

SPECIAL ISSUE ARTICLE

Energy potential of household fats, oils and grease waste

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Abstract

In comparison to fats, oils and grease (FOG) found in commercial and industrial effluents, very little is known about FOG discharged at household level. To address this shortcoming, household FOG production was calculated following a year-long monthly collection at 2.3 kg/year per household, equivalent to 0.8 kg/year per capita. In the United Kingdom, these numbers translate in an annual estimated FOG production of 62 380 tonnes. Physico-chemical characterization of household FOG showed promising results for biodiesel production. Biomethane yield was measured at 875 mL CH₄/g VS added, twice as much that of sewage sludge, making it a desirable substrate for anaerobic digestion. It was thus estimated that energy recovery from household FOG through anaerobic co-digestion or biodiesel production could generate about 490 GWh/year in the United Kingdom. However, insights from participants revealed that most of this waste is currently not recovered, requiring the development of schemes fitting with households' routine to maximize collection rates.

KEYWORDS

anaerobic digestion, biodiesel, fatberg, food waste, sewer deposits

1 | INTRODUCTION

Over the last decade, fats, oils and grease (FOG) deposits in sewerage systems (also known as fatbergs) have gained interest across the different stakeholders of the water industry but also with the general public (Engelhaupt, 2017; Moss, 2018). Food outlets, which are believed to be one of the main responsible for FOG discharges, have been accordingly under deeper scrutiny from water authorities. In contrast, domestic customers have often received a lower priority for interventions generally limited to customer awareness and education campaigns (Georges et al., 2017; Wallace et al., 2017). Yet, it is likely that the impact of household FOG discharges might not be negligible especially in densely populated areas such as London. Although a few piloted customer campaigns have tried to drive more sustainable behaviours on the domestic end, very little information has been published on household discharges, and these studies are often limited to their assumed positive

outcomes on sewerage systems (Anglian Water, 2014; Foden et al., 2017; Olleco, 2015; Yorkshire Water, 2015). Therefore, in absence of a clear waste management strategy, it is posited that most of the FOG from domestic sources will be either allowed into the drains or disposed of into the general waste bin.

As FOG is a lipid-rich material, diversion from sewers has the potential to go beyond protecting wastewater assets (i.e. through energy recovery). To date, research has largely focused on FOG collected from food service establishments (FSEs), demonstrating its potential to enhance biogas generation when used in anaerobic digestion with either sewage sludge (Kabouris et al., 2009a; Long et al., 2012) or the organic fraction of municipal solid waste (Kumar et al., 2018), as well as its potential to be converted into biodiesel (Lee et al., 2017). However, the levels of water and free fatty acids (FFAs) in some sources of FOG wastes are known to negatively affect their energy recovery. For instance, water reacts with the

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catalyst used during biodiesel conversion, leading to a more laborious and expensive process (e.g. inclusion of heating or vacuum distillation; Demirbas, 2009; Felizardo et al., 2006). High level of acidity in the oil (e.g. presence of FFAs) leads to the formation of soaps during the transesterification process (Saraf & Thomas, 2007), reducing the reaction's yields and increasing the viscosity of the biodiesel mixture (Atadashi et al., 2012). Critically, it is generally admitted that significant problems may occur in the transesterification process when the FFA content is above 3% (M. P. Dorado et al., 2002). To address this shortcoming, the most commonly employed technique is an acid esterification with methanol and sulphuric acid (Van Gerpen, 2005). Further to this, long-chain fatty acids (LCFAs), which are the most prominent component of FOG wastes, showed toxic effects of LCFA on acetoclastic methanogens in anaerobic digesters (Alves et al., 2009; Palatsi et al., 2010). This can result in their accumulation, causing sludge flotation, digester foaming and blockages of pipes and pumps (Alves et al., 2009). Therefore, understanding the physico-chemical properties of household FOG is recommended prior to utilization.

Ultimately, there is a need for both quantitative and qualitative data from domestic sources to be published to support the development of a more sustainable waste management strategy that focuses on resource recovery. To address this knowledge gap, a 1-year trial was developed to collect FOG from 31 households. The collected wastes were first characterized chemically and then evaluated for their potential as co-substrates for anaerobic digestion with sewage sludge. Using experimental data in conjunction with published literature, a high-level assessment of energy potentials was provided for the United Kingdom and put into perspectives with existing regulatory frameworks.

