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Physicochemical characteristics of grease-trap wastewater with different potential mechanisms of FOG solid formation, separation, and accumulation inside grease traps

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ABSTRACT

This work investigates the physicochemical characteristics of grease-trap wastewater discharged from a large community market. It proposes potential mechanisms of fat, oil, and grease (FOG) solid formation, separation, and accumulation inside grease traps. Sixty-four samples, i.e., the floated scum, suspended solid-liquid wastewater, and settled sludge, were collected from the grease-trap inlet and outlet chambers. A lower pH of 5-6 at 25-29 °C inside the grease trap than those reported under the sewer conditions (pH 6-7) was revealed. A significant difference in solid and dissolved constituents was also discovered between the inlet and outlet chambers, indicating that the baffle wall could affect the separation mechanism. The sludge samples had 1.5 times higher total solids (TS) than the scum samples, i.e., 0.225 *vs.* 0.149 g g^{-1} TS, revealing that the sludge amount impacted more significantly the grease trap capacity and operation and maintenance. In contrast, the scum samples had 1.4 times higher volatile solids (VS) than the sludge samples, i.e., 0.134 *vs.* 0.096 g g^{-1} VS, matching with the 64.2 *vs.* 29.7% of carbon content from CHN analysis. About 2/3 of the free fatty acids (FFAs) with palmitic acids were the primary saturated FFAs, while the remaining 1/3 of unsaturated FFAs were found in the solid and liquid samples. Although up to 0.511 g g^{-1} FOG can be extracted from the scum samples, none from the sludge samples. More diverse minerals/metals other than Na, Cl, and Ca were found in the sludge samples than in the scum samples. Grease-trap FOG solids and open drain samples exhibited similar physicochemical properties to those reported in the literature. Four potential mechanisms (crystallization, emulsification, saponification, and baffling) were presented. This work offers insights into the physicochemical properties of grease-trap wastewater that can help explore its FOG solid formation, separation, and accumulation mechanisms inside a grease trap.

1. Introduction

Fat, oil, and grease (FOG) with other waste residues from kitchen wastewater can form FOG solids and accumulate over time after entering public sewer networks (Husain et al., 2014). It costs millions of dollars yearly for many cities worldwide to remove these solids from clogged sewerage pipelines (Ducoste et al., 2009, Williams et al., 2012). Therefore, municipalities in Singapore and Malaysia mandate installing

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grease traps to limit less than 50 to 100 mg L^{-1} FOG discharging into the sewer lines (Attorney-General's Chambers of Singapore 2023, Suruhanjaya Perkhidmatan Air Negara 2022). Generally, grease traps have a relatively extended solid retention time (SRT, 14 d) with a short hydraulic retention time (HRT, 1 h) (He et al., 2017, Iasmin et al., 2014, Shin et al., 2015). They are supposed to retain as much waste as possible, notably the flo ated scum and settled sludge and some suspended solids, with the aid of baffle walls that separate the inlet and outlet chambers. However, many grease traps cannot cope during the peak flow rates, resulting in many FOG and other waste residues escaping grease traps, especially when improperly operated and maintained (Ducoste et al., 2009, He et al., 2017, Sultana et al., 2022).

Studies have offered some insights into the formation mechanisms of FOG deposits, aiming to find solutions to mitigate the issues of clogged sewer lines (Benecke et al., 2017, Court et al., 2021, Gross et al., 2017, Gurd et al., 2019, He and Yan, 2016, Kamaruddin et al., 2019, Tandukar and Pavlostathis, 2015). However, most investigated the mechanisms with the experimental studies under simulated sewer conditions (Benecke et al., 2017, Court et al., 2021, Gross et al., 2017, He and Yan, 2016). Notably, the saponification mechanism between free fatty acids (FFAs) and calcium ions (Ca^{2+}) leached from the concrete used in sewer lines (He et al., 2013, Iasmin et al., 2014, Kusum et al., 2020, Sultana et al., 2022). Nonetheless, the elucidated mechanisms may differ under grease-trap conditions, given that the physicochemical characteristics of grease-trap wastewater can differ significantly compared to those in the public sewer. For instance, grease-trap wastewater is more acidic than sewer wastewater, i.e., pH 5-6 *vs.* pH 6-7 (Aziz et al., 2012, Wang et al., 2005). This acidic nature can be ascribed to the generated organic acids such as acetic and butyric acid through acidification of anaerobic digestion inside grease traps (Kamaruddin et al., 2019). Such acidic conditions can promote concrete corrosion in the sewer system and contribute to the calcium content in the wastewater (He et al., 2013). For example, Kusum et al. reported that the availability of Ca^{2+} and pH near the concrete surface affected the FOG deposit formation mechanism (Kusum et al., 2020). Besides that, grease-trap wastewater also has a higher temperature than sewer wastewater, i.e., 20-35 °C *vs.* 20-25 °C (Shin et al., 2015, Wongthanate et al., 2014). Likewise, the total solids (TS, 59 to 173 g L^{-1}) (Davidsson et al., 2008), chemical oxygen demand (COD, 438 to 569 g L^{-1}) (Tandukar and Pavlostathis, 2015), oil and grease (O&G, 0.25 to 1.38 g L^{-1}) (Aziz et al., 2012, Wang et al., 2005), FFA (27 to 77%) (Benecke et al., 2017, Court et al., 2021, Nitayapat and Chitprasert, 2014), and minerals (0.013 to 9.1 g L^{-1}) (Gross et al., 2017, Gurd et al., 2019, Keener et al., 2008) appear to be higher than that of sewer wastewater.

Besides, regions with different dietary cultures and cooking and cleaning processes can produce kitchen wastewater with highly varied physicochemical properties (Gurd et al., 2019). For example, the settled sludge inside grease traps can comprise TS ranging from 10 to 584 g L^{-1} (Ahmad et al., 2023, Aziz et al., 2012, Davidsson et al., 2008, Tandukar and Pavlostathis, 2015, He et al., 2012, Suto et al., 2006, Shakourifar et al., 2020, Solé-Bundó et al., 2020), the wastewater pH ranging from 4 to 7.67 (Aziz et al., 2012, Davidsson et al., 2008, He et al., 2012, Wang et al., 2005, Wong et al., 2007), temperature ranging from 20 to 45 °C (Ahmad et al., 2023, Aziz et al., 2012, Davidsson et al., 2008, He et al., 2012, Shakourifar et al., 2020, Solé-Bundó et al., 2020, Suto et al., 2006, Tandukar and Pavlostathis, 2015), FFA ranging from 0.2 to 4.6 g L^{-1} (Benecke et al., 2017, Court et al., 2021, Gross et al., 2017, He and Yan, 2016, Nitayapat and Chitprasert, 2014, Suto et al., 2006), and minerals ranging from 0.91 to 14 g L^{-1} (Benecke et al., 2017, Gross et al., 2017, Gurd et al., 2019, Keener et al., 2008, Nitayapat and Chitprasert, 2014, Williams et al., 2012). Such high variation makes investigating the FOG solid formation and accumulation mechanisms under grease-trap conditions more challenging than under sewer conditions. The grease trap and sewer piping-made materials are other critical factors affecting the mechanism investigations under different conditions. He et al. reported that the high Ca^{2+} content required to form saponified solids (FOG solids) with FFA was attributed to them leaching from the corroded concrete sewer pipes under acidic wastewater conditions (He et al., 2013). Kusum et al. utilized fly ash cement-based replacement materials and discovered that the availability of Ca^{2+} and pH near the concrete surface affected the FOG deposit formation mechanism (Kusum et al., 2020). However, more grease traps and sewer piping are recently made of non-corrosive materials such as high-density polyethylene (HDPE) thermoplastic instead of cast *in situ* reinforced concrete (Market.US 2024, Plastics Pipe Institute 2024, Weida Integrated Industries Sdn Bhd 2023). Therefore, Ca^{2+} may not be the primary mineral ion promoting FOG solid formation. Other minerals, such as iron (Fe^{2+} and Fe^{3+}) and aluminum (Al^{3+}), were found to induce FOG solid formation, but these solids exhibited different physical properties (Gross et al., 2017, He et al., 2013, Iasmin et al., 2014, Williams et al., 2012).

A grease trap typically separates its wastewater into floated scum, suspended solid-liquid wastewater, and settled sludge at its top, middle, and bottom layers (Ahmad et al., 2023, Sultana et al., 2022). The top layer typically comprises less dense and free-floating FOG and solids (Sultana et al., 2022). The middle layer mainly comprises relatively stable suspended solid-liquid wastewater due to colloidal particles and emulsified FOG with surfactant (detergent) (Wong et al., 2007). Then, the bottom layer comprises denser and higher solids content sludge than the scum, which can reduce the grease trap capacity (working volume) and result in more frequent cleaning (desludging) (Long et al., 2012). In short, grease-trap wastewater properties may form and accumulate different FOG solids inside the grease traps than those under sewer conditions, ultimately affecting the grease trap design, operation, and maintenance. Therefore, it is essential to characterize the grease-trap wastewater to systematically reveal the FOG solid formation, separation, and accumulation mechanisms inside the grease traps.

