ADVANCES IN AGRICULTURAL AND FOOD RESEARCH JOURNAL

Original Research Article

Foam Reduction in Aerobic Digestion of Food Processing Wastewater Using Surfactants

Muhammad Salihin Mohd Hidzir[1], Rozita Omar[1*], Syarifah Nazura Syed Saber Ali[1], Aida Isma Mohamad Idris[2], Hairul Anuar Tajuddin[3]

[1]Department of Chemical & Environmental Engineering, Universiti Putra Malaysia, Serdang, Selangor, Malaysia, salihinhidzir115@gmail.com; rozitaom@upm.edu.my; shanazura135@gmail.com

[2]Department of Chemical Engineering, Faculty of Engineering and Built Environment, SEGi University, Kota Damansara, Selangor, Malaysia, aidaisma@segi.edu.my

[3]Centre for Fundamental and Frontier Sciences in Nanostructure Self-Assembly, Department of Chemistry, Universiti Malaya, 50603 Kuala Lumpur, Malaysia, hairul@um.edu.my

*Corresponding author: Rozita Omar ,Department of Chemical & Environmental Engineering, Universiti Putra Malaysia, Serdang, Selangor, Malaysia; rozitaom@upm.edu.my

Abstract: The aerobic digestion of food processing wastewater (FPW) with high fat, oil, and grease (FOG) and protein concentration produces foam. It diminishes treatment efficiency and raises several operational concerns. Surfactants have anti-foaming properties. This study investigates the properties of raw and pre-treated FPW (PFPW) from a food processing factory. The FOG critical point for foam formation was also examined, as well as the impact of chemical and biosurfactants on foam reduction and selected wastewater quality. In aerobic digestion, the FOG critical point for foam production was determined by gradually increasing the diluted FPW FOG input. The chemical surfactants employed were linear alkyl benzene sulfonate and sodium dodecyl sulphate. Rhamnolipid (RL) and tea saponin (SP) were used as biosurfactants in the diluted FPW. Raw FPW and PFPW showed significant chemical oxygen demand (COD) concentration reductions of 15.1 and 4.49 g/L, respectively. Treatment of raw FPW removed considerable protein and FOG at 65.3 and 64.4%, respectively, but high quantities persisted at 18.8 and 4.12 g/L. The average FOG critical point for foam formation was 15.47 g/L. In aerobic digestion, only the addition of biosurfactants SP (0.15 g SP/g dried solid) reduced foam generation, whereas chemical surfactants enhanced it. The diluted FPW treated with 0.04 and 0.10 g RL/g total suspended solid eliminated COD the most (82.1–84.8%). The study highlights that green surfactant, such as biosurfactants, are effective in reducing foam during the aerobic digestion of food processing wastewater, offering a more sustainable alternative to chemical surfactants.

Keywords: foam; food processing wastewater; fat, oil and grease; surfactant

Received: 14th August 2024

Accepted: 11th December 2024

Available Online: 12th June 2025

Published: 23rd September 2025

Citation: Mohd Hidzir, M. S., Omar, R., Syed Saber Ali, S. N., *et al.* Foam reduction in aerobic digestion of food processing wastewater using surfactants. *Adv Agri Food Res J* 2025; 6(2): a0000569. https://doi.org/10.36877/aafrj.a0000569

1. Introduction

Food processing wastewater (FPW) is an industrial effluent from the food processing industry containing high organic pollutants, fats, oil and grease (FOG), and protein contents (Li *et al*., 2019b). Aderibigbe *et al*. (2018) summarised FPW treatment includes oil removal, coagulation-flocculation, sludge removal, and aerobic digestion to meet the minimum discharge requirements. Most industrial wastewater containing oil-in-water emulsions, such as FPW, can lead to severe problems in the different treatment stages. Problems include process equipment fouling, complicated water discharge requirements, and foaming and low degradation in biological treatment stages (Shamsan *et al*., 2023). FOG negatively affects oxygen transport by decreasing biofilm oxygen transfer rates, and limiting microorganisms' oxygen levels (Chipasa & Mĩdrzycka, 2006; Lefebvre *et al*., 1998; Loperena *et al*., 2006) reducing microbial activity (Al-Khatib *et al*., 2023). FOGs are deposited on the surfaces of walls and air/water interfaces, forming grease layers, and in biological wastewater treatment systems, they can be adsorbed by bacterial flocs (Lefebvre *et al*., 1998; Loperena *et al*., 2006).

Treatment options for FOG in FPW include physical, biological, and physical approaches. These comprise adsorption (Lee *et al*., 2020), bioaugmentation utilising viable microorganisms and enzymes (Mazumder *et al*., 2020), saponification (Lefebvre *et al*., 1998), and the most common and easy method, coagulation/flocculation (Zhao *et al*., 2021). These methods have their drawbacks, such as additional pretreatment (Ahmad *et al*., 2005), process failures (Chipasa & Mędrzycka, 2006), uneconomically viable (Soares *et al*., 2019), and the generation of large amounts of toxic sludge (Lee *et al*., 2020).

Aerobic digestion is a biological treatment method in which sludge microorganisms metabolise wastewater organics. Sikosana *et al*. (2019) found that aerobic systems effectively remove soluble, biodegradable organic materials and improve biomass flocculation. However, oil and grease in wastewater tend to agglomerate, hindering the biodegradation of many microorganisms (Al-Khatib *et al.,* 2023). Due to oil and grease's limited biodegradability, aerobic digestion might not effectively remove emulsified oil from wastewater (Erfani *et al.,* 2024), especially under high loading (Matsui *et al*., 2005). Additionally, aerobic digestion of wastewater with high fats, oils, and grease (FOG) levels can cause foaming. Foams can reduce oxygen transfer, biomass concentration in the biological reactor, olfactory concerns, and management and maintenance costs (Collivignarelli *et al*., 2020; Das *et al*., 2024; Carballo *et al*., 2024).