2 | METHODS

2.1 | Collection

The trial was conducted internally within a UK water utility, and 150 employees were initially emailed from which 31 volunteered to take part in the trial. Participants resided within the utility operational boundaries, although some of them were located in different boroughs. Reusable sealable containers were provided to these volunteers, and collection was scheduled monthly over a year. Containers were pre-weighted, and masses were recorded, monthly, for each volunteer. Each volunteer corresponded to one household and were not all located within the boundaries of the same local authority. As participation varied over the course of the trial, results were adjusted to reflect volumes based on participation (i.e. total number of months participated), and average volumes collected were reported in kg/month.

Monthly, the content of each container collected was added to a 5-L glass beaker. The samples were then heated to 35°C in order to melt solid fats and, finally, sieved to remove large particulates of food waste. FOG was then stored in a cold room at 2°C for further analyses.

An initial assessment was conducted to determine demographics along with participants' current FOG disposal practices. Six months into the trial, another survey was carried out to investigate people's

experience in relation to FOG collection. Both questionnaires were emailed to participants and then collected either as digital or hard copies. This assessment was purely motivated to provide insights on FOG sources in kitchens, and it is accepted that it might not reflect practices for the wider UK population or elsewhere. FOG disposal routes were compared to information provided by local authorities located within the water utility catchment, in the London area, on their respective websites (accessed in August 2018).

Results from this trial were compared with those gathered during a similar study conducted by the water utility in 2011 (McKinney, 2012). In brief, around 220 households in a residential estate were engaged, and domestic FOG were collected from the participants' doorstep monthly over a year. Unfortunately, at this time, no information was gathered regarding the physico-chemical properties of the FOG collected. Households are not singular identities, and many factors affect food choices (Committee on Examination of the Adequacy of Food Resources and SNAP Allotments, 2013) and in turn FOG generation. Critically, it becomes important to gather additional data on production rates.

The engagement from this study was evaluated at 21%: 31 out of the 150 employees emailed expressed interest to take part in the trial. This was relatively similar to the door-to-door collection study where 59 out of the 220 properties targeted (27%) took part at least once in the trial (McKinney, 2012).

2.2 | Physico-chemical characterization

Dry solids (DS) and volatile solids (VS) were determined according to standard methods (APHA, 2005). The major organic constituents were determined by laboratory analyses: fibres by gravimetry, proteins as total Kjeldahl nitrogen and lipids through Wiebul acid hydrolysis (Sciencetec Analytical, 2018a). Carbohydrates were estimated as the remaining fraction. Theoretical methane yields were calculated from these organic constituents, considering that carbohydrates, proteins and lipids, respectively, yield 415, 496 and 1014 mL CH₄/gVS at standard conditions of temperature and pressure (STP) following Buswell's equation (Angelidaki & Sanders, 2004; Buswell & Neave, 1930).

Methylated fatty acid profiles were obtained by gas-liquid chromatography using a FFA phase column of dimensions 25 m × 0.20 mm ID and detection by flame ionization. Fats and oils were trans-esterified to fatty acid methyl esters (FAME) by heating under reflux for 2 h with a mixture of methanol and sulphuric 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 (Sciencetec Analytical, 2018b).

Peroxide, saponification and acid values were, respectively, determined in accordance with methods AOCS Cd 8-53, EN ISO 6293 and EN 14104. The ester value was calculated by subtracting the acid value from the saponification value. The percentage of FFAs, in terms of oleic acid, was calculated from the acid value as

$$\text{FFA}(\%) = \frac{\text{Acid value}}{56.1} \times 28.2 \quad (1)$$

Gross calorific values were determined experimentally using a calorimeter (Parr model 6100) equipped with a 1108CL oxygen bomb. Samples were freeze-dried beforehand (Sciencetec Analytical, 2018c). The lower heating values (LHV) were estimated from the measurement of calorific values by subtracting the heat of vaporization of water in the products as follows:

$$\text{LHV}_d = \text{HHV}_d \times (1 - M) - H_v \times M \quad (2)$$

where M is the moisture content, H_v is the latent heat of vaporization of water estimated at 2.447 MJ/kg at 25°C and HHV_d is the gross heating value in MJ/kg on dry basis determined as follows:

$$\text{HHV}_d = \frac{\text{HHV}}{1-M} \quad (3)$$

where HHV is the measured HHV on wet basis.

