FINAL REPORT

Megasonics for Separation and Recovery of Fat Oil and Grease from Abattoir Wastewater Streams: A Proof-of-Concept Study

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1.0 EXECUTIVE SUMMARY (max 2-3 pages)

Overview of project objectives: A key operation in red meat abattoirs is the recovery of fat, oil and grease (FOG) for tallow production. Large amounts of water are used in the various processing stages which become contaminated with FOG. Hence effective separation and recovery of the FOG is important for maximising tallow production and removal of FOG which can cause problems in the downstream processing of wastewater for either disposal into the sewar or reuse. With the current popular technologies such as dissolved air floatation (DAF) and decanters (tricanters) there may be incomplete separation and recovery of the FOG due to emulsification of the FOG under certain conditions.

The Commonwealth Scientific and Research Organisation (CSIRO) has a patented megasonic technology currently used at an industrial scale to effective separating and recover palm oil from emulsions from effluent. The aim of this project was to carry out proof-of-concept laboratory scale megasonic trials to explore and assess the effectiveness of this technology for the separation and recovery of FOG in wastewater streams from several abattoirs across Australia.

Approach: Four abattoirs, two in Victoria (V1 and V2) and two in Queensland (Q1 and Q2) were surveyed by questionnaire, and technical meetings were held to discuss issues around key wastewater treatment processes and technologies for FOG recovery and issues involving FOG losses in wastewater streams due to emulsions. The scientific and patent literature were also reviewed to get a better understanding of technologies for FOG separation and analysis. Site visits to V1, V2 and Q1 were conducted as part of the learning and scoping phase, however it was not possible to travel to Q2 due to flooding and the Covid-19 travel and site-visit bans, but we were able to obtain samples from each abattoir.

Project outcomes and insights:

V1, a relatively new abattoir, did not have any significant FOG issue in their wastewater treatment (anaerobic/aerobic digestion ponds) since the rendering was done off-site and the site did not have a DAF or other technology for recovery of FOG. Hence wastewater was found to contain negligible amounts of FOG, and this site was not included in sampling for the megasonic trials. Q1 and Q2 both used a DAF as their sole technology for recovery of FOG. They both had similar issues with FOG loss in the DAF outflow. This could be due to:

1. The water temperature being above the melting point range of the FOG (29-46 ^{o}C), resulting in escape of liquid-FOG emulsions in the water phase since the operating temperatures are between 48-55 ^{o}C and 45-53 ^{o}C for Q1 and Q2, respectively.
2. Large air bubbles at temperatures above 40 °C due to poor air solubility reduces the effectiveness of floatation of FOG, and
3. Overloading the DAF with very high FOG content, throughput or inadequate residence time reduces FOG floatation and causes it to flow under the baffle and be lost

However, at the time of sampling from the DAF of Q1 and Q2 the FOG loading was not excessive and the DAFs were functioning well since they had just prior to sampling received maintenance and cleaning and the levels of FOG emerging from the DAF were very low. Under these very low FOG contents (0.04-0.09%, w/v), megasonics was not able to separate the very small amount of FOG in the DAF outflow, hence megasonic treatments were not applicable for these two abattoirs. Nevertheless, cooling the wastewater coming into the DAF to below the minimum melting temperature of the FOG, and to ensure maximum air solubility and the smallest air bubbles possible as well as keeping the FOG loading below maximum limits with adequate residence time should improve the effectiveness of FOG separation and recovery.

V2 was different from Q1 and Q2 in that the red and green wastewater streams were combined before the DAF to which a cationic polymer coagulant-flocculant (Core Shell ® 71301) was added. This was very affective at removing FOG and non-FOG suspended solids as a sludge, not for separation and recovery of high quality FOG for tallow production, but for water clarification prior to output to the sewar. The issue of concern for this abattoir was poor separation of FOG from the DAF sludge in the secondary treatment, using a 3 phase decanter (tricanter). Of particular interest was the FOG-rich tallow sludge phase which was a stable emulsion of FOG, water and non-FOG suspendid solids. Both the DAF sludge and decanter tallow sludge (DTS) were key streams used in the megasonic trials. In addition, 3 further streams prior to mixing with the green stream and the DAF were identified as possible interception points for recovery of high-quality FOG for tallow production, these were: PP3 black pit, pre:PP3 tallow centrifuge washwater and PP2 rendering stickwater. These were major contriubtors to FOG.

Results and findings

For V2 megasonic treatment alone of the DAF sludge or decanter tallow sludge (DTS) at temperatures between 25-90 °C did not separate any FOG suggesting strong bonding between the FOG, non-FOG solids and water, due to the cationic coagulant-flocculant. A subsequent centrifugation step was required to affect good separation of the FOG at temperatures of 50-90 °C though there was no noticeable difference in FOG separation between the MS and non-MS treated samples. Hence centrifugation is very effective on its own at separating the FOG from these emulsions while MS treatment alone is ineffective.

At 25 °C, the MS treatment gave better FOG separation after centrifugation compared to the non-MS treated, although the benefit of MS is inconclusive since MS treatment had the effect of heating the sample to ~35°C and may have facilitated better separation after centrifugation. However, centrifugation of the MS treated DTS sample at 1717 g for 3min separated 95% of the FOG cf 48% for the non-MS control, but the difference in FOG separation was less pronounced at other conditions (5 min at 671 g and 1-2min at 2683 g). Likewise, MS treatment of samples from pre-PP3 and PP2 were ineffectual while centrifugation alone was very effective at separating high-quality FOG from these streams. Heating and cooling samples from pre-PP3 caused the FOG to flocculate and float. Interestingly, the sample from the PP3 black pit (80-95°C), which was almost exclusively FOG separated spontaneously without centrifugation showing that at this high temperature the black pit may acts as a separator for molten FOG but which is lost to the DAF if not captured at this point. It was not possible to collect a homogenous sample due to safety and no mixing occurring.

Conclusions and recommendation for further research:

Although the DTS fraction is highly concentrated in FOG it is unsuitable for recovery for tallow production due to it's dark colouration and poor quality after mixing with the green stream. However, FOG from this fraction which is currently regarded as a waste could be recovered using secondary centrifugation as a feedstock for biodiesel manufacturers.

However, a higher priority is to recover as much as possible the higher-value, high-quality FOG from the pre-DAF streams, namely,

- PP3 black pit and pre-PP3 rendering centrifuge wastewater

- PP2 red pit rendering stickwater

The recovered FOG could be fed back into the render cooker for increased high-quality tallow yields. At the same time this would reduce the FOG loads on the DAFs and decanters, thereby reducing flocculant usage and increasing the separation performance of the decanters. This would result in reduced offsite sludge disposal and treatment cost of the high FOG content decanter tallow sludge fraction.

Although megasonic treatment was ineffective for FOG separation, centrifugation was very effective at the separation and recovery of high-grade FOG, as well as removing non-FOG sediment from the PP3, pre-PP3, and PP2 wastewater. The flocculation FOG observed after heating and cooling the pre-PP3 samples suggests that the FOG could be effectively separated by using a DAF without added flocculants as in Q1 and Q2 optimised by cooling, or by using by high-speed disk centrifugation.

Two options for further research include:

Option 1.

Pilot Pilot-scale centrifugation trials on PP3 black pit, pre-PP3 rendering centrifuge wastewater and PP2 stickwater

Option 2.

Small-scale simulated DAF trials for pre-PP3 and PP2 streams with temperature optimisation.

Other abattoirs that use a similar, processes to those of the Victorian abattoir, V2 and which may also be encountering similar issues and loosing large quantities of high-grade FOG in the DAF sludge and decanter tallow sludge may benefit from the findings of this study. Furthermore, they may be interested in further research outlined in options 1 and 2 aimed at interception and recovery of high-grade FOG streams from the rendering stickwater and rendering centrifuge wastewater (PP2 and pre-PP3, respectively). Heating and cooling could be explored to increase the effectiveness of floatation and separation of the FOG in a small-scale DAF without the use of flocculants on a small bench scale, following the promising observations in this study. This could also be applied to abattoir which use DAF for FOG recovery such as Q1 and Q2.

2.0 INTRODUCTION

In red meat processing, in addition to meat production, tallow is also produced as a high value biproduct through rendering of the animal fats. Large amounts of wastewater are generated from wash-water from different parts of the factory such as slaughter floor and boning and offal processing and from the rendering stickwater and centrifuge wastewater. The wastewater is contaminated which contain large amounts of fat, oil, and grease (FOG). The FOG emulsions are separated and removed using dissolved air floatation (DAF) tanks and/or with centrifuges such as three phase decanters (tricanters) to both increase the tallow yield and remove FOG which may adversely affect secondary wastewater treatment in aerobic and anaerobic digesters through the formation of crusts and increase in bacterial growth. However, there are challenges in completely removing FOG due to escape as emulsions. This project has explored the issues and reasons with respect to FOG separation, recovery, and loss in detail from four abattoirs, two in Victoria and two in Queensland (milestone 1). A literature and patent review was carried out to examine the various technologies used for FOG capture as well as the analytical technologies used for characterisation of FOG from different sources (milestone 2). In milestone 3 a series of proof of concept laboratory-scale trials were conducted using CSIRO megasonics technology to assess the efficacy for demulsification of FOG emulsions for enhanced separation and recovery of FOG from wastewater streams. This novel technology had not been trialed before on FOG in abattoir wastewater but was industrially successful in separation and recovery of palm oil from palm oil processors effluent and was also found to enhance the separation of FOG from emulsions of restaurant grease traps.

3.0 PROJECT OBJECTIVES

Milestone 1: The project objectives in this milestone were to gain an understanding of the major wastewater treatment processes with a specific focus on various processes whose main function is the separation and removal of fat, oil, and grease (FOG) from red meat abattoir wastewater streams. Through questionnaires, discussions with the four meat processors and site visits, the main objective was to learn about the various technologies used to separate FOG from wastewater streams. These include technologies included Dissolved Air Floatation (DAF) and 3 phase decanters (tricanters) and other down-stream water refining using anaerobic and aerobic digesters. A key objective was to understand how incomplete FOG and /or emulsion carryover may impact the efficiency of wastewater treatment (e.g. digester operation). Another key objective was to identify at which processing points FOG emulsion may cause difficulties and challenges such as efficient separation and recovery of FOG, resulting in losses in tallow production and reduced water and sludge quality.

Because the focus of the broader project is involved with trialing megasonics (high-frequency ultrasound) as a novel, efficient, and environmentally friendly technology for the demulsification of FOG. It is critical to determine if there was, from the processor, significant problems with FOG emulsions in any of the processing streams (e.g. rendering, DAF, tricanter, digesters) leading to ineffective FOG separation and recovery. From these learnings, another key objective was to scope and identify points in various stages for sampling to trial megasonic treatments on a laboratory scale.

Milestone 2: The project objectives in this milestone were to:

1. Review the journal and patent literature on the methods and technologies for wastewater treatment for the removal, separation, recovery, and analysis of FOG from abattoir

wastewater streams.

2. To identify technologies which attract the greatest interest, and which might be developing and those already well established.

3. To determine if ultrasound and/or megasonics technologies/methods have been used or patented for the purpose of separation and recovery of FOG, through demulsification of FOG/oil emulsions in abattoir or other oil laden wastewater streams, and hence recommend if megasonic proof-of-concept trials should proceed and to assess the efficacy of megasonic enhanced FOG recovery.

Milestone 3: The project objectives in this milestone were to:

1. Identify key abattoir wastewater processing streams from three participating abattoirs in which fat, oil, and grease (FOG) may be lost as emulsions due to incomplete separations from: the rendering centrifuge wastewater/stickwater, the dissolved air floatation tanks (DAF), and/or three three-phase decanters (tricanters).
2. Sample and quantify the % FOG content to determine the most relevant streams containing the highest proportions of FOG.
3. Carry out megasonic proof-of-concept laboratory bench-scale trials under various conditions (temperature, frequency, mixing, treatment time, and centrifugation conditions).
4. Assess the results by visual inspection and volumetric and/or gravimetric analytical quantification of FOG separation and content in various separated/partially separated fractions to determine the effectiveness of megasonics for enhanced FOG separation and recovery.
5. Determine if megasonic treatment is of benefit and if so, consider the potential for scaleup and the minimum megasonic energy required for satisfactory separation of FOG.
6. Draw conclusions and make recommendations on the best options for further exploration and/or application of technologies for recovery of FOG for increased tallow production and to reduced residual FOG in wastewater streams.

4.0 SURVEY OF VICTORIAN ABATTOIR V1

4.1 Overview

This relatively new abattoir site which is situated in country Victoria (V1) processes around 1800 grass-fed cattle a week using water from 2 bores. The wastewater from the red and green wastewater steam is treated to produce Class B water for cattle yard and concrete apron washdown and for irrigation of on-site pasture which is fed to the cattle (Table 1). There is no on-site rendering of tallow but fat-containing material and from offal and lower grade offcuts from the boning room are collected and shipped out to secondary processors for rendering into tallow, likewise, blood and bone is processed by secondary processors off-site. The combined red and green wastewater flows by gravity feed to several dams, however, no attempt is made to capture FOG employing a DAF before going to downstream wastewater treatments or dams. It appears that dam 1 captures most of the FOG, if any, coming from the red and green stream after the Contra shear. No significant issues are apparent concerning FOG in dams or flow streams or piping although the content of FOG in the combined red and green streams before entering the dam system is not known. It is not possible to sample the individual red and green wastewater stream before they are combined. Future expansion may include the addition of DAF to separate and recover FOG for increased yield of low-grade tallow but currently is not in place.

Table 1: Key data for Victorian abattoir (V1)

Variable	Description
Water source	2 bores
Water reuse	Wash cattle yards, concrete aprons, and irrigation.
Animals slaughter weekly	1800
Animal types	beef
Animal feed	Grass-fed
Electricity cost ($/kWh)	0.21
LPG cost ($/MJ)	0.5743

4.2 Wastewater treatment

There are two main wastewater streams, red stream, and green stream. The red stream contaminated with blood and FOG comes primarily from the slaughter and evisceration areas from the slaughter floor, boning, and offal processing, and rendering stickwater (not present in this abattoir). The green stream is generated from manure and paunch wastes, which come from stockyard washing, emptying of the animal stomachs, and further processing of internal organs. All wastewater is processed by a series of 6 gravity-fed open-air dams (dam 1-6, Figure 1). Dam 1 is used for the initial and primary settling out of suspended solids. Dams 2-4 are used for anaerobic digestion, dam 5 is aerated and polyaluminium chloride (PACL) coagulant is added to clump suspended solids on the inlet to dam 6.

From dam 6 the coagulated outflow is UV treated and chlorination to kill algae, bacteria, and other microorganisms and filtering through multimedia filters. Dams 7 is filled from the treated water from dam 6 and the storage tank for backwash. Water from dam 7 goes to the reclaimed tank for yard washdown and dams 8 and 9. Water from dams 8 and 9 (winter holding water class B) is used for irrigation of nearby pasture.

The first point of treatment of the combined red and green wastewater is the separation of the paunch using a contra shear (rotary screen drum separator) (Figure 2). The paunch is sent for composting and production of soil conditioners off-site.

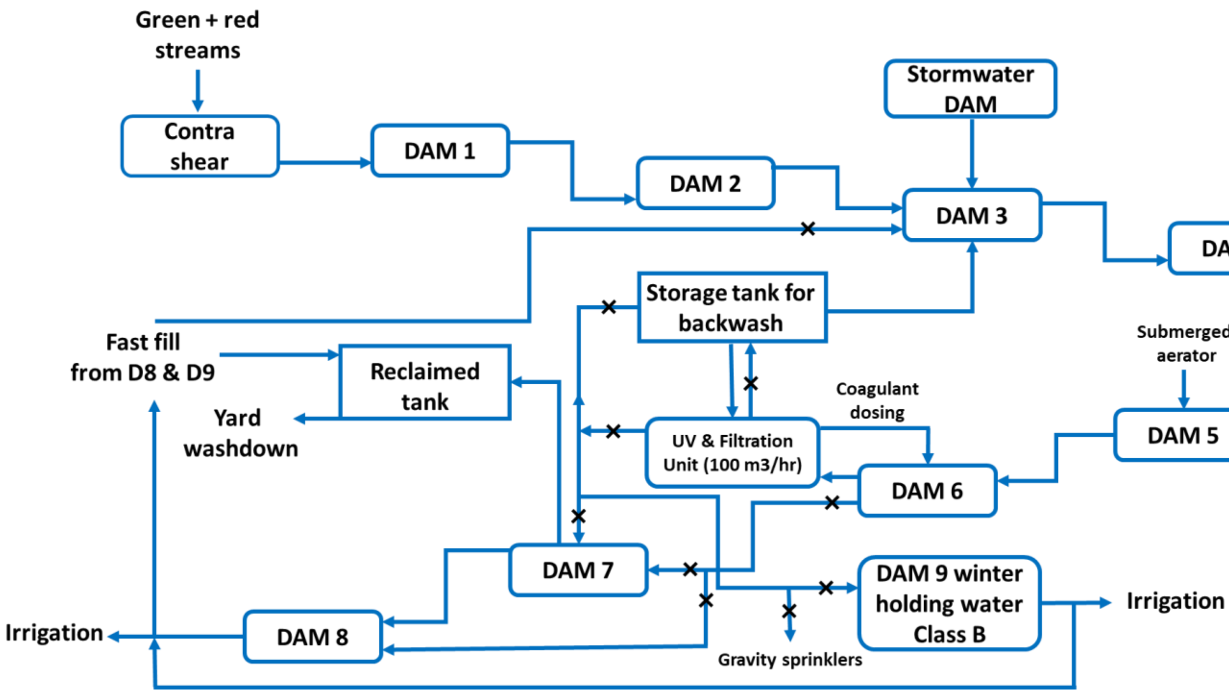

Figure 1: Wastewater process flowchart for abattoir V1. Feed from dam 7 to dam 9 and from dam 6 to dam 8 not shown for simplicity. 'x' indicates flow valves. Flowchart with full detail can be seen in Appendix 1

Figure 2: Rotary sieved drum (Contra shear) with an inclined auger for separation and removal of pau nch from combined red and green wastewater streams

Liquid from the contra shear is fed by gravity through plastic PVC piping to dam 1 (Figure 3) which is not lined with plastic. Much of the suspended solids settle out in this dam over time and some of the water is reduced through evaporation and seepage through the soil. Hence this process tends to concentrate and retain much of the suspended solids in this dam. The dam needs to be excavated to remove solids that have built up over time. This is carried out infrequently and occurs once every 2-4 years depending on the season's throughput.

It can be seen in Figure 3 that a dry "crust" of indeterminate depth has formed due to evaporative effects of sun and wind on the surface and seepage of water into the soil, while the subsurface liquid is gravity fed to dam 2 (Figure 4). Hence, it is presumed that dam 1 is the primary catchment for the retention of suspended solids and any FOG, since dam 2 which is lined with plastic seems to have only minor amounts of surface scum, assumed to contain FOG, as can be seen in Figure 4 (right). A sample obtained from the surface water containing the surface scum (Figure 5) validated this understanding and showed that most of the suspended solids were fine particles that would settle over time. Furthermore, according to the plant manager, FOG does not appear to pose any significant problems to water flow or further downstream wastewater treatment such as in the anaerobic digestion dams.

Figure 3: Non plastic-lined earth dam 1 (pre-anaerobic pond) which receives the combined red and green wastewater from the contra shear via gravity feed pipes

Figure 4: Plastic lined dam 2 which receives wastewater from dam 1 via gravity feed pipes

All subsequent down stream dams (3-9) are not lined with plastic. An aerial view of dams 3-6 which shows their relative sizes and proximity to each other is shown in Figure 6.

Figure 5: Sample of surface water with scum showing fine particles settling out with time and very little if any floating FOG

Figure 6: An aerial view of dams 3-6 which comprises the core of the water treatment dams downstream to dam 2, the second from the right (dam 5) is the aerated dam and the last (dam 6) is chlorinated and dosed with coagulant (polyaluminium chloride, PACL), UV treated and filtered

Dam 3 is near the cattle yard and the reclaimed water tank for washdown with inflow from dam 2, the cattle-yard, and reclaimed tank seen at the rear in Figure 7. A short stone overflow channel can be seen in the corner bank connected to dam 4 with the stormwater dam in the background (Figure 8). Dam 4 is shown in Figure 9. Dam 5 (Figure 10) shows 3 floating and submerged aerators with a total mass airflow of 7.2 kg/hr before the chemical and UV treatment in dam 6.

Figure 7: Non-lined dam 3, which receives wastewater from dam 2 via gravity feed pipe seen here and with nearby reclaimed tanks in the background used for yard washdown and stone overflow channel to adjacent dam 4

Figure 8: Adjacent dam 3 (left) and 4 (right) connected via gravity feed 100mm PVC pipe showing a difference in elevation and stone overflow channel with the stormwater dam in the background for supplementing water in dam 3

Figure 9: Non-lined dam 4 prior to dam 5

Figure 10: Non-lined dam 5 with 3 floating and submerged aerators with a total airflow of 7.2 kg/hr

Figure 11 shows all the components of the water treatment plant including chlorination with sodium hypochlorite, coagulant (polyaluminium chloride, PACL) addition with to aid filtration, UV sterilization, and filtration through multimedia filters into dam 6 and 7 via valves with backflush to the multimedia filters (Figure 11).

