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Effectiveness of grease interceptors in food service establishments for controlling fat, oil and grease deposition in the sewer system

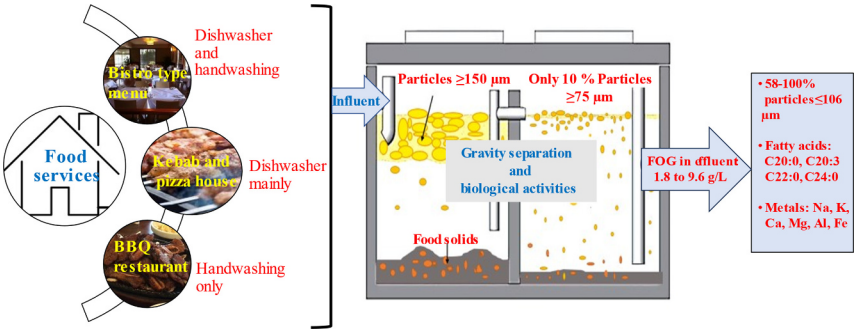
Nilufa Sultana [a], Felicity Roddick [a], Bruce Jefferson [b], Li Gao [c], David Bergmann [c], Jim Papalois [c], Mike Guo [c], Kyriakos Tzimourtas [c], Biplob Kumar Pramanik [a,*]

[a] School of Engineering, RMIT University, Melbourne, VIC 3001, Australia
[b] Cranfield Water Science Institute, Cranfield University, Bedfordshire MK43 0AL, UK
[c] South East Water, Frankston, Victoria 3199, Australia

HIGHLIGHTS

- Current commercial GIs do not completely remove FOG.
- GIs release 12–64 times higher concentration of allowable FOG.
- GIs release extra-long chain FAs.
- Food service dishwashers produced up to 80 % particles <45 μm.
- High levels of Na, Mg with Ca in GI effluents may play key role in FOG deposition.

GRAPHICAL ABSTRACT



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ABSTRACT

The water industry worldwide experiences numerous sewer blockages each year, partially attributed to the accumulation of fat, oil and grease (FOG). Managing this issue involves various strategies, including the requirement for installation of grease interceptors (GIs) installation. However, the claimed efficacy of commercial GIs of eliminating 99 % of FOG has been questioned for many years because FOG deposit formation occurs despite food service establishments (FSEs) using GIs, therefore detailed understanding of FOG wastewater compositions and its removal by GIs is required. This study provides an insight into the key FOG components such as FOG particle size, metals and fatty acid (FA) profile in GI influent and effluent, and within the GI, at three different FSEs. Analysis of FAs identified substantial proportions of extra-long-chain FAs in the effluents, including arachidic (C20:0), behenic (C22:0), mead (C20:3), lignoceric (C24:0), and nervonic (C24:1) acids. In contrast, the household kitchen released palmitic (C16:0), oleic (C18:1) and linoleic (C18:2) acids. It was further observed that scums effectively remove the larger FOG particles, leaving only 10 % below 75.4 μm. Notably, FSEs which employed automatic dishwashers produced up to 80.4 % of particles ≤45 μm, whereas FSEs and household kitchen which used handwash sinks generated only 36.9 % and 26.3 % of particles ≤45 μm, respectively. This study demonstrated that the commercial GIs do not remove FOG entirely but clearly demonstrated that they

* Corresponding author.
E-mail address: biplob.pramanik@rmit.edu.au (B.K. Pramanik).

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discharge high concentrations of FOG with extra-long FFAs which were attributed to the occurrence of microbial activity and hydrolysis of triglycerides within the GI, potentially contributing to FOG deposition.

1. Introduction

The high density of food service establishments (FSEs) in some areas creates additional pressure on sewer infrastructure, leading to frequent sanitary sewer overflows. The growing trend of dining out and consuming fast food contribute to the disposal of highly concentrated FOG wastewater into the sewer network. Upon reaching the sewer, FOG tends to solidify through hydrolysis and saponification, accumulating other debris that is flushed down toilets, causing it to adhere to and grow on the inner sewer surface, forming fatbergs. Monstrous fatbergs, such as a 250 m long, 130-t mass found in London (Oakes, 2019) and a 7.6 m long which was partially extended up to 80 m in Queensland, Australia (Stein and Miller, 2019), have been reported in recent years. The cost of clearance, the acute and complex treatment requirements, and the potential for environmental pollution and health risks during sewer overflows make this issue a concern (Ahmad et al., 2022). Water utilities have to deploy additional resources to manage sewer blockages due to the uncontrolled discharge of fat, oil and grease (FOG), for instance, annually estimated at £100 million in the UK (Collin et al., 2023), and $25 billion in the USA (Del Mundo and Sutheerawattananonda, 2017). Controlling or treating FOG at the source of generation, such as FSEs and household kitchens, could play a substantial role in reducing FOG deposition in the sewer system.

Passive and mechanized grease interceptors (GIs) are crucial for controlling FOG disposal at its source (Ducoste et al., 2008). These GIs capture and retain FOG particles by allowing heavy food particles to settle to the bottom and the FOG particles float to the top (Livingston et al., 2007). Several factors, such as inflow rate, hydraulic retention time (HRT), temperature, emulsion strength, particle size, FOG concentration, and type of fatty acids (FAs), affect the removal performance of GIs. Discharging highly concentrated FOG at high rates and temperatures can lead to hydraulic short-circuiting and washout of FOG from the GI (Ducoste et al., 2008). An HRT of at least 30 min is recommended for effective FOG removal (Metcalf et al., 1991). However, a study demonstrated that an HRT of 20 min with a short inlet configuration achieved 85 % FOG removal, with only a 12 % increase observed on tripling the HRT (Aziz et al., 2011).

Particle size plays a vital role in the gravity separation-based treatment of FOG using GI systems. Current thinking indicates that effective FOG removal by gravity separation requires free, non-emulsified oil particles larger than 150 μm (Wang et al., 2008). Colloidal or suspended FOG particles with high stability, including those $\leq$1 μm, are challenging to remove through gravity separation (Bande et al., 2008). GIs that receive wastewater from various FOG sources, such as handwashing and dishwasher washing, are likely to have a significant proportion of FOG particles $\leq$150 μm. This reduces the efficiency of the gravity separation mechanism. Barton (2012) showed a significant increase in particle size from 9 to 123 μm to 23–274 μm due to increased use of handwash sink (HS) combined with dishwashers (DWs). Similarly, Gurd et al. (2019) found the median particle size of FOG to be 18 and 27 μm from DWs and HSs, respectively. This suggests that DWs can potentially fragment FOG particles into sizes smaller than HSs, resulting in the gravity separation process being unable to remove 67 % of total FOG (Gurd et al., 2019). Emulsion strength is inversely correlated with FOG particle size, as higher strength leads to increased particle breakdown (Gallimore et al., 2011). The use of static mixers to enhance emulsion strength reduced the average particle size from 289 to 151 μm (Gallimore et al., 2011).

The two main components involved in the FOG solidification process are metals and free fatty acids (FFAs). Oleic (C18:1) acid (39–75 %) was found to dominate in most animal fats and cooking oils, followed by palmitic (C16:0), linoleic (C18:2), and stearic (C18:0) acids. The exception was soybean oil, where the poly-unsaturated linoleic (C18:2) acid level was markedly higher (55 %) than oleic (22 %) and palmitic (11 %) acids (Del Mundo and Sutheerawattananonda, 2017; Iasmin et al., 2014; Wang et al., 2008). However, in real field FOG samples, palmitic acid (22 to 97 %) concentrations were clearly much higher than oleic, linoleic, and stearic acids (Gross et al., 2017; Nieuwenhuis et al., 2018; Williams et al., 2012). Most studies claim that unsaturated oleic acid is transformed microbially by anaerobes and is hydrogenated to form palmitic acid (Iasmin et al., 2014; Williams et al., 2012).

There is limited research on what happens to the FA profile in GIs (i.e., between FOG wastewater generation and before it reaches the sewer). Wang et al. (2008) and Montefrio et al. (2010) characterized grease trap waste (i.e., scum) and found a nearly similar range (30–38 %) of palmitic and oleic acid contents. Although Wang et al. (2008) noted a small amount of long chain fatty acids (LCFAs) such as linolenic (C18:3) and arachidic (C20:0) acids in the scum, they did not determine the FA profile of the effluents from the GI. He and Yan (2016) showed in a laboratory study that microbial activity within the GI reactor can produce four times more LCFAs in the GI effluent using simulated wastewater and external microbial additives. It is likely that the number and types of LCFAs can vary in real GI samples due to the heterogeneity of FOG and food sources. In addition, hydrolysis and saponification reactions could also occur along with microbial activities within a GI system due to the retention time and lengthy cleaning cycle. Gurd et al. (2019) observed a significant variation in FOG wastewater characteristics from DW and HS in terms of particle size, emulsified FOG fraction and nutrient concentrations. However, they did not report the effect of DW and HS on the FA profile and how it changes after passing through the GI system. It can be hypothesised that the use of a dishwasher might significantly influence the input FA profile due to the mechanical breakdown of FOG in the presence of dishwasher detergent and chemical substances like rinse aid. Therefore, a detailed FA profile at each point of the GI system, taking into account both the cleaning process and microbial activities, is required to understand how GIs affect LCFAs entering the sewer system in real-world cases.