Foaming refers to the occurrence of a layer of bubbles or scum that forms on the surfaces of aeration tanks and clarifiers (Frigon *et al*., 2006). It is defined as a gas dispersion in a liquid containing a high proportion (approximately 95%) of gas. In this state, there is a thin liquid film between the gas bubbles. However, foam can only form when the concentration of a surface-active compound is exceeded, and it is innocuous at low concentrations. Surface-active compounds are amphiphilic, with hydrophilic and hydrophobic functional groups. In the beginning, foam starts as a diluted liquid bubble dispersion. As the bubbles age, they form polyhedral gas cells with thin flat walls. These polyhedral gas cells are nearly regular dodecahedra, while the channels are lamella, which are thin liquid films between foam bubbles. Foams go through two important stages. Water slowly separates two bubbles, resulting in fewer, larger bubbles or a single bubble, while headspace rupture decreases foam volume. The volume of foam produced by the treatment system is determined by foam generation and bubble rupture (Moeller *et al.*, 2012).

Foaming in activated sludge aerobic digestion has been linked to a synergistic impact of surfactants (detergents), biosurfactants (compounds produced by microorganisms), and diverse filamentous bacteria (Frigon *et al*., 2006; We *et al*., 2024; Ma *et al*., 2024), because of a reduction in the interfacial tension between the gas and liquid phases (Collivignarelli *et al.,* 2020). Foaming also can develop from temperature variations (Frigon *et al*., 2006) and high FOG loading (Lienen *et al*., 2014). Research suggests that foaming in activated sludge can suppress lipid decomposition (Chipasa & Mędrzycka, 2006).

The foam formation in the aerobic digestion tank of the FPW treatment plant under study could be associated with the high FOG content in the FPW. Current oil skimming and combined chemical coagulation and dissolved air flotation as primary treatment still resulted in foam formation in the sequencing batch reactors, as shown in Figure 1. Foaming is enhanced by aeration since lipid saponification and emulsification are both increased, as seen in Figure 1(a). However, since the foam is stable enough, it persisted even after aeration ceased, as shown in Figure 1(b).

Figure 1. Foaming in aerobic treatment of FPW: (**a**) During aeration; (**b**) After aeration ceased.

Foaming has been addressed by changing operational parameters, adding structures, or adjusting pre-oxidation reactor dissolved oxygen (Pal *et al*., 2014). Intermittent aeration may reduce foaming, according to Lienen *et al*. (2014). However, eliminating foam with a small number of antifoams is the most effective (Denkov *et al*., 2014). Molecularly dissolved surfactants and polymer molecules can occasionally reduce foam production, according to Denkov *et al*. (2014). These products are cost-effective and leave no trace on the final output.

In contaminated aqueous solutions, surfactants form micelles. When surfactant concentration reaches the critical micelle concentration (CMC), these micelles can dissolve metal ions and organic solutes (Sharifi *et al*., 2014). The investigation by Pirooz *et al*. (2018) utilised two types of industrial chemical surfactants. The first surfactant was a mixture of monoethyl amine and sulfonated lauryl alcohol, whereas the second was a mixture of nonylphenol ethoxylate and potassium hydroxide. Their testing demonstrated that these surfactants removed 80% of sewer grease fat. Industrial SDS and Span 80 reduced fat content significantly. Biosurfactants have been found to have significant implications in several environmental applications, including soil remediation (Moldes *et al*., 2011; Manickam *et al*., 2012; Karlapudi *et al*., 2018; Chaprão *et al*., 2015) and oil recovery (Xu *et al*., 2011). The mechanisms by which they exert their effects that encompass solubilisation, emulsification, and dispersion, among other processes (Bose *et al*., 2024). Biosurfactants can help biodegrade wastewater with high-fat content by dissolving fats and oils (Singh *et al*., 2024). The authors added that biosurfactants might be integrated into the biological treatment process without an additional processing step, decreasing operational costs.

Rhamnolipid is a biosurfactant used as an effective pre-treatment for enhancing the accumulation of short-chain fatty acids (SCFAs) in waste-activated sludge (WAS) (Li *et al*., 2019a). Aerobic treatment of oily wastewater from various industries increased the removal efficiency of crude oil, lubricating oil, and residual frying oil significantly (Zhang *et al*., 2009). Meanwhile, the biosurfactant tea saponin was utilised for volatile fatty acid (VFA) synthesis during WAS anaerobic fermentation (Huang *et al*., 2015). Saponin, SDS, and rhamnolipid were able to remove crude oil from contaminated soil at a rate of over 79% (Urum & Pakdemir, 2004). Biosurfactant increases the apparent aqueous solubility of organic compounds by enhancing the solubilisation of hydrophobic compounds within micelle structures (Cameotra and Makkar (2010)

The inclusion of surfactants is therefore hypothesised to mitigate the foaming issue in FPW-activated sludge treatment. This study analysed the effects of chemical and biological surfactants on form formation and treatment efficacy.

2. Materials and Methods

2.1. Materials and Source of Chemicals

FPW was taken at the holding sump tank (after skimming the floated oil) of a local food processing industry in Kuala Lumpur, Malaysia. The wastewater originated from the wash water used in the processing of fast-food products such as nuggets, sausages, breaded chicken, etc. PFPW was the feed to the aerobic treatment (Sequencing batch reactor) that has been treated via chemical coagulation (poly aluminium chloride, NaOH, polymer) and dissolved air floatation (DAF). Aerobic-activated sludge was sourced from the SBR tank after settling. Samples were kept in a chiller at 4℃ before use. EvaChem Sdn. Bhd. supplied linear alkyl benzene sulfonate (LAS) and sodium dodecyl sulphate (SDS). Rhamnolipid (RL) (95 ± 2% purity) and tea saponin (SP) (98% purity) were purchased from Wuhan Golden Kylin Industry & Trade Co. Ltd.