2.3 | Anaerobic batch testing

Digested sludge, serving as inoculum, was sampled from a full-scale anaerobic digester treating municipal sewage. The site was selected based on its stable operation and ease of access for sampling. This plant was using the Cambi thermal hydrolysis process to pretreat sewage sludge prior to anaerobic digestion. Sewage sludge samples were obtained from the same site after the thermo-hydrolysis treatment step (Table 1).

Triplicate batch testing was conducted using Automatic Methane Potential Test Systems (AMPTS) II at mesophilic temperatures (39°C). A ratio of 2:1 VS_{inoculum}:VS_{substrate} was used for this trial (Nazaitulshila et al., 2015). Batch testing was conducted in 1-L glass bottles continuously stirred with a dedicated stirrer, and each bottle was connected to a CO₂ stripping solution with a pH indicator to show solution saturation. Reactors containing only the inoculum were operated to take into account any endogenous biomethane production. Combinations of FOG and sludge were digested at different substrate ratios with identical feed concentrations of 8.1 g VS (Table 1). At the end of each experiment, DS and VS were measured to evaluate the VS destruction. Organic macromolecules were analysed from the digested samples as described in Section 2.2.

Methane production rates were adjusted to STP as follows:

$$V_{STP} = \left(1 - \frac{P_{vap}}{P_{gas}}\right) \times \frac{P_{gas}}{P_{STP}} \times \frac{T_{STP}}{T_{gas}} \times V_{gas} \quad (4)$$

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

TABLE 1 Inoculum and substrate characteristics and initial amount (expressed as g VS) added to the reactors

Material	DS (%)	VS (%DS)	Lipids (%DS)	Concentrations added (g VS)										
Inoculum	4.8 ± 0.1	61.7 ± 1.0	6.7 ± 0.5	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2
FOG	81.5 ± 12.9	99.4 ± 0.7	94.3 ± 6.6	0.0 (0%)	0.8 (10%)	1.6 (20%)	2.4 (30%)	3.2 (40%)	4.0 (50%)	4.9 (60%)	5.7 (70%)	6.5 (80%)	7.3 (90%)	8.1 (100%)
Sludge	9.7 ± 1.6	76.7 ± 0.6	12.8 ± 2.4	8.1	7.3	6.5	5.7	4.9	4.0	3.2	2.4	1.6	0.8	0.0

of methane and carbon dioxide. P_{CO_2} was assumed negligible as carbon dioxide was removed through the stripping solution. P_{vap} is the water vapour pressure calculated as follows:

$$P_{vap} = 10^{8.1962 - \frac{1730.63}{T_{gas} - 39.724}} \quad (5)$$

2.4 | Energy potential

Four energy recovery routes were considered: (1) landfilling, (2) incineration, (3) conversion to biodiesel (3) and anaerobic digestion (4). In landfills, methane is produced as a by-product of the degradation of organic wastes with reported production rates of 43 m³ per ton (Themelis & Ulloa, 2007). The calorific value of biomethane was considered to be 36 MJ/m³, whereas efficiency of electricity generation was assumed at 40% from combined heat and power plants (CIWEM, 2014). Energy generation from incineration was calculated from the LHV of domestic FOG assuming a 20% conversion efficiency (CIWEM, 2014). Experimental methane generation and biodiesel conversion yields were used to calculate energy potentials from anaerobic digestion and biodiesel production. The equivalent of 1 m³ of biodiesel was 0.78 ton of oil equivalent (toe) further corresponding to an energetic value of 11.6 MWh/toe (Eurostat, 2018).