Determining the actual FOG removal efficiency of GIs is a significant challenge due to the difficulty of collecting representative inlet samples. However, understanding the detailed chemical characteristics of the effluent can provide valuable insights into why the sewer system continues to receive significant amounts of FOG, leading to fatberg formation, despite the use of GI systems at FSEs. Thus, this study aims to understand the performance of three existing FSE GIs based on the characteristics of the effluent FOG. Moreover, there is no study found which determined the FA profile for the post GI samples. Therefore, the novelty of this research is to find out the effects of in-GI activities on FA profile and FOG particle sizes by analysing the influent, scum, middle liquid, and effluent of the GI, the primary factors affecting the removal efficiency of GIs can be identified. A deeper understanding of the chemical characteristics of FOG could provide valuable insights for developing effective strategies to control sewer clogging. The scope of this study is limited to analysing random samples from four different points of three GIs. Factors such as the temperature used during cleaning with dishwashers and handwashing sinks or the type of fats, oils and food served by the individual FSEs were not considered in this study.

2. Materials and methods

Collecting representative inlet samples for the GI proved to be challenging, and it is recognised that they do not necessarily represent the input to the current GI contents nor the resultant effluent. However,

examining the FOG concentrations within the GI and in the effluents is worthwhile, as they provide insights into the operation of the GI and the composition of wastewater being discharged into the sewer. Therefore, a total of 12 samples were collected from three different GI systems.

2.1. Site selection and collection of GI wastewater

Wastewater samples containing FOG were collected from three different FSEs and a household kitchen handwash sink (HHS) located in the South-east suburbs of Melbourne, Australia, during the month of August when the average ambient temperature was 7–15 °C. The restaurant types and GI capacities were as follows: (i) GI-1: Bistro type menu with 1989 L capacity, used both dishwasher (DW) and handwash sink (HS) for washing, (ii) GI-2: kebab and pizza house with a 605 L capacity, primarily used a dishwasher, (iii) GI-3: BBQ items with an 1825 L capacity, used only handwashing methods and, (iv) HHS-4: effluent from a typical household kitchen (menu: cooked beef with spices using canola oil, rice, vegetables and salad), used only handwashing methods. Samples from the GIs were collected at four different points: inlet, outlet, scum, and the clear liquid from the middle (supplementary Fig. S1). Each sample, approximately 5 L, was collected in an airtight container, immediately placed in an ice-tub for transportation to the laboratory and stored at 4 °C to inhibit microbial growth (Mohana et al., 2023). All samples were brought to room temperature prior every analysis.

2.2. Analysis of chemical properties

The concentration of FOG in GI wastewater was determined using HEM method 1664. This method involves the extraction and distillation of FOG to determine its mass (USEPA, 1999). Briefly, 50 mL of the sample was acidified with 3 mL of H_2SO_4 to achieve pH <2. This was followed by the addition of 30 mL of n-hexane, with the mixture being stirred on a magnetic stirrer to ensure proper mixing. The mixture was then placed in a separatory funnel to remove water from the extract. Subsequently, the hexane was evaporated by a rotary evaporator to determine the mass of residual FOG (Ducoste et al., 2008).

The pH and dissolved oxygen (DO) for BOD (biochemical oxygen demand) tests of each sample were measured immediately upon arriving at the laboratory using a portable pH and a DO meter (Mettler Toledo and OHAUS DO kit-ST400D). BOD was measured following the APHA method (1998). Chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), and total ammonia-nitrogen (NH_3−N) were measured using HACH kits with high range digestion vials, reagent sets of TNT plus, molybdovanadate and low range TNT reagent sets (AmVer-Salicylate), respectively. The absorbance of all test kits was detected using a photometer (Spectroquant ® NOVA 60). All samples were analysed in triplicate.

The total protein concentration of the wastewater samples was measured using the BCA (bicinchoninic acid) method with a QPBCA QuantiPro™ BCA Assay kit (Sigma-Aldrich) and bovine serum albumin (Sigma-Aldrich) as the standard. The concentration of total carbohydrate was measured using the phenol-sulfuric method (Dubois et al., 1956). Metal concentrations in FOG wastewater were determined by the Inductively Coupled Plasma-Mass Spectrometry (Agilent 7900 ICP-MS). A range of dilution factor (10 to 40) was used to determine the concentration of metals. Following dilution, they were acidified using 2 % nitric acid and subsequently filtered through a 0.45 μm syringe filter.

2.3. Analysis of physical properties (particle size distribution)

A Malvern Mastersizer 3000 was used to analyze the particle size distribution of the GI wastewater (influent, scum, middle liquid and effluent) using the laser diffraction technique. Approximately 30 mL of the samples were taken into separate centrifuge tubes, and the tightly sealed centrifuge tubes were hold in a beaker with warm water (35–40 °C) until the FOG particles got redissolved. This step was crucial to prevent any solidification caused by sampling and storing at 4 °C. Once the samples were brought to room temperature (20 ± 2 °C), they were poured into the Hydro unit to obtain an appropriate size and distribution curve. The resultant particle size distribution was then expressed as a volume-weighted mean calculated from an average of 30 measurements. Each sample was then analysed in triplicate.

2.4. Fatty acid (FA) analysis

The FA profiles were determined by the fatty acid methyl ester (FAME) analytical approach using the AOAC 996.06 method (AOAC, 2001). Four tubes containing standard solutions (25, 12.5, 6.25 and 3.125 ppm) were prepared using Supelco 37 component FAME mix (Sigma Aldrich) and Dichloromethane (DCM) as solvent. Concentrated FOG from 50 mL of liquid sample (extracted during the determination of FOG concentration) was heated in an oven at 80 °C for 45 min to remove moisture. 5 mL of DCM was added to each sample in test tubes and placed in a shaker water bath for 20 min to ensure the complete dissolution of FOG. The samples were then filtered through a 45 μm syringe filter to remove any fine food particles, and the test tubes were placed under an evaporating unit to remove the DCM. Each tube had 1.5 mL of methanolic NaOH (0.5 M) added and was heated to 85 °C for 10 min in a water bath. After cooling to room temperature (20 ± 2 °C), 1 mL of BF_3. CH_3OH (14 % in methanol) was added, and the tubes heated again at 85 °C for 15 min. After cooling, the FAMEs were analysed using gas chromatography (Agilent Technologies, Australia) fitted with an SP-2560 silica column and a flame ionization detector with helium as the carrier gas. The peak areas of the samples were compared with the Supelco FAME standard mixtures to determine the concentration of each FA. Each sample was analysed twice, and the average values of each concentration were provided.

2.5. Advanced characterization

2.5.1. FTIR spectrometry

A Perkin Elmer 100 Fourier-transform infrared (FTIR) spectrometer was used to identify the fatty acids and fatty acid salts. Qualitative FTIR analysis was performed on the unreacted FOG particles to determine their functional groups. The FTIR spectra were recorded with an attenuated total reflection cell equipped with a platinum single crystal. The spectrum was scanned 64 times at wave numbers of 4000–400 cm^{-1}. The readings were computed using PerkinElmer Spectrum version 10.5.2 software.

2.5.2. Confocal microscopy (CLSM)

The shape and size of unreacted FOG particles were observed under a Nikon Ti-E (7413) confocal laser scanning microscope (CLSM), A1 (Japan). A small drop of the raw hexane-extracted FOG samples was placed on a circular glass slide. Each specimen was scanned, and the image was recorded with scan properties of 2 × 12bit: 1024 × 1024 pixels and document calibration of 0.21, 0.62 and 1.24 μm/px. The image length was viewed and recorded at a scale of 100 μm. The field of observation was randomly selected, and each image was scanned in at least 30 steps. All images were processed and analysed using NIS-Elements viewer software.