This work aims to evaluate the physicochemical characteristics of grease-trap wastewater discharged from a large community market and reveal its potential FOG solid formation, separation, and accumulation mechanisms inside grease traps. Several site investigations were conducted at different food service establishments, but four identical grease traps serving the market's food court were chosen. Sixty-four samples on different days were collected from the top, middle, and bottom layers inside each grease trap, including from the inlet and outlet chambers. They were then characterized for the physicochemical properties such as pH, temperature, electrical conductivity, total and volatile solids, chemical oxygen demand, types of FFA, and surface properties, especially on the solid (scum and sludge) samples, including those collected from the open drains next to the stir-fry cafes. This work offers insights into the physicochemical properties of grease-trap wastewater, particularly concerning the FOG solid formation, separation, and accumulation at the top, middle, and bottom layers inside the grease traps.

2. Materials and methods

2.1. Site selection, monitoring, and sampling

Tables S1 to **S3** summarize Grease Traps A, B, C, and D information at the largest two-story community wet market in Kuching (Sarawak, East Malaysia), including the types of food and beverage stalls on its first floor. Fig. 1 shows the three custom-made samplers used to monitor and collect samples from the grease traps. Fig. 2 shows the plan and cross-sectional views of the grease trap, indicating the four chosen spots at the inlet and outlet chambers for daily monitoring and sampling. During the 32 days of daily monitoring, Sampler A (Fig. 1(a)) was used to profile the depths of three layers at the four chosen spots (Fig. 2(a)). Sampler B (Fig. 1(b)) and Sampler C (Fig. 1(c)) were used to collect the three-layer samples of the three spots inside the inlet chambers, but only one spot due to the limited space inside the outlet chambers (Fig. 2(b)). **Table S4** summarizes the labeling for 64 representative samples collected from the four grease traps, excluding the collected open drain (OD) samples from the nearby stir-fry cafes. For example, four collected samples from

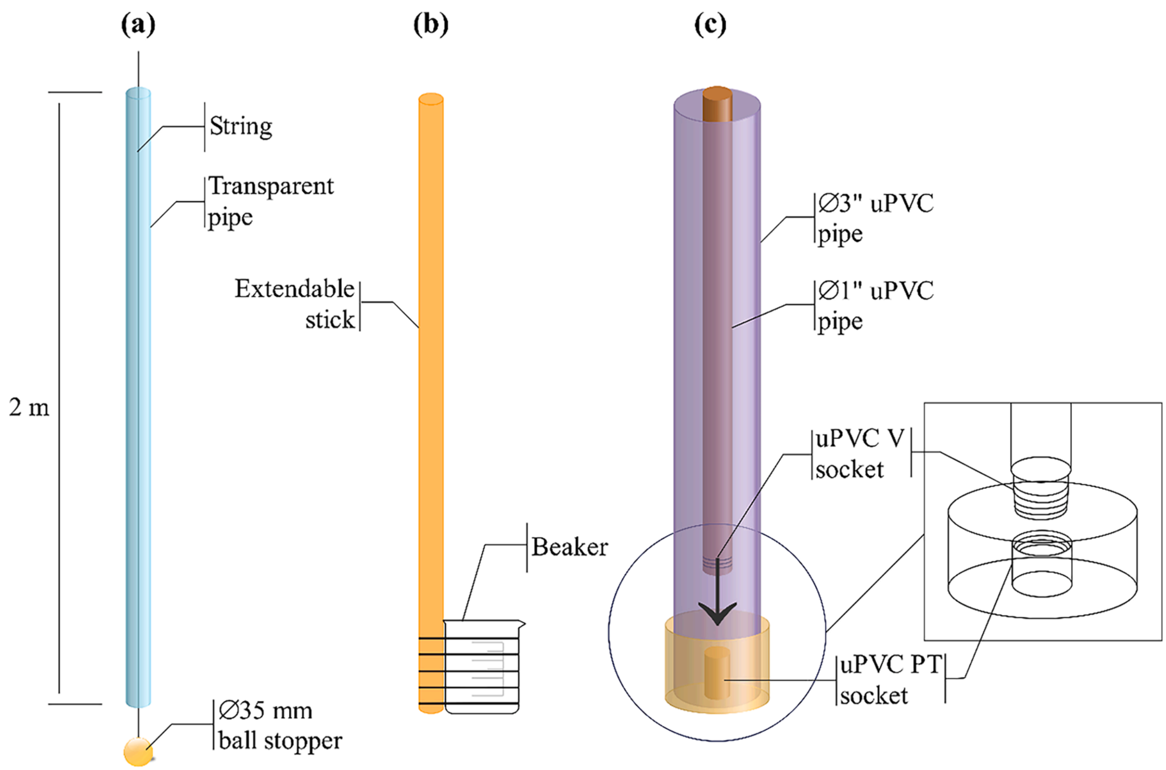

Fig. 1. Three custom-made samplers: (a) Sampler A for profiling the depths of different layers formation inside the grease traps, (b) Sampler B for collecting the floated scum samples at the top layer; (c) Sampler C for collecting the suspended solid-liquid wastewater and settled sludge samples at the middle and bottom layers, respectively.

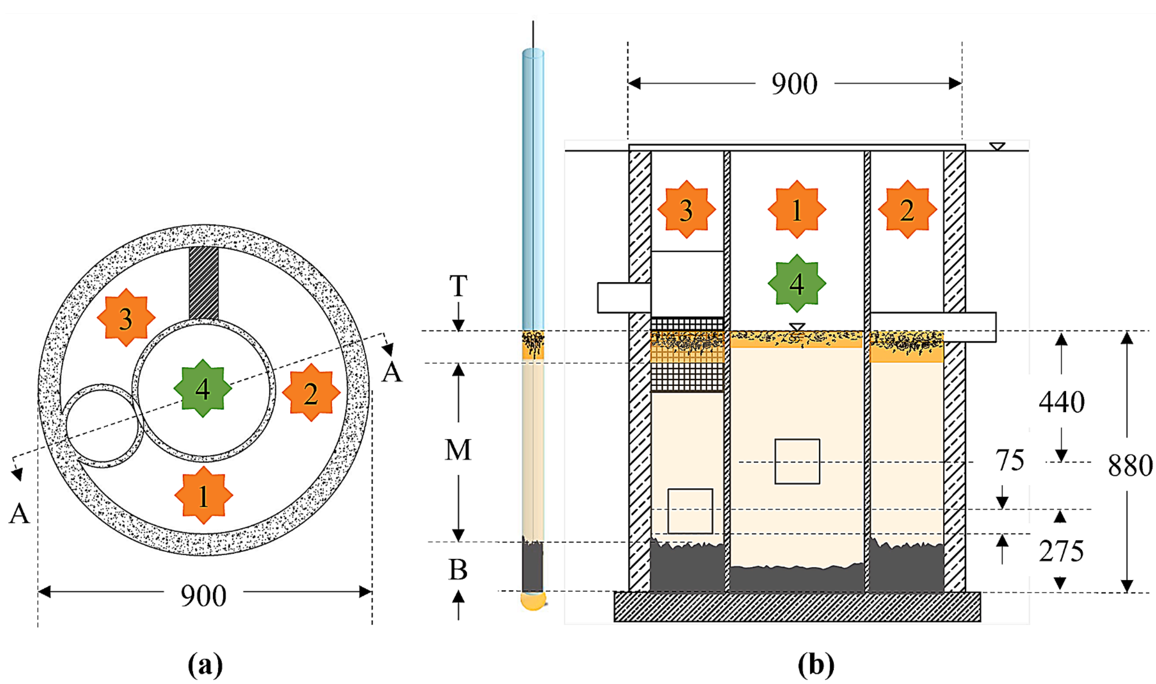

Fig. 2. Schematic diagrams illustrating (a) the Plan and (b) Section A-A views of the four chosen spots at the inlet and outlet chambers for daily monitoring and sampling using different samplers. All dimensions labeled are in mm.

the middle (M) layer at their inlet (I) and outlet (O) chambers of Grease Traps A to D were denoted as A-I-M1 to A-I-M4 and D-O-M1 to D-O-M4. More information about the aforementioned grease traps and sampling procedures can be found in **Supporting Information (Section 1)**.

2.2. Characterization

Table 1 summarizes the characterization methods for the collected samples. First, the floated scum and settled sludge samples collected from the top (T) and bottom (B) layers were characterized for the total

Table 1
Standard methods and the corresponding equipment/apparatus for characterizing the collected samples.