3 | RESULTS AND DISCUSSION

3.1 | Domestic questionnaire and FOG production rates

The questionnaire of domestic FOG generation revealed that all the respondents predominately used vegetable oil and in particular olive oil (73% of the respondents). In addition, 77% also used animal fat, predominately in the form of butter. The collected oil was from either oil residues from pans and plates (82% of respondents) or fats from cooked meats (55% of respondents), with an additional source coming from used food jars. Comparison to the previous survey revealed a shift in cooking practice as the previous surveyed identified the main cooking practices as deep fat frying (48%), shallow frying (2%), bhajee frying (2%) and wok frying (5%). In both cases, vegetable oils were identified as the main FOG source, which is consistent with practice in FSEs (Envirowise, 2008).

Production rates, from the 31 households monitored, ranged from 0.01 to 0.5 kg·month⁻¹ with an average value of 0.19 kg/month per household (Figure 2). These values were much lower than those observed in the previous survey in 2011 (McKinney, 2012) where a wider range of values were recorded from 0.01 up to 6.9 kg/month per household, with rates higher than 1 kg/month for 11 households, whereas all households in this trial produced less than 0.6 kg/month. Other reported studies are consistent with these findings, indicating an overall reduction in FOG generation per household. For instance, a

recent UK survey estimated FOG generation rates of 0.22 kg/month per month (Questaed et al., 2013) although this was reassessed to be within a range of 0.05–0.17 kg/month per household (Gelder & Grist, 2015). In Canada, the Capital Regional District in British Columbia estimated FOG from domestic sources at 0.47 kg/month per household (Blanc & Arthur, 2013). In estimating FOG production rates from households, diversity within and between households needs to be appreciated. Households are not singular identities, and food preparation, and in turn FOG generation, is strongly impacted by a variety of factors including number of occupants as well as social and cultural factors (Committee on Examination of the Adequacy of Food Resources and SNAP Allotments, 2013). One notable difference between both studies was household sizes measured at 2.7 occupants for this study and 4.4 occupants for the study by McKinney (2012). However, volumes normalized based on occupancy in this study were still found lower, at 0.07 kg/month per capita, compared with McKinney (2012), at 0.17 kg/month, suggesting other factors influencing FOG production.

Current disposal routes were further investigated from the trial participants. Disposing of the FOG in the general waste bin was the most common route, representing 65% of the respondents (Figure 1a). A further 19% recycled the FOG with the food waste and 3% into fat traps with 13%, stating that they did not have a way to dispose of FOG (i.e. potential discharge into the drains). Water companies in the United Kingdom all provide advice on FOG management in order to limit sewers' disposal and generally encourage putting this waste into the bin (Severn Trent Connect, 2019; Thames Water Utilities, 2016). However, a survey of 102 local authorities revealed

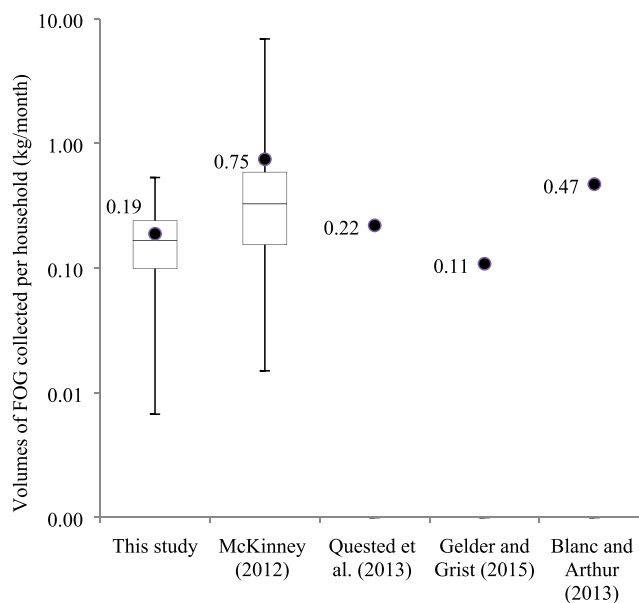


FIGURE 1 Volumes of FOG collected from this trial compared to estimates available in literature. The line in the middle of each box represents the median, the upper half of the box represents the third quartile, and the lower one represents the second quartile. The error bars represent the minimum and maximum. Black markers represent the averages across the population

that 25% of them did not provide any guidance on their website to costumers. When available, the routes recommended by the local councils for FOG collection were (1) household waste recycling centre (HWRC) (56%), (2) food waste collection (15%) and (3) waste bin (9%) (Figure 1b). Interestingly, none of the participants in this study and only a few respondents to the survey undertaken in 2011 disposed of FOG as suggested. Foden et al. (2017) proposed that the unsuccessfulness of this approach was probably due to the households' everyday busy life. In relation to collection in food waste, 72% of the surveyed councils had kerbside food waste collection scheme (estimated at 61% across the United Kingdom; WRAP, 2016a), but only 21% accepted FOG in caddies, mainly in the form of solid fats and in small volumes.