3. Results and discussion

3.1. Particle sizes of FOG in GI wastewater

Particle size is key in GI systems for FOG wastewater treatment as larger particles (≥150 μm) can be rapidly removed, while smaller ones can take hours to days to settle naturally under gravity (API, 1990). Analysing particle sizes of GI scums can provide insights into GI removal performance in terms of physical size separation (Fig. 1-(a)). Only 10 %

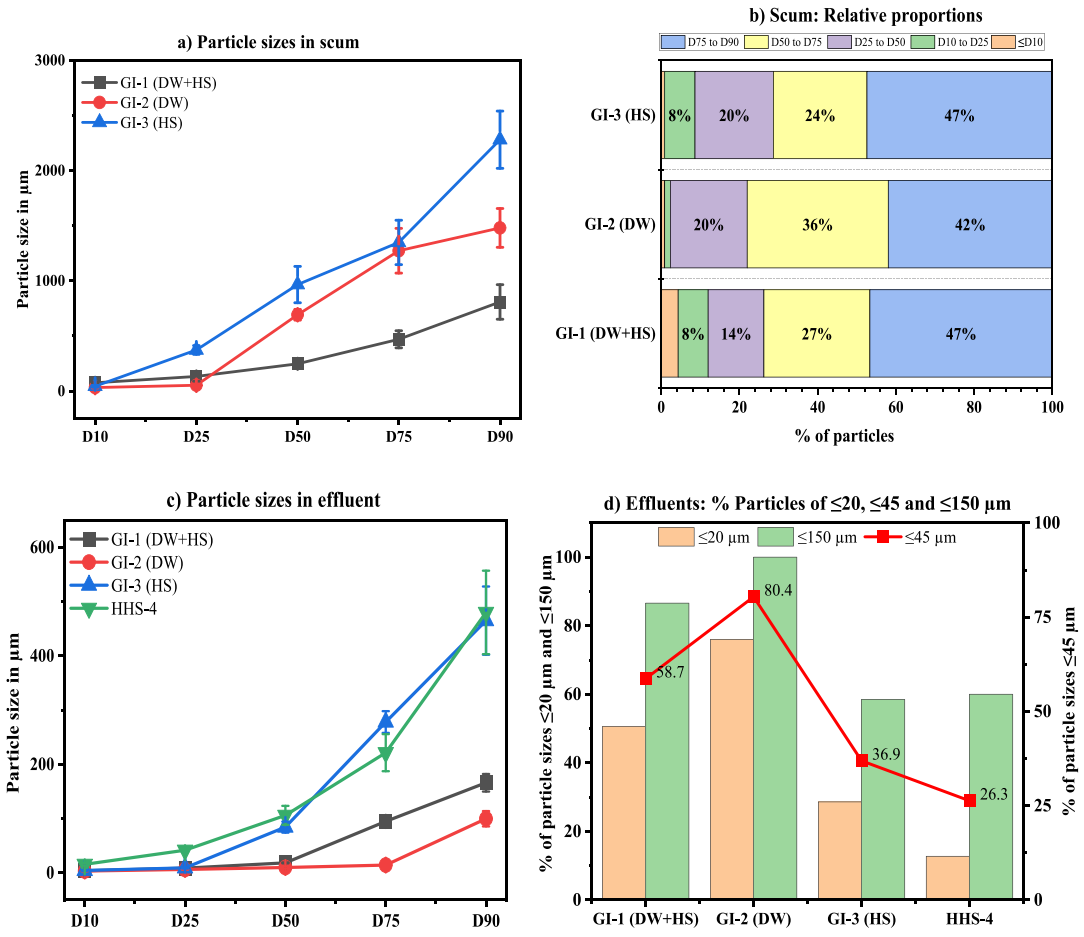

Fig. 1. (a) and (c) particle size distribution of FOG in the scums and effluents, (b) relative proportions of removal through scum, and (d) proportions of emulsified FOG particles in ranges ≤20, ≤45 and ≤150 µm present in the effluents.

of measured particles were below 75.4 µm and 25 % were below 373 µm across all the GIs. The particle size range between D_{25} and D_{90} was 373–2280 µm, with 10 % of particles exceeding 808, 1480, and 2280 µm for GI-1, GI-2 and GI-3, respectively. The relative proportion of particles by size (Fig. 1 (b)) clearly demonstrates that nearly half (42–47 %) fell within the D_{75} to D_{90} range (between 469 and 2280 µm), and 24–36 % were within the D_{50} to D_{75} range (between 247 and 1148 µm) across all the GIs. Therefore, this study provides further clear evidence that GIs are more effective in removing free, non-emulsified particles with a size of ≥150 µm (API, 1990).

The median particle diameter for all GI effluent samples and the household sample was ≤106 µm, hence 50 % of the particles in the effluent were below this size (Fig. 1 (c)). The size range between D_{50} and D_{90} was 106–480 µm. It is noteworthy that for GI effluent generated from dishwashers (GI-1 and GI-2), 50 % of particles were below 18.3 µm, and 75 % were below 95 µm. Fig. 1 (c) clearly shows that for the FSE which used an automatic dishwasher as the primary cleaning method (GI-2), 90 % of the particles were ≤99.7 µm. This was likely due to high temperature and mechanical agitation within the dishwasher enhancing FOG particle fragmentation (Sultana et al., 2024). A slight increase in particle size, with 15 % ranging between 94.8 and 166 µm, was observed for GI-1, which utilized both handwash and dishwasher processes, likely attributable to the inclusion of wastewater from handwashing. Conversely, larger particles were more prevalent in GI-3 and HHS-4, which only involved handwashing sinks, compared to GI-1 and GI-2. These results align with the findings of Sultana et al. (2024) who noted that kitchens equipped with dishwashers tend to generate a higher proportion of micro-sized FOG particles compared to those relying solely on handwash sinks.

Significant observations can also be made regarding the proportion of particles and their emulsion strength and stability. Effluents from GI-1 and GI-2 which came from dishwashers showed that 50.6 % and 76 % of their particles were ≤20 µm in size (Fig. 1 (d)). These particles are referred to as chemically emulsified micro-emulsions with strong suspension stability, requiring several days for gravity separation (Bande et al., 2008). Furthermore, 58.7 % and 80.4 % of FOG particles were ≤45 µm in the GI-1 and GI-2 effluents, respectively. In comparison, effluents from HS in GI-3 (FSE used HS only) and HHS-4 contained 36.9 % and 26.3 % of particles ≤45 µm, respectively. This is possible because a recent study by Sultana et al. (2024) showed that DWs were more prone to break down FOG particles generating up to 50 % of ≤7 µm, while HSs produced 50 % of ≤118 µm. These findings also align closely with the results reported by Gurd et al. (2019) who found that an average of 94 % of particles from dishwashers and 76 % from handwash sink effluents were below 45 µm, i.e., representing emulsified fractions. However, in their study, the samples were collected directly from the downstream pipe of the handwash sink and dishwasher. The authors noted that approximately 67 % of the total FOG was unlikely to be removed, even after passing through the GI system.

In this study, overall, 86.6 %, 100 %, 58.5 %, and 60 % of FOG particles in the effluents of GI-1, GI-2, GI-3, and HHS-4, respectively, were well below 150 µm. This clearly indicates that these particles fell into the range of chemically and mechanically emulsified FOG, consequently, the gravitational effect within the GI system failed to retain them and they were able to directly enter the sewer system. To avoid this from happening, Barton (2012) suggested employing either a long hydraulic retention time or the use of chemicals for separation.

3.2. Chemical characterization of FOG

3.2.1. FOG quantification

Extremely high concentrations of FOG were found in the scums collected from the tops of all three GIs (Fig. 2), they showed the diverse composition received by the GIs. The scums can be removed from the GIs for either landfilling or biofuel production. The maximum concentration of scum of 309.8 g/L was observed for GI-1, which used both HS and DW cleaning processes, followed by GI-3 (which used only HS, 223.6 g/L) and GI-2 (which primarily used DW, 192.6 g/L). The concentrations in the influents were significantly lower than those in the scums for every GI, due to the fact that scum accumulated in a big volume over a long cleaning cycle. Another significant factor may be the random collection of inlet samples, which may not represent the actual inflow concentrations for the GI contents at the time of collection. Furthermore, inflow concentrations can significantly vary during peak serving times such as for breakfast, lunch, and dinner, and can be very low during off-peak hours (Ahmad et al., 2023). However, the high concentrations of FOG in the scums may be attributed to a long cleaning cycle and/or the design of the GI, which allows for the accumulation of the maximum volume of scum within the designed HRT.