2.2. Wastewater Characterisation

The sample characterisation was conducted for selected wastewater parameters (chemical oxygen demand (COD), FOG, protein, and pH). The COD analysis follows APHA Method 5220C, utilising the digestion of samples with concentrated sulfuric acid and potassium dichromate and then titrated with standard ferrous ammonium (FAS) solution. FOG was extracted using n-hexane and separated via gravity following APHA Method 5520B (APHA, 2005). The protein content analysis follows the Bradford Protein Assay. Meanwhile, the pH was analysed using a pH-80 HM digital pH meter. The FPW and PFPW samples were directly taken from the plant as explained in Section 2.1 several times over a period of a month for the characterisation.

2.3. Sludge Acclimatisation

Acclimatisation of sludge was performed to ensure that the aerobic sludge used in the FOG concentration critical point experiments contained healthy biomass. At a food-to-microorganism (F: M) ratio of 70:30 (by volume), 2 L of diluted FPW (1000 mg/L COD) was added to aerobic sludge in 5-L beakers. The aerobic digestion proceeded with a dissolved oxygen (DO) concentration of 6.0 mg/L, was continuously agitated, and was aerated for approximately 19 h before settling for 5 h. Daily feeding was performed until the total suspended solids (TSS) of the mixed liquor reached between 2,000 and 2,500 mg/L. The procedure was carried out again using diluted FPW at COD values of 1500 and 2000 mg/L.

2.4. Determination of FOG Concentration Critical Point of Foam Formation

The FOG critical concentration of foam formation is the concentration of FOG at which stable foam lasts for more than 2 h after aeration during the aerobic digestion process. Table 1 shows FOG concentrations from FPW dilution with distilled water (2–20 dilution factors). Note that the sampling was done twice, with the former just enough for the determination of the FOG concentration critical point experiment, whilst the latter was needed for the surfactant addition experiment. Since the samples were taken at different times, the composition is different as the production of products may be different or of different amounts due to the company's target sales. However, since only the initial concentration of FOG that generates stable foam was the main concern for the next experiment, then it is deemed acceptable.

This experiment employed the same setup and approach as aerobic sludge acclimatisation. The foam's height was measured before, during, and after aeration. In this experiment, feed and treated FPW (after settling) COD, FOG, protein, and pH were determined.

Table 1. FOG concentration following FPW dilution with distilled water.

Sampling date	Dilution factor	Resultant FOG concentration
17 March 2022	20	3.29 g/L
	10	6.27 g/L
	4	11.8 g/L
	2	15.5 g/L
12 May 2022	6	13.6 g/L

2.5. Effect of Surfactant Addition

Chemical and biochemical surfactants were applied to counteract the stable foam generated during aerobic FPW digestion at the critical FOG concentration. LAS was employed at 1 and 3 mM, below and above its CMC of 1.2 mM (Sharifi *et al.*, 2014). Sodium lauryl sulphate (SLS), a coconut or palm kernel oil-derived chemical surfactant, was utilised at 1 mM below its CMC (8.15 mM) (Pirooz *et al.*, 2018). RL was optimally dosed at 0.04 g/g

TSS (Li *et al.*, 2019b); thus, RL additions of 0.04 and 0.10 g/g TSS were evaluated. Huang et al. (2015) study suggested adding biosurfactant tea saponin (SP) of 0.1 g SP/g dried sludge (DS) resulted in the best foam reduction. SP was added at 0.10, 0.15, and 0.20 g/g DS in this investigation. The surfactants were homogenised into the critical FOG concentration in diluted FPW feeds and fed to activated sludge at a 70:30 ratio. Similar techniques to prior tests were used. The investigation without foam overflow measured foam height every 30 mins after aeration began for 2 h. Additionally, feed and treated wastewater were analysed for foam reduction and COD removal.

3. Results and Discussions

3.1. Food Wastewater Characterisation

Figure 2 demonstrates the COD fluctuation of raw FPW measured at different dates. The wastewater treatment plant engineer explained that the weekly product changes were due to product needs (Rahman, 2021). Since the items contain carbohydrates, fat, and vegetable oil for frying, the results typically range above 15,000 mg/L. The data averages 15,100 mg/L. This study's average COD loading is substantially higher than other FPW studies, except for Bustillo-Lecompte and Mehrvar (2015). They found that blood, stomach, and intestinal fluid produced during slaughtering generate a lot of fat, proteins, and fibres in abattoir wastewater.

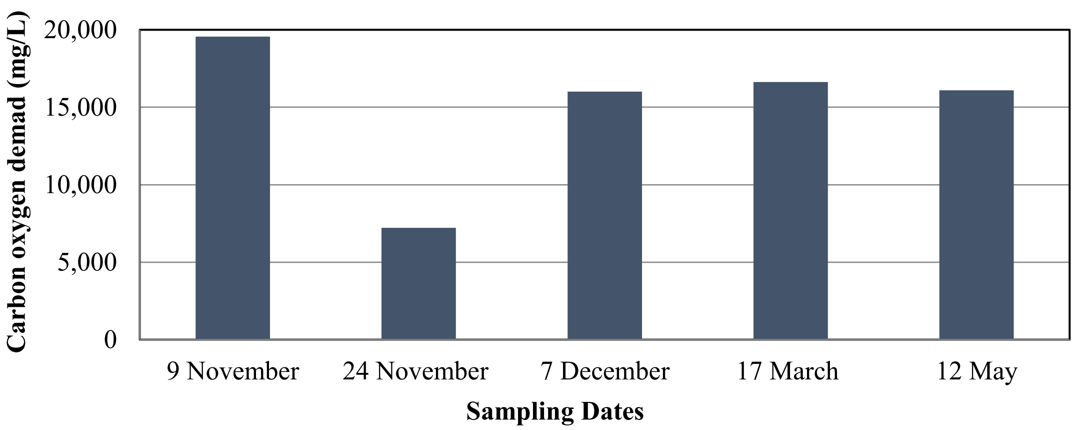


Figure 2. COD variation of raw FPW from the food processing industry

PFPW samples fed before aerobic digestion had COD variance, as seen in Figure 3. The chemical coagulation and dissolved air flotation pretreatment procedure reduced COD by 30–80%, however, it was still high, with COD between 3500 and 6000 mg/L. Different initial loadings before pretreatment may explain the large removal range. The specific contaminant contents, such as protein or FOG, differed with each FPW shown in the next sections. The average COD was 4488 mg/L, with a 69.1% decrease. This value is comparable to the meat processing and slaughterhouse plant (Asgharnejad *et al.*, 2021).