Figure 11: Wastewater treatment plant building housing polyaluminium chloride (PACL) coagulant and sodium hypochlorite disinfectant (A) for dosing into dam 6 (Figure 12), UV treatment and filtration and chemical dosing (B), UV reactor (B, centre), coagulant and disinfectant addition to raw water flow (C), four parallel flow multimedia filters (D), backflush tank for multimedia filters (E)

Figure 12 shows dam 6 with a dosing pipe (right) from the chemical treatment plant (Figure 11).

Figure 12: Non-lined dam 6 with dosing pipes from the wastewater treatment plant (right)

Flow from dam 6 can go to dam 7 (not shown) then to dam 8 (not shown) or be fed back to the treatment plant via several valves. Flow into dam 9 can also come from the storage tank for backflush and/or dam 7 via valves. Some of these connections may not be shown in Figure 1 to make the flow diagram less complex. For the complete flow diagram see Appendix 1.

Figure 13 shows dam 9 used for Winter holding water (class B) for irrigation of pasture, fast-fill of dam 3, and/or reclaimed tank (Figure 1).

Figure 13: Dam 9 used for holding Winter water (class B) used for irrigation of pasture, fast filling of dam 3 and/or the reclaimed tank (Figure 1)

5.0 DISCUSSION

Abattoir V1 does not have an on-site rendering wastewater stream or DAF set up to capture FOG. Hence there are no significant signs of any FOG issues concerning crusting in their anaerobic or aerobic ponds and water quality at the end is quite high (Class B) and is used for irrigation of nearby pastures generating feed for the cattle. However, it is difficult to determine how much FOG is removed in the pre-anaerobic pond (dam 1) as the combined green and red wastewater flows directly into it from the contra shear and suspended solids accumulate in dam 1 over time. Since the pre-anaerobic digestor (dam 1) is dredged once every 2-4 years, this seems to be a non-issue for the abattoir and pond 1 works quite well in preventing major amounts of FOG from entering subsequent dams.

Due to the lack of visible FOG accumulation in water treatment dams, it is unlikely that this processor will benefit from megasonic intervention to separate and recover FOG prior to entering the dams. It is advisable to carry out a FOG water content analysis on the incoming combined red and green wastewater stream from the Contra shear to confirm the low levels of FOG entering dam 1. However, it was not possible to sample from the red stream separately which is the major contributor to high quality FOG, useful for tallow manufacture. This data will help in deciding if the FOG content is significant to warrant investigation though from our observations of the water quality in dam 2 and with discussions with this abattoir wastewater manager, the FOG levels were not an issue with respect to wastewater treatment in the aerobic and anaerobic dams. Hence this abattoir was excluded from the megasonic trials.

6.0 SURVEY OF QUEENSLAND ABATTOIR Q1

6.1 Overview

This abattoir, which is situated in Queensland (Q1), processes around 7250 head of 100% grass-fed as well as grain-fed cattle per week (Table 2) and so is about 4 times the size of the V1 abattoir (Table 1). These can be processed at different times but are mainly mixed. Potable water (2700 kL/day) is used and supplied by the municipal water authority, 3200 kL/day is discharged, and 500-700 kL/day of treated water is recycled and used for truck & cattle wash, dust suppression, the pond system, cooling towers and irrigation of pasture for cattle feed.

This abattoir is quite modern and sophisticated in its FOG recovery and wastewater and sludge treatment technology. A DAF is used to recover FOG from the red wastewater stream which is then fed back into the rendering plant for increased tallow production. The red stream and green from the Contra shear wastewater are combined in the saveall to settle suspended matter. This combined wastewater is then fed into a covered anaerobic lagoon (CAL) for production and capture of biogas which is used to fuel the rendering cooker and blood drier for onsite production of tallow and blood meal, respectively. Also, this site uses the Biolac® aerated and non-aerated bio nutrient removal (BNR) system for removal of nitrates and phosphates from activated sludge and cationic polymer coagulant assisted clarification with belt press for the production of dewatered sludge solids for use as a soil conditioner/fertilizer.

Table 2: Key data for Queensland abattoir (Q1)

Item	Description
Water source	Municipal water authority
Water (potable) amount used	2700 kL/day
Water discharge amount	3200 kL/day
Water discharge cost	1.60 $/kL
Water recycled water use	500-700 kL/day (truck & cattle wash, dust suppressic ponds system, cooling towers and irrigation
Animals slaughter weekly	7250
Animal types	beef
Animal feed	Some 100% grass–fed as well as grain-fed processed at different times of the day but mainly mixed.
Wastewater treatment products	Tallow, paunch, biogas, recycled water, sludge sold for fertilizer/soil conditioner.
Electricity consumed for wastewater	4800 kWh/day
Electricity cost	0.15 $/kWh
Wastewater treatment technologies	DAF, CAL (covered anaerobic lagoons), aerated lagoons (Biolac® BNR biological nutrient removal)
Energy production	Biogas (methane) from CAL

Use of gas	Natural gas (4400 m³) and Biogas (9000 m³) used by boilers for rendering and furnace for drying raw bloo for blood meal production.
Most problematic treatment process	FOG separation in DAF under load

This abattoir is more sophisticated than V1 in the technology used to treat wastewater and recover FOG for onsite production of tallow and other bioproducts. The red wastewater steam is sent to the DAF, after the FOG has been separated and removed is sent back for rendering and the red water is combined with the green wastewater stream after contra shear in the saveall pit and sent to the CAL. The paunch from the Contra shear is sent offsite for composting by a third party. The biogas that is generated by the CAL, after drying to remove moisture, is used to fuel the render cooker and raw blood dryer to produce tallow and blood meal, respectively.

The liquid output from the CAL flows into the Biolac® pond for biological nutrient removal (BNR) by variable aerated and non-aerated zones or lanes and the liquid then goes to the clarifier tank with coagulant dosing and mixing to coagulation and floatation of suspended solids (sludge). The sludge is dewatered through roller press-sieve and sold to a third party as a soil conditioner.

6.2 Wastewater treatment

The wastewater process flow diagram in Figure 14 shows the combined water treatment processing technologies such as dissolved air floatation (DAF) for removal of FOG, covered anaerobic lagoon (CAL) for digestion of nutrients by anaerobic bacteria and generation of biogas, aerated Biolac biological nutrient removal (BNR), clarifier and coagulation tanks for removal of suspended solids and belt filter press, and conveyor for dewatering and removal of dewatered sludge.

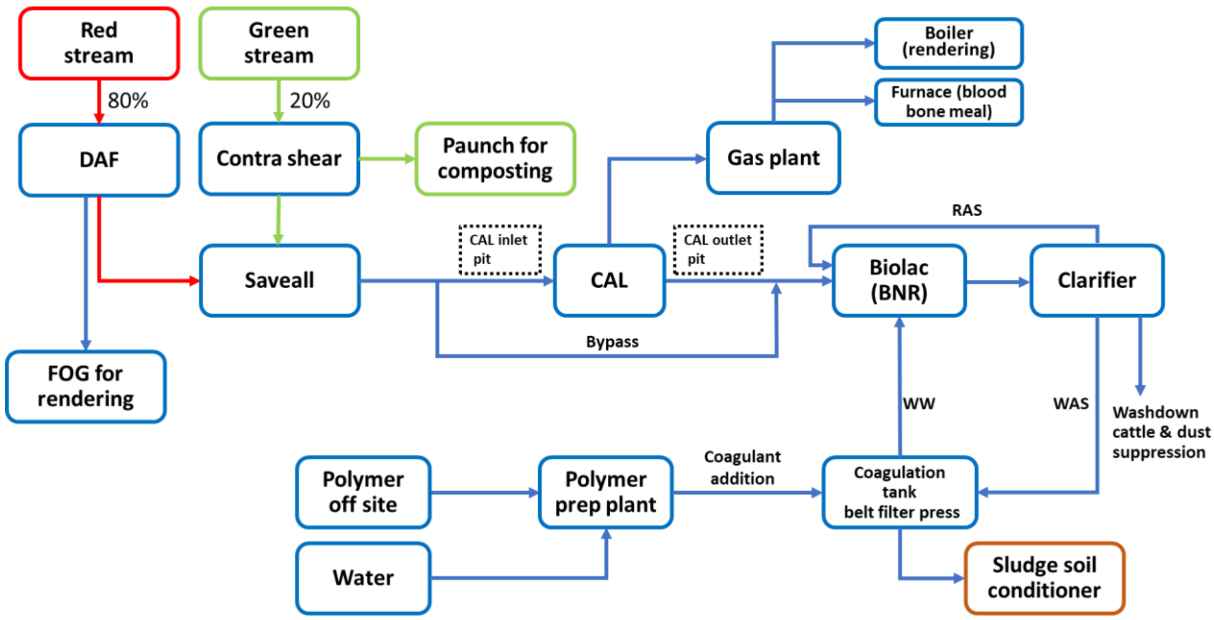

Figure 14: Wastewater process flow chart for abattoir Q1 showing water treatment processing technologies such as dissolved air floatation (DAF), covered anaerobic lagoon (CAL), Biolac biological nutrient removal (BNR), clarifier, coagulation tank and belt filter press. WW=wastewater, WAS=waste activated sludge and RAS=return activated sludge

Currently, at this abattoir, 80% of the wastewater comes from the red wastewater stream. This red wastewater stream contains blood hose water from the abattoir kill floor, edible and inedible offal processing, boning room, and rendering wash water from tallow production and hence contains blood as well as fats and it can appear red in colour in the DAF (Figure 15). The other 20% comes from the green wastewater stream from paunch washing from stomachs containing partially digested-undigested grass and grain. A Contra shear is used to separate the water from the paunch. The separated paunch is composted off-site by a third party and the sieved green wastewater is combined with the red water emerging from the DAF in the saveall (Figure 16).

6.2.1 Dissolved Air Floatation (DAF)

The DAF is the first point and primary method for the removal of FOG from the red wastewater stream and relies on flocculation and floatation of suspended FOG. The DAF involves injecting a portion of clarified wastewater pressurised and saturated with dissolved air (whitewater) into the raw wastewater stream. When the pressure is released at the bottom of the DAF tank, the dissolved air forms a mass of very fine air bubbles. These bubbles attach to particles and fat globules and lift them to the surface, where they form a float of aerated FOG which is scraped into a hopper to be sent to the rendering plant for processing and the clean water underneath is discharged for further treatment. Figure 15 shows the various parts of the rectangular DAF tank showing dissolved air floatation of FOG (A) and chain-driven surface paddles moving the FOG that slowly accumulates at the surface (B, C) to the other end for diversion into the FOG hopper (C) for return to the render cooker and the FOG free liquid (D) being siphoned off below the surface to be combined with the green wastewater stream in the saveall tank (Figure 16).

Figure 15: Dissolved air floatation (DAF) tank treating red stream wastewater, showing FOG flocculating (A), skimming off surface FOG (B), FOG collected separator tank (C, left) and separated red subsurface wastewater

Figure 16:Saveall viewed from top (A) and ground level (B) where FOG separated red wastewater from the DAF is combined with green wastewater from the Contra shear after paunch separation

The main issue for the efficiency of separation and recovery of FOG from the red wastewater stream in the DAF is that it removes only 40-50% of the FOG. Separation of FOG is affected by the temperature of the wastewater in the DAF. The temperature of the hose water used in the blood wash water and in rendering tallow washing is about 82 ^{o}C to liquefy the solid fats, oil, and greases. The aeration process in the DAF should cool the water to below 45 ^{o}C but the temperature can still be between 45-60 ^{o}C and is usually ~50 ^{o}C. The melting point range of beef tallow is 35-40 ^{o}C while mutton (lamb) tallow has a melting point range of 45-50 ^{o}C, hence if the temperature of the wastewater in the DAF is above the melting point of the FOG more of the FOG will remain liquid and can exist in the liquid phase as an emulsion, which makes it very difficult for it to be separated by the surface skimmers.

According to the plant manager, the FOG concentration of the DAF outlet water (1500 mg/L) was almost three times the concentration of the input water (560 mg/L). This higher exit concentration of FOG may be due to the temperature being above the melting point causing the FOG to liquify. This in combination with the aeration process may cause greater emulsification of FOG in the water phase increasing the overall concentration, especially if the emulsion is not homogeneously distributed in the water phase and if sampling is uneven, for example if samples are taken from the emulsion phase which may be enriched in FOG, this could result in a higher reading. This hypothesis needs investigation with a detailed analysis of the wastewater before and after the DAF treatment. If valuable FOG is escaping capture and is entering the CAL it could adversely affect the CAL performance as well as result in losses in the yield of tallow produced.

An accurate mass balance of FOG should be carried out in stage 3 of this study as this will help assess the magnitude of the loss in FOG and tallow yield. Furthermore, it will assist in measuring the impacts in terms of FOG concentration in the CAL and/or other downstream water treatment processes such as in the BNR, clarifier, and coagulation tank if FOG is entering these downstream treatments. However, at this point in the study, the DAF is the most significant step in FOG removal at this site pending a more in-depth investigation in stage 3 of FOG mass balance analysis.

The major objective of stage 3 in this project will be to investigate if high-frequency ultrasound (megasonics) treatments on FOG emulsion during the DAF treatment can enhance FOG separation and recovery since this technology has been shown to be affective in increasing the recovery of residual oil from emulsions in palm oil wastewater streams.

6.2.2 Covered Anaerobic Lagoon (CAL)

The covered anaerobic lagoon (CAL) (Figure 17) utilizes the endogenous anaerobic bacteria present in the paunch green wastewater to digest nutrients present in the wastewater coming from the saveall containing the combined red and green wastewater stream. The captured biogas (methane) produced which is a bioproduct of anaerobic digestion is used to fuel the render cooker and blood drier for processing fat oil and greases (FOG) separated from the DAF and crushed fat and bone into tallow and the blood from the kill floor into blood meal, respectively.

Figure 17: Covered anaerobic lagoon (CAL) for anaerobic digestion of treated red and green wastewater from the saveall and generation of biogas collected and transferred to gas plant for drying and distribution to rendering cooker and for drying blood drier

Before the biogas being used for the render cooker and blood drier it is sent to the gas treatment plant (Figure 18). The warm moist gas arrives from the (35-40 ^{o}C) is sent to the knockout pot and chiller for condensing the moisture in the gas using glycol at 6 ^{o}C. The chilled gas is then sent by a blower to the Dbi type block and bleed valve to seal and remove the condensed moisture. Excess gas is sent by a blower to the flare and burnt.

Figure 18: Biogas from CAL (underground pipe, centre) for drying and distribution to render cooker, blood dryer with excess gas burnt at the flare stack (top)

6.2.3 Biolac® Bio Nutrient Removal (BNR) and Clarifier

This aerobic pond is found downstream from anaerobic CAL. The main purpose is to reduce BOD concentrations to levels suitable for irrigation to land without odor and to ensure that there is a reasonable level of dissolved oxygen (DO) in the treated water. Wastewater-sludge from the CAL then enters the plastic-lined Biolac BNR lagoon (Figure 19) via a CAL outlet pit. The Biolac® BNR uses extended aeration of activated sludge with variable aeration and non-aerated lanes for aerobic bacteria to continue the digestion and removal of the remaining nitrogen and phosphorus-rich nutrients. It is where primary sludge stabilization and water clarification occurs. Minor amounts of surface crusting are seen on the edges and corners of the lagoon (Figure 19B). At the end of the BNR there is a section that skims any surface flocks (Figure 19C) before being sent to the clarifier where a positive cation polymer coagulant is added (Figure 20) and some return activated sludge is recycled back to the BNR (Figure 14). The polymer causes the suspended solids to coagulate and float to the surface (A), these are separated from the water (B) and dewatered in the belt press (C). The dewatered pressed sludge (D) is then trucked away and used as a soil conditioner. Some of the wastewater is used to wash down cattle and for dust suppression while some are recirculated back to the BNR (Figure 14).

Figure 19: Aerobic Biolac digester lagoon for biological nutrient removal (BNR) with variable aerated and non-aerated lanes (A), minor surface crusting on some edges and corners (B) and skimmer skimming flocks and weir for clarified water collection sent back to the BNR and clarifier (Figure 20)

Figure 20: Clarifier (Komline-Sanderon ROTO-KONE® High rate drainage system) main tank with flocculated sludge (A), end prior to the press showing sludge separated from water prior to filter press (B), dewatering filter press (C), and conveying of pressed sludge (D)

6.3 Production of tallow, blood, and bone meals

Figure 21A Shows the render cooker where crushed bone and fat are heated to render the beef fat into tallow. The liquid tallow is separated from the bone meal on a vibrating screen (Figure 21B). The bone meal is then passed through a render press (Figure 22A) for pressing out residual tallow from bone meal and production of bone meal. The pressed tallow is sent back to the vibrating screen while the crude hot liquid tallow is centrifuged using a decanter to produce the final tallow (Figure 22B). The raw blood from the kill floor is pumped and stored in the raw blood storage tank (Figure 23) and batch dried in the blood drier (Figure 23B). The resulting blood meal is sold to third parties to produce high nitrogen blood meal fertilisers. Blood meal can also be used as a livestock dietary supplement and is mainly added to supply dietary lysine for cattle, fish, and poultry. However, this site does not process blood into higher value blood-derived pharmaceutical co-products.

Figure 21: Render cooker (A) and vibrating screen (B) to separate tallow from bone

Figure 22: Render press (A) for pressing out residual tallow from bone meal and returned to vibrating screen (Figure 21B), and hot final tallow product (B) after centrifugation of tallow by decanter after crude separation from bone-meal by vibrating screen (Figure 21B)

Figure 23: Raw blood storage tank (A) and raw blood dryer (B)

7.0 DISCUSSION

Abattoir Q1 in addition to the production of tallow, blood meal, and bone meal, has sophisticated water treatment processes. These processes include DAF for FOG recovery for increasing the yield of tallow, CAL for biogas generation, Biolac® BNR, cationic polymer coagulation and flocculation clarification, and belt press sludge dewatering. The treated water used onsite and the dewatered sludge is sold as solid conditioner/fertiliser. Overall, it is a very efficient abattoir. However, a large amount of FOG is not recovered by the DAF due to high water temperatures causing FOG to remain in the water as emulsions. It is not known what amounts or concentration of FOG is lost in the wastewater which is sent to the CAL and how this might affect its performance. The presence of some crusting in the BNR indicates this might be the case, although the FOG content in the crust or water has not been determined. The company is concerned that it is losing large amount so FOG as emulsions in the DAF and would like to improve the DAF performance and explore the use of megasonics for enhancing the separation and recovery of FOG from the wastewater emulsions in the DAF.

Section 16.0 has examined in detail the accurate FOG content of inflow and outflow wastewater from the DAF and samples of FOG emulsions were sampled to carry out proof of concept megasonic trials controlling a variety of variables to assess the effectiveness of megasonics on separation and recovery of FOG from the DAF stream prior to combining with the green wastewater stream.

8.0 SURVEY OF QUEENSLAND ABATTOIR Q2

8.1 Overview

A detailed description of this Queensland abattoir is summarised in Table 3. This abattoir processes 2500-3000 head of both 100% grass-fed as well as grain-fed cattle per week and processing between grass and grain-fed cattle is not segregated (Table 3). The capacity is double that of V1 (Table 1) and about 1/3-1/2 that of Q1 (Table 2). Potable water (440,092 kL/yr) is used and supplied by the MacKay Regional Council and over half of this (242,000 kL/yr) is treated and recycled for irrigation of turf farms, for truck & cattle washdown, pond system and to construct and maintain wetlands.

This abattoir is more sophisticated than V1 but not as sophisticated as Q1 and has some wastewater treatment components of each of these other two abattoirs. It uses a series of open-air gravity fed ponds that are non-aerated and aerated as in V1 and incorporates a combined DAF-saveall system upfront to separate and recover FOG from the red wastewater stream before pumping into the pond system. The recovered FOG is sent to the rendering plant for an increase in tallow yield. This abattoir doesn't have a covered anaerobic lagoon (CAL) for anaerobic digestion and production of biogas, although it does utilise a series of non-aerated and aerated ponds like that of V1 for nutrient digestion. It does not have a Biolac® BNR system as in Q1, neither does it use a cationic polymer assisted sludge coagulation-flocculation to clarify the water and recover and dewater the sludge solids as in Q1. However, the recovered paunch is composted on-site and used as a fertilizer/soil conditioner on the turf farms. The major issue is incomplete FOG recovery at the DAF-saveall with the carryover of FOG into pond 1, especially under high load.

