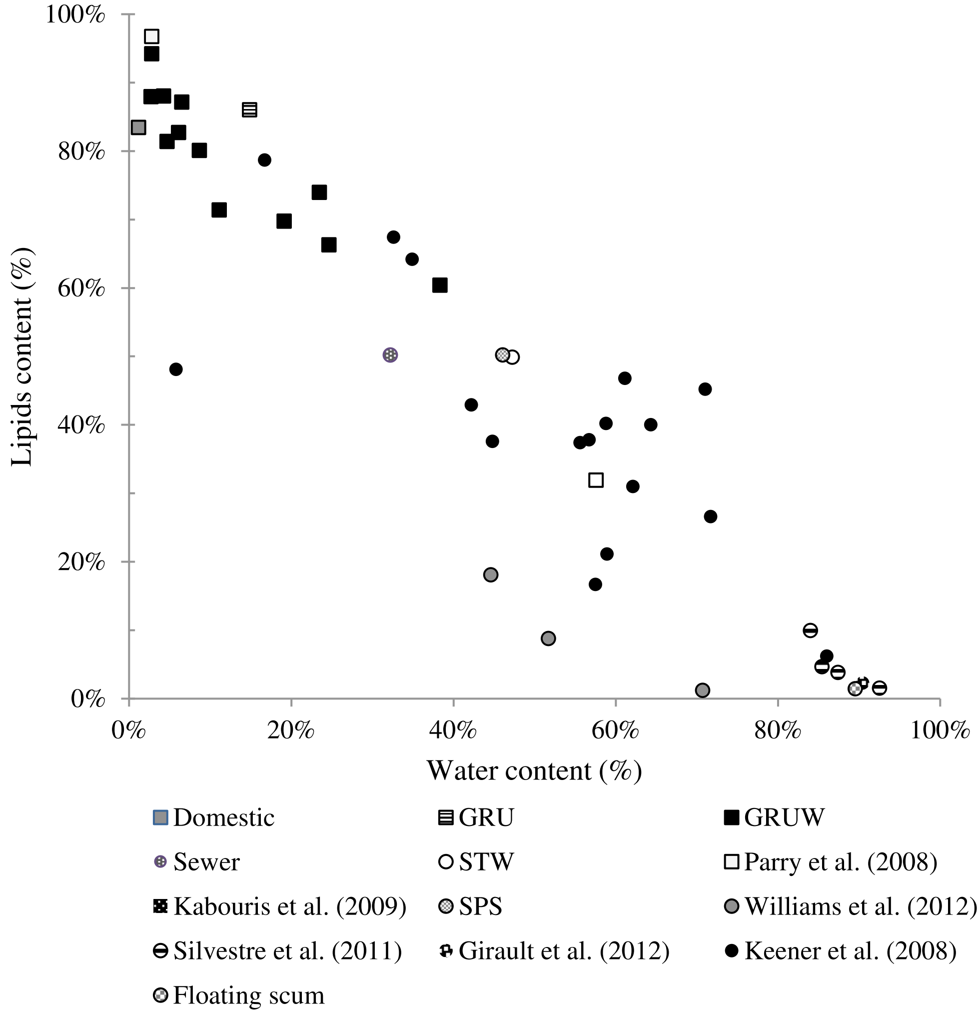


Figure 3 Lipids and water content of FOG wastes (reported as % wet weight). FOG wastes are categorised as follows: source (■) and wastewater systems (●)