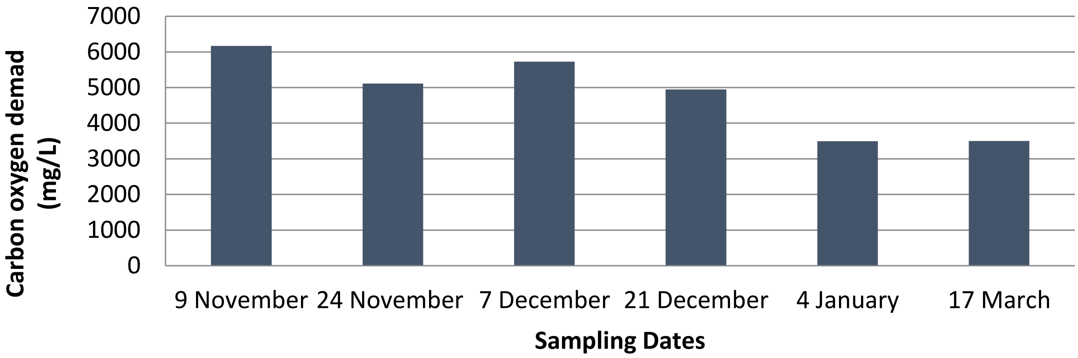


Figure 3. COD variation of PFPW from the food processing industry

The raw and pre-treated FPW samples were tested for FOG and protein. Figure 4 shows the FPW sample's FOG and protein variances. Although the 12th of May sample had a higher FOG, the COD was not the highest. This suggests that other pollutants contributed to this effect. FOG content may have varied depending on the products produced that week. Fire products such as nuggets and breaded chicken may have been produced more than sausages. The calculated average of FPW FOG was 11,588 mg/L, a high value greatly influenced by the sampling on the 17th of March and 12th of May 2022. These samples were almost triple and 10 times the first three's average. The facility only provided production statistics for November 2021, which shows a greater FOG on November 7th than November 24th, possibly owing to more beef products processed, such as beef cocktails, sausage franks, minced meat, and burgers patty. In the meat and dairy industries, FPW has high COD, FOG, protein, and TSS (Bolzonella *et al.*, 2007).

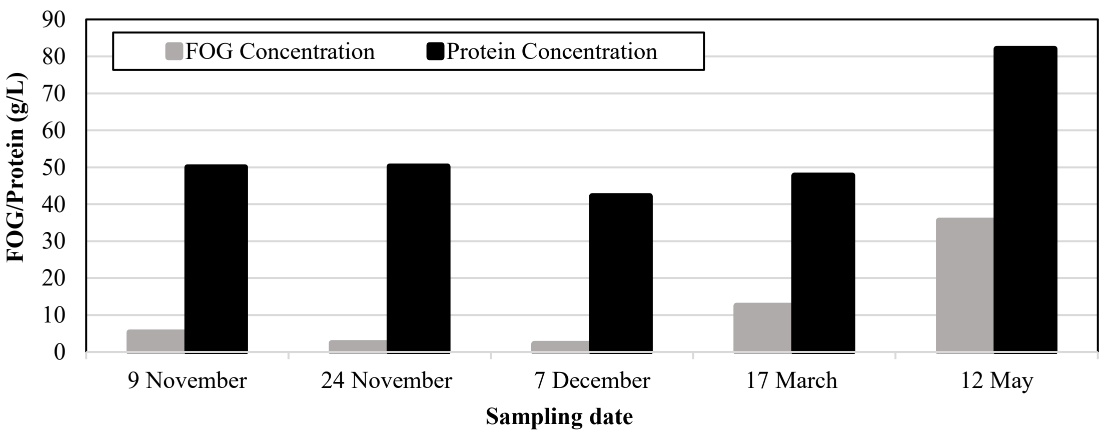


Figure 4. Variation of FOG and protein concentration of raw FPW

FPW samples have significant protein content, reaching 82 g/L on the 12^{th} of May and 54.4 g/L on average. Food manufacturing that day may have included high-protein ingredients to process fast-food products such as chicken, beef meats, and eggs (Rahman, 2021). Other days samples averaged 44 g/L, half of the 12^{th} of May samples. Similar protein content of 50 mg/L was found in items produced between November 7^{th} and 24^{th}, 2021. Production quantities were not indicated to match protein content.

Only 10.6–32.9% of FOG was eliminated after coagulation and DAF unit pretreatment. The 12^{th} of May sample lacks data to assess pretreatment efficiency if the FPW has high FOG values. Given the value of FOG removal, the existing pretreatment procedure in plant wastewater treatment facilities is insufficient. In alum and DAF treatment of vegetable oil refining industry wastewater, Azbar and Yonar (2004) found 83% FOG removal (initial concentration of 3.6–3.9 g/L). The oil in FPW in this study may be emulsified and more stable due to the ingredients such as emulsifiers and stabilisers added to the products, resisting the pretreatment. This wastewater is a complex mixture of water, oil, and chemically stabilised emulsifiers, so proper separation requires expensive physical and/or chemical separation processes. Protein removal averages at 60%, which is good. High initial protein content may cause these removal values. Protein is not an effluent discharge standard established by the Department of Environment (2009) and is not typically analysed in food processing wastewater. However, this high value may compromise PFPW aerobic treatment. Figure 5 below shows the FOG and protein concentrations of the PFPW.