3.2 | Physico-chemical characterization

The collected FOG had physical properties that were observed to be variable between households, ranging from yellow to light brown colours and either liquid or semi-solid states at room temperature (Figure S1).

The water content of the blended domestic FOG was on average $4.2 \pm 2.3\%$ (Table 2), being slightly higher than that reported for UCOs generated from the food industry, ranging from 0.04% to 1.4% with an average of 0.2% (Cheah et al., 2016; Hailei & Hui, 2014; Sanford et al., 2009; Sanli et al., 2011; Supple et al., 2002). This result was posited related to the more complex generation pathways with domestic

FOG than UCOs. By contrast, FOG collected from grease separators in food outlets were associated with much higher and variable moisture content, depending upon the type of separator installed, ranging from 0.1% to 91.3%, the higher end representing complete emptying of the separator rather than just the partitioned FOG fraction (Collin et al., 2020; Evans et al., 2012; Kabouris et al., 2009b; Miot et al., 2013).

Due to its FOG-rich nature, nearly 100% of the solids in the collected wastes were volatile. Lipids and carbohydrates accounted for most of the organics measured with concentrations, respectively, found at $94.3 \pm 6.6\%$ on DS basis and $5.7 \pm 6.1\%$ DS (Table 1). This further translated into high LHV measured on average at 38.2 ± 1.4 MJ/kg (Table 2). In comparison, reported values for UCOs are slightly higher, typically ranging between 37.2 and 40.3 MJ/kg (Ortner et al., 2016; Sanli et al., 2011; Supple et al., 2002), whereas FOG from grease separator was found between 24.5 and 41.6 MJ/kg (Collin et al., 2019). Ultimately, with low water content and lipid-rich composition, household FOG represents a valuable energy source that has the potential to be converted into biogas or biodiesel.

It is important to understand the physico-chemical properties of these wastes as parameters including water and FFA can hinder the viability of the process. The collected FOG had FFA content similar to UCOs, with FFA levels measured at $2.7 \pm 0.3\%$. UCOs typically contain between 0.1% and 9.0% FFAs and are considered a good biodiesel feedstock (Berrios et al., 2010; Cheah et al., 2016; Sanford et al., 2009; Sanli et al., 2011). By contrast, FFA concentrations are higher in FOG collected from grease separators, ranging from 0.7% to

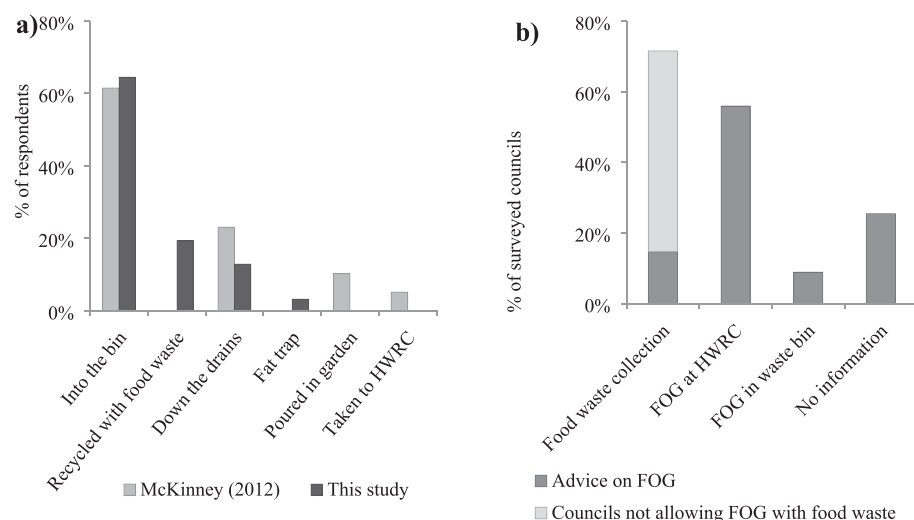


FIGURE 2 Disposal routes as reported by survey respondents (a) and suggested by local authorities (b). Websites for 102 local authorities located in the London area were accessed to gather information provided to households on FOG disposal

