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Authors(s)	Wallace, Thomas, Gibbons, David, O'Dwyer, Michael, Curran, Thomas P.
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International evolution of fat, oil and grease (FOG) waste management - A review

Thomas Wallace * [a], David Gibbons [a], Michael O'Dwyer [b] and Thomas P. Curran [a]

[a] UCD School of Biosystems and Food Engineering, University College Dublin, Belfield, Dublin 4, Ireland.

[b] Evolution Environmental Services Ltd in partnership with Noonan Services Group, The Guinness Enterprise Centre, Taylor's Lane, Dublin 8, Ireland.

Email Address: thomas.wallace@ucdconnect.ie (T. Wallace)

**Corresponding Author*

Highlights

- Review of fat, oil and grease (FOG) sewer system blockage formation.
- Review of international FOG management programmes from education and awareness to FOG preventative measures.
- Trends for FOG utilisation.
- Future strategies for FOG management

Graphical abstract

Separate figure file attached.

Abstract

In recent years, issues relating to fat, oil and grease (FOG) in sewer systems have intensified. In the media, sewer blockages caused by FOG waste deposits, commonly referred to as 'fatbergs', are becoming a reminder of the problems that FOG waste can cause when left untreated. These FOG blockages lead to sanitary sewer overflows, property flooding and contamination of water bodies with sewage. Despite these financial and environmentally detrimental effects, a homogenous FOG waste management method has not been developed internationally. However, some successful enduring FOG management programmes have been established, such as in Dublin city and in Scandinavian countries. The aim of this paper is to carry out a review on existing FOG research and management approaches. FOG management involves comprehending: (1) FOG deposition factors in the sewer, (2) FOG prevention and awareness tactics undertaken internationally and (3) potential utilisation methods for FOG waste. This review will highlight that preventing FOG from entering the sewer is the most common approach, often through simple awareness campaigns. The diverted FOG is rarely valorised to bioenergy or biomaterials, despite its potential. Thus, all facets of the FOG waste lifecycle must be identified and managed. Advancements in processes and techniques must be assessed to best determine the future evolution of FOG waste management to assist in achieving a sustainable urban environment.

Key Words Fat, oil and grease (FOG); Waste management; Sewer deposits; Grease trap waste; Bioenergy; Biomaterials

1. Introduction

Fat, oil and grease (FOG) is a by-product from food processing sites (meat plants, *etc*.), food service establishments (restaurants, *etc*.) and domestic properties. Oils and fats are a subsection of lipids that are composed of fatty acids, triacylglycerols and lipid soluble hydrocarbons (Husain *et al.* 2014). FOG exists in most spectrums of food production. FOG is obvious in the form of used cooking oil (UCO) from deep fat fryers but it is also present in salad dressing, sauces and even in dairy based foods such as ice cream and coffees (Davis *et al.* 2011). Williams *et al.* (2012) estimated the FOG consumption per capita in developed countries as over 50 kg/annum compared to less than 20 kg/annum in less developed countries. A recent European initiative (RecOil Project) estimated that 2.5L of UCO are produced per person domestically (European Biomass Industry Association 2015). FOG cannot be removed from cooking operations entirely as it is engrained in many culinary practices. It is considered a waste upon being discharged into the sewer systems. The idea of toilets and sinks as disposal units for all types of waste is common, with an out of sight, out of mind logic prevalent. It is when issues in the sewer system become apparent at ground level that reactive actions are required.

FOG waste from multiple sites can accumulate in the sewer with other non-flushable waste, such as wet wipes and sanitary items (tampons, cotton buds, *etc*.), to produce what the media is commonly referring to as ‘fatbergs’ (coined by Thames Water, UK). In recent years the reporting of fatbergs in London has been prevalent, with a 10 tonne fatberg in 2015 and a 15 tonne example in 2013 (Thames Water 2013). The term fatberg entered the Oxford online dictionary in 2015 and is defined as ‘a very large mass of solid waste in a sewerage system, consisting especially of congealed fat and personal hygiene products that have been flushed down toilets’ (Oxford Dictionaries 2015). The issues caused by fatbergs and FOG deposits can range from the local level of property flooding with sewage to city wide problems caused by a complete sanitary sewer blockage and overflow. These issues require road closures for mechanical sewer maintenance and can potentially release high concentrations of pathogens, nutrients, and solids to water bodies that impose a risk to public health and the environment (He *et al.* 2013). It has been estimated that in the UK approximately 24,750 events per year, are the result of in line blockages (Arthur *et al.* 2008), of which an estimated 50-75% are caused by FOG deposits (Keener *et al.* 2008).

Fatberg may be a new term but the issue of FOG waste deposits in the sewerage system is not recent. FOG waste has been considered an issue in sewer systems as far back as 1944 where it was referenced in the symposium on grease removal in New York regarding grease problems in sewer maintenance (Cohn 1944, Dawson and Kalinske 1944). A concise solution was not determined then; this remains the case. The reporting of fatbergs in London and the UK is not a localised problem. Without a proactive approach, the epidemic of FOG deposits and the detrimental effects attributed to them will only increase internationally due to increases in populations and food service outlets (FSOs) and the strain that this puts on urban sewer systems, which were not designed for this level of input.

Appropriate waste management is recognised as a prerequisite for sustainable development (Papargyropoulou *et al.* 2014). To effectively manage FOG, the waste hierarchy (European Parliament Council 2008) must be utilised. The waste hierarchy refers to prevention as the preferred method when tackling waste but when this is not feasible the 3Rs (reduce, reuse or recycle) are the next option (Figure 1). Sustainable resource management is grounded on the ideal that 'waste' can be a 'resource', potentially creating a circular economy and a sustainable urban environment around a renewable waste stream.

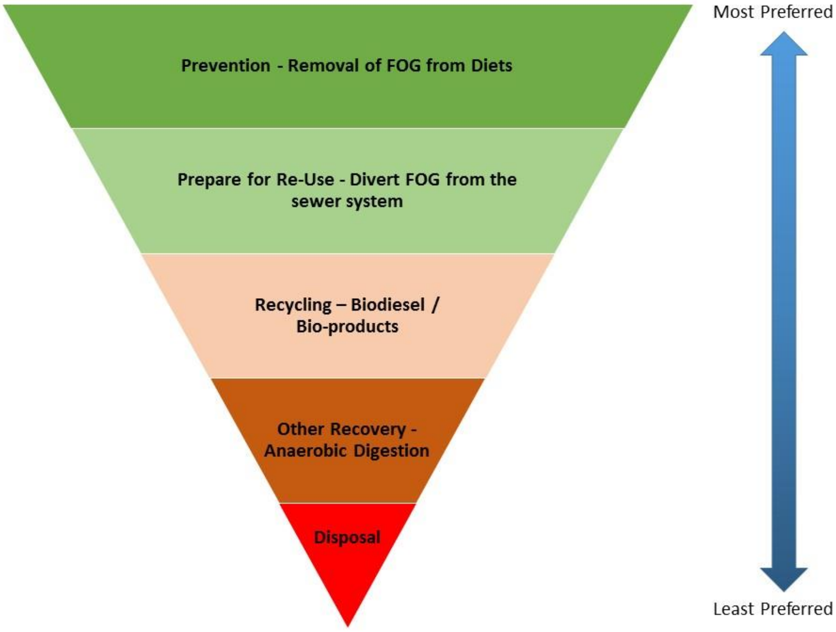

Figure 1 *Waste Hierarchy in relation to FOG management. Adapted from European Parliament Council (2008).*