Table 3: Key data for Queensland abattoir (Q2)

Item	Description
Water source	Mackay Regional Council
Water (potable) used	440,092 kL/yr
Water discharge (trade waste)	Sewerage only - 8,450 kL/yr ($12,854/yr)
Water discharge cost	1.52 $/kL
Water discharged irrigation	242,000 kL/yr
Water discharged to creek	Extended wet weather treated wastewater 1600 kL/yr
Water recycled water use	Sterilized water for cattle yard/truck wash down, dust suppression, ponds system and irrigation for turf production and constructed wetlands.
Animals slaughter weekly	2500-3000
Animal types	Beef
Animal feed	100% grass and grain fed cattle processed (not segregated)
Wastewater treatment products	Tallow 9216 T/yr, Meat & bone meal 2496 T/yr

	Blood meal 484.8 T/y, Hide treatment, Soil conditioner via paunch, manure and fly-ash composting, Turf via wastewater irrigation
Electricity consumed overall	14698182 MWhr/yr
Electricity consumed for wastewater	36000 kWh/yr
Electricity cost	$2498000/yr (0.17 $/kWh)
Wastewater treatment technologies	DAF, non-aerated/aerated Ponds, chlorination for washdown water
Gas used	LPG (134.3 kL/yr) ($103,000/yr), Liquid ammonia 15 kL/yr.
Coal use	3,659 T/yr ($1,488,000/yr)
Most problematic treatment process	FOG separation in DAF under load prior to anaerobic Pond 1

8.2 Wastewater treatment

Figure 24 shows the wastewater process flow of the red and green wastewater stream to ponds 1-4. The turf farm wastewater process flow (ponds 4-9) is shown in Figure 25. Figure 26 shows the aerial view of the abattoir and surrounding ponds, turf farm, compost pad, wetlands, and nearby creek.

The red wastewater stream comes from the rendering plant, boning room, and slaughter and offal floor and goes into a combined DAF-saveall for FOG recover and returned to the rendering plant for tallow production. The paunch is screened and sent to turkey nest 1 and 2 and the screenings are composted (Figure 27) while the green water is combined with the red stream from the DAF-saveall into the wastewater pit then proceeds to the various ponds by gravity feed.

8.2.1 The pond systems

Pond 1 is an anaerobic pond where no settling of suspended solids occurs due to suspended solid movement, however, crust formation can occur if FOG is carried over from incomplete removal by the DAF-saveall. Sediments eventually build up and need to be dredged every 5-6 years. In pond 2 settling occurs with no crust formation. Currently, no flocculant is added but there is interest in using flocculants to assist in settling. Like pond 1, it requires dredging every 5-6 years.

Pond 3 is an aerated biological nutrient removal (BNR) pond that uses denitrifying bacteria to reduce nutrients rich in nitrogen. Pond 4 still contains some nitrogen and phosphorus-rich nutrients and is sent to the wastewater chlorination tank for disinfection to make it fit for cattle yard and truck washdown while some of the "untreated pond 4 water is pumped to Pond 5 (1.5 km away) and gravity fed to dam 6-7. Excess treated wastewater in dam 7 is pumped back to Pond 5 or across to Pond 9 for a second aerated BNR treatment before being released to the nearby creek. At this point, AQIS assesses this treated water to be fit for purpose as it does not contain any pathogens due to the combined anaerobic digestion (pond 1) and aerobic BNR denitrifying treatments (ponds 3,7 & 9). At pond 6 for algae treatment may need to be applied. In a worst-case scenario, a surface spray of cipricide kills the algae on direct contact, the water is then pumped to dam 7.

In dam 7 which holds 50 ML there are 2 zones for aerated biological nutrient removal (BNR) using denitrifying bacteria. Dam 7 water is used for primary irrigation of turf production areas as well as water from dam 6 but usually, water from dam 7 is used first then water from dam 6, if needed. In turf production, the top 3 inches absorb and utilise most of N-P nutrients so that the surrounding ground is not overloaded or has nutrient build-up.

Dam 7 also flows to Dam 9 which is another aerated BNR before release into the creek.

Dam 8 is a stormwater dam of 10 ML that captures, filters, and controls the release of stormwater through the constructed wetlands into the creek. Stormwater is collected from the car park, load out and container area, improved pasture paddocks, turf paddocks, QLD Rail drains, and neighboring sugarcane farm run-off from wet weather events. The onsite stormwater collection is used for cattle yard and truck as well as some portion going to detention basin which collects water from run-off from factory roof and concreted areas. Water from the detention basin is added to Pond 1 to ensure the correct water volume is maintained.

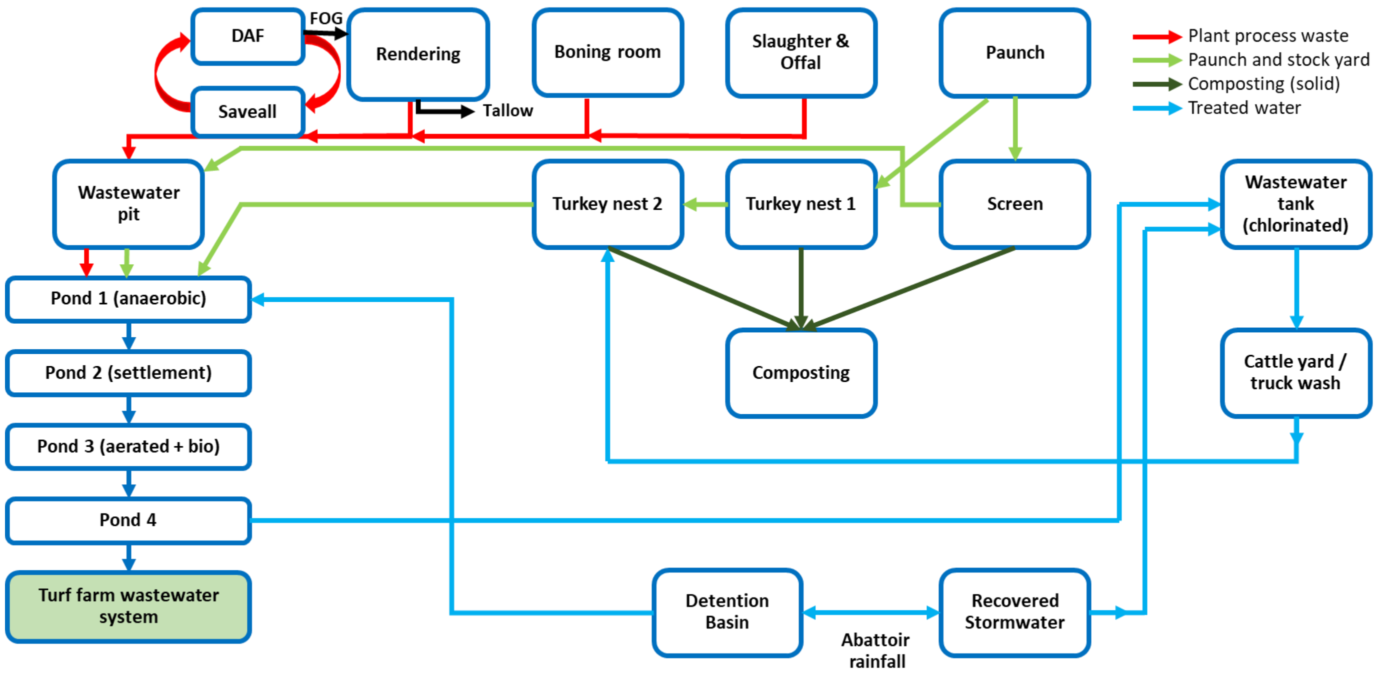

Figure 24: Green and red wastewater stream process flow diagram prior to further treatment, use in turf farm and release of treated water into the environment (Figure 25)

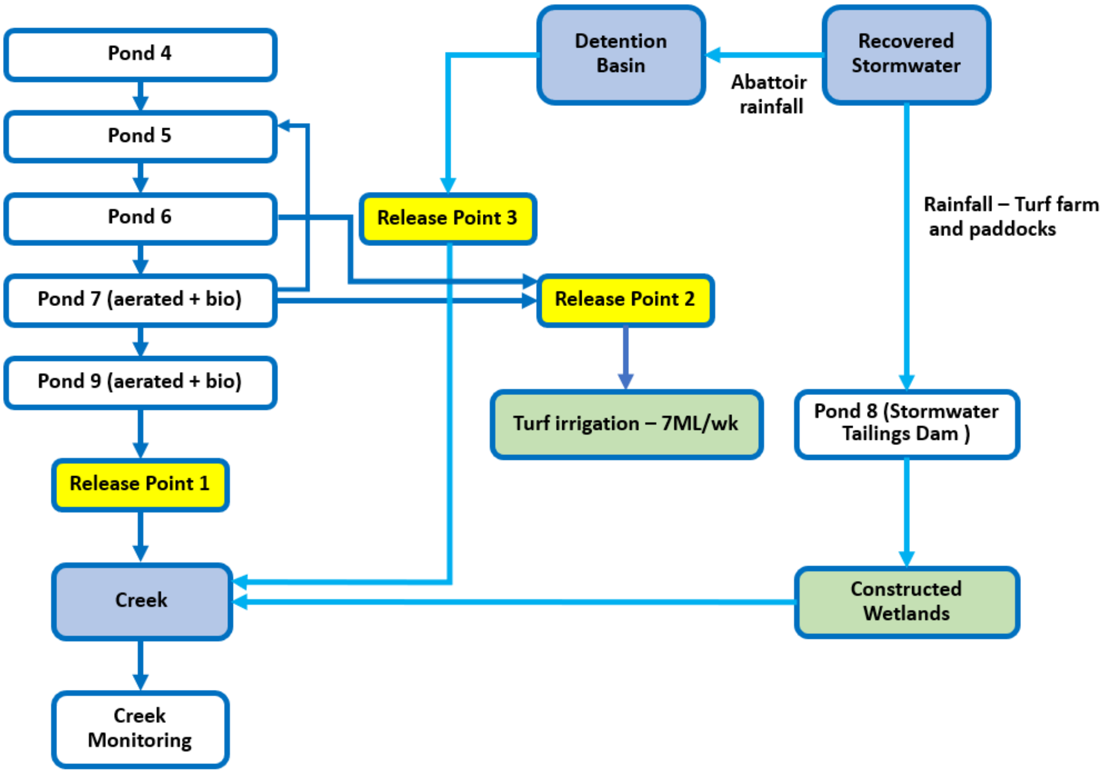

Figure 25: Wastewater treatment flow diagram for Turf farm wastewater system and release of treated water to constructed wetlands and the nearby creek

Figure 26: Aerial view of abattoir process facilities, factory site, wastewater treatment dams, turf farm, compost producti on, constructed wetlands and nearby Creek

8.2.2 Composting of paunch

Paunch from the screen (Figure 28) and turkey nest 1 and 2 (Figure 27) get sent to 2-5 acres of winrows and kept moist to complete composting or fermentation using endogenous paunch bacteria. Dried compost turns a brown colour with a soil-like texture when composting is complete and is spread over growing turf as a fertilizer.

Figure 27: View and location of green wastewater stream, including Turkey nest 1,2, paunch pad, in proximity to holding pens, stockyard and blood processing shed, turf farm, detention basin and wastewater chlorination tank used for cattle yard and truck washing

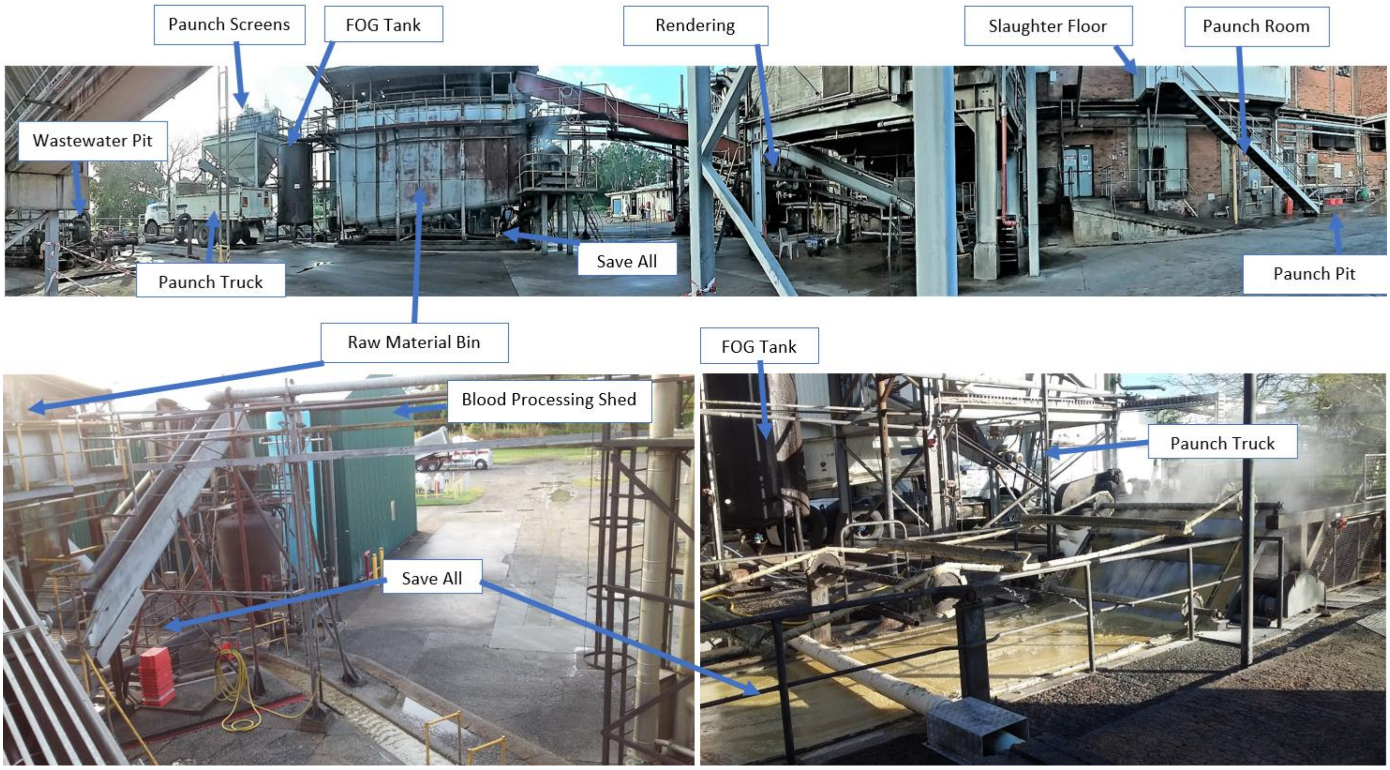

Figure 28: Major areas and processes of interest in abattoir and wastewater treatment prior to pond system including red and green wastewater stream, separation of paunch, DAF-saveall and wastewater pit

8.2.3 DAF-saveall

Fat bearing waste from the boning room and offal is transported by an auger to the blow bottle and then to the trommel screen (centrifugal dewatered) then sent to be rendered by the cooker. The FOG rich render red wastewater (stickwater) and red wastewater from the boning and slaughter floor is sent to the DAF-saveall.

Unlike Q1 the DAF here is not separate from the Saveall but is part of a combined DAF-saveall system. The DAF uses a pressurised air cylinder vessel to saturate a portion of clarified wastewater. This air-saturated water is injected into the DAF and causes tiny bubbles to be released which stick to suspended FOG particles causing them to float to the surface. It takes time for the solid floatation FOG to fully form and float to the surface. Paddles moving on the surface using a chain progressively move the surface FOG from one end of the long tank and scrape the built-up surface FOG to the hopper. The recovered FOG is sent to the rendering cooker. At the same time, subsurface paddles move the wastewater back to the DAF to be re-aerated and float more FOG to the surface. The residence time of the wastewater in the DAF-saveall is 1hr.

Figure 29 shows the DAF-saveall in operation (A) and empty (B). The pressurised air cylinder and chain-driven surface FOG skimming paddles and lower return mixing paddles can be seen. Figure 30 shows the FOG forming on the surface of the DAF-saveall (left side) and the surface skimmers separating the brownish beige surface FOG with the incline into the hopper on the right side where the recovered FOG is sent to the rendering plant for making tallow.

An important factor that adversely affects the complete recovery of FOG from the red FOG rich wastewater in the DAF-saveall is the temperature of the wastewater. The steriliser and cleaning water are at a temperature of 80 ^{o}C and 95 ^{o}C, respectively. If the temperature of the red wastewater stream coming into the DAF-saveall is too high and above 40 ^{o}C some FOG can liquify since the melting point of beef tallow is between 35-40 ^{o}C. This can cause a decrease in the efficiency of removal of solid FOG since more liquid FOG will remain in the liquid phase and not be scraped into the collection vessel. This will result in more FOG in the liquid stream exiting the DAF-saveall and wastewater pit and entering pond 1. As the temperature in pond 1 will be below 40 ^{o}C FOG can solidify and float to the surface forming a crust and can adversely affect the performance of the anaerobic bacteria. High FOG loads and throughput in the DAF-saveall can also compromise the recovery of FOG and contribute to escape of significant amounts of FOG and buildup of FOG crusts in pond 1.

Figure 31 shows poorly controlled processing with large amounts of FOG on the surface of pond 1 while Figure 32 shows normal controlled processing with only minor amounts of FOG around the edges of pond 1. Figure 33 shows pond 7 which uses aeration for biological nutrient removal which is used to water the turf farm. The system shows good utilisation and recycling of treated and recycled water, which is a valuable resource with no chemical input in terms of coagulants-flocculants. No FOG appears to enter pond 2 so critical treatment points are at the DAF-saveall for the recovery of as much FOG as possible and to minimise any FOG entering pond 1. The application of megasonics in or around the DAF-saveall could aid in the effectiveness and speed of separation and greater recovery of FOG before entering pond 1. Like Q1, quantification of the FOG content of the red wastewater stream entering and exiting the DAF-saveall during light and heavy loads is important to see how much FOG remains in the liquid phase.

In stage 3 of this project sampling will occur from these points to carry out laboratory-scale megasonic proof of concept trials. Results from these trials will determine if megasonic intervention is advantageous for FOG recovery and to assist or mitigate FOG build-up in pond 1

Figure 29: DAF-saveall full and operating with aeration DAF zone front and saveall zone rear (A) and empty (B) showing pressurised air cylinder and chain-driven surface FOG skimming paddles and lower return mixing paddles

Figure 30: DAF-saveall showing surface paddle scraping white to brownish beige surface FOG up an incline for dumping in the FOG separation and collection hopper

Figure 31: Poor controlled processing with large amounts of FOG passing through the DAF-saveall pit into Dam 1

Figure 32: Normal controlled processing with minor amounts of FOG passing through the DAF-saveall pit into around the edge of Dam 1

Figure 33: Dam 7 aerated biological nutrient removal (BNR)

9.0 DISCUSSION

Abattoir Q2 in addition to the production of tallow, blood meal, and bone meal, uses a combined DAF-saveall for FOG recovery from the red waste stream for increasing the yield of tallow. It then uses a series of open gravity-fed ponds for anaerobic and aerobic digestion but does not use CAL, Biolac® BNR, cationic polymer coagulation and-flocculation clarification or belt press sludge dewatering. Pond 2 where settling of suspended solids occurs, requires dredging every 4-5 years. The treated water is used onsite for washing cattle yards, for irrigation of turf farms and creating and maintaining of constructed wetlands. The composted paunch is used as a fertiliser on the turf farms which is a very efficient re-use of the water and paunch resource. Overall, it is a very efficient abattoir that does not use chemical coagulants-flocculants. Since it lacks a CAL, biogas is released into the atmosphere and not captured for use as a green energy source.

Like abattoir Q1, large amounts of FOG are not recovered by the DAF due to high water temperatures, causing FOG to remain in the water as emulsions which pass into pond 1 where after cooling forms FOG surface crust. This is particularly pronounced under high loads which exceeds the throughput capacity of the DAF. It is not known what amounts or concentration of FOG is lost in pond 1 which traps most of the FOG as crusts. The company is concerned that it is losing large amounts of FOG as emulsions from the DAF and excessive FOG in pond 1 may affect the performance of this pond as well as cause adverse environmental impact due to bacterial overload. There is potential to apply megasonics to enhance the separation and recovery of FOG from the wastewater emulsions in the DAF.

Section 16.0 has examined in detail the accurate FOG content of inflow and outflow wastewater from the DAF to ascertain the scale of FOG lost. Samples of FOG emulsion were taken from these streams to carry out a series of proof of concept megasonic trials controlling a variety of variables to assess the effectiveness of megasonic treatments on separation and recovery of FOG from the DAF stream prior to combining with the green wastewater stream.

10.0 SURVEY OF VICTORIAN ABATTOIR V2

10.1 Overview

This abattoir, in Victoria (V2), processes around 7000 head of cattle per week (Table 4) and so is about 4 times the size of the V1 abattoir (Table 1), twice the size of Q2 and equivalent to Q1. V2 processes both 100% grass and grain-fed beef and lamb at different times. Details of energy usage and cost are listed in Table 4. Tallow and blood and bone meal are produced on-site as well as compost from paunch. Potable water is supplied by the municipal water authority (City West Water). Unlike the other three abattoirs, no pond systems are used. The main process for treating the combined green and red wastewater streams is polymer coagulation and dissolved air floatation (DAF) of suspended solids and removal as sludge with subsequent separation of water, tallow sludge, and dewatered sludge for disposal using two three-phase decanters (tricanters). The DAF is not used to separate FOG for return to the rendering plant, so valuable FOG is lost in the wastewater stream and is coagulated in the sludge. The major difference between V2 and the other sites is that the purpose of DAF, with the aid of a chemical polymer coagulant-flocculant, is to remove solids from the wastewater to clarify it before disposal into the sewer.