TABLE 2 Physico-chemical parameters of FOG collected at source

FOG waste	LHV (MJ/kg)	Water content (%)	FFA (%)	Peroxide value (meq H ₂ O ₂ /kg)	Ester (%)
UCO	39.3 (37.2–40.3)	0.2 (0.04–1.4)	1.4 (0.1–8.9)	40.8 (0.5–200.4)	99.0 (90.1–99.9)
FSE FOG	35.4 (24.5–41.6)	18.6 (0.1–91.3)	34.3 (0.7–97.8)	6.7 (0.2–52.1)	
Household FOG	38.2 (36.3–39.3)	4.2 (1.5–8.3)	2.7 (2.3–3.1)	23.9 (12.7–31.1)	96.1 (92.9–97.7)

Notes: Average values are presented alongside minimum and maximum. Values generated for domestic FOG were obtained from this study, whereas those for UCOs and FOG from FSEs were collected from literature.

97.8% with a median value of 34.3% (Canakci, 2007; Karnasuta et al., 2007; Kobayashi et al., 2016).

3.3 | Anaerobic co-digestion of household FOG

The collected and blended FOG wastes were used as feedstock, alone or co-digested with sludge, in batch reactors, to assess their potential for biomethane generation. The biomethane yield of FOG was measured at 875 ± 108 STP mL CH₄/g VS_{added}, twice the level measured for sewage sludge at 376 ± 32 STP mL CH₄/g VS_{added}. Biomethane yields for household FOG were found in good agreement with theoretical estimates calculated at 974 ± 44 mL CH₄/g VS (Table 3). Yet, these experimental yields were found lower than those measured for FSE FOG at 938 ± 39 STP mL CH₄/g VS_{added} (Collin et al., 2020) and 993 STP mL CH₄/g VS_{added} (Kabouris et al., 2009a). Lipids degradation rates were found at $87 \pm 0.3\%$ for household FOG, translating into lower methane yields, at 840 ± 61 STP mL CH₄/g lipids_{destroyed}⁻¹, than reported from the other sources. Ultimately, several strategies could be adopted to increase these degradation rates including (1) saponification of lipids to enhance their solubilization (Battimelli et al., 2010), (2) enzymatic pretreatments (Bouchy et al., 2012; Cirne et al., 2007) and (3) the application of pulse-feeding procedures (Palatsi et al., 2009; Ziels et al., 2017).

The results from reactors digesting mixtures of FOG and sewage sludge in different concentrations showed that the methane potential was increased with increasing amount of household FOG (Figure 3a). Similar results were obtained by Davidsson et al. (2008), co-digesting grease trap waste collected from FSEs. Reactors only digesting sludge exhibited the lowest lipid degradation measured at $35 \pm 4\%$ (Figure 3b). As a benchmark, lipid degradation in full-scale anaerobic systems generally vary from 20% to 70% (Liu, 2018). As more FOG over sludge was added to the reactors, the lipid degradation rates increased, suggesting a good degradation of lipids contained in household FOG. The maximum degradation rate was reached with FOG only and was measured at $87 \pm 4\%$, suggesting not all the lipids were degradable in these conditions caused by LCFAs, which are known to inhibit acetoclastic methanogens and, in turn, biogas generation (Alves et al., 2009).