The pH increases from FPW to pretreated FPW (Figure 6). FPW may have an acidic pH due to food processing ingredients. The pH increased somewhat because caustic (NaOH) was applied during pretreatment to improve coagulation. The authors are unsure if the coagulant was coagulated at its optimal pH. During a conversation with the engineer in charge, the pH was not changed before the PFPW entered the aeration tank, but the biological tank pH was 6–7.5, which was adequate for biological treatment (Xu & Zheng, 2021).\

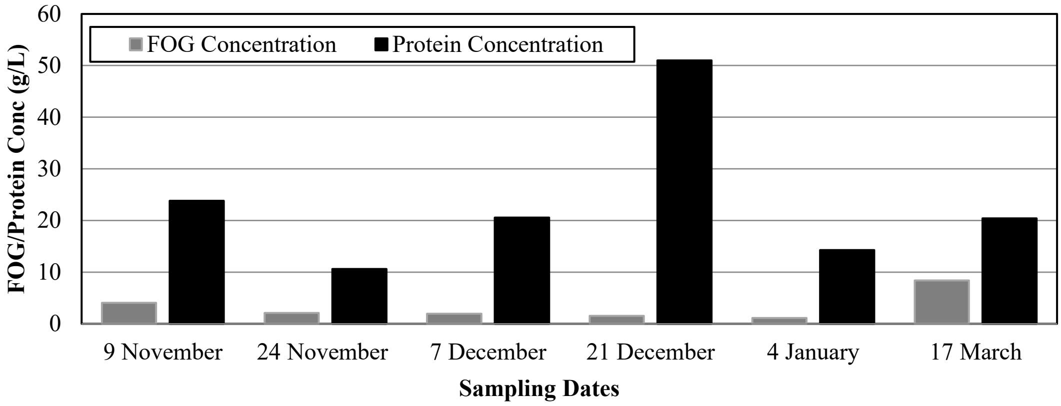


Figure 5. Variation of FOG and protein concentration of PFPW

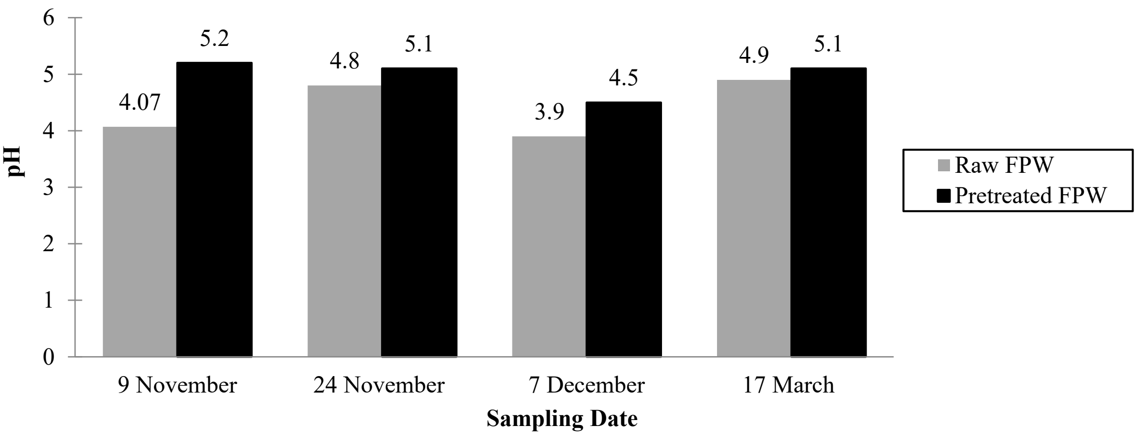


Figure 6. pH variation of raw FPW and PFPW from the food processing industry

Severe foaming issues in the aerobic treatment of wastewater at the food processing plant's sequencing batch reactor commenced in February 2022 (Rahman, 2022). Prior to that, the foaming problem was under control, where the foam did not overflow. Although comprising organic, fats, oils, and grease (FOG), proteins, and other bacteria can all induce foaming during the aerobic treatment of wastewater; nonetheless, characterisation results indicate that the primary treatment employing coagulation-flocculation-DAF was ineffective in significantly lowering the FOG concentration. Therefore, it is postulated that FOG may be a primary contributor to foam generation in aerobic treatment.

3.2. Determination of FOG Concentration Critical Point for Foam Formation

This experiment started with plant PFPW samples obtained on the 17th of March 2022. Despite repeated attempts to replicate the aerobic treatment in plants, stable foam was not achieved (Table 2). Due to aeration, only bubbles remained. Thus, FPW collected on the same date was diluted with distilled water to obtain specific amounts of FOG loadings, as shown in Table 1 above.

Table 2. Height of FOG concentration critical point of foam formation experiment using PFPW.

No.	Operating Conditions	Foam Height (cm)
1	DO: 3.0 mg/L; F/M Ratio: 50/50; Temperature: 24°C	0.0
2	DO: 3.0 mg/L; F/M Ratio: 70/30; Temperature: 24°C	0.0
3	DO: 3.0 mg/L; F/M Ratio: 70/30; Temperature: 24°C; Protein: +500 mg (gelatine)	0.0
4	DO: 7.8 mg/L; F/M Ratio: 70/30; Temperature: 24 °C	0.0

Table 3 provides foam observation and height using diluted FPW from the 17th of March 2022. Dilution 20, with the lowest FOG concentration of 3.29 g/L, was the only FPW dilution that did not foam at the start. After 2 h of aeration, only factor 2 FPW (15.47 g/L FOG) had stable foaming. After 19 h of aeration, the foam disappeared. The continual stirring and decomposition of organics (FOG, protein, and polysaccharides) during aeration may explain this observation. Hence, this value was considered the FOG critical point concentration. Ganidi *et al.* (2011) detected no foam in municipal aerobically digested sewage sludge at 1.25 kg volatile solid/m^3. Increasing COD to 2.5 produced foam, but it was unstable. Only at 5 kg volatile solid/m^3 test, the foam was stable. It is known that the municipal sewage sludge from wastewater treatment plants has a high amount of FOG, up to 26% (Abdulhussein Alsaedi *et al.*, 2022).