Most of the sludge from the DAF is processed through decanters however when sludge production exceeds decanter capacity the excess sludge is trucked away. These waste streams are costly to dispose of and the company recognises there is a significant loss of FOG in these streams. There is potential for greater separation and recovery of FOG which could be used to produce lower-grade tallow, cleaner wastewater, and more efficient dewatering of the sludge solids. No water reuse or recycling is currently occurring, but they are looking for opportunities if they could improve the quality of their wastewater to the sewer as well as other opportunities for low-grade tallow coproducts and fat-reduced dewatered sludge solids as fertilisers.

Table 4: Key data for Victorian abattoir (V2)

Item	Description
Water source	Municipal water authority (City West Water)
Water (potable) amount used	2.96 kL/head
Water discharge amount	2.72 kL/head
Water cost & discharge cost	\$2.71/kL & \$2.1/kL
Water recycled water use	none
Animals slaughter weekly	7000
Animal types	Beef and lamb
Animal (feed type)	Some 100% grass–fed as well as grain-fed processed at different times of the day but mainly mixed up.
Wastewater treatment products	Tallow and paunch compost.
Electricity consumed for wastewater	3492 kWh/day

Electricity cost	$0.2072/kWh
Electricity used overall/ wastewater	42490543.8 kWh/y and 3% (1274716.31kWh/y
Gas used	20137.32 GJ/year
Gas cost	$10.878/GJ
Wastewater treatment technologies	DAF and decanters (tricanters)
Use of gas	Rendering cookers and blood dryers.
Most problematic treatment process	Sludge separation in DAF and sludge dewatering and FOG-water emulsions separations in decanters

10.2 Wastewater treatment

This abattoir is more sophisticated than V1 in the technology used to treat wastewater and although it does produce tallow and blood and bone meal products it does not attempt to recover FOG from the red and green waste streams. Another difference is that unlike the others it does not use any ponds or lagoons. The wastewater process flow diagram is shown in Figure 34.

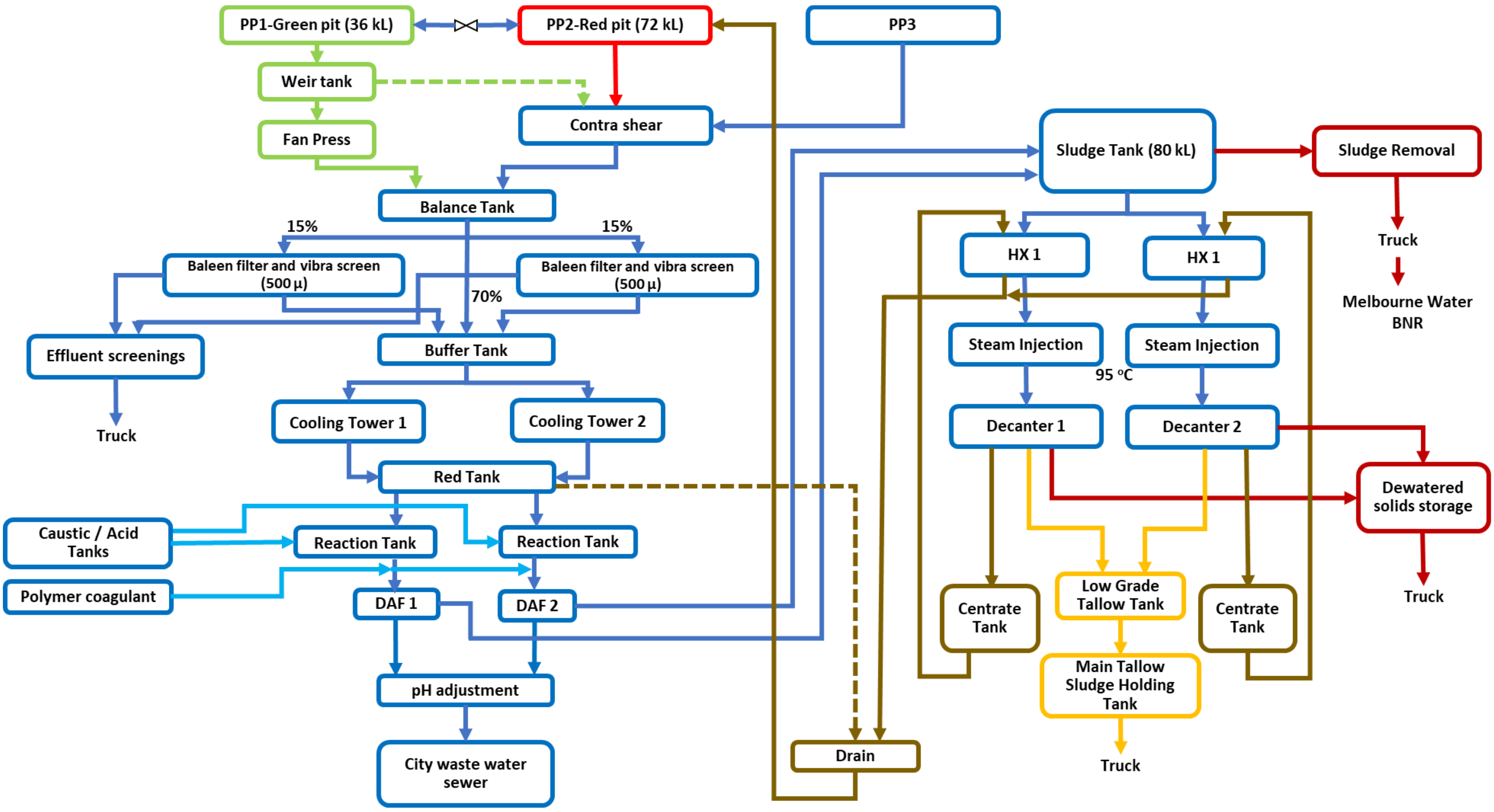

Figure 34: The wastewater process flow diagram for V2

Figure 35 shows the blackwater pit containing rendering plant stickwater which is rich in fat oil and grease (FOG) and together with FOG from process floors, boning rooms, and offal processing contribute to FOG in the red wastewater stream. Odorous volatiles from the rendering plant is removed by pumping through the bottom of a pine bark biofilter (Figure 36). The red and green wastewater underground pits with overhead mixing are connected and the flow from one to the other can be controlled (Figure 37). These streams are filtered and screened by a series of filter technologies where a fan press is used for the green stream and a Contra shear is used for the red stream.

Both streams are then combined in a balance tank and 70% of the balance tank water goes directly to the buffer tank unfiltered and 30% is pre-filtered using two streams of Baleen filters (500 μm) and Vibra screens (vibrating mesh sieve, 500 μm) which are used to separate fine particles coming from the balance tank. The effluent screenings from Fan press 1 and 2, Contra shear, Baleen, and Vibra screens are collected and trucked away for disposal (Figure 34). The filtered wastewater from the buffer tank is then cooled through two cooling towers (Figure 39) before going to the red tank.

Figure 35: Blackwater pit from rendering plant stickwater rich in fat, oil, and grease. Note the FOG crusting on the surface

Figure 36: Pine bark biofilter used to remove odorous air from the rendering plant which is pumped through the bottom with water sprinkling on the surface

Figure 37:Adjacent Red and Green underground Pits with overhead mixing

Figure 38: Level 2 shows building housing Baleen filters (A) and partially filtered wastewater sent to the Vibra screens (below) for further filtering (B)

Figure 39: Cooling towers in the background used for cooling the filtered wastewater from the buffer tank prior to going to the red tank, reaction tank, and DAF

The water in the red tank water is pH adjusted by dosing with caustic soda (alkali) and/or acid into the reaction tank with mixing. Cationic polymer coagulant-flocculant (Core Shell ® 71301) is added by inline dosing after the reaction tank and just before the two DAF tanks (Figure 40). The process flow chart in the Appendix also shows a coagulant addition to the reaction tanks 1 and 2 but this process is no longer used.

10.2.1 Dissolved Air Floatation (DAF)

Unlike the use of DAF in abattoir Q1 and Q2 which recovers FOG from the red wastewater stream for return to the rendering plant for making tallow, the function of the DAF at this site (V2) is for separation and removal of suspended solids (sludge) from the wastewater for water clarification before sending to the sewer. The other distinguishing feature is that polymer coagulant-flocculant is used to aid this separation, at abattoir Q1 and Q2 no chemicals are added to the DAF units.

Figure 40 shows the reaction tank on the right side of the DAF (A), with the agitation of added acid and base to adjust the pH (B), the pressurised air cylinder (left-hand side) (C) is used to supersaturate a portion of recycled wastewater from the DAF with dissolved air to produce "whitewater". The whitewater is pumped into the DAF raw wastewater after the addition of the polymer coagulant-flocculant. The polymer causes the suspended solid particles to stick together and agglomerate into flocs. When the whitewater and raw wastewater are mixed the tiny evolved air bubbles adhere to the flocs causing them to rise to the surface.

Figure 40: Reaction tank (A), inside of mixing tank (B), DAF 1 and reaction tank showing coagulant-flocculant addition and compressed air tank (C) and close-up view of compressed air tank and pump (D)

A thick dense surface floatation sludge which forms on the surface of the larger DAF 1 tank is skimmed by chain-driven skimmers into a sludge hopper (Figure 41A) and sent to the sludge tank and the separated treated water (Figure 41B) can be seen to still contain some suspended solids which is pH adjusted to pH 6-7 before going to the local water utility sewer. A similar arrangement occurs in DAF 2, however, there are significant differences in the efficiency of separation of sludge and clarification of water between DAF 1 and DAF 2. DAF 2 is a smaller unit and has different optimum flow conditions which allow for a more clarified water outflow compared with DAF 1. The DAF 2 unit is shown in Figure 42. It can be seen that the treated water outflow from DAF 2 is clearer than that from DAF 1. The sludge and water are treated in the same way as those from DAF 1.

Figure 41: The surface of the DAF 1 tank showing the surface floatation sludge and chain-driven skimmers skimming the sludge into the sludge hopper (A) and separated treated water (B)

Figure 42: The surface of the DAF 2 tank showing the surface floatation sludge and chain-driven skimmers skimming the sludge into the sludge hopper (A) and separated treated water (B)

10.2.2 Decanter treatment of DAF sludge

The floatation sludge from DAF 1 and DAF 2 is sent to the sludge tank, passed through two heat exchangers, and further heated to 95 ^{o}C using steam injection before being pumped through the three-phase decanters (tricanters, Figure 43) for separation of FOG, sludge, and centrate.

Figure 43: Three phase decanters (tricanters) for separation of low-grade tallow sludge, dewatered sludge solids and centrate (water)

However, a significant portion of the sludge from 6-20 Tonne? per fortnight are removed and not processed through the decanters due to the exceeding of the capacity of the decanters but is sent to Melbourne Water for BNR treatments. Of the sludge that is sent to the two decanters for separation of low-grade tallow, solids, and water, the top FOG phase is sent to the low-grade tallow sludge tank for disposal and not sent to the rendering plant for the production of low-grade tallow because there is too much water in this phase and because of its low-grade nature.

The high water content in the low-grade tallow sludge is due to ineffective separation at the high process flowrates used (8 T/h). However, there is interest in trialing lower flowrates through the decanter to see if a better separation can be attained, though this is not practical at normal processing rates. Better separation and increased recovery of FOG from the sludge is highly desirable since tallow is a high priced coproduct and sales from 30-40 T/day of rendered high-quality tallow is a major money earner which covers the salaries of all staff.

In addition to FOG loss occurring in the low-grade tallow sludge, losses also occur in unprocessed sludge, the centrate (water) phase, which also contains substantial amounts of FOG and possibly in the dewatered sludge solids as a result of the ineffective separation of emulsions in the decanters.

The centrate (water phase) and low-grade tallow sludge (FOG), have a similar appearance of a stable emulsion indicating a poor separation between water, FOG, and solids. The centrate is collected in the two centrate tanks (Figure 44) and is passed through the heat exchanger and recycled back to the red tank. However, if too much centrate is recycled it can increase the viscosity in the red tank and in the decanters due to increased sludge loading so the proportion that is sent back to the red tank must be carefully controlled. Figure 45 shows a typical sample of the centrate in which it can be seen that it is a stable emulsion and is similar in appearance to the low-grade tallow sludge. The dewatered sludge solids phase is transported from the decanters via a belt conveyor for storage and removal (Figure 44).

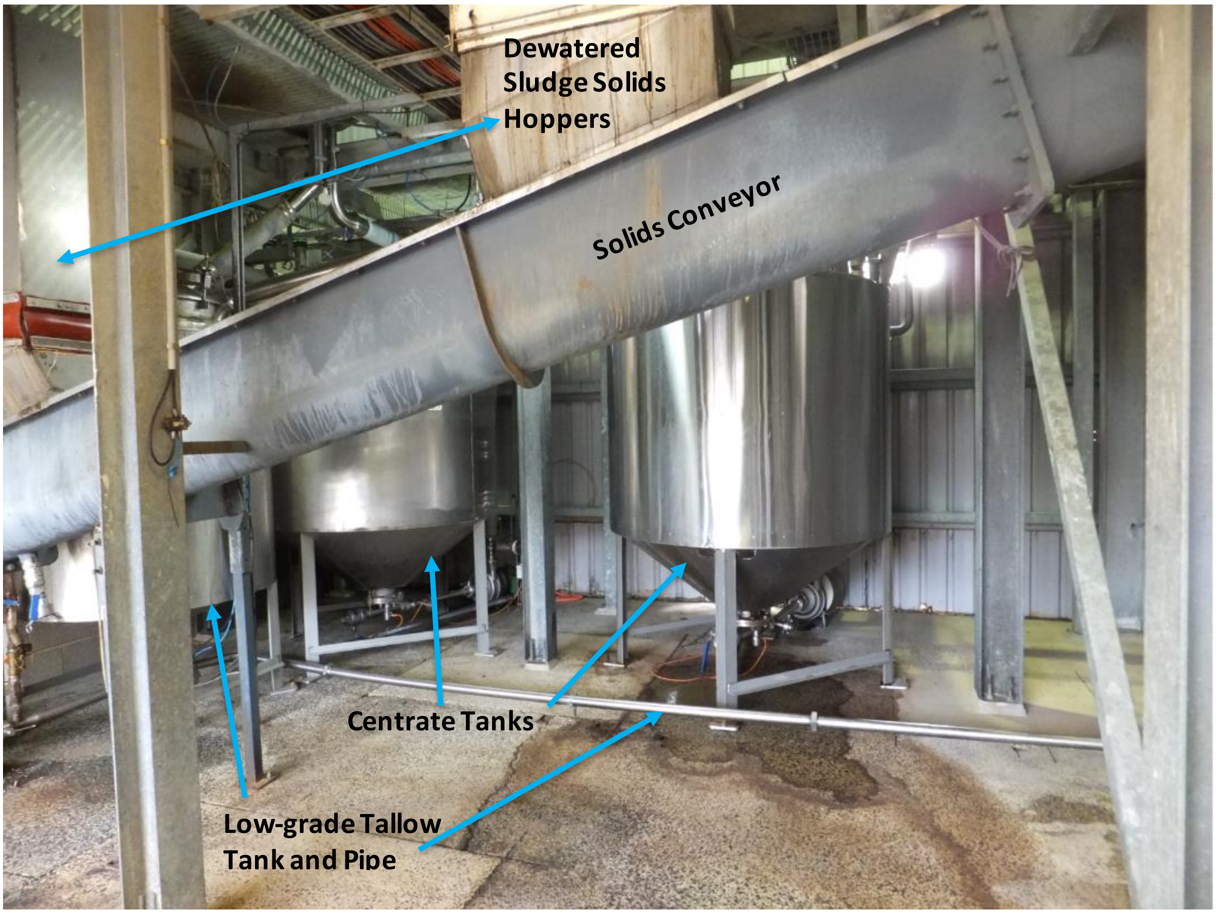

Figure 44: Centrate tanks, low-grade tallow tank (left), dewatered sludge solids hoppers and tanks conveyor to storage and removal

Figure 45: Centrate water showing thick emulsion likely to contain large amounts of solids (FOG) as well as some unseparated sludge

11.0 DISCUSSION

The inadequate separation of each of the three phases (tallow, centrate, and dewatered sludge) by the decanter occurs under high load and high throughput with a short residence. Also, the injection with steam to heat the sludge to 95 ^{o}C before the decanter and shear forces in the decanter may contribute to the formation of emulsions which once formed are difficult to separate. While decreasing the throughput and loading, or extending residence time may help with the separation; these remedies may not be practical given the normal scale of operations. Current processing suggests that there is significant loss of FOG and excess water in the tallow sludge phase leading to significant loss of yield of tallow and poor water quality. There are also large costs for disposal of the low-grade tallow sludge, centrate water and dewatered solids with high FOG content. Improved separations could lead to higher tallow production or the creation of a new second-grade tallow coproduct, better quality water, and greater recovery of tallow from sludge. Due to the high FOG content of dewatered sludge, this can impart off-odors due to bacterial growth and prohibits the dewatered sludge solids being sold for applications in gardens and on farms as a soil amendment product and lead to reduced disposal costs.

In addition to the DAF sludge, decanter tallow sludge, centrate and sludge solids other processing points of interest included several pre-DAF steams such as the black pit (PP3), rendering plant stickwater (PP2) and rendering centrifuge wastewater (pre-PP3) as these contained high-quality FOG not contaminated with the green stream and represent opportunities to recover and return high-quality FOG into the render cooker for increased tallow production and decrease FOG load on the DAF and decanters and section 16.0 and section 17.0 reports and discusses in detail the FOG contents these streams and megasonic trials for FOG separation.

12.0 LITERATURE AND PATENT REVIEW

12.1 Overview of methods of FOG recovery

The literature in this review is concerned with improving DAF effectiveness by improved DAF designs or through improved coagulation-flocculation and floatation methods. Vessels developed can vary greatly in size and design and can use a wide range of chemical coagulants-flocculants, however their operation relies on the same physicochemical principles as those currently used in abattoirs. Other less widely used technologies in abattoirs included electrocoagulation-flocculation-floatation, and hydrocyclone and membrane separation. Some of these and other technologies are used in wastewater treatment in other industries but are less widely used in abattoirs. In abattoirs secondary wastewater treatments can use biological treatment such as anaerobic, aerobic, activated sludge digestion, de-sludging with coagulants and flocculants for water clarification. These and other technologies are described in detail and compared in the next sections.

Patent review was carried out using the following databases: Google Patents ((GP) simple and advanced search), Web of Science (Derwent Innovations index (DI)), Espacenet Patent search (ESN) and the international patent classification (IPC). Most of the patent literature was focused on physicochemical separations of FOG with innovations in machine design for improved DAF FOG separation efficiency using multiple-annular floatation zones, and in the types of chemical and natural coagulants-flocculants used including: salts, tannins, clays, polyelectrolyte and polymers with a few patents describing the use of chemical emulsion preventatives or demulsifiers. These include cyclodextrin, multiple-charged ionic polyamines, lytic agents, polyglycidyl compounds. Other methods used high heat and pressure to separate the FOG phase.

Interestingly, several patents report solvent extraction of FOG using a variety of liquids such as terpenes with salt demulsifiers, solvents with membrane filtration, solvent extraction of dewatered/dried sludge, toluene extraction of FOG float and using volatile oils of low viscosity and supercritical CO_2, although this is impractical on a large scale.

We found no patents or papers which disclose the use of ultrasound or megasonics for the separation of FOG in abattoir wastewater steams. However, we did locate two patents which used at a frequency of 360 kHz (Megasonic Sweeping Incorporated) to recover palm oil from emulsions. The other patent by the Commonwealth Scientific Research Organisation (CSIRO) includes megasonic frequencies above 400 kHz into the megahertz range and has been shown to be very effective in separating palm oil form emulsion in palm oil wastewater streams. This information is useful as it seems that megasonics may be a novel and yet untested approach for the separation and recovery of FOG from meat processors wastewater streams and hence supported the proposed laboratory scale megasonic trials.

It is critical that most of the FOG is removed early in the wastewater treatment process otherwise it can obstruct biological treatment processes and cause losses in tallow production. Therefore, it is important to be able to monitor the levels of FOG in the wastewater streams and characterise the composition of the FOG in the water and in the separated FOG, so a section on analytical technologies for FOG analysis in included.

12.2 Introduction

The red meat processing (RMP) industry is Australia's largest food manufacturing and exporting sector. It consists of more than 150 slaughterhouses, which for the financial year of 2013–2014 produced 20.8 gigalitres of untreated wastewater [2]. Large amounts of potable water are consumed during processing, which result in large amounts of wastewater contaminated with suspended solids, blood, fat, oil, and grease (FOG), from washings from different areas within the abattoir. The cost and regulatory restrictions around wastewater treatment for recycle, reuse and disposal therefore need to be considered when evaluating wastewater treatment options which are fit for purpose. Other important factors which will influence the choice of technologies and the extent to which the wastewater is treated include the end uses and destinations of the wastewater such as for: dams, irrigation, release into rural wet lands and waterways, cooling towers, biogas generation, on-site washing of cattle yard and trucks. These reuse options perhaps are more suited to abattoirs situated in rural settings or where there is enough land space. In abattoirs with limited land space the use of dams and technologies which require large spread out areas for covered anaerobic lagoons (CAL) and bio-nutrient removal (BNR) may not be possible and the main purpose for wastewater treatment may be to reduce the loadings of contaminants below the regulation limits to allow disposal to the municipal sewer.