One of the most common methods to reduce the detrimental effects of FOG waste is through awareness and education campaigns with stakeholders. Many of these initiatives entail promotion of simple practices which can prevent large volumes of FOG waste from entering the drains. These practices range from dry wiping dishes prior to washing operations to allowing waste oil to cool and dispose of it with general waste. These practices do not prevent the residual FOG in washing operation wastewater from entering the sewer, therefore further preventative measures are required, particularly in food service outlets (FSOs), which are one of the main contributors of FOG to sewer systems in urban centres (Curran 2015).

Thus the main objective of this review is to examine studies which research the following material and assess the future implications for FOG management strategies:

A. Formation of FOG blockages;
B. FOG preventative systems;
C. International programmes from education and awareness to FOG preventative initiatives utilising licensing and site inspections;
D. Existing and potential trends for FOG utilisation.

2. Data collection protocol and search strategy

A literature search was performed using scientific databases such as ScienceDirect, Web of Science, Scopus and Google Scholar. Keywords covering the topic of the review were inserted and combined and relevant secondary references were reviewed and included. Based on this search, FOG management at food service outlets (FSOs) will be the primary focus of this review. This paper will review the factors which contribute to understanding FOG and the existing management strategies in urban areas; this includes reviewing utilisation trends of diverted FOG.

3. Fatberg formation and detrimental effects of FOG

3.1. Detrimental effects of FOG

The damaging consequences of FOG range from local issues such as the blockage of a domestic kitchen pipe to the complete disruption of the sewer system. This section will detail the various detrimental effects attributed to FOG entering the sewer system.

3.1.1. FOG sewer problems and improper disposal

FOG can reduce sewer diameters and can completely block pipes (Ashley *et al.* 2000) causing flooding or sewer overflows, especially in combined systems. A sewer blockage outside a site does not necessarily signify that the primary polluter is at that location. A study made in the US suggested that FOG accumulates between 50 m and 200 m downstream from the source of FOG (Keener *et al.* 2008). The sewer age, diameter and gradient contribute to the location of FOG blockages. The UK has one of the oldest sewer systems in the world with 26% of UK sewers built between 1914 and 1945 and 24% built prior to this period (Clarkson 2014). In Dublin city, the oldest intact sewer dates back to 1852 (Whitney 2014). These sewers were not designed for the current populations. In Dublin, the populations have increased by 340% from the year 1841 to 2011 (Central Statistics Office 2011).

Upgrading the sewer network is financially not feasible. In the UK, to replace the 302,000 km of existing sewers, it would cost circa £104 billion (Clarkson 2014). In contrast, the annual UK cost of pipeline maintenance by removing FOG deposition ranges from £15-£50 million (Pastore *et al.* 2015).

FOG deposits can impact human health and the environment. FOG tends to clog drains and sewers, causing odour nuisance and leading to the corrosion of sewer lines under anaerobic conditions (Lemus *et al.* 2004, Husain *et al.* 2014). The release of sewage causes water contamination and exposure to pathogens (Bridges 2003). FOG is thought to contribute to 25 – 37.5 % of sanitary sewer overflows (Keener *et al.* 2008). The Hong Kong Drainage Services Department (DSD) claimed in 2000 that more than 60% of sewer blockages were due to excessive build-ups of grease (Chan 2010). To put this in context in the UK, 24,750 flooding events per annum are due to sewer blockages (Arthur *et al.* 2008) with approx. 12,000 blockages/annum due to FOG deposits (235 sewer blockages a week across the UK). The processes which lead to FOG deposit formation will be covered in Section 3.2.

In China, an additional concern is 'gutter oil', which is the oily material recovered from drains and grease traps which is reused in cooking applications (Lu *et al.* 2013). Because of oxidation and hydrogenation this 'gutter oil' can cause health problems in humans (Lu *et al*. 2013, Lu and Wu 2014). In China, it has been estimated that 10% of meals are cooked with FOG from sewers (Williams *et al.* 2012). This is not only illegal but also the most detrimental use of FOG directly affecting the public's health.

3.1.2. Wastewater treatment plant (WWTP) difficulties

FOG may pass through the sewer system and enter WWTPs where it can cause overloading of the system. FOG is primarily separated at WWTPs in the skimming tanks, at the first stage of treatment (Martín-González *et al.* 2011). Additional techniques to remove FOG in WWTPs include dissolved air flotation, centrifugation, filtration, biological removal and ultrafiltration (Beldean-Galea *et al.* 2013). The FOG that is not removed in the primary skimming tanks can cause blockages in the plant infrastructure causing impedance of treatment processes such as disruption of settlement and clarification facilities. These issues lead to increased operational and maintenance costs. The EU – RecOil Project estimated that 25% of sewage treatment costs can be attributed to the FOG component (European Biomass Industry Association 2015). The slow degradation of FOG in WWTPs can also affect the activity of micro-organisms at the plant by preventing the transfer of oxygen or slowing down the degradation of other organic material. Failure to remove the FOG can result in its discharge with treated water. This can affect the designation of Blue Flag status to surrounding recreational waters.

3.2. FOG waste deposit formation

FOG-related blockages in sewer lines were once portrayed purely as the cooling of fats. It was originally hypothesised that the liquid fats produced during the cooking process passed through grease traps (if present) and discharged into sewer pipes. Due to the low temperature and hydraulic pressure of sewage, FOG solidified gradually and adhered to walls of the sewer interior. This then restricted the flow of wastewater (Gu *et al.* 2015). However, Keener *et al.* (2008) theorised that FOG deposits are basically metallic soaps. The reaction begins at the FSO discharge. FOG is removed from dishware during cleaning, and interacts with excess cleaning products and sanitizers to begin the saponification process (conversion of a fat to a soap by treating it with an alkali). The sanitary sewer system contains wastewater with minerals and naturally present metal ions. Within the sanitary sewer system, the strong oxidizing agents hydrolyse (breakdown in the presence of water) the FOG in the presence of metal ions to produce metallic soaps (Ducoste *et al.* 2008b, Williams *et al.* 2012). Keener *et al.* (2008) showed that the FOG deposits contain high concentrations of saturated acid, which is primarily palmitic acid, and contain calcium as primary metal. According to He *et al.* (2013) and Williams *et al.* (2012), the formation of FOG deposits on sewer pipe walls is strongly correlated to four main components: (a) calcium (Ca2+); (b) free fatty acids (FFAs); (c) FOG and (d) water. All of these components are required for FOG deposits to occur.