The 17th of March sample was not enough for the next experiment (impact of biosurfactant addition); thus, the authors collected more on 12th of May 2022. Another series of experiments indicated that 13.0 g/L FOG concentration with a factor dilution of 6 generated stable foam (Table 3). The foam remained after 19 h of aeration. A possible cause is the high suspended solids loading (3375 ± 375 mg/L). Meat processing and abattoir wastewater had a stable form even at 1,164 mg/L (Bustillo-Lecompte & Mehrvar, 2015) and 1,400 mg/L (Atikah *et al.*, 2019). The present diluted FPW sample has twice the TSS of the other investigations. A high organic loading rate exceeding 0.6 kg/m^3/day produced a lot of white particles on the immobilised support in an activated sludge treatment for fat and oil-containing wastewater (Matsui *et al.*, 2005). The white material comprised calcium di-stearate and di-palmitate, suggesting saturated fatty acid breakdown was limited compared to unsaturated. The foam sample in this study was sent for lipid analysis. Similar to Matsui *et al*. (2005), foam from this study comprises high saturated fatty acid at 48/7%, with 37.7% palmitic acid, and degrades slowly.

The treatment performance of diluted FPW was assessed. Selected wastewater parameters, including pH, COD, FOG, and protein, were characterised. Maximum FOG removal was 50% at Dilution 2, the highest FOG concentration tested. Aerobic treatment with a sequencing batch reactor cannot efficiently treat FOG. Protein removal of 100% at 9.29 g/L FOG shows greater treatment efficiency. Even at maximum FOG, 86% removal was observed. Aerobically treated 12th of May samples (13.0 g/L FOG) generated more foam but still had 87.9% protein removal. Gorini *et al*. (2011) found that in an aerobically treated slaughterhouse wastewater, only 21% of the protein fraction remained in the total COD compared to 32% of the lipid. At 29 and 28% fractions contained in the raw wastewater, the percentages were practically comparable in raw wastewater. This shows aerobic digestion degrades proteins faster than FOG. The aerobic treatment is decent for FOG, with higher removal at the highest FOG concentration of diluted FPW, 15.47 g/L. This illustrates that FOG, not protein concentration, affects treated wastewater COD levels. The maximum COD removal was 84% (at dilution 2), yet the treated wastewater remains at 940–1620 mg/L, far from Standard B effluent discharge of 200 mg/L (Department of Environment, 2009). After aerobic treatment, pH rises from 5 to almost neutral, like plant wastewater treatment.

Table 3. Foam observation and height of FOG critical point of foam formation experiment using FPW.

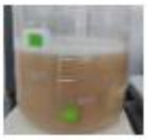
Dilution [FOG]	Before aeration		Start aeration		During (2 hours)		After (19 hours)	
	Picture	Height (cm)	Picture	Height (cm)	Picture	Height (cm)	Picture	Heigh t (cm)
20 3.29 g/L (17 March 2022)		0.0		0.0		0.00		0.0
10 6.27 g/L (17 March 2022)		0.0		0.1		0.1		0.0
4 11.78 g/L (17 March 2022)		0.1		0.5		0.0		0.0
2 15.5 g/L (17 March 2022)		0.1		0.3		0.4		0.0
6 13.0 g/L (12 May 2022)		0.0		0.7		2.7		3.0

3.3. *Effect of Surfactant Addition*

This study examined chemical surfactants (LAS and SDS) and biosurfactants (rhamnolipid, and tea saponin). The experiment used diluted FPW at the FOG critical point of foam formation (15.47 g/L for the 17th of March 2022 sample and 13.04 for the 12th of May 2022). The chemicals and biosurfactants' foam reduction ability were measured by foam height and observation before and after aeration and at 30-mins intervals within 2 h. Tables

4 and 5 show foam observations and heights when diluted FPW is blended with chemical and biosurfactants.

Table 4. Foam observation and height of diluted FPW with chemical surfactant addition

Chemical surfactant concentration	Before aeration		Start of aeration		After 10 minutes		After 19 hours	
	Observation	Height (cm)	Observation	Height (cm)	Observation	Height (cm)	Observation	Height (cm)
1 mM LAS		1.15		3.3		15.0		0.0
3 mM LAS		1.7		10.0		15.0		3.5
1 mM SDS		0.18		2.5		15.0		0.0

Upon addition of any concentration of LAS and SDS, it immediately induced soapy bubble-type foam. Aeration was stopped 10 mins into the experiment because foam rose quickly almost overflowing the beakers. LAS added above the CMC caused bubbles to rise to 10 cm at the commencement of the aeration process, 3–4 times more than 1 mm LAS and SDS. The foam remained in the 3 mM LAS treatment after 19 h of mixing. The different foam structure observed after the addition of LAS and SDS was due to foams induced by chemical surfactants, called white foam, being less viscous and stable compared to the biological foams (Collivignarelli *et al*., 2020).