Parameter	Unit	Equipment	Methods [Ref.]
pH	–	Merck pH meter (Mettler Toledo EL 30 Germany)	–
Temperature	°C	Thermometer	–
Electrical conductivity (EC)	μm cm^{-1}	EC meter (BANTE 520, China)	APHA 2510B (Baird et al., 2017)
Total solids (TS)	g g^{-1}	Memmert UF260Plus oven, Carbolite Gero AAF 1100	APHA 2540B (Baird et al., 2017)
Volatile solids (VS)	g g^{-1}	Memmert UF260Plus oven, Carbolite Gero AAF 1100	APHA 2540E (Baird et al., 2017)
Fixed solids (FS)	g g^{-1}	Memmert UF260Plus oven, Carbolite Gero AAF 1100	APHA 2540E (Baird et al., 2017)
Total suspended solids (TSS)	g L^{-1}	Memmert UF260Plus oven, Carbolite Gero AAF 1100, Sartorius (Germany) Glass Microfiber Filter	APHA 2540D (Baird et al., 2017)
Volatile suspended solids (VSS)	g L^{-1}	Memmert UF260Plus oven, Carbolite Gero AAF 1100	APHA 2540E (Baird et al., 2017)
Total dissolved solids (TDS)	g L^{-1}	Memmert UF260Plus oven, vacuum filtration set	APHA 2540C (Baird et al., 2017)
Chemical oxygen demand (COD)	g L^{-1}	Hach DRB200 Reactor (Hach, USA), Hach COD digestion vials HR range (USA)	APHA 5220 (Baird et al., 2017)
Oil and grease (O&G)	mg L^{-1}	Partition-gravimetric method	APHA 5520B (Baird et al., 2017)
Fat, oil, and grease (FOG)	g g^{-1}	Memmert UF260Plus oven, stainless steel strainers, and glass beakers	–
Free fatty acids (FFAs) composition	% or g g^{-1}	Gas chromatography-flame ionization detector (GC-FID) Agilent 7890B (USA)	APHA 5560D (Baird et al., 2017) & AOAC 996.06 (Horwitz, 2010)
Mineral and heavy metals	mg L^{-1}	Perkin Elmer Atomic absorption spectroscopy (AAS) PinAAcle 900F (USA)	APHA 3030E & 3111B & 3112B & 3114B (Baird et al., 2017)
Mineral and heavy metals	mg L^{-1}	Varian 715-ES Inductively coupled plasma optical emission spectrometry (ICP-OES) (USA)	APHA 3030E (Baird et al., 2017) & US EPA 6010B (U. S. EPA 1996)
Chloride (Cl)	mg L^{-1}	Titration method	APHA 4500-Cl^- (Baird et al., 2017)
Surface chemical properties (organic and inorganic)	–	Fourier transform infrared spectroscopy-attenuated total reflection (FTIR-ATR), Tensor II, Bruker (Germany)	–
Surface structural/ material composition	–	Scanning electron microscope-energy dispersive X-ray (SEM-EDX), Hitachi SU3500 (Japan)	–
CHN elemental analysis	%	Leco CHN 628 analyzer (USA)	–

solids (TS) and volatile solids (VS). Then, the TS test method was adopted and modified using beakers and stainless-steel strainers to extract and quantify the FOG of the scum and sludge samples (Fig. 3). The extracted FOG samples were further processed to fatty acid methyl esters (FAME) according to AOCS 996.06 (Horwitz, 2010). They were then analyzed using gas chromatography (GC) according to APHA 5560D to determine the types and concentrations of FFAs (Baird et al., 2017).

Next, the dried solid samples, including the OD samples, were further characterized using Fourier transform infrared spectroscopy-attenuated total reflection (FTIR-ATR), scanning electron microscopy-energy dispersive X-ray (SEM-EDX), and CHN elemental analysis to determine the surface chemical properties, surface structural/material composition, and organic composition, respectively. At the same time, the suspended solid-liquid wastewater samples collected from the middle (M) layer were tested for pH, temperature, and electrical conductivity (EC) during the daily monitoring and sampling. These samples were also characterized for total suspended solids (TSS), total dissolved solids (TDS), volatile suspended solids (VSS), chemical oxygen demand (COD), and oil and grease (O&G). The mineral and metal contents of these samples were also determined using atomic absorption spectroscopy (AAS) and inductively coupled plasma optical emission spectrometry (ICP-OES). The aforementioned O&G, FFA, AAS, ICP-OES, FTIR, SEM-EDX, and CHN tests were outsourced to accredited laboratories. Other characterizations were conducted in-house, with triplicates for each test and sample. More information about the characterization methods and procedures can be found in **Supporting Information (Section 2)**.

3. Results and discussion

3.1. Grease trap capacity

Table 2 summarizes the measured heights of the total liquid depth (D) of each grease trap, including the floated scum, suspended solid-liquid wastewater, and settled sludge at the top (T), middle (M), and bottom (B) layers, respectively, and estimated grease-trap capacity (working volume). The average heights and ratios between T and D (T/D), M and D (M/D), B and D (B/D), and T plus B and D ((T+B)/D) were determined to evaluate the effective working volume that governs the grease-trap capacity. Compared to the average values of floated scum among the grease traps (10 mm), the suspended solid-liquid wastewater (733 mm) and settled sludge (101 mm) exhibited significantly larger depths. In other words, the sludge (B/D) contributed more significantly to the grease trap capacity compared to the scum (T/D) based on T/D (0 to 4.26%) and B/D (2.37 to 21.9%) ratios. However, Grease Trap B exhibited nearly double the scum amount compared to the other grease traps (16 *vs.* 8 to 9 mm), suggesting that the operating food and beverage stalls contributed more FOG and other waste residues to it although its wastewater loading was lower than Grease Trap A (28.5 *vs.* 22.8 m^3 d^{-1}, **Table S3**). Likewise, Grease Trap B also exhibited the highest accumulated sludge (B/D, 18.8%) compared to other grease traps (3.42 to 12.9%), matching our argument that those food and beverage stalls might contribute more FOG or other waste residues to it. Grease Trap B, therefore, exhibited the highest total accumulated scum and sludge ((T+B)/D, 20.7%) compared to the lowest total accumulated scum and sludge (4.41%) of Grease Trap C. In short, the accumulated scum and sludge amount can be a determining factor in when to clean (desludging) the grease traps.

3.2. Physicochemical properties

Fig. 4 shows the characterization results of the collected samples from the top layer of inlet chambers, including the OD samples. However, A-I-T3, B-I-T3, C-I-T3, and D-I-T3 samples were not collected due to only 0 to 4 mm floated scum (Table 2) observed the day after the clogged grease traps (**Fig. S3**) were cleaned. As a result, Grease Traps A (0.316 g g^{-1}), C (0.276 g g^{-1}), and D (0.263 g g^{-1}) exhibited 1.3 to 1.5 times higher extracted FOG from the scum samples than Grease Traps B (0.210 g g^{-1}) (Fig. 4(a), **Table S5**), indicating contradicting results for Grease Trap B had more scum (16 mm, Table 2) but less FOG extracted than other grease traps (**Table S5**). This result may be ascribed to other waste residues instead of FOG could have contributed to the scum (solid) formation, separation, and accumulation inside Grease Trap B compared to other grease traps.

Nonetheless, the extracted FOG from the scum samples could reach up to 0.511 g g^{-1} FOG, with an average of 0.266 g g^{-1} FOG **(Table S5)**. These scum samples also exhibited up to 96.1% VS/TS ratios (Fig. 4(b)), revealing high organic content in the samples (90.1% average) and matching well with the CHN elemental analysis results with up to 66.1% (64.2% average) of carbon (C) content (Fig. 4(c)). It can be deduced that the scum formation in the grease traps could have depended on the FOG and other waste residue content and properties (Court et al., 2021, Gross

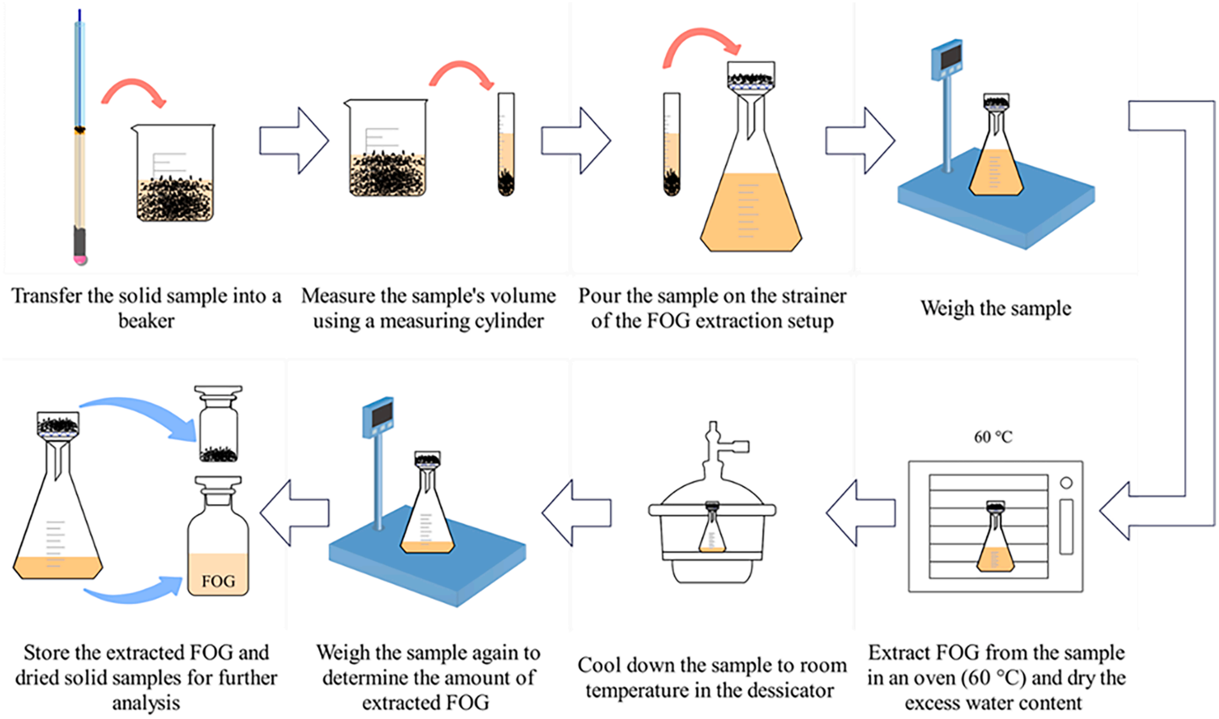

Fig. 3. Schematic diagram illustrating FOG extraction from solids samples before and after heating in an oven at 60 °C for 24 h.