The mechanism of FOG deposit mainly involves three processes: 1) the aggregation of excess calcium compressing the double layer of FFA; 2) saponification between FFA and positive metal ions like calcium ion; 3) the previously formed deposit acts as a core attracting un-reacted FFAs and calcium ion, also debris in wastewater (based on the effects of Van der Waals attraction and electrostatic repulsion (DLVO theory) (Figure 2). Fatty acids are produced either from cooking processes, from microbial activities on FOG or FOG natural degradation processes (He *et al.* 2013). Calcium ions can be either naturally present in the wastewater or a product of microbial induced concrete corrosion (MICC**)** where microbial activity in wastewater and on concrete surfaces will result in the production of sulfuric acid and subsequent corrosion of concrete (Keener *et al.* 2008, He *et al.* 2013).

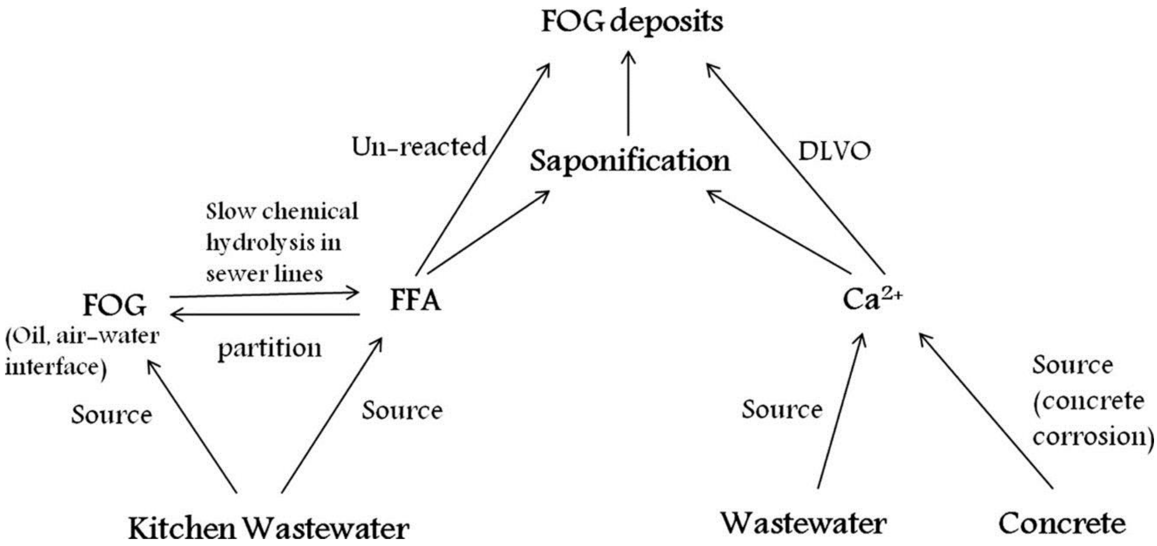

***Figure 2** Mechanism for FOG deposit formation (He et al. 2013)*

The aforementioned research has shown that it is not merely FOG accumulation as originally perceived. The formation of FOG deposits can be affected by many factors like calcium salt and FFA types, FOG concentration, water hardness, pH value and temperature (Iasmin *et al.* 2014). By researching the specific chemical breakdown of the various FOG streams, which has been initiated by Iasmin *et al.* (2016) with beef tallow and canola oil, the ability to track the chemicals which make up the saponified solids can be achieved. This may aid in providing a framework to predict the spatial formation of FOG deposits in municipal sewers using system wide sewer collection modelling software. This could assist in pre-empting and highlighting potential high risk FOG deposit zones. Once an understanding of what causes FOG deposits and where they will potentially form is determined, preventative procedures can be introduced.

4. FOG preventative source control equipment and FOG waste categorisation

The "Polluter-Pays Principle" (PPP) was developed by the organisation for economic cooperation and development (OECD) in 1972. The OECD stated: "…the polluter should bear the expenses of carrying out the [pollution control] measures decided by public authorities to ensure that the environment is in an acceptable state." Article 9 of Directive 2000/60/EC, states that Member States of the European Union shall recover the costs for water and wastewater services in accordance with the PPP. Therefore, those responsible for causing FOG deposits should be held responsible for the detrimental environmental effects caused. Thus, processes and devices for removal of FOG from grease containing wastewater streams, including grease trapping systems and the use of microorganisms (da Silva Almeida *et al.* 2016a), are commonly required.

4.1. Grease trapping systems: Installation and maintenance standards

Grease trapping systems (GTSs), also referred to as grease abatement systems, grease interceptors, grease separators or grease recovery units, separate FOG and fine food waste from wastewater through gravitational separation. Patents for grease traps date back to 1884 (Whiting 1884). Grease traps are often multi-compartment tanks where the grease-containing discharge is retained long enough so that grease can rise to the water surface and solids can settle to the bottom, and treated water can be discharged to the sewer (Ragauskas and Ragauskas 2013). Grease trap is often the term used to classify kitchen grease separation devices smaller than 55 gallons (US) while grease interceptors is the term used to denominate larger outdoor devices with a minimum size of 750 gallons (US) (Engle 2006). For the purpose of this study, passive grease trap will refer to all grease traps which function solely by gravitational separation and retention capacity, regardless of size. Grease recovery unit (GRU) will refer to any unit which separates the FOG-rich lipid layer (recoverable organic fraction from GTW) with a skimming mechanism on site.

In Europe, the EN 1825 Part 1 & 2 standards are used in determining the design and maintenance required for the GTS:

- EN 1825-1: (2004) Grease Separators – Part 1: Principles of design, performance and testing, marking and quality control.
- EN 1825-2: (2002) Grease Separators – Part 2: Selection of nominal size, installation, operation and maintenance.

These standards define grease as ‘substances of vegetable and/or animal origin, of a density less than 0.95 g/cm^3, which are partially or totally insoluble in water and saponifiable’. These standards state that the frequency of inspection, emptying and cleaning of the grease traps should be determined with regard to the grease and sludge storage capacity of the separator and in accordance with operational experience. These standards declare that unless otherwise specified, grease traps should be emptied, cleaned and refilled with clean water at least once a month and, preferably, every two weeks.