Large volumes of abattoir wastewater (SWW) are generated from two main streams: the red stream and the green stream. The red stream includes water used in washings from the kill floor, boning rooms, meat processing plants and offal processing, and from FOG-rich stick water from the rendering plant. The rendering plant produces saleable products such as tallow, bone meal and blood meal [3]. Wastewater from the green stream contains water used in the washing of the stomach of cattle and sheep and so is rich in partially digested feed known as paunch which can be composted. Therefore, slaughterhouse wastewater, after the FOG is removed requires further treatment to achieve regulation standards for a safe and sustainable reuse or release to the environment either for irrigation purposes or disposal through the sewer while the sludge solid can be used as fertiliser or land fill. SWW is considered detrimental worldwide due to its complex composition of fats, proteins, and fibres from the slaughtering process [4]. The major contaminants are derived from FOG, blood and stomach and intestinal mucus. SWW samples also include nutrients, heavy metals and the FOG and blood contribute to discoloration and turbidity of the wastewater. It is also important to note that disinfectant, cleaning agents, and pharmaceuticals for veterinary purposes can also be present in the SWW [5].

The wastewater can be treated after an initial screening by physical and chemical means to separate major contaminants of the SWW. Typically the separation of solids from the liquor is achieved by sedimentation or coagulation/flocculation, and removal of pollutants using electrocoagulation (EC) and membrane technologies [6]. Biological treatments are divided into anaerobic and aerobic systems as well as con-structed wetlands. Aerobic systems are more common since they commonly operate at a higher flowrate than anaerobic systems; whereas, anaerobic systems require less complex equipment since no aeration system is required; nevertheless, both anaerobic and aerobic systems may be further sub-divided into other processes, which have their own advantages and disadvantages [7].

This review aims to identify the most recent trends and advances in meat processing effluent management and SWW treatment technologies, for recycle and disposal, characteristics, guidelines, and regulations. This study presents current technologies describing technical advances in efficiency, design, performance, and optimization of SWW treatment processes for organics and nutrient removal, including biological treatment, combined processes, advanced oxidation processes (AOPs), and water reuse.

12.3 Abattoir wastewater treatment

12.3.1 Preliminary treatment (Screening-catch basin-equalisation)

The initial treatment of wastewater generated from the slaughter, offal, and stomach contents (paunch) cleaning, boning, and rendering processes is to remove all solids and large particles. This can be achieved by the use of screens such as contra shear, baleen filters and vibrating sieves, catch basins, floatation, equalisation and settlers for recovery of proteins and fats [8]. Typical unit operations for the preliminary removal of total suspended solids (TSS) in wastewater includes screens, strainers, or sieves. Large solids in wastewater with a diameter of 10-30 mm are retained on the mesh of the screen. Rotary screens (contra shear) are used to retain solids with a diameter of more than 0.5 mm to avoid fouling, clogging, or jamming of the equipment. Screw screen compactors are used to transport, dewater, and compact all the remaining solids from the previous screeners, greatly reducing the moisture content, weight and volume for it to be treated as solid waste and to minimise transport costs [9, 10]. Screening can separate up to 60% of the solids from the SWW and remove more than 30% of the biological oxygen demand (BOD) [9].

Catch basins or settling tanks separate the FOG and finely suspended solids by floatation and sedimentation, respectively, due to the low-density FOG and higher density protein. Sedimentation is a common primary treatment technique used to separate solids from wastewater influent [8] where sedimentation can occur in a primary dam or tank. The minimum standards for new plant construction require a 30 x 30 cm metal, PVC, or fiberglass basin. A skimmer is used to remove the FOG off the top and a scraper removes sludge from the bottom. Typical BOD is reduced by 25% to 40% and suspended solids (SS) removal is between 50–70%. Due to very high BOD of blood, it is desirable to collect the maximum amount of blood during slaughter so that wastewater BOD load can be reduced and this blood is dried to make blood meal which can be sold as a phosphorus rich fertilizer [9, 11].

Multiple inline flow equalization tanks can be installed to avoid the necessity of scaleup of subsequent treatment units to handle peak flows and loads. Odour can be eliminated by treatment of the air using biological scrubbers and adsorption beds such as blowing the odorous air through wetted pine bark or wood chip mounds containing natural digesting microorganisms. These are environmentally friendly alternatives to chemical scrubbers. Sedimentation is a common primary treatment technique used to separate solids from wastewater influent. About 40–60% of the solids or approximately 25–35% of the BOD load can be separated by screening and sedimentation [9].

12.3.2 Land application

In land application, biodegradable materials can be used to provide nutrients to the soil by directly placing them into the land. One drawback of the land application is related to the temperature and the geography [10]. Land application in temperate countries is not feasible throughout the year due to the winter season. Therefore, the suspended wastewater (SWW) requires to be storage during that period, therefore there is an additional cost for transportation and storage as part of the treatment. Other disadvantages include poor aesthetics of the surrounding area, particularly for nearby populations due to increase of odour, soil contamination, possible surface and groundwater pollution, and the presence and persistence of harmful pathogens. On the other hand, advantages of land application include the application of useful nutrients containing nitrogen and potassium from the SWW which act as natural fertilizer, and can improvement of soil fertility and structure [11]. If the SWW is treated to an acceptable level, it can be safely used to irrigate pastures for cattle feed and cattle yard, truck washing and dust suppression in rural abattoirs thereby recovering some of the cost of the water used. Treated wastewater can also be used to maintain wetlands and be safely released into nearby creeks or rivers. The separated solids from the green wastewater stream containing mainly paunch can be composted and used to fertilize soils for growing turf or for production soil amendments.

12.3.3 Floatation

The basic idea in the floatation process is the solid–liquid separation process using bubbles. There are several methods of producing bubbles gives rise to different types of floatation processes, namely, electrolytic floatation, dispersed air floatation, and dissolved air floatation (DAF) [12, 13] The bubbles are produced using any gas that is not highly soluble in liquid. However, in abattoirs the most common method for separation and recovery of FOG is DAF in which compressed air is used because it is easily accessible, safe to use, and not expensive.

Electro-floatation

Electrolytic floatation is also known as electro-floatation. Electro-floatation is not commonly used in abattoir wastewater treatment. The bubbles are produced by passing a direct current between two electrodes and by generating oxygen and hydrogen in an aqueous solution by splitting the water molecule. Bubbles produced from electrolytic floatation are smaller compared with those produced from dispersed air floatation and DAF and so this process is amenable for the removal of low-density fragile flocs. This process is suitable for effluent treatment sludge thickening, and water treatment installations of 10–20m^3/h [14]. Figure 46 shows a schematic of a typical electro-floatation tank.

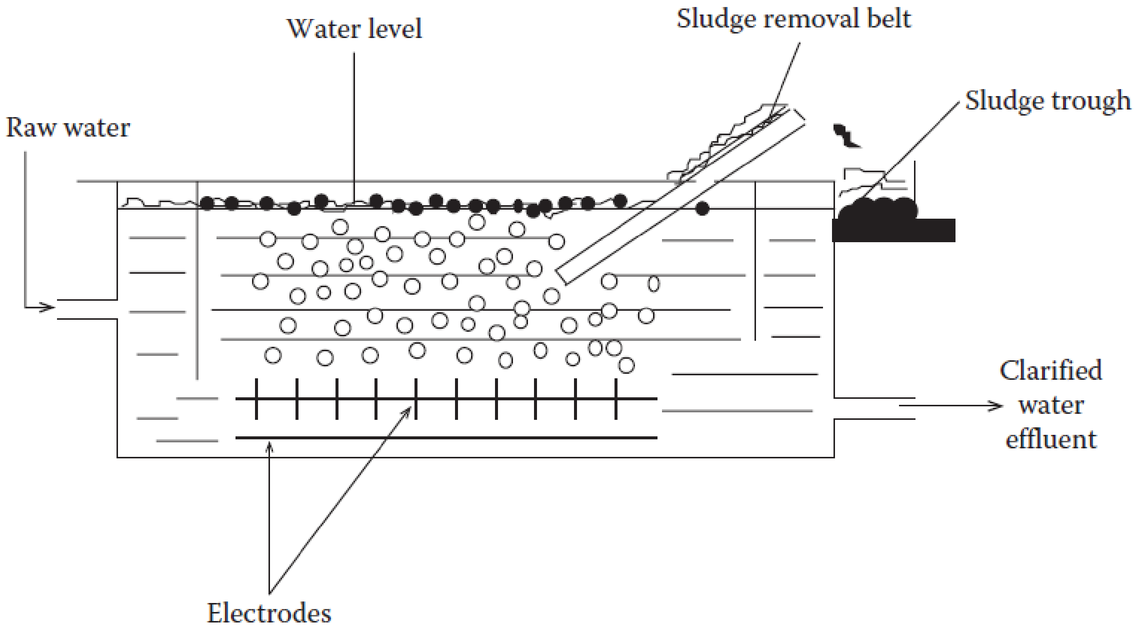

Figure 46: Electro-floatation tank [15]

Dispersed air floatation

Dispersed air floatation has two different systems to generate bubbles, namely, foam floatation and froth floatation. In the foam floatation system, bubbles are generated by forcing air through a porous media made of ceramic, plastic, or sintered metal as shown in Figure 47 [16]. In the high speed impeller froth floatation system, as shown in Figure 48, a high-speed impeller or turbine blade rotating in the solution is used to produce air bubbles. Dispersed air floatation normally produces large air bubbles measuring >1mm in diameter. It is used mainly for the separation of minerals and removal of hydrophobic materials such as fat emulsions in selected wastewater treatment. However, this process was assessed for potable water treatment but was found unsuitable [12].

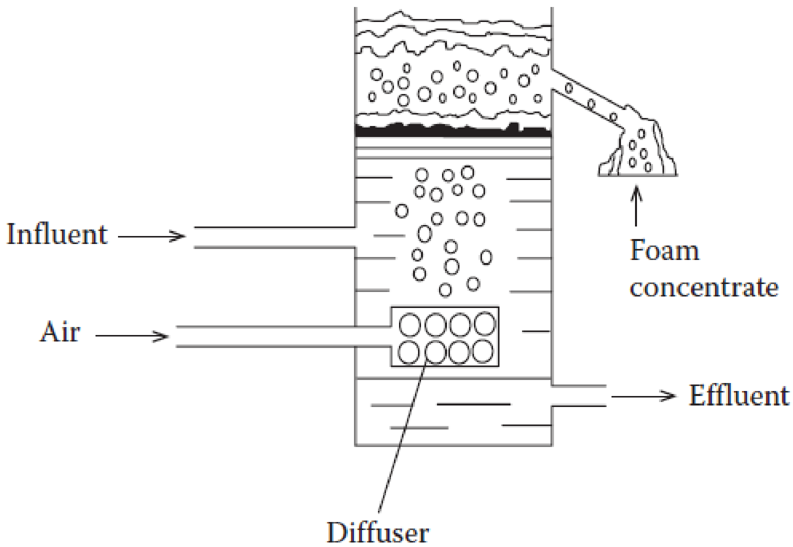

Figure 47: Dispersed air floatation ***[16]***

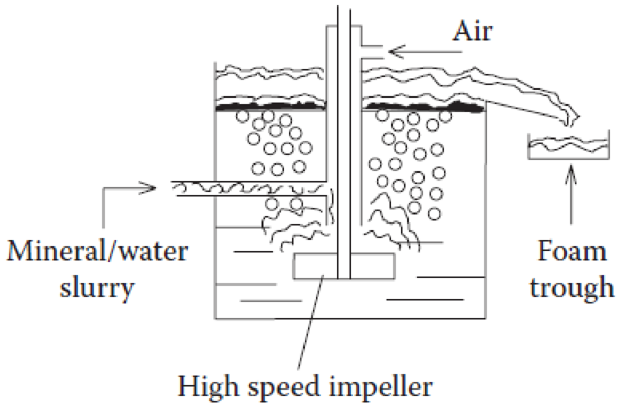

Figure 48: High speed impeller froth floatation [1]

Dissolved air floatation (DAF)

The DAF process is currently being used as the main technology for separation and removal of FOG and solids from abattoir wastewater[1]. Variables for DAF processing system can be divided into hydraulic load, rate of recycle, saturation pressure and ratio of air/solids which are dependent on wastewater characteristics and the effluent requirements [17, 18].

The main mechanism at work in DAF is to float the particles that have a specific gravity equal to the specific gravity of water. This should be carried out using low-density gas such as air. The bubbles in DAF are produced by the reduction in pressure of a water stream saturated with air. The three types of DAF designs are vacuum floatation, micro-floatation, and pressure floatation, of which the pressure floatation is the most important and widely used in water and wastewater treatments. In the pressure floatation, the air is dissolved in water under high pressure and released at atmospheric pressure through a needle valve or nozzle, which produces small air bubbles [1, 13].

Del et al. [19] evaluated the performance of a DAF system for poultry slaughterhouse wastewater (PSWW) treatment. The instability of performance observed was due to the variability of the effluent composition, load and the amount of flocculant-coagulant added in the DAF system. Hence, in order to produce treated wastewater of a certain quality through the reduction of suspended solids, it was important to manage the amount of flocculant-coagulant added as well optimize the operating conditions of the DAF system. Separation of solids from water using DAF systems is carried out by bringing air into a (PSWW) influent, through the bottom of the tank. The efficiency of DAF in removing suspended solid (SS) from PSWW ranged between 38% and 70%, while the removal of fats was between 63% and 95%. The maximum reduction in the chemical oxygen demand (COD) and BOD of PSWW after DAF treatment was 90%. Paulista et al. [20] examined DAF system performance using poly-aluminium chloride as a flocculant operating under 300 kPa dissolved air pressure for PSWW treatment. The SS removal was 43%, while 49% the FOG was removed. The study showed that at an air saturated effluent with a pressure of 450 kPa, removed 99% and 74% of FOG and SS, respectively. Del et al. [19] reported that the removal efficiencies of COD, BODs and FOG in PSWW using a modified DAF system with a hydraulic retention time (HRT) of 24 hours were 97.9%, 98.6%, and 91.1%, respectively. According to Paulista et al. [20] DAF treatment was able to achieve moderate to high NO_3 and NO_2 removal. In contrast, DAF disadvantages are corresponding to poor total suspended solid (TSS) separation and regular malfunctioning [3]. Some processors use DAF for recovery of FOG from hot wastewater without adjusting pH and without the addition of flocculants and coagulants. Under these circumstances separation and capture of FOG is not ideal due to the temperature being above the melting point of the FOG and emulsion formation leading to loss of FOG. The FOG that is not captured by the DAF flows to downstream processes such as in aerobic/anaerobic ponds and can result in the formation of FOG crusts as the water temperature decreased.

The efficiency of the DAF system can be enhanced by addition of acids and bases to adjust pH and adding chemicals such as polymers and other chemicals to flocculate and coagulate suspended and colloidal solids. Blood coagulants such as ferric chloride and aluminium sulphate can be also added to the SWW to promote protein aggregation and precipitation in addition to fat and grease floatation [21]. Removal of FOG by the DAF process can help to reduce COD and BOD to levels in the range between 30% and 90% and between 70% and 80%, respectively. DAF systems are also capable of achieving moderate to high nutrient removal [22]. Conversely, DAF drawbacks are related to low probability of bubble–particle capture phenomena which can result in poor TSS separation [17].

12.3.4 Coagulation and flocculation

Chemical coagulation–flocculation processes are commonly used in abattoirs for treating abattoir wastewater [3, 23] either in the DAF or in subsequent downstream wastewater treatment after aerobic/anaerobic digestion ponds, Biolac® BNR, clarifier, and prior to UV treatment and filtration. Coagulants and flocculants are added into a mixing vessel where the floc is conditioned. The ideal floc size is set by optimising the reaction conditions and adjusted the pH to maximise coagulation-flocculation [3, 10] and achieve maximum separation and removal. The coagulation process involves interactive forces between organic particles and coagulant, type and dosage of coagulant, pH, and temperature. The coagulation mechanism takes place in a series of four steps starting with enmeshment, adsorption, charge neutralisation and precipitation [12]. Ferric sulphate, $Al_2(SO_4)_3$ and poly-aluminium chloride ($PACl_2$) have been used as coagulants to treat abattoir wastewater. In addition, inorganic products have been used as coagulant aids, these include silica, powered activated carbon, precipitated calcium carbonate, synthetic polyelectrolytes, cationic polyacrylamide, poly acrylic acid, anionic polyacrylamide, and polyvinyl alcohol. Coagulation-flocculation is very efficient in removal of phosphorus containing species with almost 100% removal of orthophosphate, and between 98.9% and 99.9% for the total phosphorus. However, the removal of phosphates through chemical precipitation is affected by the alkalinity, organic matter, and the presence of other metals. Nitrogen removal in the form of ammonia was very low, although there is appreciable removal of albuminoid nitrogen (73.9–88.8%) through the removal of colloidal matter [24].

The use of coagulant aids has also been found to reduce the sludge volume by 41.6%. The reduction in COD (chemical oxygen demand) varied between 45% and 75%. The effectiveness of these compounds varied widely with pH [23]. The three common coagulants used are aluminium sulphate, ferric chloride and ($PACl_2$). Of these three, the best results were obtained when using $PACl_2$.

Satyanarayan et al. [25] studied the physicochemical treatment of SWW using anionic polyelectrolyte, ferrous sulphate, lime (calcium oxide and/or calcium hydroxide), and alum (potassium, aluminium, and, sulphate) as coagulants. The use of lime alone results in reductions in BOD, COD, and TSS of 38.9%, 36.1%, and 41.9%, respectively. However, when ferrous sulphate is combined with lime the reduction in COD is reduced by 56.8%. Similarly, the combination of alum with lime also results in greater reduction in COD by 42.6%. Alternatively, combinations of ferrous sulphate and anionic polyelectrolyte, although not cost-effective, results in good reductions in BOD, COD and TSS of 49.6%, 43.8% and 54.2%, respectively. A disadvantage of combining alum with lime is that the amount of sludge generated is increased. Tariq et al. [26] used lime and alum individually and in combination as coagulants for the treatment of SWW. They reported that as the alum dose increased, the proportion of the COD was decreased up to 92% with an increase in the sludge volume, which makes the process not feasible. Increasing in lime dosage increased the COD reduction to a maximum of 74%, but the sludge settling was high, and the sludge volume was decreased compared with the use of alum alone. They concluded that a combined dosage of lime and alum resulted in an optimum decrease in COD of 85% with a low sludge volume.

12.3.5 Electrocoagulation (EC)

Electrocoagulation as a wastewater treatment technology for meat processors has been reviewed in detail by Price et al. (2018) for AMPC and by Chanjiang et al. (2017) [27, 28]. The EC system is an advanced technology used for PSWW treatment. An electric current is passed through the effluent in a reactor without any chemical additive. It can effectively remove nutrients, heavy metals and pathogens removal from PSWW [21]. Figure 49 and Figure 50 illustrates a typical EC reactor and electrochemical coagulation process for a commercial reactor, respectively. Al, Fe, Pt, SnO_2, TiO_2, among other metals, can be utilized as electrodes for the EC process, with Fe and Al electrodes among the most common. For Fe and Al as sacrificial anodes where oxidation occurs, the EC process generates of Fe^{3+} or Al^{3+} ions using. In addition, these sacrificial electrodes might be interacting with H^+ ions in an acidic medium, or with OH^- ions in an alkaline medium [29, 30]. Metal ions promotes coagulation and flocculation of the organic material, which subsequently separates as a floating, frothy sludge in the downstream sludge separation unit [31].