With respect to the effluent FOG concentrations, GI-3 discharged the highest concentration of 9.6 g/L of FOG into the sewer system, followed by GI-2 and GI-1 with 5.4 g/L and 1.8 g/L, respectively. Despite an extremely high concentration of FOG (223.6 g/L) being found in the scum of GI-3, it still discharged highly concentrated FOG into the sewer. This was possibly due to short-circuiting caused by high inflow rates during sampling (Aziz et al., 2012; Ducoste et al., 2008). However, GI-3 was supposed to be more efficient because it has a large number of particles with ≥150 μm (63 %). The effluent concentrations for GI-1 and GI-2 were 1.8 g/L and 5.4 g/L, respectively, suggesting that higher removal through scums results in lower concentrations in the effluents, as evidenced by these values. The effluent from the household HS (HHS-4) directly discharged 3.1 g/L of FOG into the sewer system (supplementary Table S1). Overall, it is evident that both household kitchens and FSEs with GIs were discharging remarkably high concentrations of FOG into the sewer systems, much higher than the allowable limit for FSE effluent of 50 to 150 mg/L (Metcalf et al., 2014). However, according to the Tennessee Division of Water Pollution, this limit can be varied up to 300 mg/L for animal and vegetable-based sources.

3.2.2. Fatty acid (FA) compositions

A wide variety of both saturated and unsaturated FAs, ranging from C6:0 to C24:1, was found across the different restaurant types (Fig. 3). The FA profile found in the scums demonstrated the effectiveness of the gravity separation mechanism for accumulating common FAs such as palmitic, oleic, stearic, and linoleic acids along with a very small percentage (varies from 1 to 6 %) of extra-long-chain FAs such as arachidic, behenic, paullinic, erucic and lignoceric acids. However, it is noteworthy that a significant proportion of extra-long-chain FAs remained and dominated in the effluent compared to the common FAs. In the scum of GI-1, which originated from a bistro-style restaurant, the mono-unsaturated oleic acid (C18:1) was dominant at 55 %, followed by 16 % linolenic acid (C18:2) and 14 % palmitic acid (C16:0) (Fig. 3 (a)). Significant variations in FAs were observed in the middle liquid and effluents. The liquid phase was characterized by 40 % oleic acid (unsaturated), 27 % palmitic acid (saturated), and 18 % stearic acid (saturated), the others being short chain and extra-long chain FAs. However, no oleic acid was found in the effluent; instead, behenic acid (C22:0) constituted 46 % of the FAs, accompanied by 10 % arachidic acid (C20:0). Significantly lower contents of stearic acid (by 10 %) and palmitic acid (decrease from 27 % to 8 %) were observed when comparing the effluent to the liquid phase.

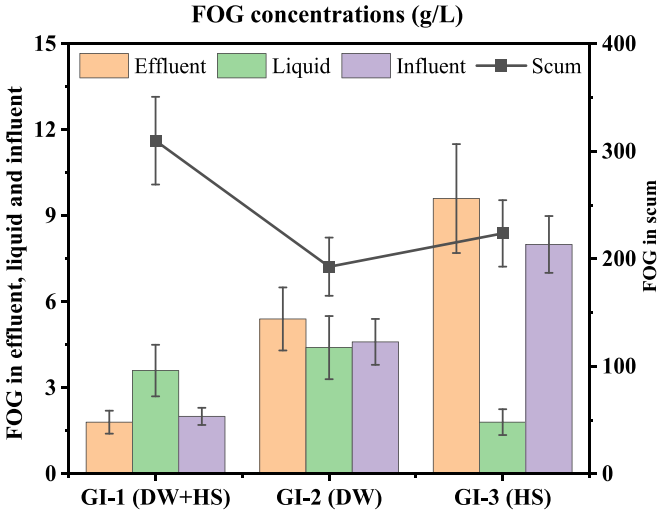

Fig. 2. Total FOG concentrations in the effluent, liquid, influent and scum of three GI sites. Note: The FOG concentrations of the influent may not necessarily reflect the FOG concentrations of the liquid, scum and effluent.

The scum of GI-2, which receives wastewater from a kebab and pizza restaurant primarily using animal fats (e.g., chicken and beef), cheese, and sauces, contained palmitic acid as the most abundant and prevalent FFA (65 %) (Fig. 3 (b)). This indicates that GI-2 effectively removes saturated fats like palmitic acid (C16:0). The liquid phase contained 42 % oleic acid, 21 % linoleic acid and 17 % palmitic acid. Although the influent sample did not necessarily fully represent the characteristics of FOG wastewater, it contained 63 % lignoceric acid and 20 % behenic acid. The effluent contained 31 % lignoceric and 9 % behenic acid suggesting that the gravity separating mechanism in the GI did not fully remove these FAs, however, only half of those were found in the influent. Interestingly, an uncommon FA, mead (C20:3) acid, accounted for 38 % of the FAs in the effluent, suggesting that microbial transformation of FAs occurred within the GI system (He and Yan, 2016). The proportion of arachidic acid (C20:0) was 16 % higher in the effluent compared to the scum and liquid phases, indicating the lower efficiency of the GI for removing extra-long-chain FAs such as arachidic or lignoceric acid. He and Yan (2016) found similar types LCFAs, such as arachidic (C20:0), paullinic (C20:1) and behenic (C22:0) in their GI reactor. These LCFAs resulted from adding microbes to the simulated FOG wastewater containing canola oil and cooked rice. Therefore, it is possible that the diverse sources of FOG waste and long HRT in the real field GIs could exhibit the production of extra-LCFAs in this study.

The GI-3 at the BBQ-type restaurant contained consistent types of FAs in the influent, scum, and liquid samples (Fig. 3(c)). Oleic, linoleic, palmitic, and stearic acids were commonly present, ranging from 27 to 39 %, 20–34 %, 15–21 % and 7–15 %, respectively. Surprisingly, the effluent revealed the presence of several extra-long-chain FAs, with 42 % behenic acid (C22:0), 21 % lignoceric acid (C24:0), and 12 % nervonic acid (C24:1) (Fig. 3(d)). The arachidic acid (C20:0) content was 6 % greater in the effluent compared to the liquid phase. These findings may be attributed to the structural transformation of FAs during the high-heat cooking process involved in BBQ cuisine (Omidvar et al., 2023; Yusuf et al., 2023).

A markedly different observation was made when examining the effluent from the household kitchen handwash sink (Fig. 3(d)), where limited production (6–7 %) of extra-long-chain FAs was detected. Notably, FAs such as oleic (44 %), palmitic (18 %), linolenic (15 %), and stearic (8 %) acids were found in the effluent represents the standard FA profile of beef tallow and canola oil (Iasmin et al., 2014). Therefore, there were no changes in FA profile and no formation of extra-LCFAs due to the handwashing.

Overall, it is evident that FA proportions varied significantly at different sampling points within the GI systems. Long and Extra-long chain FAs (more than C20:0) were dominant in the effluents whereas the common FAs (C14:0 to C18:3) were dominant in the scum and liquid