Table 2
Estimated grease trap capacity (%) based on the measured heights of total liquid depth (D), top (T), middle (M), and bottom (B) layers using Sampler A inside the inlet chambers of Grease Traps A to D. All units are in mm unless otherwise specified.

Sample	D	T	M	B	T/D (%)	M/D (%)	B/D (%)	(T+B)/D (%)
A-I-T1	845	10	715	120	1.18	84.6	14.2	15.4
A-I-T2	850	8	708	133	0.94	83.3	15.6	16.6
A-I-T3	840	1	751	88	0.12	89.4	10.5	10.6
A-I-T4	830	11	727	92	1.33	87.6	11.1	12.4
Average	841±4	8±2	725±9	108±11	0.89±0.27	86.2±1.4	12.9±1.2	13.7±1.4
B-I-T1	865	11	689	165	1.27	79.7	19.1	20.3
B-I-T2	845	36	653	157	4.26	77.3	18.6	22.8
B-I-T3	835	4	699	132	0.48	83.7	15.8	16.3
B-I-T4	845	11	649	185	1.30	76.8	21.9	23.2
Average	848±6	16±7	673±13	160±11	1.83±0.83	79.4±1.6	18.8±1.2	20.7±1.6
C-I-T1	830	18	789	23	2.17	95.1	2.77	4.94
C-I-T2	825	9	767	48	1.09	93.0	5.82	6.91
C-I-T3	845	0	822	23	0.00	97.3	2.72	2.72
C-I-T4	845	6	819	20	0.71	96.9	2.37	3.08
Average	836±5	8±4	799±13	29±7	0.99±0.45	95.6±1.0	3.42±0.8	4.41±1.0
D-I-T1	855	12	698	145	1.40	81.6	17.0	18.4
D-I-T2	845	15	692	138	1.78	81.9	16.3	18.1
D-I-T3	855	2	762	92	0.23	89.1	10.8	11.0
D-I-T4	845	5	780	60	0.59	92.3	7.10	7.69
Average	850±3	9±3	733±22	109±20	1.00±0.36	86.2±2.7	12.8±2.4	13.8±2.7
Average (All)	844±3	10±2	733±13	101±13	1.18±0.25	86.8±1.68	12.0±1.58	13.2±1.69

et al., 2017, He et al., 2013, Sari et al., 2013). Therefore, the compositions, such as FFA and mineral contents, were evaluated further and discussed in the subsequent sections. Besides that, the OD sample exhibited minimal FOG that can be extracted compared to the scum samples (Fig. 4(a), **Table S5**). This result may be ascribed to the sample being exposed to the OD conditions for an extended time (> 6 months), resulting in its FOG content being decomposed over time. Nonetheless, it still consisted of a high 73.4% VS (Fig. 4(a)), suggesting that the formation of OD solids (FOG solids) might have involved other waste residues from the kitchen wastewater.

Fig. 5 shows the characterization results of the collected samples from the middle layer of inlet and outlet chambers. First, the pH and temperature values exhibited mainly acidic with a pH of around 5-6 at 25-29 °C that could corrode sewer collection systems (Fig. 5(a)), matching the values in the literature (Ahmad et al., 2023, Aziz et al., 2012, Davidsson et al., 2008, He et al., 2012, Shakourifar et al., 2020, Solé-Bundó et al., 2020, Tandukar and Pavlostathis, 2015, , , Suto et al., 2006,). Although alkaline cleaning products are generally used in the kitchen (Aziz et al., 2012, Ducoste et al., 2009), they could have been diluted during cleaning and neutralized by the produced organic acids such as butyric and acetic acids due to the decomposition of food and other organic waste residues inside the grease traps (Kamaruddin et al., 2019). Besides that, higher wastewater temperatures can be an essential factor in the formation of FOG solids in the drainage systems because different types of FOG may need different temperatures to enable the saponification process (Iasmin et al., 2014).

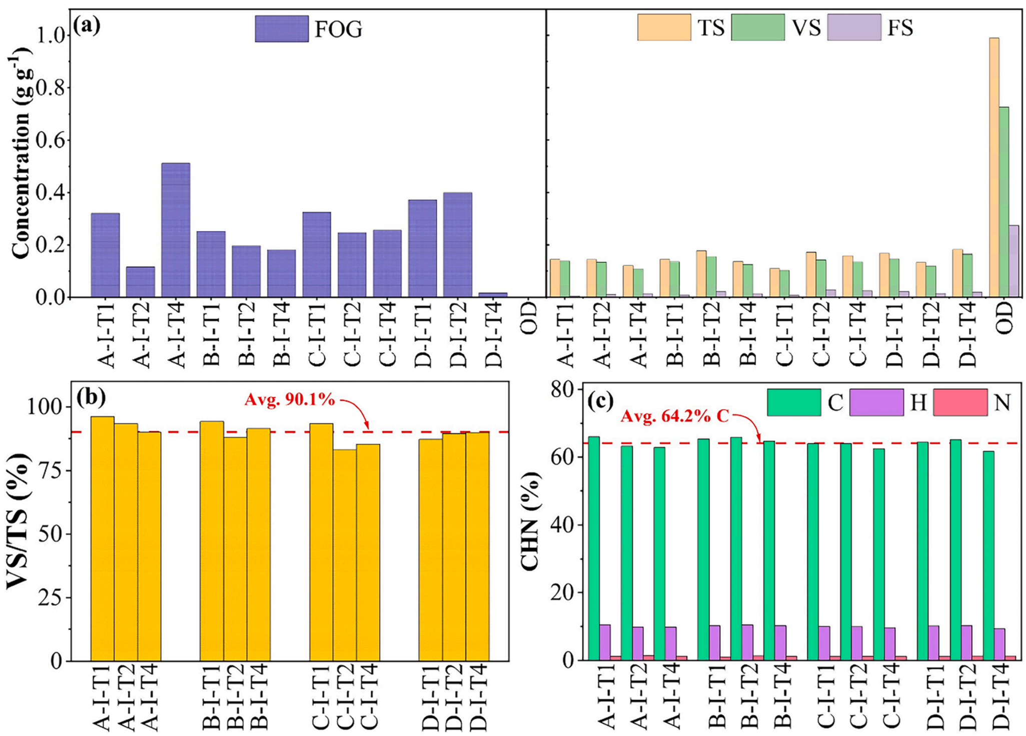

Fig. 4. Characterization results of the collected top (T) layer samples from Grease Traps A to D at the inlet (I) chambers and OD sample, including the (a) FOG, TS, VS, and FS compositions, (b) VS/TS ratios, and (c) C, H, and N compositions after the FOG were extracted. [Note: TS + FOG = VS + FS + FOG]

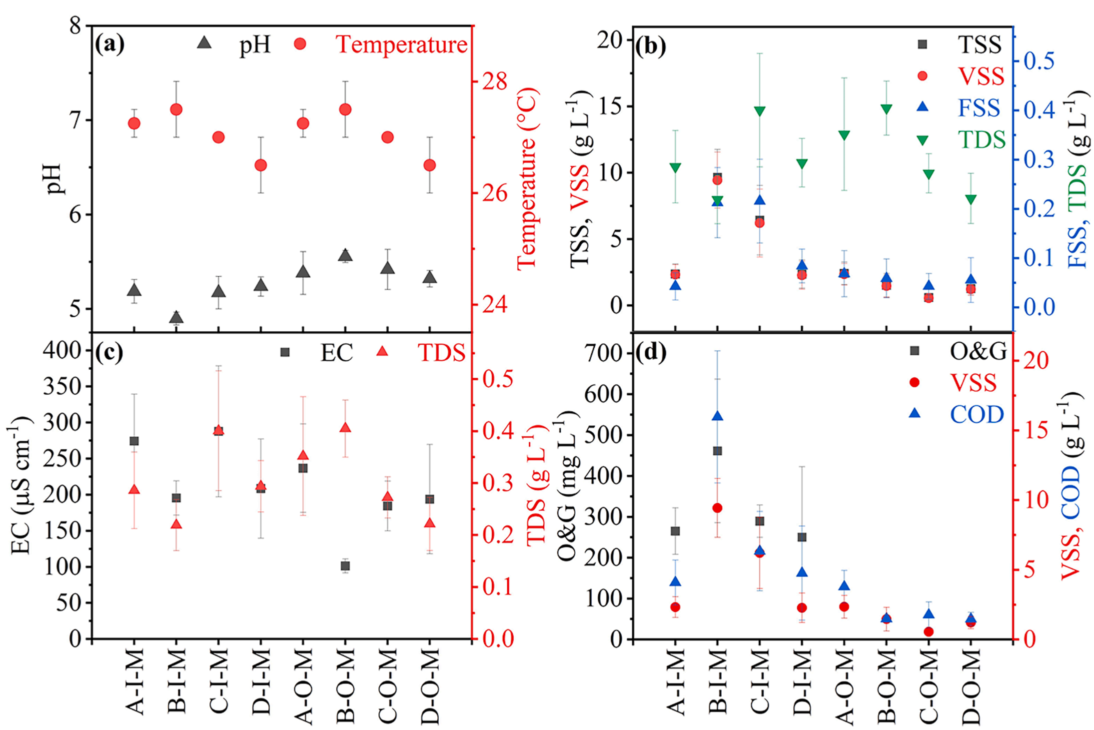

Fig. 5. Characterization results of the collected middle (M) layer samples from Grease Traps A to D at the inlet (I) and outlet (O) chambers: (a) pH and temperature, (b) TSS, VSS, FSS, and TDS, (c) EC, and TDS, and (d) O&G, COD, and VSS.