Cheap, non-toxic, and widely used, these two anionic surfactants clean domestic sewage and wastewater (da Silva *et al*., 2020). They were chosen because they responded well to sewer line FOG (Pirooz *et al*., 2018). Their study revealed FOG weight decrease after adding surfactants directly to their samples and mixing before adding pure acetone and chloroform solvents. In aerobic digestion of fat and oil-containing waste, Matsui *et al*. (2005) added anionic alkyl ether sulfate-based commercial surfactant (sodium lauryl sulphate) to disperse oil (long-chain saturated fatty acids) for improved degradation. No white solids formed after adding surfactant. In their investigation, foam appearance was not mentioned.

Table 5 presents the recorded measurements of foam height obtained from the use of diluted FPW in conjunction with the addition of biosurfactants. The foam production in diluted FPW (FPW collected on the 12th of May 2022) was effectively mitigated, as evidenced by the visual representations provided in Figure 7 when compared to the control group (Table 3). Qin *et al*. (2012) reported the presence of suspended particles that appeared white and exhibited a floating behaviour during the aerobic digestion process of frying oil wastewater, specifically in the absence of rhamnolipids. The introduction of RL resulted in the disappearance of the floating white suspended solid. The article does not provide sufficient clarity regarding the physical state of the white suspended solid, specifically whether it exists in the form of foam. This finding demonstrates the efficacy of including rhamnolipid as a viable solution for the remediation of oil in wastewater. To date, there is a lack of information regarding the inclusion of saponins in wastewater treatment processes.

Table 5. Foam observation and height of diluted FPW with biosurfactant addition

Biosurfactant concentration	Height (cm)						
	Before aeration	Start of aeration	30 mins aeration	1-h aeration	1.5-h aeration	2 h aeration	After 19 h (aeration stopped)
0.04 g RL g^{-1} TSS	0.40	1.10	0.35	1.70	2.20	2.30	2.35
0.10 g RL g^{-1} TSS	0.00	1.05	2.60	2.00	1.25	2.50	1.40
0.10 g SP g^{-1} DS	0.00	0.75	1.50	2.00	1.45	1.45	2.75
0.15 g SP g^{-1} DS	0.00	0.10	1.00	1.50	1.50	2.00	2.25
0.20 g SP g^{-1} DS	0.00	0.00	1.00	1.00	1.50	2.00	2.50

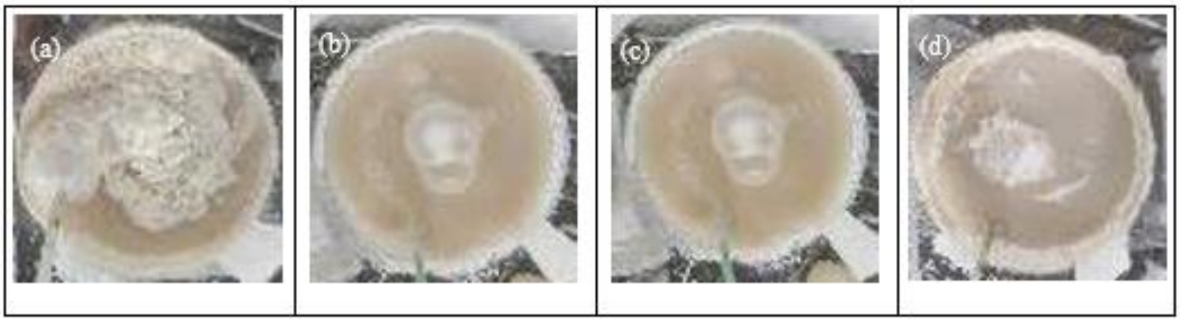


Figure 7. Foaming of diluted FPW aerobic digestion added with biosurfactants after aeration for (a) 30 mins, 0.04 g RL/g TSS; (b) 2 h, 0.04 g RL/ g TSS; (c) 30 mins, 0.15 g SP/g DS; (d) 19 h, 0.15 g SP/g DS.

The observed pattern indicates that, in general, the height of foam tends to grow as the duration of aeration increases. However, it is worth noting that at a concentration of 0.10 g SP/g DS, there is a minor decrease in foam height after 1.5 and 2 h of aeration. All the supplementary biosurfactant introductions failed to achieve complete eradication of the foam. Among all the experimental conditions tested, the use of 0.15 g of SP/g DS consistently resulted in foam heights below 2.25 cm. In the control experiment, Zhang *et al*. (2009) noted the presence of oil floating in the aerobic treatment of waste frying wastewater following aeration. An attempt was made to add 0 and 22.5 mg/L RL without observing any foam production. However, when greater dosages of 45 and 90 mg/L were used, sustained white foaming occurred for a minimum duration of 20 minutes. This finding demonstrates that a precise quantity is necessary to eliminate foam formation.

Figure 8 below presents the COD reduction of feed with different types and concentrations of chemical surfactants and biosurfactants, respectively. The highest COD removal was recorded in the control aerobic digestion when no surfactant was added (81.6%). Reduction of COD removal when feed was added with chemical surfactants shows they affect aerobic digestion negatively, especially at 1 mM LAS. The longer digestion time of the control experiment might be because the experiments of LAS and SDS addition were cut short due to excessive foaming. Nonetheless, increasing the LAS concentration leads to better organic degradation. It is interesting to note that the COD removal when added with 1 mM SDS was like that at 3 mM LAS. LAS better emulsification as an anionic surfactant compared to SDS may have contributed to this effect (Matsui *et al.*, 2005).