TABLE 3 Results from the batch testing of sewage sludge and household FOG

Parameter	Sewage sludge	FOG
Experimental methane yield (STP mL/g VS _{added})	376 ± 32	875 ± 108
Theoretical methane yield (STP mL/g VS)		974 ± 44
VS destruction (%)	57 ± 7	87 ± 11
Lipids destruction (%)	35 ± 4	87 ± 0.3
Experimental methane yield (STP mL/g VS _{destroyed})	645 ± 141	942 ± 36

From waste characterization, the five most common LCFAs in domestic FOG were: oleic (C18:1), linoleic (C18:2), palmitic (C16:0), stearic (C18:0) and linolenic acids (C18:3) with respective concentrations of $41.4 \pm 10.3\%$, $31.5 \pm 9.1\%$, $12.2 \pm 1.7\%$, $4.8 \pm 1.0\%$ and $3.8 \pm 3.2\%$ of total fatty acids (Table 4). Data on the toxicity of LCFAs, reported as the concentration causing a 50% relative activity loss of the specific methane production (IC₅₀), have been published in literature by several authors (Alves et al., 2001; Lalman & Bagley, 2000; Pereira et al., 2005; Prinst et al., 1972; Shin et al., 2003). Using these values, inhibitory loadings were calculated for the main LCFAs measured in household FOG (Table 4), thus identifying oleic and linoleic acids with inhibitory concentrations to the anaerobic digestion process with loadings as low as 0.1 g VS. Consequently, without a proper feeding strategy, the addition of FOG to anaerobic digesters is risky if the accumulation of LCFAs is not prevented.

3.4 | Prospective energy potential from household FOG

With 27.6M households in the United Kingdom, it is estimated that there is the potential to collect 62 380 tonnes of FOG annually. The London region only would account for 23% of this volume, equating to around 14 240 tonnes of FOG per year. In comparison, for the same catchment, it was previously estimated that 79 810 tonnes of FOG was produced annually from FSEs (Collin et al., 2020). The comparison of the energy potential that the domestic FOG could yield reveals similar levels when processed as a co-substrate in anaerobic digestion or biodiesel production (assuming conversion yields at 86%; Lee et al., 2017), at yields of 490 and 487 GWh/year, respectively. In other words, this would represent 22% of the estimated 2220 GWh-year⁻¹ generated in the United Kingdom from sewage sludge (Mills, 2015). These potential yields greatly exceed the equivalent levels achievable from landfill or incineration at 27 and 126 GWh/year, respectively. In assuming a conversion efficiency of 40% to generate electricity from biogas (CIWEM, 2014), using biogas generated from anaerobic digestion or biodiesel produced from household FOG in combined heat and power engines would power 46 980 houses (considering an average domestic energy consumption of 4.2 MWh/year; UK Department of Energy & Climate Change, 2014). In comparison, using FOG in waste-to-energy plants would generate enough power to supply 30 340 houses.

A common challenge, irrespective of processing preference, is the collection of the material and hence what proportion of the total estimate is practical. This depends on collection mode, be it door-to-door or centralized collection schemes. Maximum collection rates have been hypothesized to occur from kerbside collection, which also presents a better fit with household routines (Seyring et al., 2015). However, the logistical, financial and environmental implications of such a service (Foden et al., 2017) mean that co-collection with food wastes appears a more practical option. Currently, only a small percentage of local councils providing a kerbside food waste collection were accepting FOG due to difficulties in handling FOG in food waste caddies (Figure 2b).

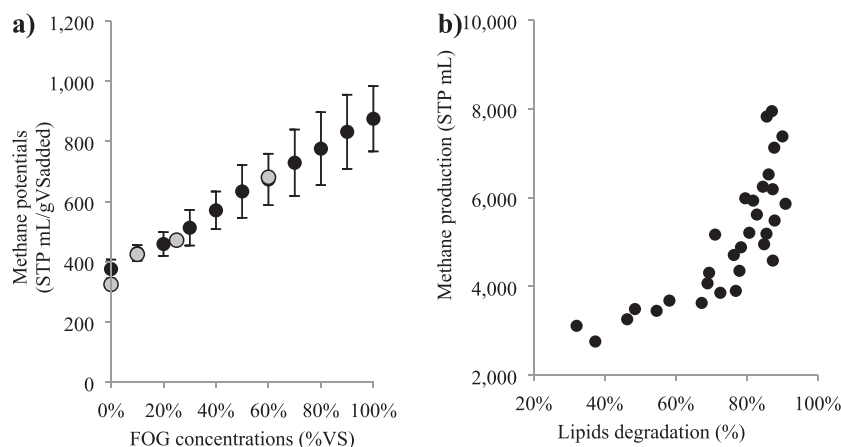


FIGURE 3 Cumulative biomethane production reported against FOG concentrations (expressed as % VS added) (a) and lipids removal rates (b)