Unlike the insignificant difference in pH and temperature values between the inlet and outlet chambers, the total suspended solids (TSS), volatile suspended solids (VSS), and chemical oxygen demand (COD) at the inlet chambers exhibited a higher average of 72.2% (5.20 g L^{-1}), 72.5% (5.06 g L^{-1}) and 72.7% (7.78 g L^{-1}), respectively, than those of the outlet chamber samples (Fig. 5(b) and Fig. 5(d), **Table S6**). Similarly, the electrical conductivity (EC) exhibited an average of 25.9% higher for the inlet chamber samples than the outlet chamber samples. However, the total dissolved solids (TDS) indicated an insignificant difference between the chambers (Fig. 5(c)). These results revealed that the baffle wall could significantly impact grease trap designs to trap suspended solids and potentially some dissolved constituents (Aziz et al., 2012).

On the other hand, the VSS/TSS ratios exhibited insignificant differences between the inlet and outlet chamber samples (0.4%), suggesting minimal biodegradation activity inside the grease traps, given the short HRTs (**Table S3**). This phenomenon agrees well with the COD/VSS ratios of the inlet (2.09%) and outlet (2.99%) chamber samples, showing that a high COD/VSS ratio represents a significant portion of the organic matter in the wastewater is readily biodegradable by microorganisms (Parker et al., 2008). Similar to the high average concentrations of TSS (5.20 g L^{-1}) and COD (7.78 g L^{-1}), the inlet chamber samples of Grease Traps A to D exhibited up to 812 mg L^{-1} oil and grease (O&G) with a high 316 mg L^{-1} average concentration (**Table S6**), and this value has exceeded the 50-100 mg L^{-1} effluent discharge standard guidelines from Singapore and Malaysia (Attorney-General's Chambers of Singapore 2023, Suruhanjaya Perkhidmatan Air Negara 2022).

Fig. 6 shows the characterization results of the collected samples from the bottom layer of inlet chambers, including the comparison between the scum and sludge samples for the TS and CHN analyses (Fig. 7). Compared to the average TS of the scum samples (0.149 g g^{-1}, Fig. 4, **Table S5**), the sludge samples exhibited a significantly higher average TS (0.225 g g^{-1}, Fig. 6 and 7(a), **Table S7**). Likewise, the scum samples exhibited a higher average VS than the sludge samples, i.e., 0.134 *vs.* 0.096 g g^{-1} VS, with 90.1 *vs.* 61.9% VS/TS ratios, respectively (**Tables S5** and **S7**). These results also accorded well with the findings from the CHN analysis, with an average of 64.2 *vs.* 29.7% of carbon (C) identified and about 28.2% VS/TS and 34.5% carbon (C) differences between the scum and sludge samples, respectively (Fig. 7(b), **Table S13**). Besides, negligible FOG was extracted from the sludge samples compared to 0.266 g g^{-1} of extracted FOG from the scum samples (**Table S5**), suggesting that the characteristics of sludge samples may be similar to the OD samples. In short, the differences in organic and inorganic constituents between the scum and sludge samples could have contributed to the different FOG solid formation, separation, and accumulation mechanisms inside the grease traps.

3.3. *Free fatty acids composition*

Fig. 8 shows the free fatty acid (FFA) compositions of the collected samples from the middle and top layers of inlet chambers based on gas chromatography-flame ionization detector (GC-FID) analysis. FFAs can be classified into saturated and unsaturated FFAs. For example, palmitic, stearic, and myristic acids are saturated FFAs, but oleic and linoleic acids are mono-unsaturated and polyunsaturated FFAs, respectively. As a result, up to 96.80% (78.65% average) saturated FFAs with 64.81% average of palmitic acid were the predominant ones, compared to up to 49.06% (21.35% average) unsaturated FFAs for the middle-layer samples (**Table S8(b)**). Next, in the order of decreasing content, was oleic acid (17.91%), stearic acid (9.534%), myristic acid (4.308%), and linoleic acid (3.437%). In contrast, the top-layer samples (A-I-T1 and D-I-T1) exhibited more saturated FFAs (68.74 to 72.29%) than unsaturated FFAs (27.71 to 31.26%) (**Table S8**). Palmitic acid (57.44 to 60.96%) and oleic acid (21.92 to 22.15%) were the predominant FFAs, showing similar FFA compositions to the suspended solid-liquid wastewater samples. In short, about 70 to 80% of the FFAs in the suspended solid-liquid wastewater and scum samples were saturated FFAs, with the remaining about 20 to 30% being unsaturated FFAs. This phenomenon verified that the type of FOG or FFA compositions in kitchen or grease-trap wastewater can affect the FOG solid formation, separation, and accumulation mechanisms inside the grease traps, agreeing well with those reported in the literature (Court et al., 2021, Gross et al., 2017, He et al., 2013, Sari et al., 2013).

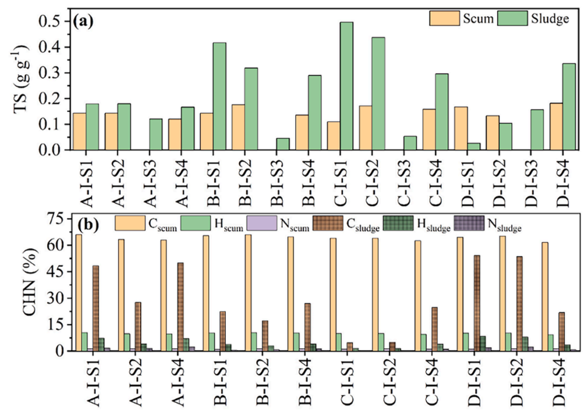

Fig. 7. Comparison of the (a) TS and (b) CHN compositions between the floated scum and settled sludge samples.

Consequently, a mass balance for each layer inside the grease trap on FOG, O&G, FFA, COD, TS, and TSS content was conducted based on the average values of four grease traps (**Table S9)**. First, the total mass of each layer (i.e., scum, suspension, and sludge) was estimated based on the measured thickness of each layer over the 32-day monitoring period. The densities of the top floated scum and settled sludge was assumed as 0.95 g cm^{-3} (U. S. EPA 2004) and 1.18 g cm^{-3} (El-Nahhal et al., 2014), respectively. Then, the mass of each parameter was estimated based on their concentration (g g^{-1} or g L^{-1} for solid or liquid samples, respectively). For example, 0.266 g g^{-1} of the extracted FOG was multiplied by 4,608 g of total scum to obtain 1,227 g of FOG. Similarly, each FFA species, such as 0.576 g g^{-1} of palmitic acid, was multiplied by 1,227 g to obtain 706.2 g palmitic acid. Interestingly, a majority of the extracted FOG from the scum samples was O&G (87.4%, 1,072 g), and most of them were saturated FFA (68.6%, 841.8 g) with the remaining 29.1% unsaturated FFA (**Table S9**). The total mass balance for FFA was close to 100% (i.e., 97.7%), highlighting our reasonable assumptions. This result also revealed high FOG deposition *via* a crystallization mechanism due to excessive FOG (O&G and FFA) yielding the FOG solids (scum) at the top layer inside the grease traps (Gross et al., 2017).

Next, the mass balance also showed that only 4% (113.1 g) of O&G

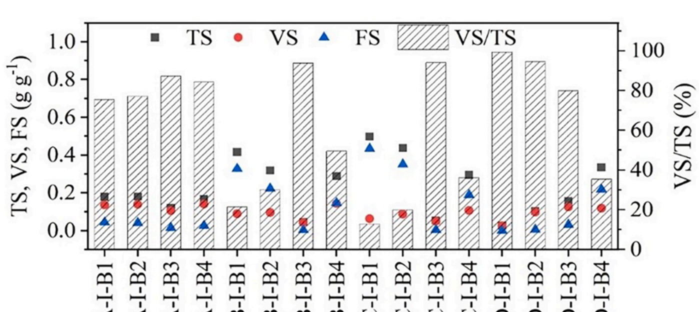

Fig. 6. Characterization results of the collected bottom (B) layer samples from Grease Traps A to D at the inlet (I) chambers, including TS, VS, FS, and VS/TS.