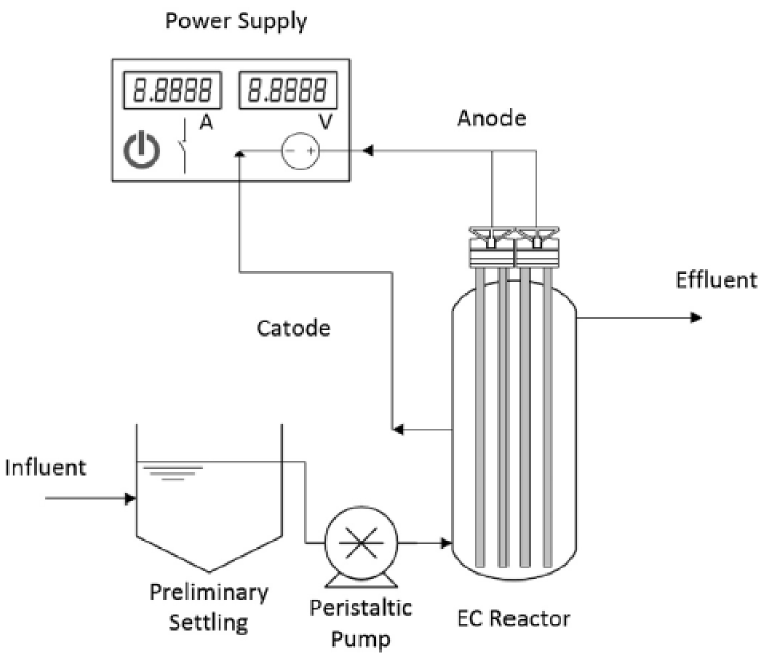

Figure 49: Electrocoagulation reactor [15]

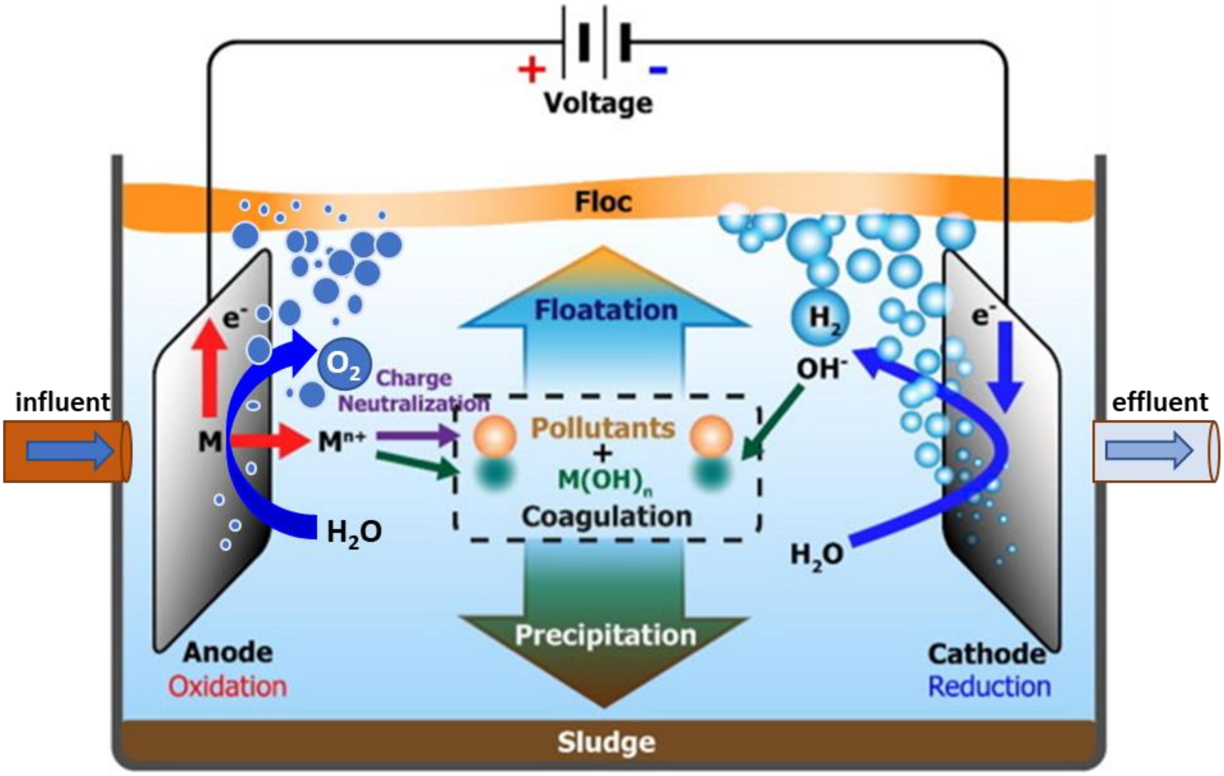

Figure 50: Diagram of electrocoagulation wastewater treatment process (modification of Chanjiang et al. (2017) [28])

Bayar et al. [29] examined the effectiveness of EC in reducing the COD and BOD5 levels in PSWW and reported that they were able to reduce the concentrations of COD and BOD5 from 2171 mg/L and 1123 mg/L, by 85.0% and 96.8%, respectively. The degree of reduction of COD, BOD5 and colour during the EC treatment depends on the optimisation of the operating parameters. In many studies the EC system was optimised using response surface methodology (RSM) and factorial level design based on reaction time, current density, and influent parameters.

Kobya et al. [15] studied the influence of pH, operating time, electrode material, and current density of the EC process for PSWW treatment on reduction in FOG content and COD, sacrificial anode and electrical energy consumption. Up to 93% of COD was reduced using Al as the anode material, whereas the highest FOG removal of 98% was obtained using Fe as the anode material. However, further work is required at the pilot-scale to assess the cost-effectiveness of the EC process.

Awang et al. [32] used response surface methodology (RSM) with a 3-level factorial design to investigated the effect of current density, reaction time, and influent COD on the efficiencies colour removal and reduction in COD, and BOD. The optimum conditions were obtained at COD influent concentrations of 220 mg/L, 55 min reaction time, and current density near 30 mA/cm2 which resulted in a reduction in colour, BOD, and COD of 96.8%, 81.3%, and 85.0, respectively.

Bayramoglu et al. [15] carried out a cost-effectiveness analysis (CEA) for the treatment of PSWW using EC with a particular focus on COD removal. Total operating cost included operations and maintenance (O&M) costs electricity, sacrificial anode material (Fe and Al) depreciation, and sludge handling costs.

Other performance parameters included pH, current density, and operating time. The results showed that Fe as the sacrificial anodes are more cost-effective than Al anodes, with total operating costs between 0.30 and 0.40 $/m^3$, which is 50% of the total costs of using Al anodes. Ozyonar and Karagozoglu [30] reported similar results of total costs of 2.76 and 0.87 $/m^3$, for Fe and Al anodes, respectively.

Similarly, Asselin et al. [33] evaluated the EC process in economic terms for the removal of organic compounds from SWW. Experiments were conducted at laboratory pilot-scale by using mild steel and Al as sacrificial anodes. Results showed that using mild steel as bipolar electrodes achieved reductions in COD, BOD, TSS, turbidity, and FOG removal of 84%, 87%, 93%, 94%, and 99%, respectively. resulting in a total cost, including energy and electrode consumptions, chemicals, and sludge disposal, of 0.71 $/m^3$ of treated PSWW effluent, which is comparable to that found by Bayramoglu et al. [15].

12.3.6 Biological treatment

Reducing the BOD in SWW is the main purpose of the secondary treatment and is achieved by removing the soluble organic compounds that remain after primary treatment [34]. Biological treatment is usually applied as a secondary treatment process in meat processing Plants (MPP) through the application of separate or combined aerobic and anaerobic digestion, depending on the characteristics of the SWW being treated [35]. Aerobic and anaerobic biological treatments utilises microorganisms to digest the organic compounds, removes pathogens and can reduce the BOD by 90% [36] from SWW effluents. Biological treatment may include different combinations of various processes including anaerobic, aerobic ponds, stabilization ponds and facultative lagoons. Stabilisation ponds are designed to be aerobic throughout its depth and the facultative lagoon will be anaerobic at the bottom and aerobic at the top and do not require primary treatment and can handle large solids content (https://www.waterworld.com/home/article/16192273/introduction-to-wastewater-treatment-ponds). Other treatments include aluminium sulphate and trickling filters among others [37, 38]. The efficiency of aerobic and anaerobic treatment of PSWW depends on the composition of PSWW [24]. Both methods are used to reduce the dissolved organic content to form inactive sludge which can be removed through coagulation, flocculation and clarification [39].

Anaerobic treatment

During anaerobic treatment, organic compounds are consumed by different bacteria and converted into carbon dioxide (CO_2) and methane (CH_4) biogas in the absence of oxygen. In addition to the high nutrient and biogas recovery, anaerobic systems have several other advantages such as high COD reduction, low sludge production (5-20%) compared to those of aerobic systems, and less energy requirements [4, 40]. Although anaerobic treatments are efficient processes, the high organic loads in SWW makes it difficult to achieve complete stabilization of the organic compounds [40]. Hence, anaerobically treated effluents usually need post-treatment, to complete the removal of organic matter, nitrates, phosphates and pathogenic organisms [41]. Therefore, the combination of anaerobic and aerobic systems is affective in satisfying current effluent discharge standards [42]. Typical configurations for SWW anaerobic treatment include anaerobic baffled reactor (ABR), anaerobic filter (AF), anaerobic lagoon (AL), up-flow anaerobic sludge blanket (UASB), and anaerobic sequencing batch reactor (SBR) [43-45].

Anaerobic baffled reactor (ABR)

ABRs are considered an optimised version of a common septic tank. ABRs have a series of compartments and baffles under which the SWW flows under and over from the inlet to the outlet. Since there is an increased contact time with the active biomass, a greater biodegradation occurs. The up flow compartments provide an improved removal of organics with up to 90% reduction in BOD and COD [46]. Bustillo-Lecompte et al. [4] evaluated the effectiveness and performance of the ABR in the treatment of SWW using a cost effectiveness analysis (CEA) by assessing the total electricity cost, hydraulic retention time (HRT), and reduction in TOC. The results showed that costs increase with the degree of reduction in TOC, especially if very low levels of TOC are required. A laboratory scale an ABR was used by Bustillo-Lecompte et al. [42] to study the anaerobic digestion of SWW from red meat plants with a TOC and total nitrogen (TN) influent concentration of 183.35 mg/L and 63.38 mg/L, respectively. The highest reductions achieved in TOC and TN were 88.9% and 51.5%, respectively. Cao and Mehrvar [2] evaluated the performance of the combined ABR and UV/H_2O_2 processes to treat SWW at a laboratory-scale. Combining these processes achieve a higher reduction in TOC (95%) after 3.8 days of treatment than using individual processes for effluent with a TOC concentration of 973 mg/L.

If low or intermediate reductions in TOC are required, then the ABR used alone is comparable, in terms of cost to the combined processes. The biogas produced is captured as for CAL and can be used to fuel boilers in the rendering plant and dryers used to dry blood meal. Hence the energy generated can offset plant energy costs [4].

Anaerobic filter (AF)

Anaerobic filters (AFs) are fixed-bed biological reactors with filtration chambers in which the digestion column may be packed with different types of filtration media such as ceramics, glass, engineered plastics (https://www.sciencedirect.com/topics/engineering/anaerobic-filter [47, 48]. Anaerobic bacterial biofilms are retained within the reactor on the filter media surfaces. When the SWW flows over the filtration media surfaces, organic material meets and is digested by the bacteria. AFs are used in secondary treatment due to the high solid removal and biogas recovery rates and are commonly used in series. The designed of a typical anaerobic filter is presented in Figure 51.

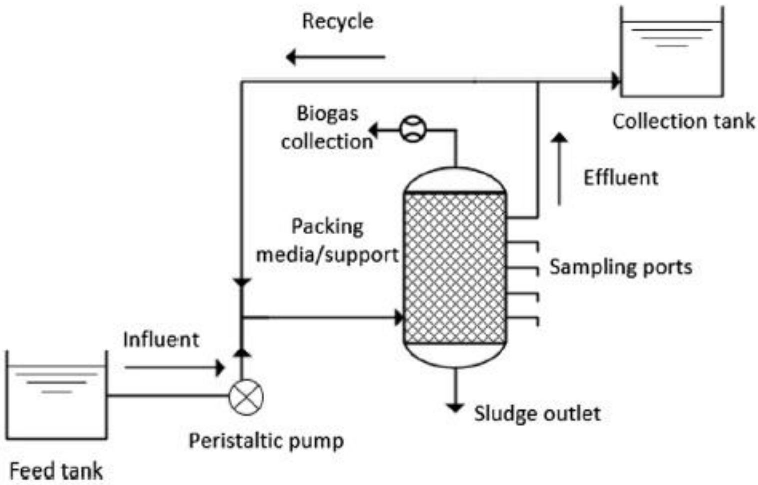

Figure 51: Anaerobic filter [40]

The performance of up-flow anaerobic filters (UAFs) has been examined under thermophilic and mesophilic conditions for SWW treatment [47]. The results showed that reductions in COD of up to 90% can be achieved for abattoir wastewater with organic loading rates (OLRs) of 9000 mg/L day under mesophilic conditions and 72% under thermophilic conditions [47, 48]. Martinez et al. [49] compared the effectiveness of two up-flow anaerobic packed-bed filters (UAPFs) for SWW treatment at a laboratory-scale, under mesophilic conditions using different packing material. The production of methane biogas (CH_4) was assessed at various OLRs and feeding conditions. The highest reduction of COD was 60% for an influent concentration of up to 15,800 mg/L. The UAPF was able to produce enough biogas for the heating requirements of the SWW treatment plant [50].

Open and covered anaerobic lagoons

Anaerobic lagoons (ALs) are popular in countries where weather and land availability permit the construction of lagoons for the treatment of SWW [9]. These were in operation in the two Queensland abattoirs we visited and in one Victorian abattoir. The wastewater influent usually flows from the bottom of the lagoon, and although some gas mixing may be present, ALs are not mechanically mixed. Thus, a scum layer typically appears on the surface of the ALs, ensuring anaerobic conditions and low heat loss. Typical ALs are constructed with a depth of 3-5 m for HRTs of 5-10 days. High efficiencies for reduction in the levels of BOD, COD, and TSS have been reported, (97%, 96%, and 95%, respectively) [9, 51, 52].

The main drawbacks of ALs are related to odour regeneration and sensitivity to weather conditions and escape of valuable biogas. Therefore, covered anaerobic lagoons (CALs) have been designed with synthetic floating covers are used to trap odour and collect biogas; these covers must be durable to resist inclement weather, temperature change, wind, ice and snow accumulation [9]. On the other hand, ALs are the preferred option because of their simplicity and low O&M costs [52].

Up-flow sludge blanket and sequencing batch reactors

Anaerobic sludge blanket reactors (SBR) requires low capital and O&M costs. The feeding, reaction, settling, and decanting stages take place in the same basin. Anaerobic sequence batch reactors (SBR) also eliminate the need for complete mixing during the reaction residence time. However, intermittent mixing may occur during the reaction cycles [9, 53]. Moreover, in order to optimize the performance of anaerobic SBRs, an intermittent feeding strategy of the SWW influent eliminates the need for a recycling stream or an equalizing tank [54].

The UASB process uses granules of inert media covered with bacteria to digest dissolved organic nutrients. The SWW enters from the bottom of the reactor, flows upward through the sludge blanket which contains the biomass film, and exits at the top of the vessel. Essentially, UASB reactors consist of three stages: liquid as SWW, solid as biomass, and the biogases carbon dioxide (CO_2) and methane (CH_4) produced during digestion [9]. Miranda et al. (2005) assessed the performance of an 800 m3 UASB for SWW treatment. Influent concentrations of COD and oil and grease (O&G) were in the range of 1400-3600 mg/L and 413-645 mg/L, respectively. They showed that the performance of the UASB was enhanced at an influent COD/O&G ratio of 1:10. resulting in reductions in O&G and COD of 27-58% and 70-92%, respectively. Mijalova Nacheva et al. [55] analysed the performance of a UASB reactor under ambient conditions for SWW treatment after solid separation and showed that reductions in COD increased in proportion to the organic loading rates (OLRs) such that the level of COD was reduced by 90% at an influent COD level of 3437 mg/L. Although UASB reactors are found to be efficient for SWW treatment, a posttreatment is required to comply with current water quality standards for water body discharge.

Aerobic treatment

In aerobic systems, aerobic bacteria are used for the removal of organic materials in the presence of oxygen obtained by aeration. The treatment time and the amount of required oxygen increase suddenly with the concentration of organics in the SWW. Aerobic treatment is commonly used for final decontamination and removal of nutrients after using physicochemical or anaerobic techniques [56]. Aerobic reactors may have several configurations. However, the biological process is very similar, and is necessary to reduce the nitrogen levels as per the final specifications required. Typical configurations for SWW aerobic treatment include activated sludge (AS), rotating biological contactors (RBCs), and aerobic SBR [10].

Activated sludge (AS) process

The activated sludge process (AS) is an aerobic treatment method that brings the effluent into contact with air and free-floating flocs of microorganisms including bacteria and protozoa. The AS process is a cost-effective method which is widely used in different industries including in the meat processing industry for the treatment of SWW. The purpose of the AS process is to remove soluble and insoluble organics from the wastewater and to change this material into a flocculent microbial suspension that is then settled in a clarifier. Two distinct mechanisms are applied in AS process: adsorption and oxidation of the organic matter [57]. A typical AS system is shown in Figure 52.

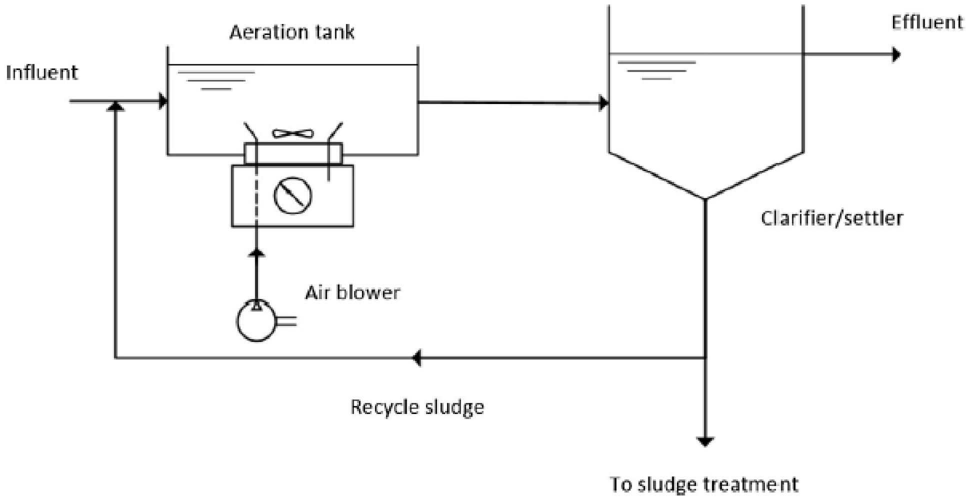

Figure 52: Activated sludge process [1]

AS systems treating SWW produce poor settling flocs because of FOG present in SWW influents and low dissolved oxygen (DO) levels, hence it is desirable to remove as much FOG at earlier processing stages such as using the DAF. An important factor for the AS process for SWW treatment is the need for extended aeration to minimize sludge production. The HRT are longer than that of typical municipal wastewater treatment plants to ensure a sludge age of 5-20 days as recommended for SWW treatment [57].

Pabon and Glvez [58] evaluated the performance of a 144 m^3 full-scale AS reactor for SWW treatment. The average flow was 1.38 L/s with a 2-day HRT. Oxygen was injected using a high efficiency air equipment (compressor). Bulk BOD, COD, and TSS levels in SWW were measured before and after treatment. Influent with levels of BOD, COD and TSS of 5242 mg/L, 9040 mg/L, and 2973 mg/L, respectively, were after AS treatment, reduced by 89.7%, 89.0% and 94.1%, respectively. Bustillo-Lecompte et al. [4, 42] evaluated the effectiveness, performance, and costs of an AS reactor for the treatment of SWW using CEA. The aerobic AS reactor displayed the best performance with influent TOC and TN concentrations under of 1009 mg/L and 254 mg/L, respectively which resulted in the maximum reduction in the levels of TOC and TN of 95.0% and 73.4%, respectively. Removal of TOC and TN was less efficient at lower TOC and TN influent concentrations. For an influent TOC and TN concentration of 639 mg/L and 144 mg/L, respectively, the reduction in TOC and TN was 89.6% and 43.2%, respectively at a HRT of 5 days, whereas at a HRT of 8 days, TOC and TN concentration was reduced by 94.2% and 75.1%, respectively showing that the hydraulic retention time is an important factor for the degree of removal of TOC and TN. Cost effectiveness analysis (CEA), showed that the AS process is an efficient process with optimum TOC removal of up to 88% at a cost of 4 $/kg of TOC removed. Thus, if low or intermediate amounts of TOC are to be removed, the cost of the AS process is comparable to other combined processes.

Rotary biological contactor (RBC)

The RBC process allows the wastewater to come into contact with the aerobic bacterial medium in order for it to absorb and metabolize the organics and other pollutants before discharge to the environment [9]. However, the performance of an RBC to treat SWW has been reported as inadequate in literature compared to conventional aerobic treatment systems such as the AS process [59]. Al-

Ahmady [59] studied the COD removal in RBC systems as a function of the OLR. A wide range of reductions in COD 40-85% was seen when treating SWW with the wide range of OLR of the influent, especially during the first stages of the system. On the other hand, the performance of a 6-stage RBC pilot plant for post-treatment of SWW was investigated by Torkian et al. [60] and the overall removal efficiencies for reducing the BOD and COD concentrations decreased with increasing OLR but were a sufficient pre-treatment to allow post-treatment of SWW to meet regulatory requirements with a reduction of BOD levels of up to 88%.

Aerobic sequencing batch reactor (ASBR)

In an aerobic SBR, there are five stages including filling, reaction, settling, decanting, and idle. In the first stage, the feed enters the reactor while mechanically mixing in the absence of air (anoxic phase). In the second stage the mixed liquor is aerated (aerobic phase). Mixing and aeration are stopped and in this third stage and the TSS settle out of the liquid phase. In the fourth stage the treated effluent also known as the supernatant liquor exits the tank [11, 57, 61]. Zhan et al. [61] examined the total nitrogen (TN) removal from SWW using a laboratory-scale SBR and compared intermittent and continuous aeration treatments, at low DO conditions. Under intermittent aeration, the maximum DO was kept low at 10% saturation while under the continuous aeration protocol, the DO was maintained at 10% saturation during the first hour of the reaction phase, and then reduced to 2% for the rest of the reaction phase. The TN level was reduced by 91 and 95% using continuous and intermittent aeration, respectively. Therefore, on-site measurements of DO levels during SBR operation can be used to maximise the reduction of TN removal. Kundu et al. [62] obtained similar reductions of TN and COD from SWW using a laboratory-scale SBR. The influent concentrations of TN and COD were 90-180 mg/L and 950-1050 mg/L, respectively. The COD level was reduced by 95% using an 8 h treatment. The reduction in TN was dependent on the influent TN concentration with a reduction of 74.7% and 90.1% achieved for TN influent concentrations of 176.85 and 96.58 mg/L, respectively.