Through operational experience, many municipalities have introduced the 25% rule which requires a complete pump out of a GTS before the top floatable layer and bottom sludge layer account for a combined 25% of the device grease retention volume (Long *et al.* 2012). Currently this capacity is assessed by inspecting the GTS to determine the grease cap depth, which will always amass on top of the aqueous level due to its lower density. Recent developments have utilised ultrasonic sensor technology to more accurately determine the FOG capacity of a GTS. Since 2007, new grease traps in Finland have to be equipped with a filling alarm to assist in determining the level of FOG within a unit, that alternatively has to be recorded by physically inspecting the GTS to determine the thickness of sludge and FOG present (Van der Veen 2013).

The EN 1825 standards state that the size of passive grease traps is based on the nature and quantity of wastewater (excluding wastewater from toilets). It takes into account maximum flow rate of wastewater, maximum temperature of water, density of grease that is to be separated and influence of cleaning agents and detergents. The maximum flow rate of wastewater must be evaluated to calculate the nominal size (NS) for the required grease trap.

Additional volume, based on NS, is included to accommodate a grease separation zone (NS x 240 litres), accumulated sediment (NS x 100 litres) and FOG (NS x 40 litres). A NS 1 is the smallest possible unit that can be installed and by the calculations mentioned above the minimum capacity of the grease trap would be 380 litres (Barton 2012). Based on these capacities, in dense urban centres it may not be feasible to install units of this size in FSOs, due to space limitations.

The national water service authorities have the option to permit a GTS, despite it not meeting the sizing requirements, if they deem it suitable. GRUs, which skim the FOG layer out of the system daily, are also an option as they are smaller in size but they require daily maintenance by staff. The Plumbing and Drainage Institute (PDI) G 101: Testing and Rating Procedure for Hydro Mechanical Grease Interceptors (2010) is often used for testing and sizing these grease traps. This standard is used in Europe as there is currently no official standard for the sizing of GRUs.

Additional GTS sizing standards include the American Society of Mechanical Engineers (ASME) A112.14.3 and ASME A112.14.4. The ASME standard requires that grease interceptors remove a minimum of 90% of the incoming FOG (Ragauskas *et al.* 2013). ASME A112.14.4 governs the automatic grease removal devices and dictate that the removed FOG is 95% free of water.

GTSs are only effective if the maintenance of the units is adhered to. Gallimore *et al.* (2011) determined that a grease trap could reach a FOG removal of 80% but could be as low as 8%. The model of grease trap and its location was a strong determining factor on the unit's performances, as is the size of the FOG globules within the units (Ducoste *et al.* 2008a, Gallimore *et al.* 2011). He and Yan (2016) investigated whether GTSs were a source of long chain fatty acids (LCFAs) entering the sewer systems. As mentioned in section 3.2, FFAs are a key component in the formation of FOG deposits and LCFA make up the majority of these. Cooking practices on site can cause hydrolysis in food waste residues and form LCFAs, however additional LCFAs were found to be produced in the GTS due to the stratified nature of the contents through microbial activity. The LCFAs were most prominent in GTSs with high hydraulic retention time. Disturbance in the units, when FOG capacity is high, due to influent flow causes these LCFAs to discharge into the sewer, despite low solubility of LCFAs in water. Frequent grease trap maintenance can reduce the LCFA discharge from the GTS. Aziz *et al.* (2010) carried out studies assessing GTS performance; this study established that FOG retention effectiveness ranged from 80% to less than 20% if the grease traps are incorrectly designed or poorly maintained. Therefore, maintenance of the units is essential to reduce FOG from entering the sewer system.

4.2. FOG categorisation

FOG produced by FSOs can be divided into two distinct categories:

Category 1: Used cooking oil (UCO)

Category 2: Grease trap waste (GTW).

The main published difference between these is the free fatty acid (FFA) composition. UCO has a FFA content <15% and GTW has a FFA content >15% (Canakci 2007, Husain *et al.* 2014). The higher FFA content is due to the presence of detergents and sanitizers which enhance the hydrolysis of triglycerides in GTW (Weiss 2007). This difference is a determining factor on the final utilisation method available. Table 1 from Wallace *et al.* (2015) details how these streams are designated from a waste collection perspective, which was also highlighted by Van der Veen (2013).

Table 1 *FOG categorisation in European Waste Catalogue and Hazardous Waste List (Wallace et al. 2015)*

EWC (European Waste Catalogue) code	*Description of waste*	*Category of FOG*
20-01-25	Municipal wastes (household waste and similar commercial, industrial and institutional wastes) including separately collected fractions: Edible oil and fat	Used cooking oil
20-01-08	Municipal wastes (household waste and similar commercial, industrial and institutional wastes) including separately collected fractions: Biodegradable kitchen & canteen waste	Grease trap waste
19-08-09	Wastes from waste management facilities, off-site wastewater treatment plants and the preparation of water intended for human consumption and water for industrial use: Grease and oil mixture from oil/waste separation containing only edible oil and fats	Grease trap waste

4.2.1. Used cooking oil

UCO (often referred to as yellow grease in literature) is primarily waste oil from deep fat fryers. It can also include residues from frying pans/woks and waste oil produced from cooking operations such as oven roasting meats or grilling. UCO should be diverted at source and through education and awareness campaigns should never be disposed of in the sewer. The estimated UCO collected in Europe annually is 100,000 – 700,000 tonnes (Iglesias *et al.* 2012).

4.2.2. Grease trap waste

Grease trap waste (GTW), often referred to as brown grease, is a complex mixture consisting of residual fat, aqueous phase (wastewater), and suspended solids (da Silva Almeida *et al.* 2016b) retained in grease trapping systems (GTSs). GTW has a higher water content and more contaminants than UCO. Various studies have indicated that the most dominant contents of the lipid fraction of GTW are saturated fat in the form of palmitic acid, primary unsaturated fat in the form of oleic acid and polyunsaturated fat as linoleic acid (Karnasuta *et al.* 2007, Wang *et al.* 2008, Nisola *et al.* 2009, Montefrio *et al.* 2010, Neczaj *et al.* 2012, Ragauskas *et al.* 2013). A 1998 National Renewable Energy Laboratory report estimated that in the United States, FOG is generated at a rate of 6 kg of GTW FOG per year per person, while the estimated volume of restaurant UCO is about 4 kg/person/year (Wiltsee 1998, Montefrio *et al.* 2010). Long *et al.* (2012) reported that approximately 22 billion litres of GTW are generated annually in the United States and 10% of this volume is the lipid rich residual FOG.