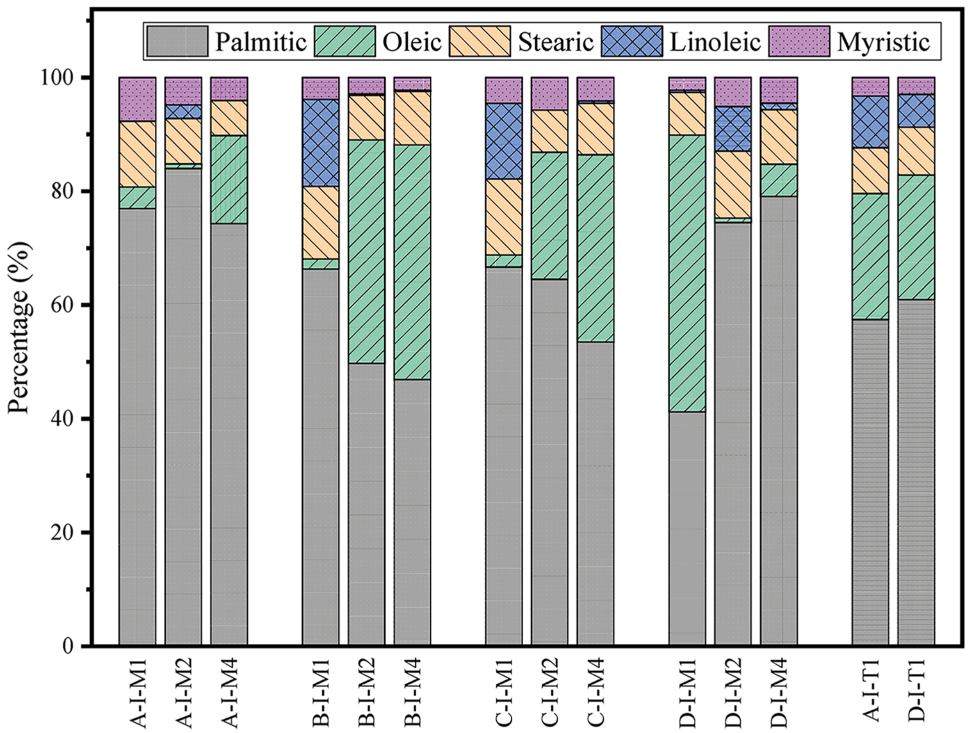

Fig. 8. FFA compositions based on GC-FID analysis of the collected samples from the middle (M) and top (T) layers at the inlet (I) chambers of Grease Traps A to D.

was associated with COD, followed by 24% (670.4 g) of palmitic and 29% (814.6 g) and 10% (265.8 g) of saturated and unsaturated FFA, respectively (**Table S9**). Although the suspended solid-liquid wastewater samples at the middle layer of grease traps exhibited a lower O&G than the floated scum samples, i.e., 113.1 *vs*. 1,072 g, the total FFA mass (75% saturated and 25% unsaturated) exhibited similar results, i.e., 1,080 *vs*. 1,199 g, at the middle and top layers (**Table S9**). Hence, FOG deposition *via* the saponification mechanism could have occurred in the middle layer of grease traps, given that there are more minerals than FFA content in the middle layer than in the top layer (**Table S10**) (He et al., 2011, He et al., 2013, Iasmin et al., 2016). Moreover, the FFA emulsification mechanism with surfactant (detergent) and other colloidal particles generated during food preparation and cleaning could have yielded a relatively stable suspended solid-liquid wastewater in the middle layer (Wu and Firoozabadi, 2021). Lastly, the settled sludge had a very high amount of solid (TS, 13,113 g) accumulated at the bottom layer of grease traps (**Table S9**). Interestingly, FOG was not detected in the sludge, unlike the other study that found a significant amount of FOG

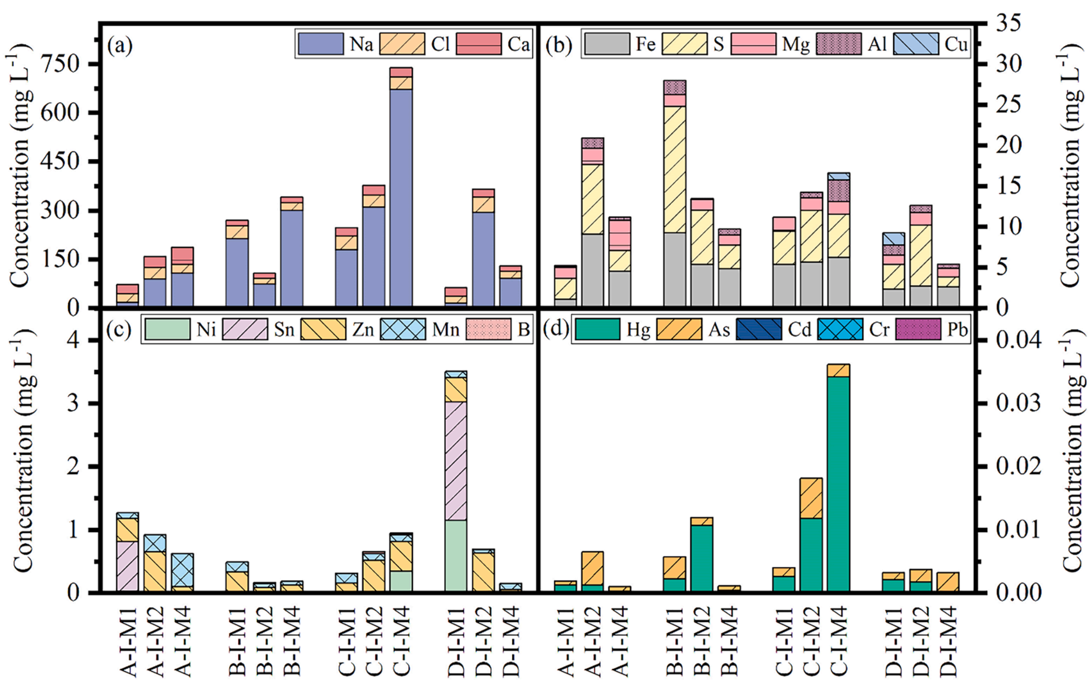

Fig. 9. Composition and concentration of primary and secondary minerals and heavy metals for the collected middle (M) layer samples from Grease Traps A to D inlet (I) chambers.

in the settled sludge at the bottom of grease traps (Canakci, 2007, Wong et al., 2007). This phenomenon can be ascribed to the type of cooking oils and animal fats involved during cooking, affecting the density of FOG deposits formation inside grease traps (Del Mundo and Sutheerawattananonda, 2017). However, this mechanism is undergoing verification in our upcoming work.

3.4. Minerals and heavy metals composition

Fig. 9 shows the mineral and heavy metal composition and concentration of the collected samples from the middle layers of inlet chambers. Based on the average values, sodium (Na, 196.8 mg L^{-1}), chloride (Cl, 31.40 mg L^{-1}), calcium (Ca, 26.38 mg L^{-1}), sulfur (S, 5.518 mg L^{-1}), and iron (Fe, 4.903 mg L^{-1}) were primary species in the samples (**Table S10**), matching the reported concentration in literature (Benecke et al., 2017, Gurd et al., 2019, Gross et al., 2017, Keener et al., 2008, Nitayapat and Chitprasert, 2014, Williams et al., 2012). The secondary species were magnesium (Mg, 1.650 mg L^{-1}) and aluminum (Al, 1.003 mg L^{-1}). On the other hand, tin (Sn, 0.423 mg L^{-1}), zinc (Zn, 0.323 mg L^{-1}), copper (Cu, 0.210 mg L^{-1}), manganese (Mn, 0.145 mg L^{-1}), and nickel (Ni, 0.133 mg L^{-1}) were the least significant. Heavy metals, such as chromium (Cr, 0.060 mg L^{-1}), lead (Pb, 0.050 mg L^{-1}), boron (B, 0.007 mg L^{-1}), mercury (Hg, 0.005 mg L^{-1}), cadmium (Cd, $<$0.002 mg L^{-1}), and arsenic (As, 0 mg L^{-1}) were either present in trace amount or below the detection level. In other words, there is minimal concern about heavy metal pollution from grease-trap wastewater. This result also accorded well with the literature (Benecke et al., 2017, Gurd et al., 2019, Gross et al., 2017, Keener et al., 2008, Nitayapat and Chitprasert, 2014, Williams et al., 2012). Similar results were also found with high Ca (70.6 mg kg^{-1}) and Na (10.6 mg kg^{-1}) for the scum samples (A-I-T1 and D-I-T1), but Al (21.5 mg kg^{-1}) and Zn (14.1 mg kg^{-1}) in the scum samples were 21 and 44 times significantly higher than the suspended solid-liquid wastewater samples, respectively (**Table S10**). These results verified that high contents of Ca and Na and other potential minerals (Al and Zn) can affect FOG solid formation not only under sewer conditions but also inside grease-trap conditions.

Interestingly, Grease Trap C samples were found to have the highest mineral/metal content among other grease trap samples. This phenomenon may be ascribed to Grease Trap C having the longest HRT (16.8 min) compared to the other grease traps (8.4 to 11.2 min) (**Table S3**), suggesting that the wastewater and its constituents (both suspended and dissolved solids) can stay longer inside Grease Trap C. However, the relatively lower concentration of the predominant minerals in grease-trap wastewater, especially Ca (26.38 mg L^{-1}, **Table S10**), may affect the future investigation of FOG solid formation mechanisms since other studies have suggested much higher concentrations (i.e., 9.1 to 14 g L^{-1}) (Gross et al., 2017, Keener et al., 2008, Williams et al., 2012). On the other hand, compared to the Ca concentration of 12.08 mg L^{-1} in the tap water samples collected from different food service establishments (**Table S11**) (Law and Wong, 2020), the grease-trap wastewater samples exhibited more than 2-fold higher Ca (26.38 mg L^{-1}) concentration, suggesting that other Ca sources in addition to tap water might have contributed to FOG solid formation.