12.3.7 Advanced oxidation processes (AOP)

AOPs such as ozonation using UV light with hydrogen peroxide (H_2O_2) oxidant solutions are an alternative to conventional biological pre-treatment or post-treatments and can also be used as a complimentary treatment. AOPs can inactivate microorganisms without the addition of chemicals to the SWW hence avoiding the possible formation of hazardous by-products which can be formed using chemical disinfection with chlorine which is commonly used [3]. Figure 53 shows a schematic diagram of a single lamp UV/H_2O_2 photoreactor.

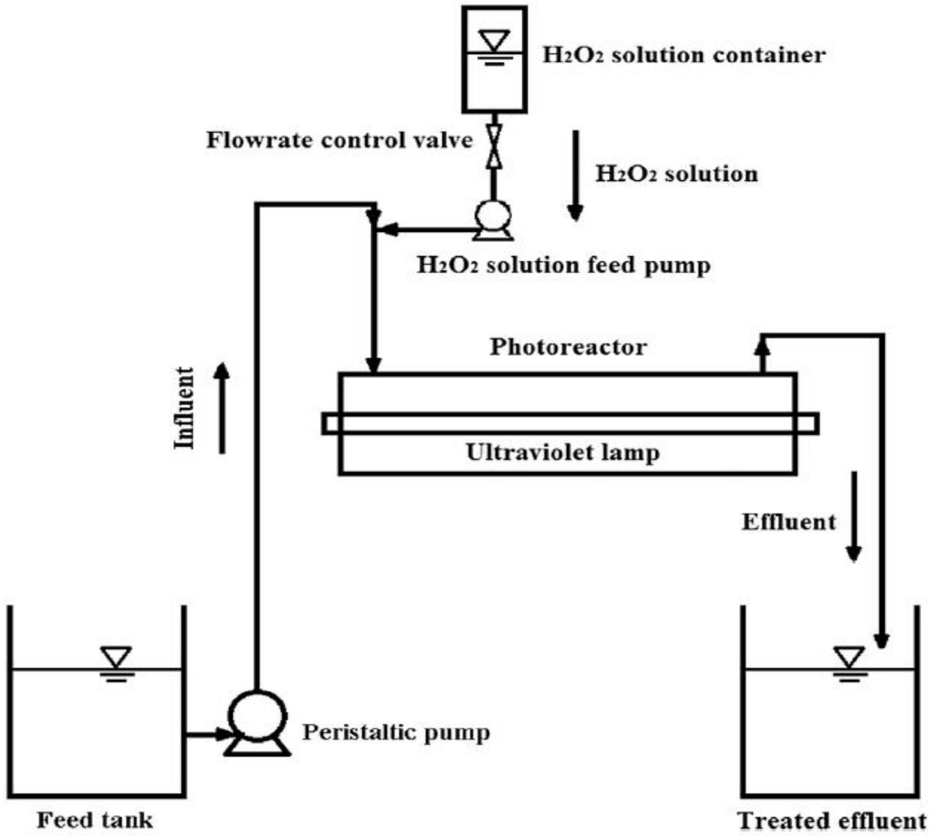

Figure 53: Schematic diagram of a single lamp UV/H_2O_2 photoreactor [46]

Ozonation was also used by Wu and Doan [63] for the treatment of SWW. They showed that ozone was effective in disinfecting SWW after 8 min using an ozone dosage of up to 23.1 mg/min and Up to 99% of the microorganisms were inactivated. However, the COD and BOD removal were only 10.7% and 23.6%, respectively. Therefore, this method cannot be used alone for SWW treatment.

Gamma radiation (GR) was evaluated by Melo et al. [64] for the treatment of SWW. It was found not to be effective for reducing COD, BOD, and TSS at a dose rate of 0.9 kGy/h. Although a decrease in BOD level of 38.6-85.7% was achieved at high irradiation dosages (25 kGy/h). However, the high costs of this technology are its main drawback.

The UV/H_2O_2 process is one of the most widely used AOPs. The UV/H_2O_2 process has been found to be effective for SWW treatment. Oxidation and degradation of pollutants by UV/H_2O_2 rely on hydroxyl radicals (OH), a highly reactive species produced from the reaction of the H_2O_2 with the UV light [3, 65, 66]. Luiz et al. [67] evaluated the UV/H_2O_2 process for the treatment of a secondary SWW effluent. The results showed that the UV/H_2O_2 treatment was more effective than conventional UV alone in degrading organic compounds. The UV/H_2O_2 process was five times faster in degrading aromatics than UV only and the level of COD was reduced by 95% after 5 h of treatment.

De Sena et al. [67] studied the effectiveness of AOPs for the treatment of SWW using UV/H_2O_2 and a photo-Fenton process which combines iron II (Fe2+) ions with UV radiation at a laboratory scale. They reported that these AOPs on pre-treated SWW samples reduced the COD and BOD levels by 97.6% and 95.70%, respectively showing that AOPs could be used to improve the quality of SWW effluents to a standard suitable for reuse.

Cao and Mehrvar [2] evaluated the performance of a UV/H_2O_2 photoreactor as the post-treatment of a synthetic SWW at a laboratory scale. The TOC influent concentration was 157.6 mg/L and after treatment with UV, a H_2O_2 dosage of 529 mg/L and a HRTs of 2.5 h, the BOD, TOC, and COD levels were reduced by 84%, 64%, and 83% of removals, respectively. A H2O2 dosage of 3.5 mg/h per mg TOC in the influent was found to be the optimum for the UV/H2O2 process.

Bustillo-Lecompte et al. [42] also tested the performance of the UV/H_2O_2 process for SWW treatment with TOC loadings of up to 350 mg/L in the influent. An optimum TOC removal of 75% was obtained for influent concentrations of up to 65 mgTOC/L and HRTs of 180 min with H_2O_2 dosages of 900 mg/L and an optimum molar ratio dosage of H_2O_2: TOC was determined to be 14.0 mg H2O2/mg TOC. Bustillo-Lecompte et al. [4] compared other treatment technologies to UV/ H_2O_2 and found that the use of UV/ H_2O_2 alone was found to be the least efficient process with optimum removals of up to 50% at a cost of 67 $/kg of TOC removed. Moreover, the TOC removal was not significantly increased by increasing the treatment time. Therefore, although the UV/ H_2O_2 process is effective in treating SWW when combined with other process such as DAF pre-treatment to remove most of the FOG and anaerobic and aerobic secondary treatments, using UV/ H_2O_2 alone is an unrealistic option for it to be implement industrially due to the low efficiency and high cost. Consequently, SWW treatment using a combination of AOPs and biological processes is recommended with residence time in each reactor each being optimized.

12.3.8 Membrane separation technology

Membrane technology is becoming an alternative for SWW treatment which could be used in combination with other filtration secondary or tertiary treatments after coagulation and flocculation processes. Reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF), and microfiltration (MF) processes can remove particles, colloids, and macromolecules depending on the pore size Table 5 [3, 68]. Membrane processes are also increasingly used for removal of bacteria, microorganisms, particulates, and organic matter in SWW treatment [6]. Yordanov [69] investigated the feasibility of using UF for SWW treatment. Results showed that the UF could be an efficient purification method by achieving reductions in TSS and FOG of 98% and 99%, respectively while the reductions in BOD and COD were 98% and 95%, respectively. Borowitzka [70] used UF process to treat PSWW with 68.5 mg/L of total nitrogen (TN) and 181.4 mg/L of COD. This treatment reduced the level of COD and TN by 94% and 44%, respectively. Similar results obtained by Almandoz et al. [6] who evaluated the effectiveness of a MF ceramic composite membrane (CM). A 100% removal of the total insoluble was achieved in addition to a high proportion of bacteria removal (87-99%). The reductions in total organic carbon (TOC), TN, and COD were 44.8%, 45.2%, and 90.6%, respectively showing that ceramic membranes (CM) are suitable for MF treatment of SWW. Gürel and Büyükgüngor [71] investigated the performance of a membrane bioreactor (MBR) using an UF membrane for the removal of nutrients and organic compounds from SWW. The initial COD, total phosphorus (TP), and TN concentrations were 571 mg/L, 16 mg/L, and 102 mg/L, respectively. This MBR system was able to reduce to TN, TP, TOC, and COD levels by 44%, 65%, 96%, and 97%, respectively showing that although organic matter was almost completely removed, a high nitrate and moderate phosphate concentrations remained in the treated wastewater. Hence a denitrification treatment needs to be added in addition to this process [71]. A major problem associated with the use of membrane processes is that of fouling due to the formation of thick biofouling layers on the membrane surfaces when treating highly concentrated feed streams such as SWW. These biofilms are difficult to remove and can greatly restrict the permeation rate through the membranes [72]. Nevertheless, membrane separation processes are a very important wastewater treatment technology particularly when, applied as a tertiary treatment of secondary effluent when the objective is to obtain a high-quality final effluent that can be reused for different purposes [6].

Table 5: Comparison of different membrane pore size used in SWW treatment

Membrane type	Pore size (μm)
Microfiltration	0.080-0.550
Ultrafiltration	0.030
Nanofiltration	0.010-0.100
Reverse osmosis	0.001-0.005

12.3.9 Decanters/tricanters

Decanter continuous flow centrifuges typically separate solids from liquids but in the three-phase decanter systems also known as tricanters, as shown in Figure 54, it is possible to separate two liquid phases from one solid phase at the same time. The Tricanter separates these three phases based on their different densities. the solid phase must be the heaviest phase and the liquid phases must have different densities. Otherwise, the scroll of the decanter will not transport the solid at all, or only inadequately, which affects the separation result. There are two liquid phases in a Tricanter — a "heavy" liquid phase (higher density and discharged under pressure) and a "light" liquid phase (lower density and discharged without pressure). An adjustable impeller discharges the heavy liquid phase. The operator can use the adjustable impeller to adjust the pond depth of the heavy liquid without difficulty during ongoing operation. An adjustment mechanism causes the position of the impeller to change, thereby changing the separation line of the liquids. The process results can be influenced to achieve the required separation result. Most three-phase separation machines require disassembly to change the weir ring, which sets the separation line. The Tricanter can extract about 10% fat and use it for biodiesel fuel, the solids are separated via the same machine and sent to the rendering plant for pet food and the water remains inside the system for further processing. Rather than sending material to land applications, which requires special equipment [73, 74].

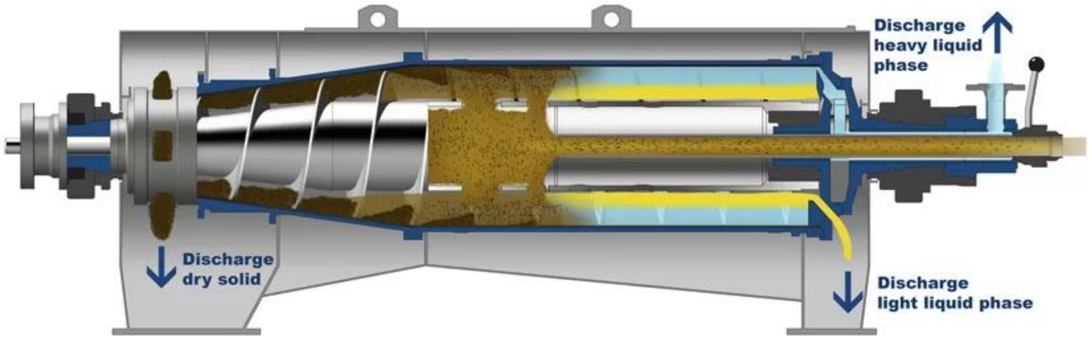

Figure 54: Three-phase centrifuge (decanter) separation of water, oil and solids with the Flottweg Tricanter® (https://www.flottweg.com/product-lines/tricanterr/)

12.3.10 Hydrocyclone separators

Hydrocyclones have been assessed for fat removal from meat processing wastewater streams in a MLA final report (2003) [75]. This technology uses centrifugal force to separate solid–liquid or liquid–liquid phases of different densities that are forced into rotational motion due to tangential entry of the feed stream. A primary vortex, rich in a heavy phase and formed along the inner wall, exits the hydrocyclone as the underflow stream at the far end from the feed port. A secondary vortex, essentially free of a heavy phase and formed near the centreline, leaves the hydrocyclone as the overflow stream through a centrally located orifice at the opposite end of the hydrocyclone. Hydrocyclones have long been used to separate solid particles from process water in the mineral industry and to remove oil from water on ships and drilling platforms. Although the more common method for removal of FOG from commercial abattoirs wastewater uses dissolved air floatation (DAF), the use of hydrocyclone compares well with the DAF units for its ability to recover FOG but costs less to install and operate as well as having a smaller footprint. Hydrocyclones accomplish separation with shorter residence time yielding a higher FOG quality and so has advantages over Save-all [76]. Canmet ENERGY in Devon (Canada) has developed a novel hydrocyclone that is specifically suited for processing difficult-to-separate oily emulsions such as those encountered in the secondary treatment of heavy oil production fluids but also allows for simultaneous removal of solid impurities that are inherent to the Western Canada heavy oil industry [77]. This technology is scalable so is suited for abattoirs of different capacity.

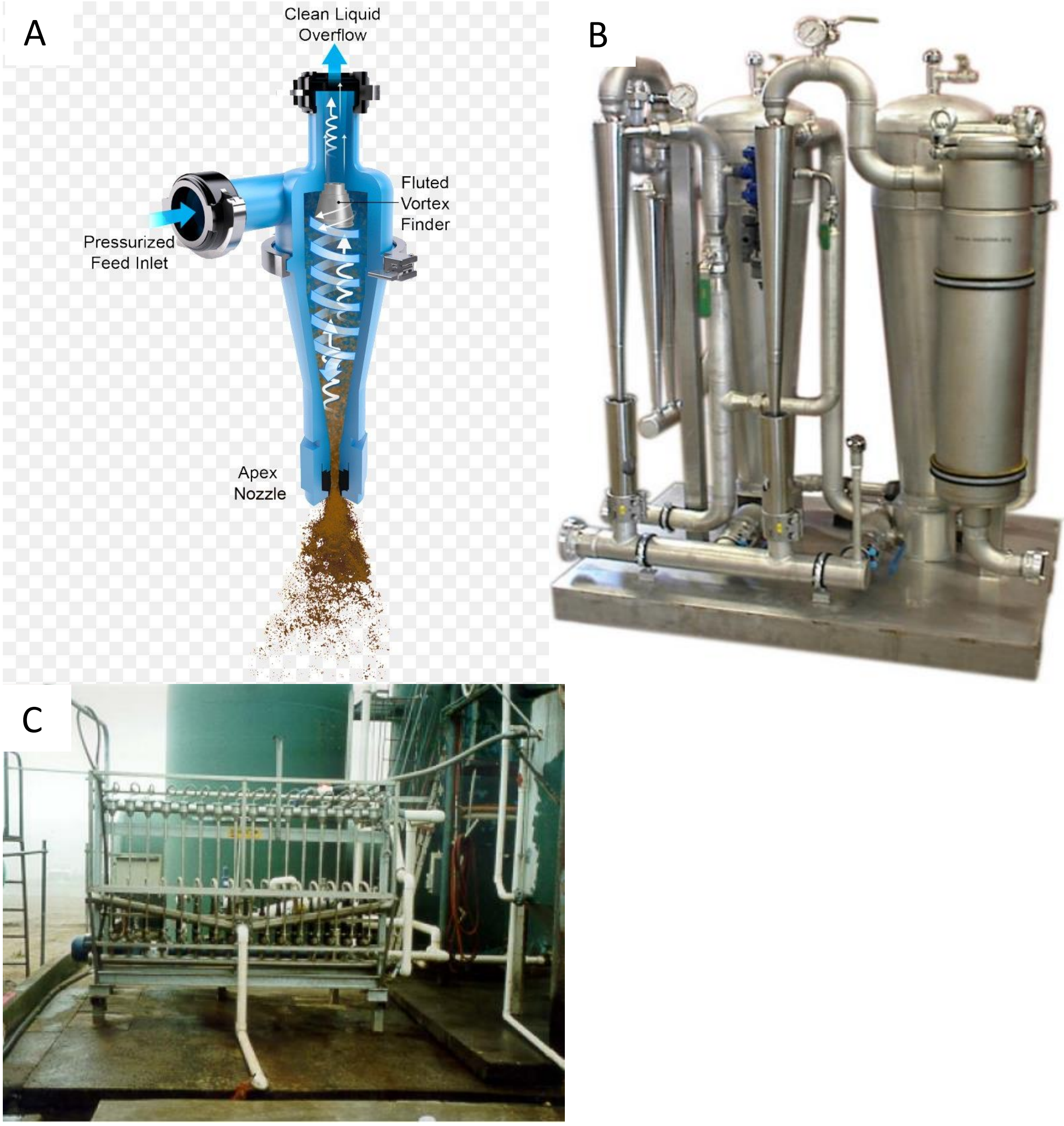

Figure 55: Drawing of interior of a hydrocyclone showing centrifugal vortexes for separation of solids water and fats (A) https://www.pngwave.com/png-clip-art-wetjd, larger scale unit (B) sold by WyanaSep https://wyunasep.com/lib_docs/WyunaSep_Meatwork_Brochure.pdf, and an operational hydrocyclone installation at a meat processing plant (C) [75]

Table 6 shows the effectiveness of hydrocyclone (WyanaSep, https://wyunasep.com/lib_docs/WyunaSep_Meatwork_Brochure.pdf) in separating oil and grease from abattoir wastewater stream compared to tank settling ("saveall"), DAF without chemicals and DAF with coagulants and flocculants. Hydrocyclones can be as affective as DAF with and without chemical so is a real option for abattoir wastewater treatment and recovery of FOG.

Table 6: Performance of hydrocyclone compared to settling and DAF with and without chemical coagulant and flocculant addition (https://wyunasep.com/lib_docs/WyunaSep_Meatwork_Brochure.pdf)

Separation	Hydrocyclone WyanaSep	Tank (e.g. "Saveall")	DAF (no chemicals)	DAF (full chemical treatment)
Oil and Grease % reduction	75-95	50-60	60-80	Up to 95
Suspended Solids % reduction	65-75	50-60	50-65	Up to 70

12.3.11 Combined processes

It is beneficial, in terms of efficiency, day to day operation and economics of running a SWW treatment plant, to include combined processes for the treatment of SWW since it couples the benefits of different technologies to cope with high load industrial abattoir wastewater management [4, 42, 78, 79]. Del Pozo and Diez [80] evaluated a combined anaerobic-aerobic fixed-film reactor for SWW treatment under sub mesophilic (25 ^{o}C) conditions. Overall COD level reductions of up to 93% were obtained for OLRs of 0.77 kg/m^3 day, along with TN level reductions of up to 67% for a TN influent load of 0.084 kg N/m^3 day. Denitrification contributed to a 12-34% reduction in TN levels being limited by DO levels above 0.5 mg/L in the anaerobic section.

Bohdziewicz and Sroka [81] considered combined activated sludge-reverse osmosis (AS-RO) system for the treatment of SWW. The raw SWW was first pre-treated using an AS system prior to RO treatment. The results showed a high removal of contaminants from the SWW by the combined processes, for COD, BOD, TP, and TN of 99.8%, 99.8%, 99.7% and 99.7%, respectively.

A combined coagulation/adsorption process was trialled by Mahtab et al. [82] for SWW effluents using various coagulants, such as alum, ferrous sulphate, ferric chloride, and lime. The highest reduction in COD levels was 92% using alum as the coagulant. Nevertheless, it was concluded that the combined coagulation/adsorption process made not significant improvement in COD removal from SWW.

Bazrafshan et al. [83] assessed the performance of combined chemical coagulation (CC) and EC for the SWW treatment. It was reported that the reduction in the BOD and COD levels was directly proportional to the applied voltage and coagulant dosage with up to 99% reduction for both parameters. Thus, the combined CC-EC processes was found to be more efficient than EC alone.

Bustillo-Lecompte et al. [4, 42] evaluated the performance and operating costs of treating SWW using combined biological and AOPs. A comparison was made in terms of the treatment capability and overall costs for different technologies, including ABR, AS, and UV/H2O2. Overall efficiencies reached using UV/H_2O_2, ABR, AS, combined AS-ABR, combined ABR-AS, and combined ABR-AS-UV/H2O2 processes 75.2%, 89.4%, 94.5%, 96.1%, 96.3%, and 99.9%, respectively. A Cost effectiveness analysis was performed at optimal conditions for the SWW treatment by optimizing the total electricity cost, H_2O_2 consumption, and HRT. The combined ABR-AS-UV/H_2O_2 processes reached a maximum reduction in TOC of 99% in 76.5 h with an estimated cost of 6.79 $/m^3$ day. The combined ABR-AS-UV/ H_2O_2 system was shown to be the most cost-effective treatment method compared with the other processes under these conditions. Selecting the most suitable treatment methods requires an understanding of the composition of the SWW being treated and the efficacy and cost of the treatments to comply with the final effluent standards for effluent discharge or reuse.