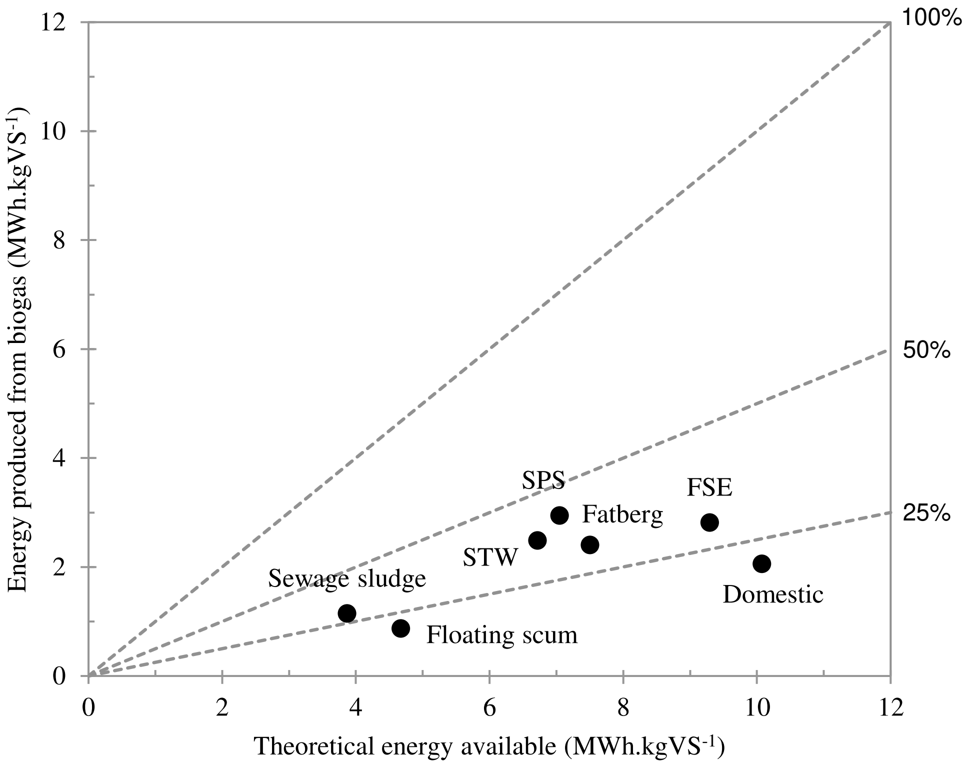


Figure 4 Calorific values of FOG and sewage sludge plotted against biomethane produced for: household FOG (Domestic); FOG from FSEs grease removal units (FSE); FOG/fat balls from pumping station (SPS) and at the sewage treatment works (STW); FOG from sewers deposit (Fatberg); FOG from floating scum at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

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

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

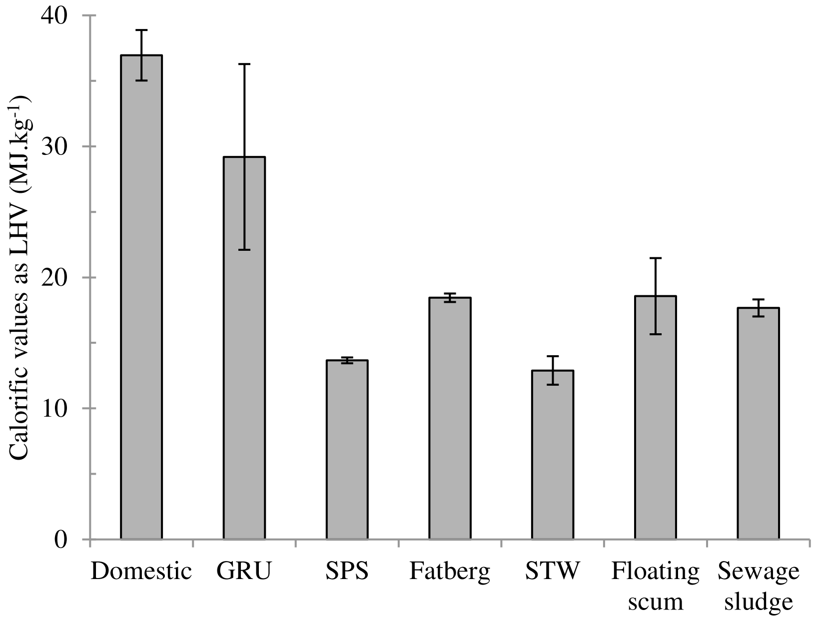
Table 2 Composition in water and organic compounds of different types of FOG wastes available in the catchment

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

[1] Value below the limit of detection

Table 3 Biogas production for FOG and sewage sludge.