3.5. FTIR spectra

Fig. 10 shows the FTIR spectra of the collected scum, OD, and sludge samples, including those FOG deposits (FD), calcium soap (CS), and pure soybean oil (PSBO) samples from other studies (He et al., 2013, Shin et al., 2015). First, the scum, OD, and sludge samples exhibited similar characteristic peaks among the samples compared to the FTIR spectra of FD 1 and FD 2 collected from Chinese and non-halal restaurants (Shin et al., 2015). These spectra exhibited the presence of bound water associated with calcium soap at 3,400 cm^{-1}, aliphatic of aliphatic chains of the calcium soap at 2,800-3,000 cm^{-1}, FFAs at 1,745 cm^{-1}, carboxylate group of saponification at 1,422-1,468 cm^{-1}, glycerol at 970 cm^{-1}, and metal-oxygen bond at 665 cm^{-1} (He et al., 2013, Shin et al., 2015), revealing that the properties of FOG solid (settled sludge) formed inside the grease traps were similar to those formed in the open drains, even though the OD sample took more than six months to form and accumulate without any FOG could be extracted. However, some peaks shifted slightly from the abovementioned wavelength, suggesting that the samples underwent specific reactions before achieving the defined wavelength range (He et al., 2013). In other words, different

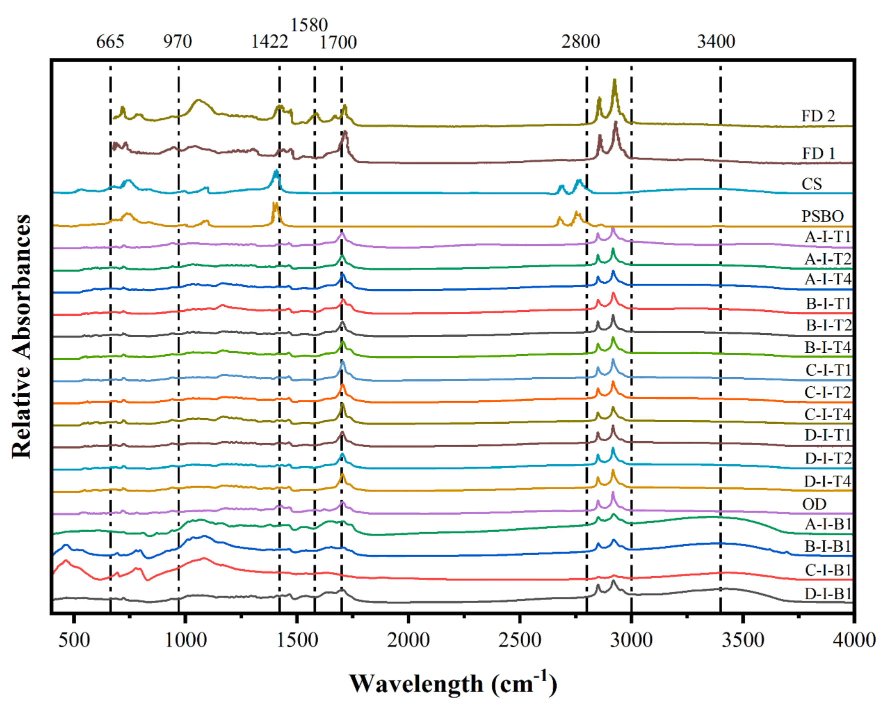

Fig. 10. FTIR spectra of the collected scum, OD, and sludge samples from Grease Traps A to D, compared to samples of FOG deposits (FD 1, FD 2), calcium soap (CS), and pure soybean oil (PSBO) in the literature (Shin et al., 2015, He et al., 2013).

physicochemical mechanisms may be involved in the FOG solid formation and accumulation inside grease traps, as suggested in other studies (He et al., 2013, Husain et al., 2014, Shin et al., 2015).

3.6. SEM-EDX

Fig. 11 shows the surface morphology and elemental composition of the collected scum (A-I-T1) and sludge (A-I-B1) samples using scanning electron microscopy (SEM) coupled with energy dispersive X-ray (EDX) elemental mapping. Similar images and mappings for other scum samples can be found in **Supporting Information** (**Fig. S4** to **Fig. S10**). All the scum and sludge samples exhibited insignificant differences among Grease Traps A to D based on the SEM images, suggesting consistent characteristics in the generated kitchen wastewater that formed the scum and sludge (solids) inside the grease traps. However, the sludge samples exhibited the presence of a significant number of voids in between the sludge particles compared to the sticky scum samples (Fig. 11 (a_2) and 11(b_2)). This result verified the significant differences in the physicochemical properties between the scum and sludge samples, including the aforementioned FOG, TS, VS, CHN, and mineral contents.

Table S12 summarizes the EDX elemental mapping for all 12 scum samples but only four sludge samples and one OD sample. For example, high concentrations of carbon (C, 85 wt.%) and oxygen (O, 14.4 wt.%) were detected for the A-I-T1 (scum) sample. In contrast, a significantly lower C average content (57.7 wt.%) but higher average O content (32.4 wt.%) with slightly higher Na (0.04 wt.%), Mg (0.12 wt.%), Al (1.59 wt.%), Si (1.54 wt.%), P (0.81 wt.%), S (0.89 wt.%), K (0.08 wt.%), Cl (0.17 wt.%), Ca (2.02 wt.%), Ti (0.11 wt.%), Fe (2.46 wt.%), and Zn (0.09 wt.%) were detected from the sludge samples. In other words, more diverse mineral/metal elements were present in the sludge samples compared to the scum samples.

Nonetheless, it can be deduced that C and O could have originated from the organic constituents of food and other waste residues, including FOG. Then, the minerals/metals found in the scum and sludge samples were found to be similar to those found in the sewage treatment plants. Notably, Si, Cu, Fe, P, and Zn were commonly found in sewage treatment plants (Metcalf et al., 2014). These minerals/metals in the scum and sludge samples could originate from cooking ingredients, cooking ware, and cleaning agents. For instance, cooking processes using table salts could have contributed to Na and Cl (Liu et al., 2014, Mattes and Donnelly, 1991). Using detergents for cleaning could add Na and K content to the FOG solid samples (Gurd et al., 2019). Ca, Mg, Cu, Zn, and Fe were also commonly detected in food waste (Barik and Paul, 2017). Besides that, Al, K, Ca, Pb, Cr, Cd, Cu, Ni, Fe, and Zn were found leached from the aluminum, steel, and copper cookware under acidic conditions during the cooking processes (Ali Sultan et al., 2023). In short, the sources of the minerals/metals could significantly affect the FOG solid formation inside the grease traps.

On the other hand, average contents of 74.5 and 22.1 wt.% of C and O were detected from the scum, sludge (**Table S12**), and OD samples, which made up almost 97 wt.% of the composition in the samples, revealing that the samples were highly organic and matched the aforementioned 61.9 to 90.1% VS/TS and 29.7 to 64.2% C of CHN results of the scum and sludge samples (Figs. 4 and 6) and from other studies (Benecke et al., 2017, Court et al., 2021, Gross et al., 2017, He and Yan, 2016, Nitayapat and Chitprasert, 2014, Sari et al., 2013, Suto et al., 2006). However, the scum samples exhibited significantly lower Ca content, ranging from 0 to 1.07 wt.%, disagreeing with the literature on FOG deposits found in the public sewer (Benecke et al., 2017, Gross et al., 2017, Gurd et al., 2019, Keener et al., 2008, Nitayapat and Chitprasert, 2014, Williams et al., 2012). In short, there may be significant differences in forming FOG solids under different conditions, such as inside grease traps, open drains, and sewer lines. Hence, different physicochemical mechanisms of FOG solid formation and accumulation under grease-trap conditions should be conducted to verify the differences in sewer conditions. **Table S13** summarizes the average values obtained from the aforementioned characterization results for the collected floated scum, suspended solid-liquid wastewater, and settled sludge samples.