As mentioned in the previous section there are two types of GTS - passive grease traps and grease recovery units (GRUs). GTW can be divided into the following sub-categories:

- Passive GTW: Content of a passive gravitational separation grease trap. The emptying of these grease traps includes removing all contents of the unit including the lipid rich layer, the aqueous phase and the solids waste layer. It has been estimated that raw GTW can have a FOG concentration of 4.23 wt%, water concentration of 86.35 wt% and a solids concentration of 9.42 wt% (Tu and McDonnell 2016). This is variable depending on the site that produces it and the frequency of the grease trap pump out.

- GRU-GTW: These are units which are smaller in size and remove the lipid rich layer daily by skimming and sometimes heating the lipid-rich FOG layer into a separate receptacle. This lipid-rich FOG layer is the most similar to UCO and has less impurities than the contents of passive GTSs.

4.3. Microbial additives

To improve the performance of GTSs, bio-augmentation has been examined. The use of some products such as emulsifiers and free enzymes break down FOG but allow it to reform in the sewer network. Excessive use of surfactants, solvents or bleach in FSOs can adversely impact downstream collection systems. Therefore, control of the products and additives used in FSOs is required to prevent the temporary breakdown of FOG in GTSs.

The use of microbial additives for reducing FOG deposits is often debated. Studies have stated that some GTSs are unable to efficiently retain dissolved and emulsified fats (Nisola *et al.* 2009). Additives to degrade FOG waste have been introduced to GTSs in some cases to improve this. The first step of the biodegradation of fats is the hydrolysis of the ester bonds that links the molecule of glycerol to the fatty acids or phosphoric acids that compose the triglycerides. The hydrolysis of FOG is catalysed by fat degrading enzymes: lipases. The reactions of FOG with lipases leads to the hydrolysis of triacylglycerol’s to diacylglycerols, mono-acylglycerols, fatty acids and glycerol (Alves 2013). Wakelin and Forster (1997) showed that a mixed lipase culture displayed a FOG removal efficiency of 73% for restaurant discharge effluent.

Brooksbank *et al.* (2007) stated that some multi-species supplements are capable of significantly enhancing the degradation of several fats and oils by 37–62%. However, the issue that municipal authorities have with microbial additives is that they may degrade the FOG to congeal further down the line in the sewer or in the WWTP. Bacteria associated with wastewater preferentially degrade unsaturated fatty acids producing semi-solid, sticky material likely to block sewers. Brooksbank *et al.*

(2007) concluded that multi-species microbial inoculate can degrade significant amounts of a variety of fats and oils without significantly modifying the fatty acid composition and may thus help keep sewer lines free of grease deposits.

A study by Tang *et al*. (2012) showed that the use of a certain additive reduced FOG deposit formation by 40%. This study dosed the product into a grease trap. It also concluded that even with the use of this product, grease trap maintenance was still required.

This conclusive result appears to be that the use of degradative additives is not a sole solution for FOG management. Certain lipase cultures, used in conjunction with passive GTSs, can increase the efficiency but the grease traps must still be maintained. The FOG must still be diverted from the sewer system.

5. FOG waste management

Arthur and Blanc (2013) outlined the state of knowledge regarding best practices for FOG waste management at UK and international level. The aim for any effective waste management is to minimise the production of waste and reuse waste produced (Figure 1). Education and awareness campaigns with the stakeholders are the foundation for all FOG management initiatives. International FOG management requires approaches that integrate local policy and legislation such as waste licensing (as seen in Dublin) which puts the onus on the potential polluter. Overloading of WWTPs and sewer systems with FOG is common without proactive steps. The following sections will detail various international FOG management approaches.

5.1. FOG waste management and awareness campaigns

The importance of public educational campaigns to mitigate domestic sewer deposits was highlighted by Mattsson *et al.* (2015). All facilities with a trade effluent discharge are potential FOG producers.

Many authorities around the world reduce FOG waste entering the sewerage system by requiring or enforcing the installation of GTSs (He *et al.* 2013). However, in most developing countries, regulations related to grease traps either do not exist or are not enforced. A study in Thailand determined that only 25% of 10,304 hotels and restaurants had grease traps installed (Stoll and Gupta 1997). Data of this type from other countries is not readily available and should be the focus of future studies.

The human diet includes fat in various forms. Without a complete restructure of cultural eating habits, FOG will exist. FOG cannot be eliminated, therefore reducing the volumes used and redirecting it from the sewer system is the only option. There are innumerable water service authority initiatives internationally promoting good practices in domestic and commercial sites in regard to FOG management, such as the European RecOil Project or the Cease the Grease initiative in Dallas, US. Many of the programmes are small scale with no expansion to national level. All FOG management programmes involve some level of education and awareness promotion with stakeholders. Table 2 details some international FOG campaigns and initiative.

Although it is assumed that these campaigns have a positive outcome, there is little published information to endorse this. Regardless, education and awareness campaigns are the foundation for the effective extension of any FOG management programme. The next step is to identify practices that promote the complete cradle to grave management of FOG and that do not distribute the waste to another sector, like landfill or composting, where it could attribute to alternative negative effects, such as increased greenhouse gas emissions.

***Table 2** International FOG awareness campaigns & studies*

Country	Awareness campaign	Requirements & results
US	CalFOG – Put a lid on it the State of California has launched 44 projects	Targeted food service outlets. Public engagement outreach programme. Reported a significant drop in the number of beach closures due to sewer overflows. Surveys suggested increased awareness of the problems caused by FOG disposal; from 63% of the surveyed population to 82%.
	Dallas – Cease the Grease	Reduced FOG blockages in the sewer system by 96% over five years through grease trap installation
	New York City Environmental Protection: Preventing Grease Discharges into Sewers	Guidelines for FSOs regarding best management practices for FOG reduction including GTS installation by licensed plumbers. Non-compliance comes with potential fines of $10,000.
	Fight FOG & FOG Monsters (School based awareness programme) 2013	30 separate utility companies and material specifically targeted at children
	Tri-City District Campaign	Routinely cleaning kitchen exhaust system filters. Reducing dishwasher temperature to 70°C and ensuring dishwashers are positioned as far as possible from any grease trap to allow the wastewater time to cool before reaching the trap
UK	Wessex Water – Wrap Up the Fat	Includes phone app with sewer maintenance contact details and advice.
	Welsh Water – Stop & Think – Not Down the Sink	Awareness campaign on disposing of FOG in the bin.
	Water UK – Disposal of FOG & Food Waste: Best Management Practices for catering outlets.	Promotes staff training, pre-washing preparation, the use of grease traps, the use of food macerators, enzyme dosing for enhanced fat breakdown in the grease trap/sewer system and waste oil storage and collection.
	Severn Trent Water "Trim the fat this Christmas" 2012	Seasonal FOG reduction campaign (Domestic)
	Severn Trent Water – "Sewer Savvy Campaign" 2016	Promotion of binning non-flushable waste in high risk Gloucestershire and Worcestershire area. Free 'Gunk Pot' for storage of waste cooking oil to cool and dispose.
China	Chan, H. (2010) 'Removal and recycling of pollutants from Hong Kong restaurant wastewaters'	Fight against illegal use of gutter oil in Hong Kong. Highlighted the criminal aspect which must be combatted. The Hong Kong Drainage Services Department claimed in 2000 that more than 60% of sewer blockages were due

		to excessive build-ups of grease.
India	Robbins *et al*. (2011) 'Developing programs to manage fats, oil, and grease (FOG) for local governments in India'	Services and equipment to collect, transport, and process FOG into biodiesel. Promotion campaigns educate people. Installation of higher efficiency grease traps. Provide the policies and procedures that define and regulate the programme.