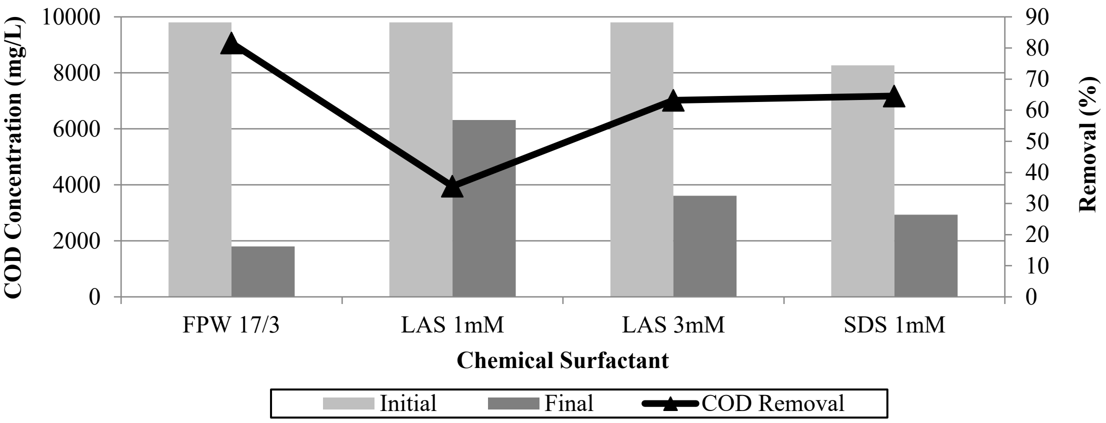


Figure 8. COD removal by the addition of different chemical surfactants and concentrations

The COD removal by adding biosurfactants is shown in Figure 10 below. The COD removals achieved by the rhamnolipid addition were higher (82.1–84.8%) than tea saponin (56.5–64.2%) and the control (68.8%). It is possible that the initial COD reading was significantly lower. The biosurfactant added before the analysis may have also contributed to this effect, although the analysis was done directly after the addition. RL enhanced the solubility and dispersion of oil and grease in aqueous solutions (Shah Zainal Abidin *et al.*, 2023). Increased COD removal with the addition of RL agrees with the observation by Qin et al. (2012) that COD removal is higher by 90% regardless of influent COD concentration. It was also found that RL addition at concentrations lower than its CMC (0.1 mM) could increase association with hydrophobic substrates, resulting in increased degradation rates (Al-Tahhan *et al*., 2000).

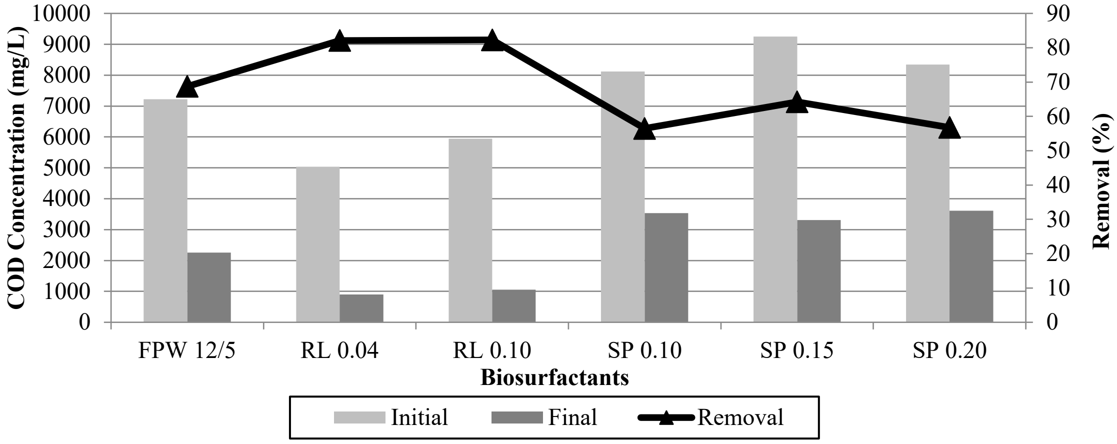


Figure 9. COD removal by the addition of different chemical biosurfactants and concentrations

4. Conclusions

The concentrations of chemical oxygen demand (COD), FOG, and proteins were assessed in a wastewater sample obtained from the food processing plant. The application of chemical coagulation/flocculation and separation techniques resulted in a moderate reduction in the concentrations of COD, FOG, and protein by 64.6%, 64.4%, and 65.4%, respectively. However, despite these reductions, the remaining levels of these parameters are still considered to be very high. The aerobic treatment of the PFPW resulted in the appearance of significant foaming. The experimental results revealed that a FOG concentration of 15.5 g/L was identified as the essential threshold for inducing foaming. The introduction of chemical surfactants resulted in the formation of smaller bubbles that exhibited rapid ascent. The incorporation of biosurfactants, specifically tea saponin and rhamnolipid, has been found to effectively mitigate foam formation. The application of tea saponin at a concentration of 0.15 g per g of dry substance effectively mitigated foam formation, resulting in a maximum foam height of 2.25 cm. Nevertheless, the efficacy of the treatment was diminished when used in conjunction with all surfactants, resulting in a decrease in FOG removal.

The adoption of green surfactants as an alternative to chemical surfactants requires addressing the constraints of cost and production scalability. Advances in biotechnology and process engineering may alleviate these obstacles, enhancing the competitiveness of biosurfactants. The creation of hybrid systems that integrate the advantages of both green and chemical surfactants may provide a balanced solution, utilising the ecological benefits of biosurfactants while preserving the performance attributes of chemical surfactants in rigorous applications. This dual strategy may facilitate more sustainable manufacturing operations while mitigating the shortcomings of each surfactant category.

Author Contributions: Conceptualization, MSMH, RO, SNSSA, HCM and AIMI; methodology, MSMH, SNSSA, RO, HCM and AIMI; validation, RO, HCM and AIMI ; formal analysis, MSMH, SNSSA, and RO; investigation, MSMH; resources, RO and HCM; data curation, MSMH; writing—original draft preparation, MSMH and RO; writing—review and editing, RO; visualization, MSMH; supervision, RO, HCM, and AIMI; project administration.

Funding: There is no official funding for the project.

Acknowledgements: The authors would like to acknowledge Universiti Putra Malaysia for the resources (chemicals, space, and analysis) for the project.

Conflicts of Interest: The authors declare no conflict of interest

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