3.7. Potential solid formation, separation, and accumulation mechanisms

Fig. 12 shows the plan and cross-sectional views of incoming kitchen wastewater flows through a grease trap from the inlet to outlet

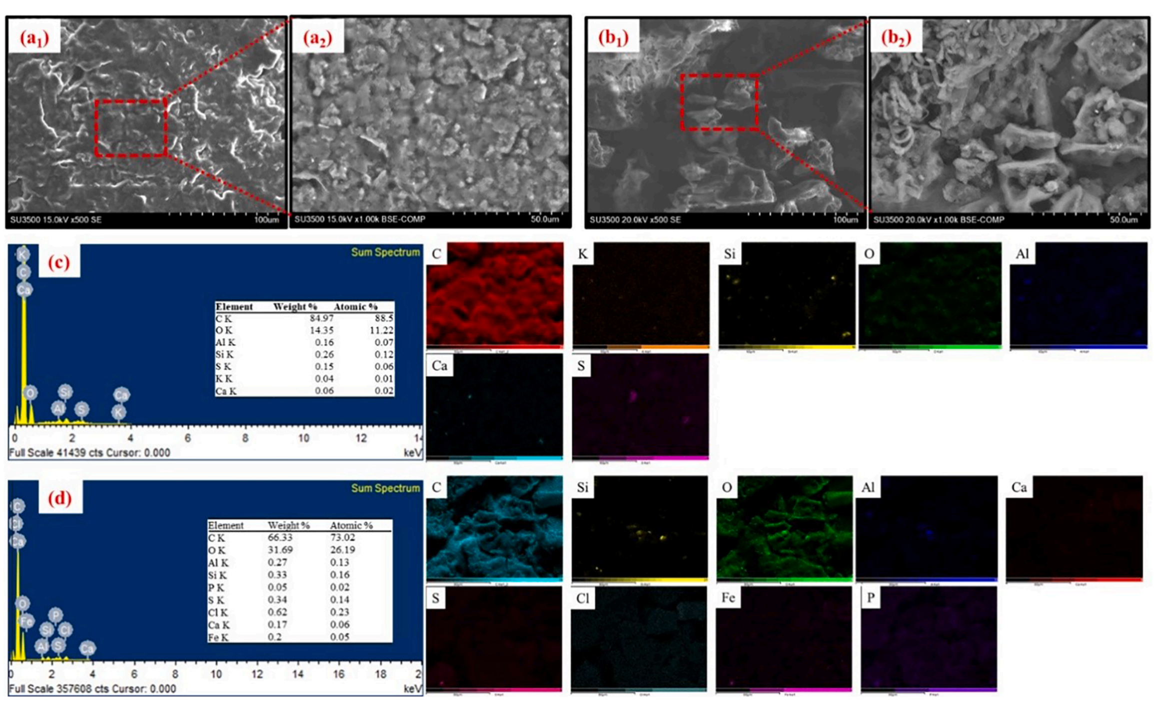

Fig. 11. SEM images captured under secondary electrons (SEs) and backscattered electrons (BSEs) methods for the (a_1, a_2) scum (A-I-T1) and (b_1, b_2) sludge (A-I-B1) samples with 100 and 50 μm magnifications, respectively, and (c, d) the corresponding EDX elemental mapping, respectively.

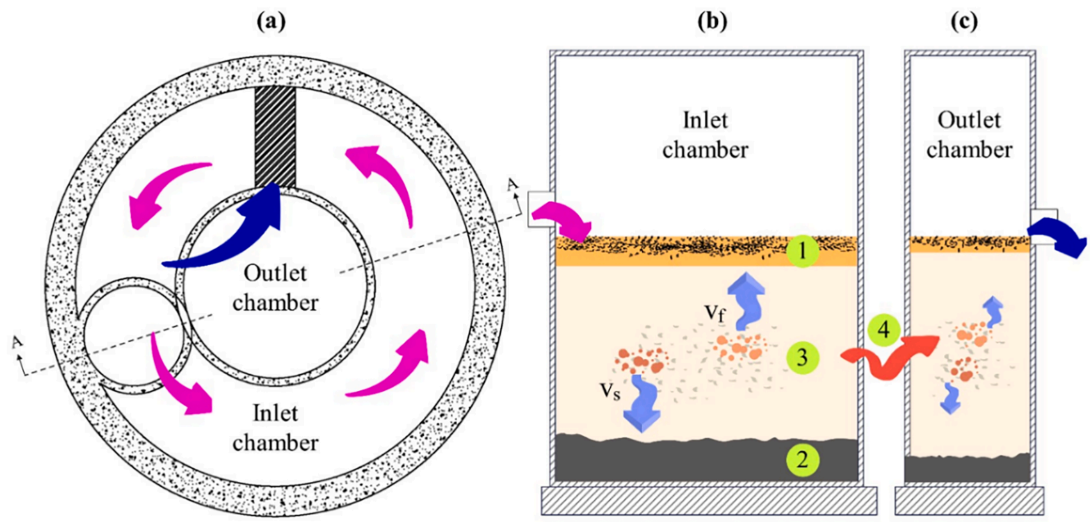

Fig. 12. Plan and cross-sectional views of (a) incoming kitchen wastewater flows through a grease trap from the (b) inlet to (c) outlet chambers, with four potential FOG solid formation, separation, and accumulation mechanisms.

chambers, including four proposed potential mechanisms of FOG solid formation, separation, and accumulation inside a grease trap (Fig. 12(b) and 12(c)). First, a crystallization mechanism of excessive FOG and FFA produces the FOG solids (scum) at the top layer (denoted as "1"). Then, a saponification mechanism of forming FOG solids with more minerals than FFA might have occurred at the bottom layer (denoted as "2") since more diverse mineral ion content and minimal FOG were found in the settled sludge. Third, the FFA emulsification mechanism with surfactant (detergent) and other colloidal particles generated during food preparation and cleaning processes yields a relatively stable suspended solid-liquid wastewater in the middle layer (denoted as "3"). Lastly, a separation mechanism by the baffle walls aids in separating and retaining the scum, suspended solid-liquid wastewater, and sludge (denoted as "4"), preventing a significant amount of FOG, FOG solids, minerals, and other waste residues from escaping the grease trap. More studies should be conducted to verify these mechanisms, thus providing us with more insights into designing and operating a more effective grease trap.

4. Conclusion

In this work, several site investigations revealed that kitchen wastewater separates into three layers inside grease traps, i.e., the floated scum (solids) at the top layer, the suspended solid-liquid wastewater at the middle layer, and the settled sludge (solids) at the bottom layer. Consequently, 64 samples were collected over the 32 days of daily monitoring using customized samplers and characterized according to the standard and modified methods. The liquid samples exhibited more acidic (pH 5-6 at 25-29 °C) than those reported under the sewer conditions (pH 6-7), suggesting that the scum and sludge formation and accumulation may be different inside grease traps compared to that under sewer conditions. They also showed a significant difference in TSS, COD, and EC readings between the inlet and outlet chambers but not for the minerals (TDS), revealing that the baffle wall that separated the inlet and outlet chambers can affect the separation of suspended solids-liquid wastewater inside grease traps. Moreover, the sludge samples had 1.5 times higher solids than the scum samples, i.e., 0.225 *vs.* 0.149 g g^{-1} TS, revealing that the sludge amount had more impact than the scum on the grease trap capacity (i.e., working volume and HRT), resulting in more frequent cleaning (desludging). In contrast, the sludge samples exhibited 1.4 times lower organic constituents, including FOG, FOG solids, and other waste residues, than the scum samples, i.e., 0.096 *vs.* 0.134 g g^{-1} VS, matching with the 61.9 *vs.* 90.1% VS/TS ratios.

On the other hand, up to 0.511 g g^{-1} of FOG can be extracted from the scum samples, with an average of 0.266 g g^{-1}, but none can be extracted from the sludge and OD samples. This occurrence was likely due to each grease trap serving different types of food and beverage stalls operated in the community market, which needs further investigation, especially for those waste residues and types of FOG or FFA that may bind/stick together and settle to the bottom of the grease trap. Besides that, it was observed that more saturated (70-80%) than unsaturated (20-30%) FFAs were found in the grease traps, with palmitic acid as the dominant FFA, comprising 59-65% of the total FFAs. Sodium (Na, 68 wt.%), chloride (Cl, 13 wt.%), and calcium (Ca, 12 wt.%) were found to be significant ions in the liquid samples, but more diverse elements (Al, Si, and Fe) were found in the sludge samples. FFA, calcium soap, and glycerol were also consistently identified in the collected FOG deposit samples using FTIR-ATR and SEM-EDX analyses, including 57.7 to 79.6 wt.% of C and 16.7 to 32.4 wt.% of O for the scum, sludge, and OD samples, respectively, and agreeing well with the 29.7 to 64.2% of C found in the same samples using the CHN analysis. In other words, different types (sources) of FOG/FFA and minerals/metals involved in FOG solid formation during the food preparation and cooking processes have influenced the physicochemical properties of FOG solid, including different densities between the scum and sludge samples. These properties, in turn, have resulted in different separation and accumulation mechanisms for the FOG solids inside grease traps.

Therefore, four potential FOG solid formation, separation, and accumulation mechanisms inside the grease traps were proposed based on the physicochemical characterization results. Since 76% more FFA than minerals (Ca, Fe, Al, and Na) was found inside grease traps, the crystallization of FFA could be a more significant mechanism under grease-trap conditions than the saponification mechanism (FFA reacts with minerals) presented in other studies under the sewer conditions. However, future studies should further verify these mechanisms, notably inside the grease-trap conditions compared to under sewer conditions. This work offers insights into different grease-trap wastewater properties that can significantly impact the physicochemical mechanisms of FOG solid formation, separation, and accumulation, not only inside grease traps but also under sewer conditions when excessive FOG and/or FOG solids enter the public sewer lines.

CRediT authorship contribution statement

Ling Ying Tang: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation. **Ngie Hing Wong:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Thion Am Chieng:** Investigation, Formal analysis, Data curation. **Alex Kwong Jun Kiu:** Investigation, Formal analysis, Data curation. **Chung Siung Choo:** Writing – review & editing. **Yali Li:** Writing – review & editing. **Chin Ping Tan:** Writing – review & editing. **Abu Zahrim Yaser:** Writing – review & editing. **Deni Shidqi Khaerudini:** Resources, Formal analysis. **Gui Hua Chen:** Resources, Formal analysis. **Jaka Sunarso:** Writing – review & editing, Supervision, Resources, Formal analysis.

Declaration of competing interest

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

Ngie Hing Wong reports financial support was provided by Malaysia Ministry of Higher Education. If there are other authors, they 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

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.watres.2024.121607.

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