5.2. International FOG management case studies

FOG management programmes are often run by water service authorities and results are frequently not readily available or published. Table 3 details various international FOG management programmes which have been studied, from city scale pilot programmes to multi-country initiatives. There are very few homogenous national approaches, with the positive Swedish and Norwegian approach varying between several water service authorities. The management approaches are often pilot programmes in areas with historic detrimental FOG problems, which react to the areas with high level of sewer problems.

The campaigns mentioned in the previous section may require GTSs but standards are rarely included to regulate the installation of properly sized GTSs or the maintenance of the units. Successes are often recorded by the reduction of blockages but the benefits to the sewers and WWTPs are rarely assessed. The following sections will detail some approaches that various countries have taken, from the multi-country RecOil Project to the various methods that other countries have integrated to various degrees of success.

Table 3 *International FOG management and utilisation strategies*

Country	*Author*	*Details of FOG management*
US	Jolis *et al*. (2010) 'Co-location of brown grease to biodiesel production facility at the oceanside wastewater treatment plant in San Francisco, CA'. Miot *et al.* (2013) 'Restaurant trap waste characterization and full scale FOG co-digestion at the San Francisco Oceanside plant'	San Francisco Oceanside Wastewater Treatment Plant, 2,500 Food service outlets. 60 million gallons (US) of fats, oil and grease (FOG) annually. Spends approximately $3.5M annually for sewer grease accumulation related problems. Free pick-up of UCO for biodiesel.
Spain, Portugal, Italy, Greece, Belgium & Denmark	European Biomass Industry Association (2015) Transformation of used cooking oil into biodiesel: From waste to resource.	RecOil project. Promotion of used cooking oil recycling for sustainable biodiesel production. Estimations that biodiesel produced from UCO could replace 1.5% of the EU27 diesel consumption.
Ireland	Gibbons *et al.* (2015) 'Assessing Dublin City Council's Fat, Oil and Grease (FOG) Programme through Grease Trapping System (GTS) Installation and Maintenance'.	Dublin FOG Programme: 2200 FSOs, licensed and inspected frequently. All FSOs require GTSs and must be maintained. All GTW and UCO must be collected by permitted hauliers. Installation of suitable GTSs increased from 14% in 2008 to 80% in 2014. $110x10^3$ litres of GTW diverted from sewers in a study area of 150 FSE. Development of innovative software for FSO inspection.
Sweden & Norway	Mattsson *et al*. (2014) 'Fat, oil, and grease accumulation in sewer systems: Comprehensive survey of experiences of Scandinavian municipalities'.	Survey of Swedish and Norwegian water management authorities surveying FOG management approaches. 84% of Swedish respondents and 40% of Norwegian respondents considered the existing GTSs adequate despite lack of control and maintenance.
	Mattsson *et al.* (2015) 'Impacts and managerial implications for sewer systems due to recent changes to inputs in domestic wastewater – A review'.	This review highlighted the importance of educational campaigns directed to the public to mitigate deposition as many of the observed problems have been linked to domestic behaviour in regard to FOGs in conjunction food waste disposal units and toilet flushing.

Japan	Kobayashi et al. (2014) 'Dual-fuel production from restaurant grease trap waste: Bio-fuel oil extraction and anaerobic methane production from the post-extracted residue'.	Dual-Fuel approach (See also Jolis in the US). Utilisation of the grease trap waste as a feedstock for both biodiesel and anaerobic co-digestion in one site to achieve a higher energy yield.
Australia	Scoble and Day (2002) 'Grease Under Control at South East Water'.	Greasy Waste Program had contributed to a 50% reduction in sewer blockages caused by fats.
	Alam, A. (2003) 'Control and management of greasy waste in Melbourne: performance review and optimization options'.	Melbourne Greasy Waste Programme. City West Water (CWW) and South East Water (SEW) have been running grease control programs since 1995. Approximately 80% of the fats in the sewers came from commercial premises, such as restaurants, cafes, takeaways, *etc*. In 1997: 1,650 premises were identified as requiring installation of a new or upgraded grease interceptor. By 2000, this was achieved.

5.2.1.EU – RecOil Project

The RecOil project was a multi country initiative involving Spain, Greece, Italy, Portugal, Belgium and Denmark. The RecOil project found that it was possible to collect 2.5 litres of UCO per household per month (European Biomass Industry Association 2015). It determined that 60% of used cooking oil is improperly disposed of. Information among 44 different UCO collection systems implemented in Spain, Greece, Italy, Portugal and Belgium was analysed. 180 tonnes of used cooking oil from restaurants was collected, which is about 45% of the estimated potential of 400 tonnes per year. 80 tonnes of used cooking oil were collected from private households, about 16 % of the estimated potential of 500 tonnes. Approximately €30,000 was saved from the cost of maintaining the wastewater treatment plants. The RecOil implementation will potentially result in energy savings estimated at 1.3 tonnes of oil equivalent/year and the reduction of GHG emissions of 14.413 tonnes of CO_2 through the conversion of collected UCO into biodiesel (Paraíba *et al.* 2013). This project integrated a multi country approach to achieving reduced FOG blockages through education approaches with the public and utilising the collected waste oil. It highlighted the benefits of utilising this waste stream and the potential available.

5.2.2.UK

Despite the fact that all FSOs in the UK have an obligation to manage effluent content under the Water Industry Act (1991), a homogenous national approach has proven challenging to implement and enforce from a legal perspective, especially given that water management is split between 11 private water service companies in the UK. Barton (2012) has reported that FOG from commercial food preparation premises is implicated in 75% of the estimated 200,000 sewer blockages in the UK every year, with the related cost of unblocking the sewers running to millions of pounds per annum, according to Water UK. The addition of microorganisms directly to the drain or to small grease traps has been reported as the most common FOG management system in the UK (Barton 2012).

Since the year 2000, the UK Building Regulations have required all new and converted premises to install grease management systems. Before the year 2000, FSOs generally only had a GTS if they had been identified as problematic or in a risk zone. Developments in early warning systems for sewer overflows has assisted in identifying these risk zones before flooding occurs (Thames Water 2011). Even when GTSs were installed, maintenance was often poor, which resulted in FOG entering the sewer systems (Williams *et al.* 2012).