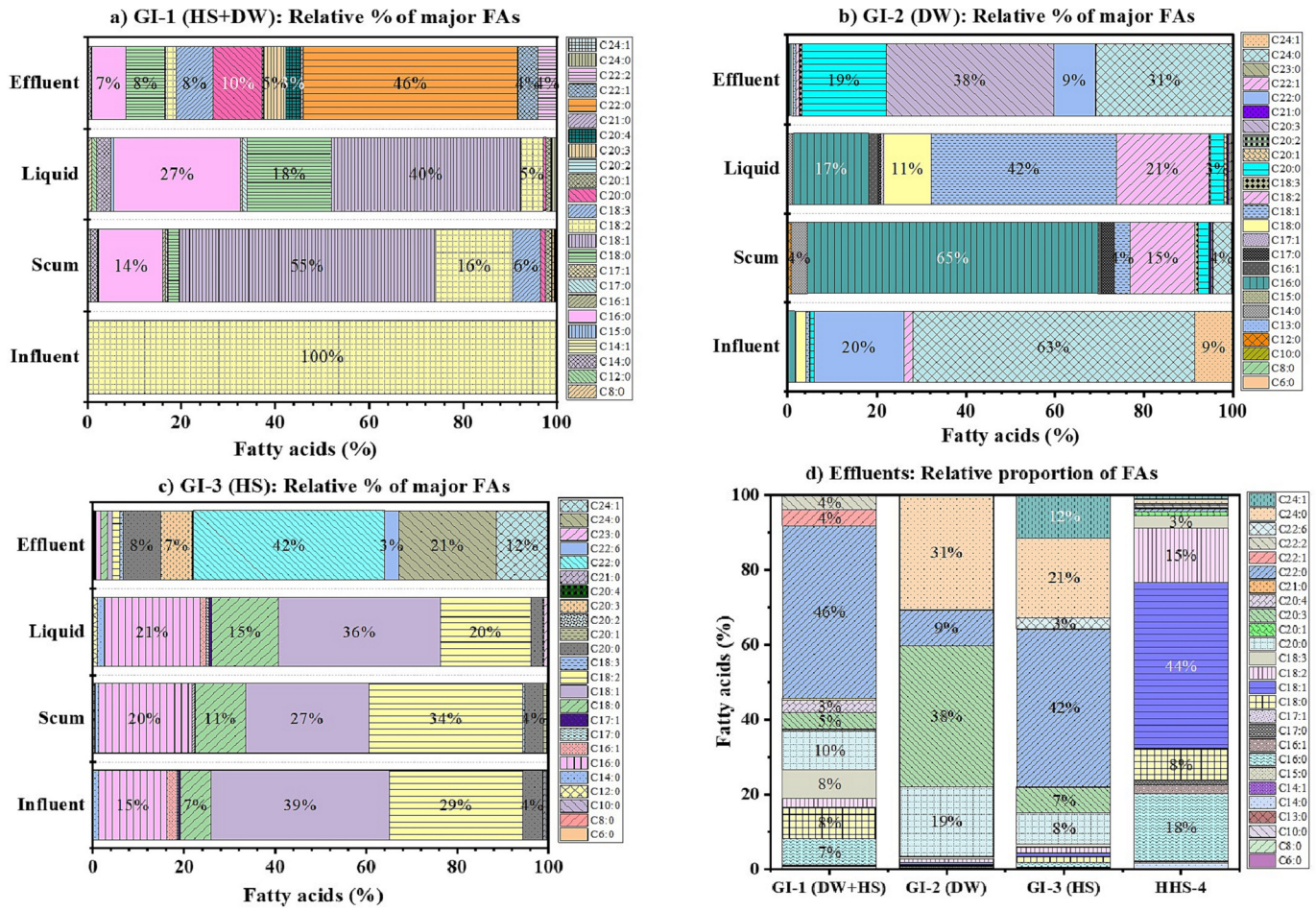

Fig. 3. FA compositions of FOG wastewater from FSEs. Fig. (a), (b), and (c) depict the relative proportions of FAs in GI-1, GI-2 and GI-3, respectively, (d) illustrates FAs in GI effluents, as well as the household kitchen source, that pass directly to the sewer. Data used for the relative proportions was the average value of duplicate samples. Note: The FA content of the influents may not necessarily reflect the FA contents of the liquid, scum and effluent.

in the GIs. Unsaturated long chain FAs could pose a potential threat to the sewer system due to the fact that metal salts of unsaturated FAs have greater adhesiveness and soap production. These compounds contribute to increased corrosion of concrete sewers leading to the significant amount of calcium leaching which could enhance the formation capabilities, attributed to the higher number of double bonds and higher molecular weight (He et al., 2013; Sultana et al., 2022). Consequently, enhance the formation of FOG deposits (He et al., 2013).

3.2.3. *Analysis of chemical properties of GI wastewater*

Some chemical parameters including pH, COD and nutrient concentrations can have significant consequences on the treatability of GI waste and solidity of FOG deposits. The GI samples and household samples exhibited a moderately acidic to neutral pH range (Fig. 4 (a) and Table S1). All influents had a neutral pH, ranging from 6.8 to 7.7. The scums displayed a slightly acidic to moderately acidic pH, ranging from 5.7 to 4.6 (Fig. 4 (a)), which aligns with the average pH value of 4.6 ± 0.6 observed in fifteen GI samples installed at a FSE hub (25 restaurants) in Malaysia (Ahmad et al., 2023). This shift in pH values is likely attributed to microbial activity resulting from the presence of organic food compounds in the wastewater (Barton, 2012). The pH levels remained consistent for the liquids collected from the middle of the GIs and for the effluents, ranging from 5.2 to 5.9. An exception was recorded for the liquid from GI-2 which had a pH of 7.0, the FSE which mainly utilized a dishwasher. However, the pH range of 5.2 to 5.9 observed in the effluents, including the household sample (HHS-4) (Table S1), confirmed the discharge of slightly acidic wastewater into the sewer system. The accumulation of acidic effluents has the potential to corrode sewer pipes. This corrosive effect is further exacerbated when combined with excessive FOG, leading to the leaching of calcium through microbially induced concrete corrosion and degradation of sewer pipes, ultimately contributing to fatberg formation (Iasmin et al., 2014).

A wide range of BOD and COD was recorded depending on the sampling points (Fig. 4 (b) and Fig. 4 (c)). The trends for BOD and COD values were consistent although for GI-2 (DW) the BOD (137–140 mg/L) values were similar for both liquid and effluent, while the COD value of the effluent (315 mg/L) was slightly higher than that of liquid (289.5 mg/L). Although the highest removal of BOD and COD occurred through scum in GI-3, the highest concentrations of BOD and COD of 702 and 401 mg/L, respectively, were discharged from that GI. In contrast, the trend was opposite for total protein and carbohydrate in the scums (Fig. 4 (d) and Fig. 4 (e)). The concentration of protein was higher in the scum of GI-1 (19,308 mg/L), followed by GI-2 (8095 mg/L) and GI-3 (4282 mg/L). Consequently, an increasing trend in protein concentrations from 73 mg/L to 130.6 mg/L was observed in the effluents among GIs. On the other hand, the total carbohydrate concentration was higher in the scum of GI-3 (9228 mg/L), followed by GI-2 (7230 mg/L) and GI-1 (3183 mg/L). However, the presence of carbohydrates in the effluents did not align with the scums. The lowest carbohydrate concentration in the effluent and scum of GI-1 indicates the bistro restaurant served less carbohydrates. Conversely, the highest effluent carbohydrate concentration of 4990 mg/L, as well as the highest in the scum (9228 mg/L), suggested that GI-3 experienced a high inlet volume, leading to short-circuiting and the flushing out of raw wastewater without adequate

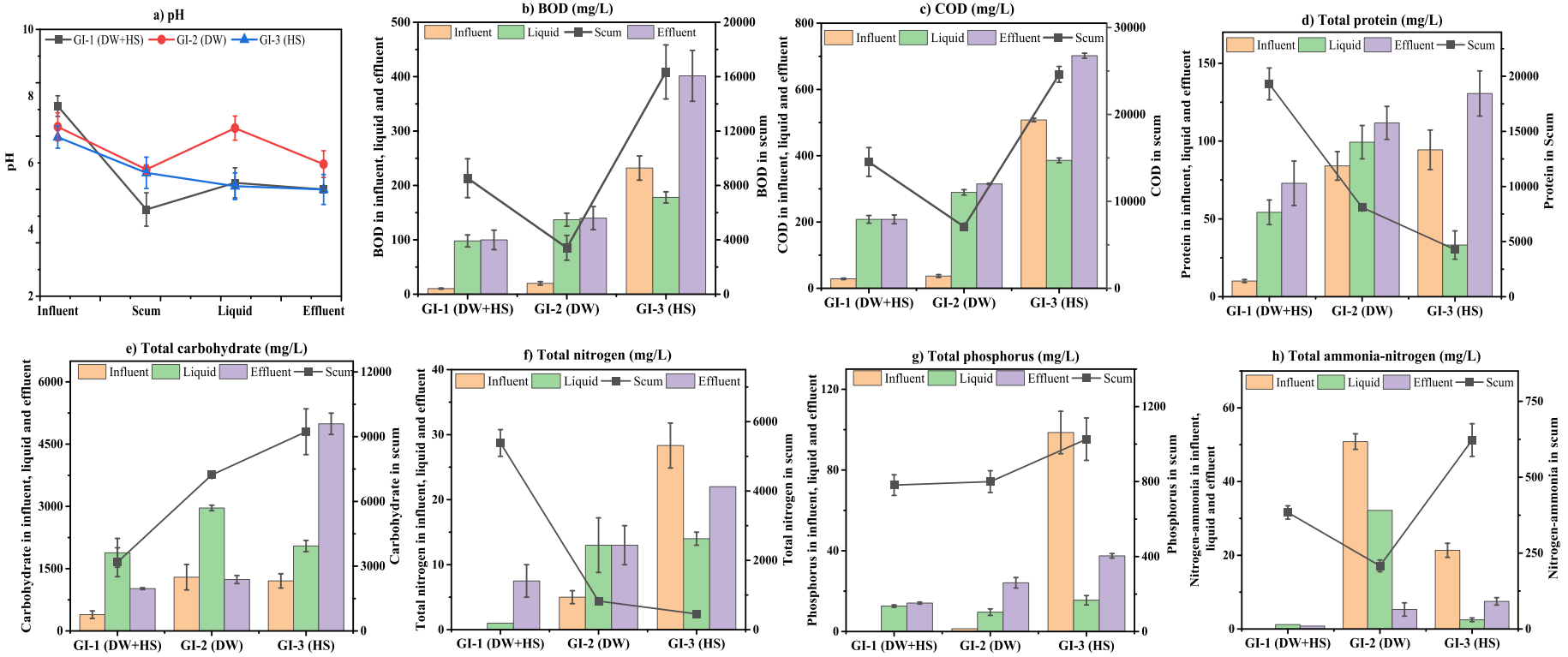

Fig. 4. Chemical properties of the GI samples in influent, effluent, liquid and scum, (a) pH, (b) BOD, (c) COD, (d) total protein, (e) total carbohydrate, (f) TN, (g) TP, and (h) total NH_3-N. All values were measured in a triplicate. Note: The chemical properties of the influents may not necessarily reflect the chemical properties of the liquid, scum and effluent.

separation of FOG.