Samples	**Theoretical biogas production (mL CH_4.g VS^{-1})**	**Biomethane yield (STP mL CH_4.g VS_{added}^{-1})**	**VSd (%)**	**Biomethane specific yield (STP mL CH_4.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



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

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

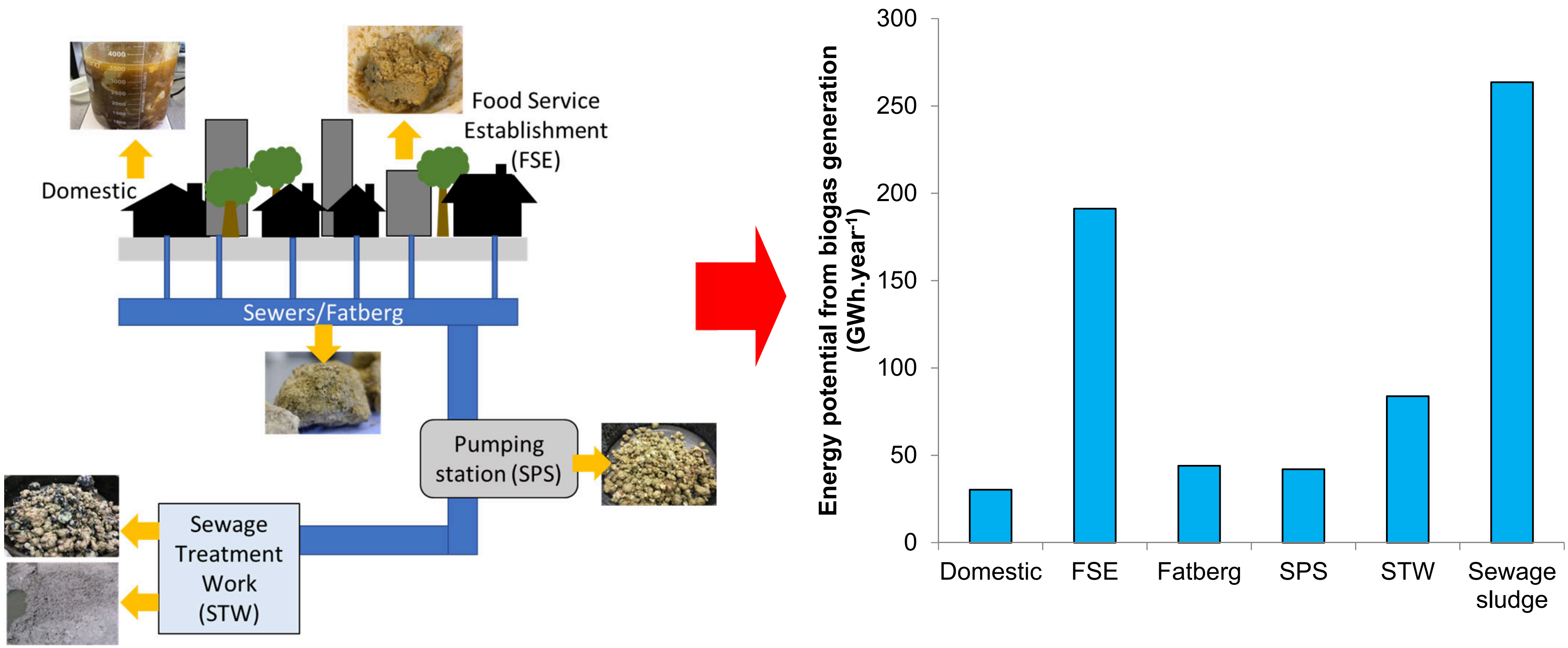
Waste	**LHV ($MJ.kg^{-1}$ wet basis)**	**LHV ($MJ.kg^{-1}$ dry basis)**
Domestic	35±4	36±4
GRU	28±7	33±4
SPS	14±0.2	26±0.3
Fatberg	19±0.3	27±0.4
STW	13±1	25±2
Floating scum	2±0.2	19±2
Sewage sludge	2±0.1	18±1

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

[1] Reported as ton DS per year

Graphical Abstract



E-Component

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***Declaration of Interest Statement**

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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Collin, Thomas

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