5.2.3. Ireland

FOG blockages in Dublin city were reduced from over 1,000 per annum pre-2008 to less than 100 blockages in 2014 (Gibbons *et al.* 2015) due to a FOG control programme. This contrasts with other urban centres in Ireland where Melia (2016) reported that up to 90% of food businesses had inadequate levels of FOG reduction in place.

The success in Dublin was achieved through the implementation of the Dublin FOG Programme, which since 2008 has involved over 7,000 annual inspections of the existing 2,300 FSOs. The inspections involve the promotion of best management practices to reduce FOG from entering the sewer and to review the condition of GTSs on site. Wastewater discharged from sites is sampled regularly to confirm that FOG content is under 100 mg/L, which is the limit required by the discharge licence. Legal action against the FSO is an option for continued failure to comply with the standards of the trade effluent discharge licence. A critical assessment of this programme is currently being carried out.

Irish Water, the Water Services Authority in Ireland, was established under the Water Services Act 2013. One of their stated objectives is to ‘develop a standard approach for the effective utilisation of FOG using the existing legislative tools and harnessing the data present within the Local Authorities and relevant companies’ (Irish Water 2015). This compliments the potential expansion of a national FOG management programme based on the positive results of the Dublin FOG programme. This programme has evolved since its inception in 2008 and has developed with the input from all involved stakeholders.

Future development of source control programs such as this may involve introducing an information and communications technology (ICT) platform like the SwiftComply© system which can reduce the impact on FSOs with a decrease in site inspections. SwiftComply© can potentially connect regulators, food service businesses, and service providers on one platform (Weckler 2016). This can simplify recording of the waste stream volumes and the utilisation routes taken, while decreasing the manpower required for inspections. This could provide a feasible strategy for urban centres with large numbers of FSOs, where intensive site inspections are not practical.

5.2.4.Sweden & Norway

Mattsson *et al*. (2014) determined that educational campaigns directed at the public to control FOG depositions were successful. They revealed that 64% of the surveyed Swedish municipality public respondents and 80% of Norwegian municipality public respondents stated that the majority of the restaurants had GTSs installed. Mattsson *et al*. (2014) also determined that 84% of the Swedish respondents and 40% of Norwegian respondents considered the GTSs adequate despite lack of control and maintenance. Based on GTS efficiency studies, the maintenance of the units is paramount to increasing GTW retention. Stockholm Water has reported decreased FOG problems with a 98% decrease since the mid-1990s with approximately 25 blockages/year in the entire Stockholm area.

5.2.5.USA

The United States Environmental Protection Agency (EPA) (2012) have stated that “grease from restaurants, homes, and industrial sources are the most common cause (47%) of reported blockages” in sewers. Requirements for FOG regulatory controls (e.g. best management practices including the use of GTSs) for sites to reduce FOG blockages and WWTP interference fall under the National Pre-treatment Program, which ensures achieving goals set up in the Clean Water Act. This sanctions the local authorities to introduce levels of management based on existing knowledge and history of the area. Therefore, cities within the same state may have separate approaches. The large size of many of the US cities remove the capability of monitoring every FOG producing site, therefore education and outreach campaigns are essential to promote FOG preventative measures. Table 2 and Table 3 detail some US initiatives.

6. FOG waste utilisation potential

FOG not redirected from the sewer system will have detrimental effects on the sewer system, as discussed throughout this paper. Diverting the FOG will produce a waste stream which must be managed properly; however, it is commonly disposed of at landfill or at rendering plants. To reduce costs, FSOs will often maintain the GTS in-house and unless stipulated will dispose of the GTW into general waste bins. Disposal of this waste to landfills is no longer permitted in many jurisdictions (Razaviarani *et al.* 2013), therefore utilisation methods such as anaerobic digestion, biopolymer / biochemical production and biodiesel processing are attractive alternatives. Development of these processes could greatly improve the upcycling potential of this waste stream. In Europe, the energy value of FOG generated by the urban population is estimated to be approximately 1,000 GWh per annum and most of this value is wasted when FOG is discarded into sewer networks. The economic value of recoverable biochemical products lost in wasted FOG is approximately €100 million, which is often lost due to a lack of cost-effective utilisation routes.

6.1. Biodiesel

Biodiesel produced from used cooking oil has the lowest greenhouse gas (GHG) emissions among biofuels and could replace 1.5% of EU28 diesel consumption (European Biomass Industry Association 2015). Alkaline-catalysed transesterification is a common reaction for biodiesel production. In 2009, the biodiesel production in Europe exceeded 10 billion litres, resulting in approximately 1 billion litres of glycerol (Du *et al.* 2012). Glycerol is a co-product of the transesterification process which can be utilised for biopolymer production. For biodiesel production it is preferred that the starting feedstock has the lowest concentration possible of free fatty acids (FFAs) (Pastore *et al.* 2015). High FFA content hinders the conversion of GTW by transesterification due to soap forming with alkaline catalysts and reducing the yield of the biodiesel and glycerol production (Hasuntree *et al.* 2011). FFA content of <2.5% does not yield significant processing difficulties for biodiesel production (Ragauskas *et al.* 2013). Use of waste streams such as UCO avoids the food vs fuel debate (growing crops specifically for biofuel when developing countries suffer famine) (Monbiot 2004, Zhang *et al.* 2010). GTW is a lower grade feedstock than UCO with a higher FFA content, thus it is inexpensive to purchase but requires pre-treatment (acidic esterification) and FOG separation to reduce the FFA and water content and produce a feasible feedstock for biodiesel (Park *et al.* 2010). The FOG element of GTW can be recovered efficiently for biodiesel production (Montefrio *et al.* 2010). The physical and chemical properties of the feedstock significantly influence biodiesel production reaction as well as the final fuel properties. Frying oils which are used in various facilities under different conditions have significantly different physio-chemical properties (Sanli *et al.* 2011). As GTW is heterogeneous depending on the site that produces it, a profile of the FOG a site produces would be beneficial in calculating the potential biodiesel yield. Characteristics of GTW as a biodiesel feedstock, such as strong odour, can be mitigated during the pre-treatment stages, thus benefitting the final biodiesel product by removing what could be perceived as potential nuisances of a product (Thompson *et al.* 2013).