An extremely high concentration of TN (5385 mg/L) was found in the scum of GI-1 compared to 824 mg/L in GI-2 and 455 mg/L in GI-3. The range of TP was observed to be narrow between 781 and 1026 mg/L, while NH_3-N ranged from 208 mg/L to 622 mg/L. Interestingly, no nitrogen, phosphorus or ammonia-nitrogen was detected in the influent of GI-1, which was likely due to the apparently inappropriate timing of sample collection. In the effluents, TN, TP and NH_3-N ranged over 7.5–22 mg/L, 9.6–15.5 mg/L, and 0.8–7.5 mg/L, respectively. The findings for TP and NH_3-N align with those of Gurd et al. (2019), who reported TP in the range of 4.4 to 28.9 mg/L for samples from handwash sinks, dishwashers, and mixed conditions. However, the range for TN was higher in their study, 24 to 79 mg/L. This difference could be attributed to the fact that Gurd et al. (2019) collected samples directly from the washing appliances, while in this study, the samples were passed through the GI system.

3.2.4. Metal ion concentrations

The level of metal concentration was notably higher in all scum samples compared to the influent, effluent and liquid samples. GI-1 had significantly lower concentrations of metals compared to GI-2 and GI-3, except for potassium and iron, which could be attributed to the specific types of food served by the restaurant (Fig. 5 (d) and 5 (f)). Interestingly, the concentration of potassium was significantly higher in the effluent of GI-1 compared to the scum and liquid samples, suggesting that GI-1 was less efficient in removing potassium. Notably, higher concentrations of potassium were found in the liquid (80.6 mg/L) and effluent (96.4 mg/L) of GI-2 compared to the amount retained in the scum (38.6 mg/L). The maximum levels of sodium were recorded in GI-2, with 175, 355 and 304 mg/L in the effluent, liquid and scum, respectively, indicating the extensive use of detergent containing sodium hydroxide during dishwasher operations.

Significant levels of calcium and magnesium were detected in the GI-2 and GI-3 samples (Fig. 5 (a) and Fig. 5 (b). The scums of GI-2 and GI-3 contained significant concentrations of calcium (up to a maximum of 108.7 mg/L) and magnesium (up to a maximum of 18.7 mg/L). However, a considerable concentration of calcium (9.3 to 28.0 mg/L) and magnesium (2.9 to 5.3 mg/L) was detected in the effluents (Fig. 5 (g)). Calcium plays a crucial role in the formation of fatbergs as it actively participates in saponification to produce solid residues (Gross et al., 2017). The GI samples also exhibited significant levels of aluminium and iron. Gross et al. (2017) demonstrated the different effects of Fe^{2+} and Fe^{3+} on the density of FOG deposits. The presence of Fe^{3+} can increase the density as it is less soluble than Fe^{2+} and more prone to forming deposits (Cornell and Schwertmann, 2003). However, this study did not differentiate between Fe^{2+} and Fe^{3+}. Although the scums were able to retain high concentrations of aluminium and iron, small amounts were still released in the effluents. While the significant role of calcium in the solidification of FOG and the formation of fatbergs in concrete sewers is evident (He et al., 2013), the impact of other metals elements such as sodium, potassium, magnesium and aluminium on FOG deposition remain unclear. However, those multivalent metal elements may have the potential to create respective metallic soaps. Further studies are necessary to understand the influences of these metals on FOG deposition.

3.3. Advance characterization of FOG samples

3.3.1. FTIR analysis

FTIR spectra with distinct absorption bands in several characteristic regions served as a fingerprint in determining the possible type of fat and oil within the GI system as well as released into the sewer system. In both the scum and effluent samples, strong absorbances were observed in different regions. In the scum, absorbance around 3400 cm^{-1} represented hydroxyl functional group (O—H stretching vibration) with bound water associated with calcium soap (He et al., 2013). Peaks observed around 2851 cm^{-1} (symmetric stretching vibration) and 2950 cm^{-1} (asymmetric stretching vibration) displayed in the scum indicated the triglyceride functional group (Del Mundo and Sutheerawattananonda, 2017). These peaks represented the frequency of aliphatic chains of metal soaps (Poulenat et al., 2003). GI-1, GI-2, and GI-3 exhibited moderate, weak, and strong absorbance band, respectively, at 1745 cm^{-1}. This suggests that GI-2 consumed a greater amount of FFAs to react with calcium compared to GI-1 (Fig. 6 (b)). In contrast, the strong peak observed in GI-3 indicated a high volume of triglyceride characteristics, representing unreacted fat/oil, as signified by the carbonyl bond (Del Mundo and Sutheerawattananonda, 2017). The carboxylic functional group was consistently identified at an absorption of 1160 cm^{-1} in all GIs. Moreover, the scum samples displayed distinct soap bands, particularly the symmetric stretching vibration of carboxylate ions within the range of 1300 to 1500 cm^{-1}. Interestingly, a strong absorbance at around 953 cm^{-1} was observed in the scum of GI-1 and GI-2, which aligns closely with a peak (920 cm^{-1}) identified by Dominic et al. (2013), suggesting the presence of glycerol resulting from hydrolysis. Across all GIs, weak bands near 670 cm^{-1} were frequently observed, reflected the presence of metal-oxygen bond, and peak around 720 cm^{-1} confirmed the production of calcium soap (Poulenat et al., 2003).

A slightly different observation was made for the FTIR spectra of the effluents, as shown in Fig. 6 (d). The absorbance in the region 3000–3400 cm^{-1} represented the presence of the hydroxyl (O—H stretching bond) functional group, suggesting the presence of water associated with calcium soap (Del Mundo and Sutheerawattananonda, 2017). A strong peak in the GI-3 effluent and moderate peaks (between 3000 and 3400 cm^{-1}) in GI-1 and HHS-4 indicate the disposal of metallic soaps into the sewer system. However, low absorbance of this band in the GI-2 effluent indicated a lower disposal of soap. Notably, no absorbance was found at 1745 cm^{-1} for the GI effluents, which is attributed to the presence of triglyceride ester bond, except in the effluent from the household kitchen (HHS-4). This could be due to the majority of the FFAs produced within the GI system undergoing the saponification reaction, with a moderate amount of FFAs discharged from HHS-4. A peak at 1450 cm^{-1} was observed in the GI-3 effluent which aligns with the symmetric stretching vibration of the carboxylate ion indicating the ionized structure of calcium soaps (Iasmin et al., 2014). This is possible because a significant concentration of calcium was found in the effluent of GI-3. The peak at 2950 cm^{-1} (asymmetric stretching vibration) for the household effluent was displayed the same characteristics as the scum samples, confirming the sufficient presence of FFAs to react with metals such as calcium. As expected, the spectra of influent and liquid clearly showed that the influent did not correspond to the actual influent and liquid samples that had significantly lower FOG concentrations compared to the scum and effluent.

3.3.2. Confocal imaging

Concentrated FOG samples were collected during the FOG quantification process using the HEM method. These particles were then examined under a confocal microscope to obtain their size and microstructure. The microscopic images presented in Fig. 7 confirm the particle sizes previously determined using the laser diffraction technique (see Section 3.1). The breakdown of FOG particles, influenced by the type of food source at various sampling points in the GI, is clearly evident due to the cleaning process employed. As indicated in Section 3.1, in the effluents resulting from dishwasher use after passing through GI-1 and GI-2, 90 % of the particles were ≤166 μm. Fig. 7(a) shows that most of the effluent particles for GI-1 were well below 42 μm. The extensive fragmentation of FOG particles as a result of dishwasher use in GI-2 effluent (Fig. 7(b)) was evident. The image of the scum from GI-1 (HS + DW) (Fig. 7(d)) shows fibre-like particles, which could be unbroken large food particles that floated to the top with the FOG due to handwashing. The scum for GI-2 (DW) exhibited scattered, non-uniform small-sized flocs, with the majority being below 100 μm (Fig. 7(e)).