● Domestic FOG ○ Davidsson et al. (2008)

TABLE 4 Five most common LCFAs measured in household FOG and their associated IC_{50}

LCFA	Concentration in FOG (% total fatty acid)	IC_{50} (mg L ⁻¹)	Inhibitory loading (g VS)
C16:0	12.2 ± 1.7	1100 (Pereira et al., 2001)	9.3
C18:0	4.8 ± 1.0	1500 (Shin et al., 2003)	32.4
C18:1	41.4 ± 10.3	50 (Alves et al., 2001)	0.1
C18:2	31.5 ± 9.1	30 (Lalman & Bagley, 2000)	0.1
C18:3	3.8 ± 3.2	500 (Prinst et al., 1972)	13.4

Note: The inhibitory loadings were calculated from the characterization of FOG.

However, assuming that food waste is produced at a rate of 22 kg/month/household (Quested & Parry, 2016), FOG would typically represent less than 1% of this volume and so should not cause any difficulties. With 61% of UK local authorities collecting food waste from households and estimated participation rates of 45% (WRAP, 2016a), around 17 120 tonnes of FOG could be recovered through co-collection (equating to 27% of the total volume generated nationwide). The alternative is *bring schemes* where the FOG is collected in local drop-off points (Seyring et al., 2015) with illustration of such approaches in some US municipalities including co-development with retailers to improve the fit of these methods with household's routine (City of Dallas, 2019). Assessing participation rates for *bring schemes* is a difficult exercise; nevertheless, a study published on food waste collection from flats using *bring schemes* estimated participation rates of 14% (WRAP, 2016b). Ultimately, assuming similar rates, around 8730 tonnes of FOG would be collectable annually from *bring schemes*.

The collection approach adopted will impact the potential downstream processing routes. Co-collection with source-segregated food waste directs preference towards anaerobic digestion. In contrast, segregated FOG collection enables high yield route to be used. Such collection could be processed in either food waste or municipal sewage digesters. In the case of the latter, current regulations in some countries, such as the United Kingdom, means that inclusion of FOG into the digester changes the regulatory regime such that the co-digestate produced is still a waste under the revised Waste Framework Directive requiring potential expensive permitting for its

disposal to land or treatment (Iacovidou et al., 2012). As such, this favours the use of collected food in purpose food waste digesters. In contrast, no such barriers exist for inclusion of collected FOG for biodiesel conversion with full-scale facilities already operating within the United Kingdom (UK Department for Transport, 2019). This is supported by existing regulatory drivers encouraging the production of biofuels such as the Renewable Transport Fuel Obligation. The challenge then becomes one of source quality and the financial impacts of the collection system.

4 | CONCLUSIONS

This study showed that on average 2.3 kg of FOG per year could be collected from every household (0.19 kg/month). In the United Kingdom, the amount of household FOG potentially collectable would represent 1% of the total food waste arising nationwide from households, equating to 62 830 tonnes annually.

The physico-chemical characterization of household FOG revealed water and FFA contents of $4.2 \pm 2.3\%$ and $2.7 \pm 0.3\%$, respectively, suggesting additional pretreatment might be required for biodiesel production. Although these wastes also demonstrated high methane potential, measured at 875 mL CH₄/gVS_{added}, high concentrations of potentially inhibitory LCFAs, such as oleic and linoleic acids, might require further attention to determine the process safe boundaries.

Recovering energy from FOG through biodiesel conversion or anaerobic co-digestion was estimated with the potential to generate 487 and 490 GWh/year, respectively, in the United Kingdom. Co-collection with food waste was suggested as one of the potential options to maximize penetration rates. However, this will require understanding stakeholders' drivers and potential barriers to implementing sustainable schemes.

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DATA AVAILABILITY STATEMENT

Due to confidentiality agreements with research collaborators, supporting data can only be made available upon reasonable request and with permission of the collaborator. Details of the data and how to request access are available at 10.17862/cranfield.rd.9862553.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.



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