Velazquez Abad *et al.* (2015) stated that used cooking oil and burger fat arising from British restaurants could generate enough energy to power up to 3891 heavy goods vehicles with fatty acid methyl ester (FAME) biodiesel (B100) or 1943 with biomethane annually. In the UK, there are 30 registered biodiesel producers with the capacity to process 250 million litres of UCO per year (Environmental Audit Committee 2012). In the US, GTW generation ranges from 1,406-11,000 kg/annum/restaurant with a range of 0.1-40% lipid content. An estimated 1.8 billion kg/annum of lipids could be recovered from GTW in the US which could produce 1.3 billion kg of biodiesel/annum

(Ragauskas *et al.* 2013, Hums *et al.* 2016). Wiltsee (1998) estimated that over 400 million gallons (1.5 billion litres) of biodiesel could be produced from GTW annually in the US which is equivalent to approximately 31.5% of the total biodiesel production in 2014 (Tu 2015).

6.2. Anaerobic co-digestion

Anaerobic treatment of fat-containing wastes presents the potential for biomethane production but also inhibitory challenges to long chain fatty acid (LCFA) content (Martín-González *et al.* 2011). Co-digestion of high-fat containing wastes with other biodegradable wastes, such as organic fraction of municipal solid wastes (OFMSW), has been shown to be applicable. The addition of GTW to sewage sludge digesters has shown an increase of the methane yield of 9–27% when 10–30% of sludge from grease traps was added *(*Davidsson *et al.* 2008*).* A co-product of the process is bio-fert which can be utilised for agricultural fertiliser. Various studies show similar trends that low input of GTW increases the biomethane yield up until they inhibit the process. The biogas production and process limitations were reviewed by Long *et al.* (2012).

It has been reported that biogas generation is a less efficient way of utilizing the energy content of the FOG when compared with biodiesel production (Tu 2015). A third option that has been investigated is a dual-fuel approach where the GTW is separated for use in biodiesel and anaerobic co-digestion, preferably in a co-located location.

6.3. Dual-fuel integrated approaches

Dual-fuel production from restaurant grease trap waste involves the transesterification process of the lipid rich FOG layer and anaerobic co-digestion of the dewatered food waste layer (Kobayashi *et al.* 2014). This study showed that the energy produced from 1 L of GTW in a dual fuel process compared to a co-digestion system only was 13.4 MJ/L-GTW compared to 9.6 MJ/L-GTW. It was also investigated by Tu and McDonnell (2016) by carrying out a life cycle analysis to evaluate the energy consumption and greenhouse gas (GHG) emission from the trap grease-to-biodiesel production process. They hypothesised that utilizing the solids in the trap grease for anaerobic digestion (AD) reduced both energy consumption and GHG emissions (Tu and McDonnell 2016). This appears to be the most effective approach to GTW utilisation as it separates the lowest grade layer and produces biogas while the higher grade FOG layer is pre-treated and used for biodiesel.

A circular economy projects the highest grade products from lowest grade raw materials with little to no waste. Research is ongoing into innovative approaches to move away from bioenergy to produce biomaterials from FOG, with a higher value.

6.4. Biomaterials

Valorising FOG waste into high value biopolymers and other biochemical building blocks offers greater economic benefit (Carus *et al.* 2011). The infrastructure for these processes requires development compared to the more mature processes discussed in this section. Recent studies have shown UCO (which is more readily reusable) and free fatty acids (FFAs) have potential as a substrate for biopolymers (non-toxic, biodegradable plastics) which could replace plastics from petrochemical sources in many applications (Ruiz *et al.* 2014). Polyhydroxyalkanoates (PHAs) are biopolymers produced by bacterial fermentation with the potential to replace conventional hydrocarbon-based polymers (Babu *et al.* 2013). Biodegradability and biocompatibility are important characteristics of PHAs. PHAs can be degraded to carbon dioxide and water by a large variety of micro-organisms in nature. PHAs and their derivatives are now used in the field of agricultural, food and biomedical materials. PHA can be produced by varieties of bacteria using several renewable waste feedstocks.

FFA content of GTW is >15%. By removing impurities of GTW and reducing the moisture content there is potential as a viable feedstock for PHA, however this pre-treatment increases the expense of the process. The raw material cost contributes significantly to the manufacturing cost of PHA. Therefore, renewable inexpensive raw materials should reduce the overall production cost. Crude glycerol, a by-product of the biodiesel transesterification process, is also a viable feedstock for value-added conversion into biopolymers or biochemicals (Luo *et al.* 2016).

Recent studies have detailed that bio-oil derived from used cooking oil can be utilised as an asphalt modifier, to increase resistance of pavement surfaces to thermal cracking and reducing additional maintenance (Sun *et al.* 2016).

A recent paper highlighted the potential of GTW from restaurants as a binder in metal injection moulding (MIM). MIM is a manufacturing process which produces intricate and small parts in high volume. The process involves developing the feedstock from metal powder and multi components of binder which through injection moulding form the desired shapes (Ibrahim *et al.* 2016). This highlights another potential utilisation route for diverted FOG waste, which is constantly evolving to produce the highest possible value product from the lowest grade feedstock.

7. Conclusions and further research

The previous sections have detailed:

- Detrimental effects attributed to FOG entering the sewer system;
- International approaches to FOG mitigation with specific review of grease trapping systems;
- Potential utilisation of diverted FOG waste.

This review has clarified the manner in which FOG has been diverted from the sewer system and in doing so illuminates the route that future FOG management programmes can take. Although this paper focused primarily on FSOs, it is evident that further development of domestic campaigns is essential to disrupt the discharge of FOG into the sewer network. The fact that FOG-related problems continue to plague cities is proof that current processes for managing FOG waste are inadequate and a complete diversion of FOG from the urban sewer system is unrealistic. FOG deposits are caused by multiple factors and must therefore be mitigated using various methods.

Public education campaigns, integrating social media initiatives, are the foundation to reducing FOG and other non-flushables from entering the sewer system. Promoting awareness at school level will engrain the importance of proper FOG treatment at a young age and will deliver it to households from another outlet. A homogenous national or international approach is not apparent due to the related legislation and variety of stakeholders involved in FOG management.

Ignoring FOG waste can only have detrimental effects. FOG management must evolve with the industries and trends that exist. An extensive study of a developed FOG programme (e.g. Dublin) is required to critically assess the management approach and develop national strategies. With advanced methods of FOG management, greater volumes of GTW and UCO can be diverted from the sewers. Development of utilisation routes is required to cater for this diverted waste.

The formation of a site specific FOG profile could assist in creating a tool to trace the source of FOG-causing issues so that the polluter pays principle could be better enforced by determining the sites responsible. Although studies have been carried out on the composition of FOG deposits and what causes them, further research is required on profiling fatty acid composition of FSO grease trap waste in urban environments.

The studies on utilisation trends are primarily pilot studies or bench scale. Further studies are required to determine the actual disposal routes that are currently in place and the opportunities available to upcycle FOG waste into a viable resource for bioenergy and bioproducts.

Despite some international successes in FOG management, a need exists for both improved technology and policy measures in capturing the potential economic and environmental benefits of this wasted resource globally.

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