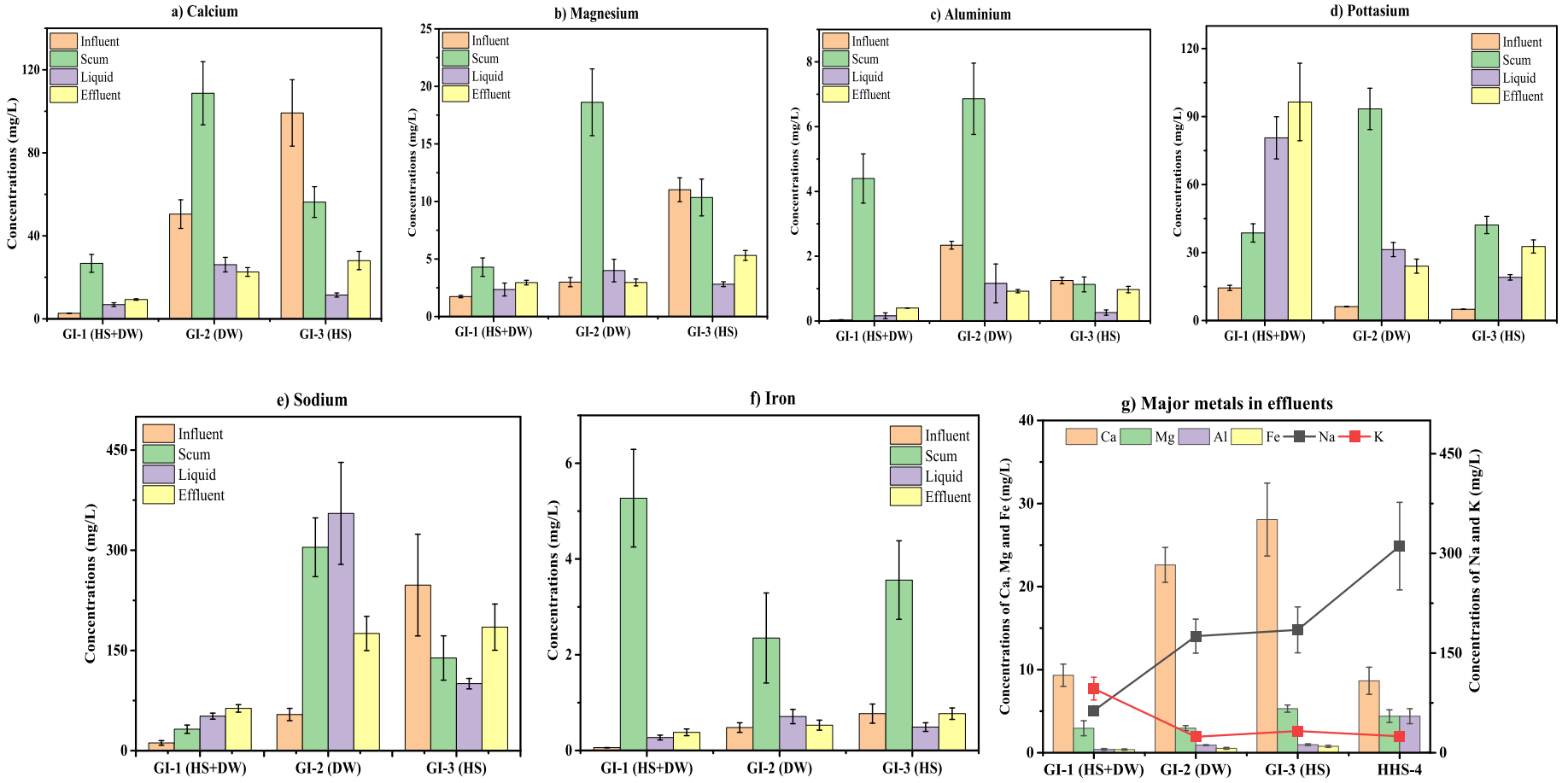

Fig. 5. Major metal concentrations (average of triplicate tests) in GI wastewater samples at different intake points. Fig. (a), (b), (c), (d), (e), and (f) show the concentrations of Ca, Mg, Al, K, Na and Fe, respectively, in GI-1, GI-2 and GI-3 samples. Fig. 6 (g) shows the major metals passing through the GI system and from a household to the sewer network. Note: The metal content of the influents may not necessarily reflect the metal content of the liquid, scum and effluent. All values were measured in duplicate.

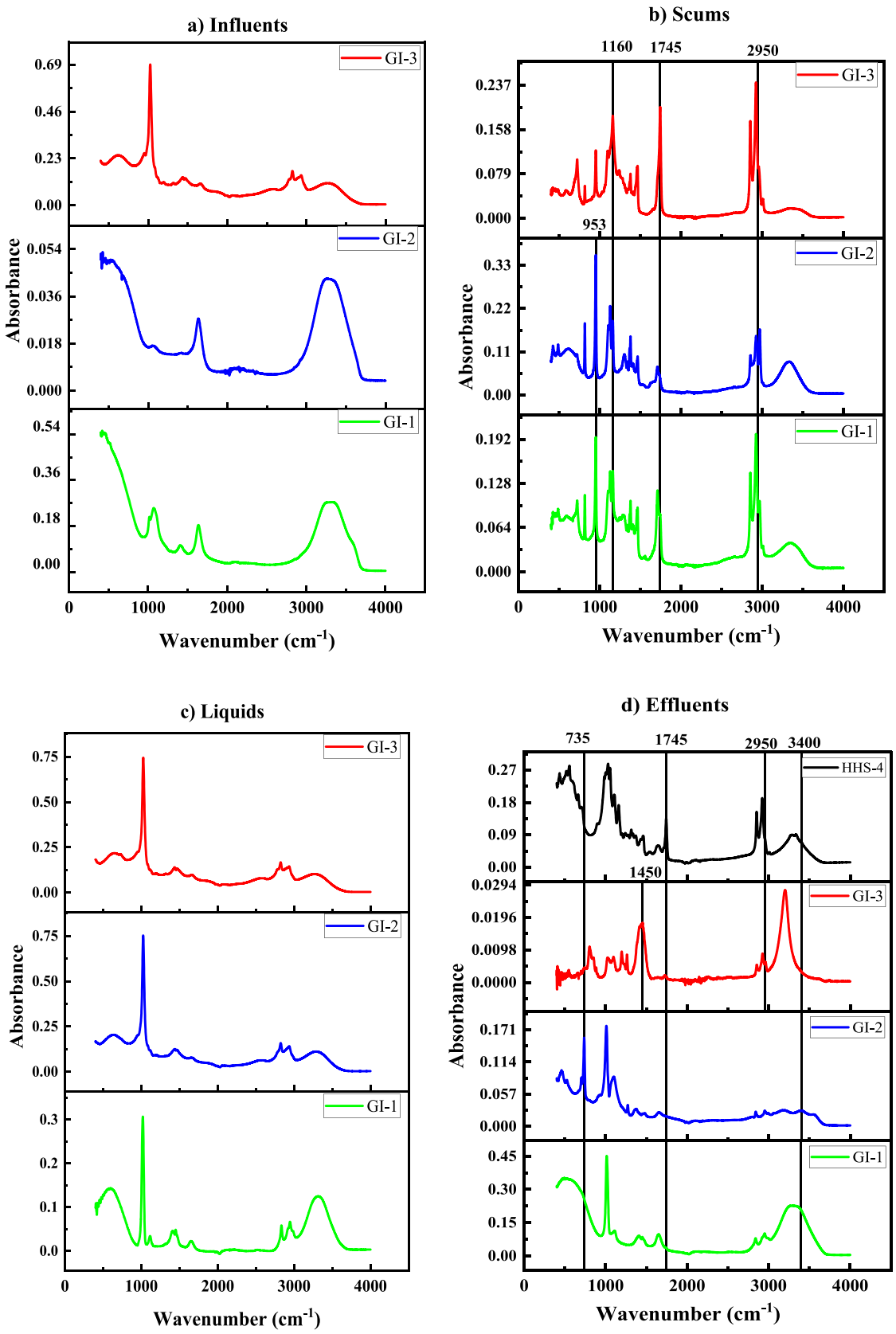

Fig. 6. (a), (b), and (c) represent the FTIR spectra of FOG samples collected from the influent, scum, and liquid of the three commercial GIs, respectively, and (d) represents the spectra of the effluents from the three GIs and a household kitchen. Duplicate tests were conducted, and the trend of peaks was consistent, thus one set of data is presented.

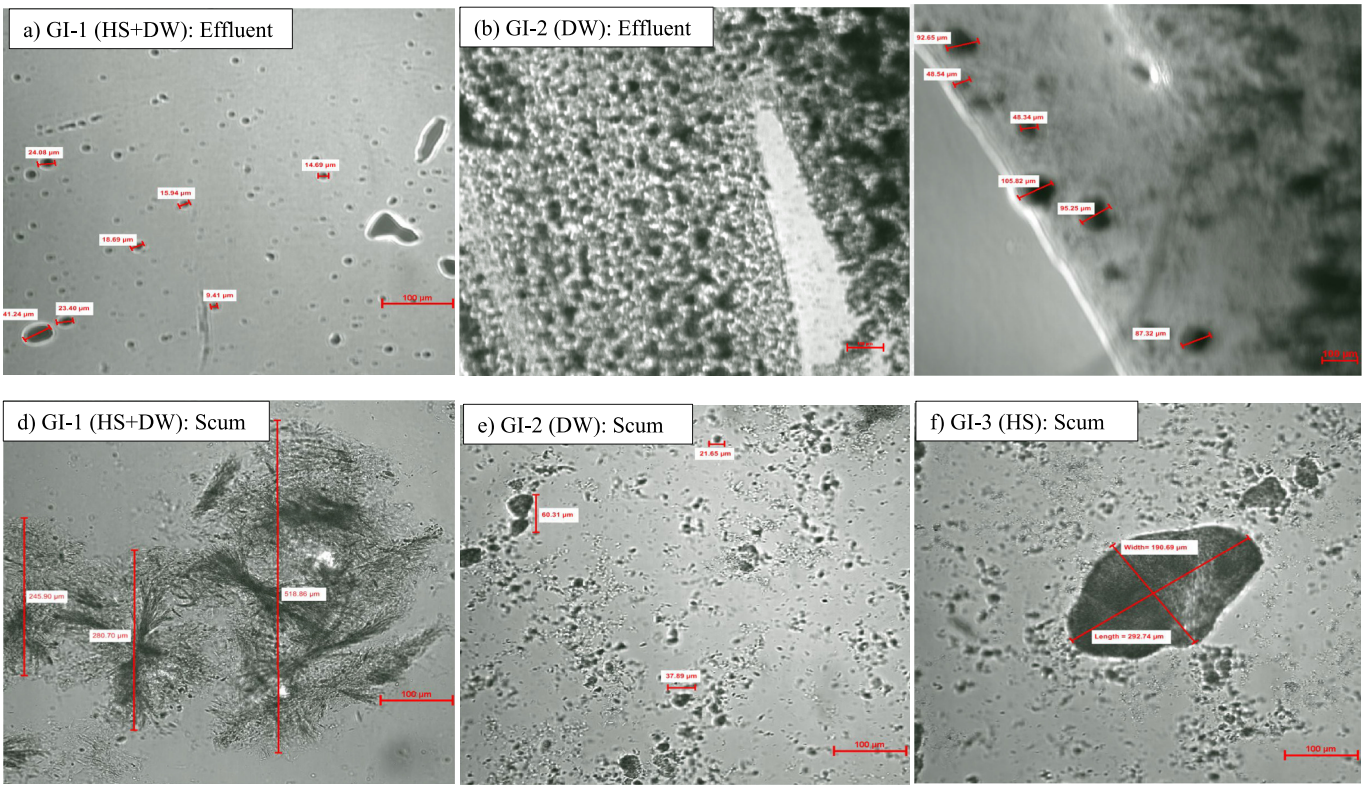

Fig. 7. Microscopic images of FOG collected from various points within the GIs: (a), (b), and (c) represent effluents from GI-1, GI-2 and GI-3, respectively, while (d), (e), and (f) illustrate scum from GI-1, GI-2, and GI-3, respectively. Bar represents 100 μm. Duplicate imaging tests were conducted and found to be consistent, and one set of images is presented.

GI-3, which receives wastewater exclusively from the handwash sink, exhibited different particle sizes depending on the sampling location. Some particles ≥84 μm (the value of D_{50} in GI-3) were observed in the effluent, in addition to a large proportion of very small particles (Fig. 7 (c)). There was a clear link between the image of GI-3 liquid in Fig. S2 (f) and the effluent (Fig. 7 (c)). Similar sizes and shapes were observed, but the middle liquid appeared more transparent compared to the effluent, indicating that the effluent received high volume of FOG due to sudden high inflow rates. This observation supported the initial suggestion (Sections 3.2.1 and 3.2.3) that GI-3 failed to maintain the proper hydraulic retention time required for gravity separation, leading to the discharge of smaller FOG particles into the sewer system. The image for scum showed the presence of a larger particle of 190.7 × 292.7 μm, which was consistent with previous results (Fig. 7 (d) to 7 (f)). Supplementary Fig. S2 (g) and S2 (h) represent the characteristics of FOG particles from the handwash sink in the household kitchen, where the volume of food particles was lower than in a GI. The raw, unbroken, and large FOG particle is clearly visible in the HHS-4 sample, along with some small scattered floating FOG particles.

3.4. Implications

FOG waste, containing a high percentage of biodegradable organics and lipids, has significant potential for resource recovery in the form of biomethane. The biodegradability of waste greatly depends on the carbon-to-nitrogen (i.e., COD/N) ratio and the ratio of 20–25 facilitates better anaerobic digester performance (Gurd et al., 2019; Li et al., 2011). However, due to the bioavailability of mixed organic matter, the COD value is preferred over carbon content to reflect variations in oxidation state of different substrates and thus the electrons available for donation (Gurd et al., 2019). In this study, the COD/N ratios in the scum were approximately 3, 9, and 60 for GI-1, GI-2, and GI-3 respectively, indicating the need for adjustment/mixing to achieve optimal biodegradation. The average BOD:COD ratio of 0.59 for each GI scum suggests high biodegradability making it suitable for biomethane production (≥ 0.5) through anaerobic digestion (Gurd et al., 2019). Furthermore, the scums from the GIs were enriched with nutrient concentrations of 455–5385 mg/L and 781–1026 mg/L of total nitrogen and total phosphorus, respectively, indicating a potential source of nutrient-rich digestate that can be utilized in agriculture. Recovering these resources from FOG scums avoids their disposal to landfill.

4. Conclusions

The characteristics of the scum and effluents of three different GIs, in terms of FOG concentration, FA profile, particle size and metals, underscore the limited effectiveness of the current GI systems for removing FOG components. Despite the gravity-based GI systems separating a significant proportion of FOG, forming a scum layer, the results reveal that a substantial amount of FOG still passes through, with concentrations ranging alarmingly from 1800 to 9600 mg/L. This exceeds the allowable limit and is accompanied by high levels of COD and nutrients. In the scum, 88–98 % of FOG particles were between 373 and 2280 μm (D_{25} to D_{90}), whereas in the effluents, 36.9–80.4 % of particles were ≤45 μm, varying with the dish cleaning methods of FSEs. In contrast, a household handwash sink produced 26.3 % of particles ≤45 μm. These findings were corroborated by confocal imaging, verifying the sizes of the FOG droplets in the effluents. Notably, the effluents contained significant proportions of extra-long-chain saturated and unsaturated FAs, indicating their disposal into the sewer network. Even in low concentrations, these FAs can produce solids in the sewer, owing to their high molecular weight. Additionally, we observed notable concentrations of metals like calcium (8 to 28 mg/L), magnesium, aluminium, iron, sodium and potassium, which could significantly contribute to FOG deposit formation in sewer pipes made of materials like PVC, clay or cast-iron. Given that GIs in FSEs consistently encounter complex FOG

and food solids, along with intermittent large inflows, the resulting effluents can exacerbate deposition issues. Therefore, it becomes imperative to upgrade existing commercial GIs by the placement of baffles of appropriate dimensions at appropriate points. The aim of such enhancements is to improve gravity separation and effectively remove FOG, encompassing all types of FAs, particles of varying sizes and metals.

CRediT authorship contribution statement

Nilufa Sultana: Writing – original draft, Validation, Investigation, Formal analysis, Data curation, Conceptualization. **Felicity Roddick:** Writing – review & editing, Supervision, Conceptualization. **Bruce Jefferson:** Writing – review & editing, Conceptualization. **Li Gao:** Writing – review & editing, Resources, Funding acquisition. **David Bergmann:** Resources, Funding acquisition. **Jim Papalois:** Writing – review & editing, Resources. **Mike Guo:** Visualization, Resources. **Kyriakos Tzimourtas:** Resources. **Biplob Kumar Pramanik:** Writing – review & editing, Supervision, Project administration, Conceptualization.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.169441.

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Effectiveness of grease interceptors in food service establishments for controlling fat, oil and grease deposition in the sewer system

Sultana, Nilufa; Roddick, Felicity; Jefferson, Bruce; Gao, Li; Bergmann, David ...

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