SWWs are always pre-treated by screening, settling, blood collection, and fat separation. These are followed by physicochemical treatment, including DAF without coagulants and/or flocculants, to recapture FOG for tallow production or with coagulation/flocculation to remove most of the FOG with suspended solids as sludge, with and without secondary biological treatment [84, 85] such as uncovered and covered anaerobic lagoons (CALs) and aerobic ponds such as Biolc ® biological nutrient removal lagoon with various aeration-nonaerated zones. Some final stages may include further flocculation-coagulation in clarifiers followed by sludge dewatering. Although the organic matter and nutrient removal can achieve high efficiencies, the treated SWW effluent usually need further treatment by membrane technologies, AOPs, or other appropriate treatment methods as combined processes. AOPs may also provide high-quality treated water allowing water recycle in the meat processing industry [56, 86]. Therefore, combined processes have evolved into a reliable technology that are being successfully used in many types of SWW effluents. There are diverse SWW treatment processes which can depend on the type, age, size of an abattoir, current processing technologies and circumstances. For example, there may be significant differences between abattoirs in a rural and metropolitan setting. Abattoirs in a rural setting may find that the use dams is a cost effective options for biological treatment compared to compact reactors. Other factors which affect the type of treatment systems in use may be the desire to capture FOG or generate biogas, and other biproducts such as nutrient rich sludge as soil amendment. Another example may include the use of coagulation-flocculation using a DAF followed by the use of tricanters to physically, separate and remove residual sludge solids from residual FOG and water where the biological secondary treatments is carried out offsite by a municipal water treatment plant or where the sludge is dumped into landfill. The selection of a specific abattoir wastewater treatment ultimately, depends on the characteristics of the SWW being treated, the best available techniques (BAT), and the compliance with current regulations under different political jurisdictions [87, 88].

12.4 Concluding remarks

Increasingly stringent environmental regulation for wastewater discharge and a desire to reuse greater volumes of water due to water security issues drives interest in complementary technology options for the treatment of red meat processing wastewater. Ideally, for space constrained processors, these technologies need to be capable of high removal efficiencies whilst being compact in size, easy to operate and energy efficient. Table 7 compares the typical performance of each wastewater treatment technology with respect to their effectiveness at reducing the levels of BOD, COD, TSS and TN. However, there is expected to be a diversity of methods adopted depending on the historical technologies in use at specific processors, the needs of the abattoir and the desired end use of bioproducts such as FOG and water. In addition existing issues with adverse impacts on downstream wastewater treatment due to inefficient removal/recovery of residual FOG resulting in crusting in anaerobic/aerobic ponds, lakes and lagoons and which could adversely affect their performance may be of concern as well as deleterious impacts of contaminated wastewater effluent on the environment.

Table 7: Levels of abattoir wastewater quality markers with different wastewater treatment technologies

Technology	Parameters			
	BOD (%)	COD (%)	TSS (%)	TN (%)
Screening	5-20	-	5-30	-
Floatation	20-25	20-25	50-60	-
DAF	30-40	30-40	50-65	-
Coagulation and flocculation	75	-	-	90
Chemically dosed DAFs	90	90	50-90	-
Land application	-	-	-	65-80
Anaerobic treatment	90	89	85	80
Aerobic treatment	50-80	50-80	-	10-20
Membrane treatment	95	-	-	70-90

13.0 ANALYTICAL TECHNOLOGIES FOR CHARACTERISING FOG

13.1 Introduction

Wastewater analysis is predominantly conducted for regulatory purposes and typically provides analysis of the major constituents of water such as total carbon, nitrogen, phosphate, ash and a combined content of fats, oil, and grease (FOG). This review summarises and discusses the analytical technologies used in FOG analysis. Due to the limited analysis of FOG in abattoir wastewater, this review will also look at FOG analysis of relevant meat products and a variety of wastewater streams such as municipal wastewater, restaurant and fast-food grease traps and seed oil mills.

The main research focus related to abattoir wastewater is concerned with separation processes to recover and decrease of the concentrations of protein and fat in effluent. Therefore, quantitative methods are needed to determine the degree of contamination in the wastewater after different stages in wastewater treatment processes. These include after recovery of FOG in the DAF which is used for the production of tallow, biodiesel and other products, and before it is sent to covered anaerobic digesters for methane production and before it enters the sewer or is reused for other purposes, such as in the cattle yard for washing down the cattle and trucks or for irrigation.

Wastewater analysis of red meat abattoirs in Australia can include: total solids (TS), volatile solids (VS), chemical oxygen demand (COD), total (TCOD), soluble fractions (SCOD), total Kjeldahl nitrogen (TKN), total phosphorus (TP), ammonia-nitrogen (NH_4-N), phosphate-phosphorus (PO_4-P), fat, oil and grease (FOG), sodium and potassium [89]. Some studies also looked at bacterial degradation and products produced, aerobic and anaerobic degradation, effect on methane production [90]. Whilst

FOG can be readily removed, it can have an impact on microbial growth for methane production, whilst also promote the growth of filamentous bacteria, cause foaming and floc flotation [91].

FOG in municipal wastewater is typically at lower concentrations than in abattoir wastewater. However, major issues occur with the formation of 'fatburgs", which are congealed fat oil and grease in sewers when cooking fats oils are discarded directly into drains [92]. It was initially speculated that fatburgs were caused by condensation of FOG with cooler temperatures and hydrophobic interaction of triacylglycerols from cooking and waste fat solidifying in sewers. However, current hypothesis suggests that calcium soaps are formed by hydrolysis of FOG which then form insoluble salts with calcium that is leached from concrete sewers. Hydrolysis of lipids into fatty acids is catalysed under acidic or basic conditions and there is evidence to suggest that bacteria in sewers produce sulfuric acid [92]. Thus, municipal waste with detergents and acidifying conditions are more likely to produce fatburgs than abattoir waste waters which operate at higher temperatures.

In municipal water chemical analyses have been carried out to detect and measure the levels of pharmaceuticals, hormones and drugs of abuse which may have deleterious effects on ecosystems and human health. Other non-lipid, chemical contaminants that have been found to be potential markers for the assessment of contamination by human wastewater have been reviewed by [93] and, include nitrates and nitrogen isotope ratios, fluorescent whitening agents, artificial sweeteners, pharmaceuticals and personal care products. The work on FOG from municipal wastewater may not be directly related to FOG from abattoirs but highlights how compound analysis may be used to study population dynamics or even issues with a population. For instance, the macrocyclic lactones used for treatment of nematodes is highly lipophilic, stored in fat [94] and may be detected in FOG.

13.2 Defining fat, oil, and grease (FOG)

Definitions of fat, oil, and grease as it pertains to animal products is well described by the National Renderers Association. Key to the definitions are where the FOG has been obtained from (such as: Beef fat edible tallow – rendered from fat trimmings and bones) and what the chemical composition is, including fatty acid content, unsaponifiable and insoluble compounds and other factors such as moisture content, hardness and colour (https://lipidlibrary.aocs.org/edible-oil-processing/animal-fats). For the purposes of this review the classification of a lipid is important as the major constituent of FOG in these samples will be fatty acids and their derivatives as described by Christie as a lipid [95]. However, there will also be other hydrophobic compounds or metabolites in the hexane extract, which are not strictly lipids, including polyketides, sterols and prenols [96].

13.3 Composition and characteristics of abattoir FOG

The major component of FOG is predominantly triacylglycerols/triglycerides (TAG/TG) which are comprised of a glycerol (3 carbons back bone) which have three fatty acyl chains (fatty acids, FA) esterified to each of the 3 glycerol hydroxy groups (Figure 56) and is the major energy storage for many animals and plants in seed oil. At room temperature TAG can either be solid or liquid depending on the chain length and number of double bonds in the acyl chains. The chain length is determined by the number of carbon atoms in the FA and the number of double bonds (Iodine number) which refers to how saturated a FA is; a saturated FA has no double bonds, monounsaturated has 1 double bond and polyunsaturated has two or more double bonds. The melting point of the TAG decreases as chain length decreases and as the degree of unsaturation increases. Table 8 shows the melting temperature ranges and iodine value ranges (degree of unsaturation) for fats from common abattoir animal and Table 9 shows the proportion of triacylglycerols (TAG) and phospholipid (PL) in several abattoir animal meats.

Table 10 *shows the melting point of the common FA and their proportions found in beef and la fats. The range in melting temperatures is dependent on the fatty acid (FA) composition containing FA with a range of different chain length and degree of unsaturation.*

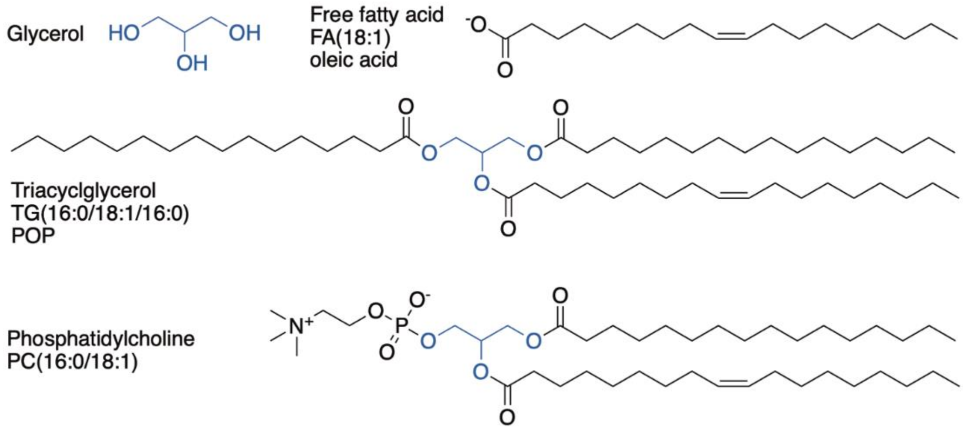

Figure 56: Chemical structures of major lipid classes and glycerol (blue) and fatty acid moieties which are esterified to form triacylglycerols and membrane lipids such as phospholipids (e.g. phosphatidylcholine)

Table 8: The melting point ranges and iodine value ranges of FOG in abattoir animal fats (from Craher meatscience.org)

Fat type	Melting point range (°C)	Iodine value range (°C)
Beef tallow	40-50	25-45
Pork lard	34-44	45-75
Poultry fat	23-40	65-75
Lamb tail fat*	42-48	37-47

Table 9: Content of TAG and PL (mg/g) and proportion of PL in rump (beef), chop (pork and lamb) and breast (chicken). Phospholipids were separated from triglycerides using TLC, from [97]

Species	Total lipid	Phospholipid	TAG	% Phospholipid
Beef	19.6 ± 2.6	4.4 ± 0.4	15.2 ± 1.5	22.4
Lamb	24.8 ± 3.1	4.2 ± 0.6	20.6 ± 2.4	16.9
Pork	21.6 ± 2.1	6.0 ± 0.9	15.6 ± 2.0	27.8
Chicken	15.1 ± 2.1	4.4 ± 0.7	10.7 ± 1.6	29.1

Table 10: The melting point of common fatty acids and their proportion found in beef and sheep, from AMPC https://meatupdate.csiro.au/data/MEAT_TECHNOLOGY_UPDATE_08-2

Fatty acid	FA	Melting point (°C)	Beef (%)	Sheep (%)
Myristic	C14:0	53	2-4	2.5-4
Palmitic	C16:0	63	22-28	22-27
Palmitoleic	C16:1	0	1-12	1-2
Stearic	C18:0	70	4-30	17-30
Trans-vaccenic	C18:1	45	1-12	0.3-4
Oleic	C18:1	16	35-50	19-31
Linoleic	C18:2	-9	1-2	2-4

If the temperature of the wastewater is too high and close to or above the melting temperature range of the FOG, it can hinder a solid float from forming and reduce the effectiveness of the DAF system in separating and removing the FOG. This could lead to losses in FOG from the DAF because of emulsion formation and cause issues downstream from the DAF with FOG crusts forming on the surface of anaerobic and aerobic digesters on cooling and adversely affect their performance. Increased loading in the DAF and/or high FOG loads could exacerbate the issue. Hence it is important to closely monitor the FOG content in abattoir wastewater streams.

13.4 Bulk analysis of FOG

FOG is quantified by obtaining the dry weight of the hexane extractable compounds expressed as %w/v. Over the last several decades the US EPA has modified its methods for the analysis of fats oils and grease from wastewater. Currently, the extraction is being conducted using n-hexane of at least 85 % purity (but is likely to increase to 95 % purity due to changes in the production of hexane) using method 1664A from the clean water act (https://www.epa.gov/cwa-methods/approved-cwa-test-methods-organic-compounds). This method is only used to measure the amount of FOG (based on mass) extracted using hexane per Litre of wastewater based on the US-EPA method (https://www.epa.gov/sites/production/files/2015-08/documents/method_1664a_1999.pdf.)

Most analysis of FOG from wastewater has been conducted using either thin layer chromatography (TLC) or gas chromatography mass spectrometry GC-MS analysis of fatty acid methyl esters (FAME). GC-MS FAME analysis provides the fatty acid composition of fats, oils, and greases. This is particularly suited to the measurement of medium chain fatty acids, saturated, unsaturated, and polyunsaturated fatty acids.

13.5 Thin Layer Chromatography (TLC)

Thin layer chromatography has been used to identify the major lipid classes found in FOG. TLC separates and quantifies the different lipid classes, but not the fatty acid composition. The lipid classes are separated as they migrate up the silica TLC plate in as the solvent is drawn up the plate by capillary action. Each lipid class migrates up the plate at a different rate and can be determined using authentic standards and/or a known retention factor (Rf). Developing the TLC plate by spraying with colouring or UV fluorescing reagents (2′,7′-Dichlorofluorescein) and image analysis using modern imaging analysis software can be of assistance in quantifying the lipid classes. An alternative Instrument (Iatroscan) based on TLC separation can quantify each lipid classes using TLC with flame ionisation detection (TLC-FID) [98] after developing the lipid extract which has been applied on silica coated quartz rods in a suitable developing solvent. After development and air drying, the rods are scanned through a flame and give a signal proportional to the amount of each lipid class. However, this is a destructive method and so separation of lipid classes on a plate covered with silica or a column packed with silica can be used to separate and recover different lipid classes for further analysis of derivatised fatty acids and analysis of their FAME by GC and GC-MS.

The major lipid classes assessed by TLC for wastewater analysis are TAGs DAGs and MAGs (Table 11), [99]. Others have used TLC to determine the rate of bacterial lipase degradation of TAG into FA Figure 57 [90] and its use in increasing biogas yields when mixing digested FOG with abattoir wastewater. Higher FOG concentrations from offal and rendering streams produce higher methane potential. However, concentrations of FOG over 10 000 mgL^{-1} can cause inhibition of the bacterial process [89].

Table 11: Percent lipid class as detected by thin layer chromatography (TLC). Table adapted from Effimova et al. (2013) [99]

Lipid Class	Palm oil Mill Effluent	Municipal Wastewater
	(% of total lipids)	
TG	45	15
DG	15	10
MG	10	5
PL	10	10
FFA	10	20
Sterols	-	15

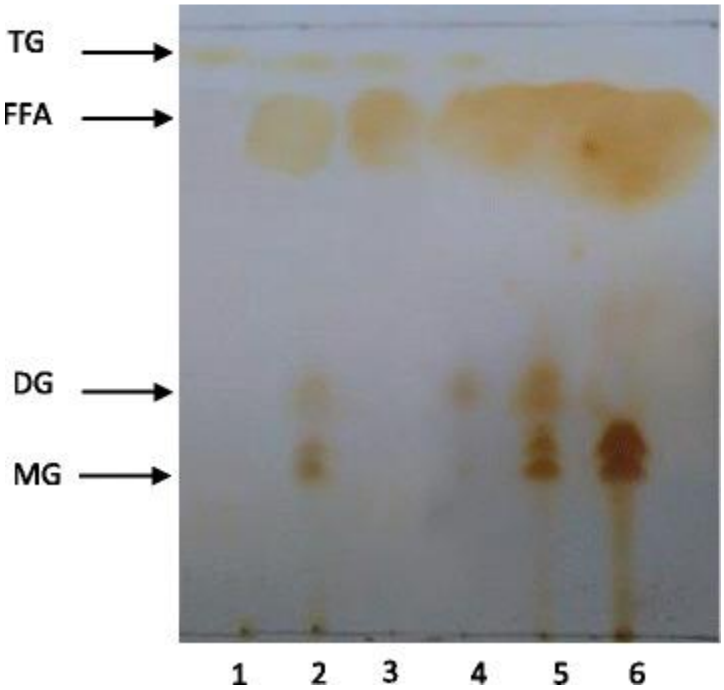

Figure 57: TLC of FOG incubated with staphylococcus xylosus for 1, 2, 4 and 6 days. Lane 1, TG- triolein; Lane 2, olive oil; Lanes 3-6, wastewater Image from Affers et al. (2017) [90].

13.6 Gas chromatography analysis of fatty acids

Gas chromatography (GC) analysis Fatty Acid Methyl Ester (GC-FAME) has been one of the major chromatographic and analytical tools used for a broad variety of organic compounds in nature. The chromatographic technique requires that the samples are volatile and able to enter a gaseous phase. For this reason, many compounds are chemically modified, or derivatised with methylating or silylating reagents to form methyl esters or trimethyl silyl ethers compounds to increase their volatility when they are injected into the hot injector inlet of the GC and volatilised before entering into the capillary column. For the analysis of FOG and other similar lipid samples fatty acid methyl ester (FAME) analysis has become the stalwart of the derivatisation techniques for the analysis of fatty acids from organic solvent extracts of biological samples derived from animals, algae, yeasts, bacteria and plants, and is commonly referred to as GC-FAME analysis. Importantly, the preparation of FAME's involves hydrolyses or transmethylation the fatty acyl chains from the lipid to which they are esterified and converts the hydroxy group from the liberated free fatty acid to a methoxy ester group. Therefore, for each TAG molecule three corresponding fatty acid methyl esters are produced. Likewise, each DAG, PC, PE molecules each have two acyl chains and corresponding to the production of two FAMEs. FAME's can be detected by several detectors coupled to the gas chromatograph. Mass spectrometry can be used for the confirmation the fatty acid species or a flame ionization detector (FID) can be used for quantification and has less initial outlay and is simpler and more economical to operate for routine analysis of well characterised samples. Fatty acids identification is carried out by comparison of retention time of pure standard or standard mixtures. FAME analysis of meat and dairy products is well characterised and is routine. Different derivatisation techniques have also been employed to characterize and identify different acyl chain compositions including double bond position and *cis/trans* isomerisation. TLC and associated wet chemistry techniques for the separation of lipid classes can be paired with other techniques for lipid analysis. An example of a FAME analysis of the phospholipid fraction isolated from the total lipids from goat, sheep and beef is shown in Table 12.

13.7 Gas Chromatography-Mass Spectrometry (GCMS)

Unsaponifiable lipids can be detected using GCMS without FAME derivatisation, such compounds include cholesterol, vitamin A, squalene, and carbonyls [98]. Cholesterol is an essential sterol for the formation of cellular membranes and the correct functioning of cells. Techniques of cholesterol analysis in the meat and poultry industry have been reviewed of [97, 99] and it was found that cholesterol levels were 35-55 mg/100g for different cuts of beef. There have been many different measurement techniques used in the past including spectrophotometric, gravimetric, and enzymatic assays. These assays lack the selectivity required, often leading to overestimating the concentration of sterols, however the major techniques currently used which can easily identify and quantify different sterols are GCMS or liquid chromatography-mass spectrometry (LCMS).

Ruminants do not obtain cholesterol from their diets, rather they synthesize cholesterol from acetyl CoA in the liver. The plant phytosterols stigmasterol and β-sitosterol play important roles in gut biochemistry and are absorbed into the mammalian blood stream. Recent reports highlight the importance of the phytosterols in the diet of sheep, helping protect from acidosis. Sterols are also converted to stanols via gut bacteria. In municipal wastewater coprostanol, a derivative of dietary cholesterol, is present at 40-60% of all the total sterols [89] (https://www.mdpi.com/2073-4441/9/2/143/htm). However, herbivores do not have cholesterol in their diet and the major stanols are 24-ethylcoprostanol which is 55 % and 30 %of total sterols of sheep and cattle, respectively and 24-ethylepicoprastanol which is 12 % and 30 % of total sterols of sheep and cattle, respectively [100] which are derived from the plant based β-sitosterol. Analysis of the sterols and stanols from FOG by GCMS or LCMS will provide information on the waste streams. The red waste stream should be higher in cholesterol, but the levels of other plant sterols may give an indication of their diet. The green waste stream will be higher in the stanols and the ratios of phytosterols, cholesterol, and the coprostanols may provide information about the food the animals have been eating prior to entering the slaughterhouse. Furthermore, analysis of these compounds may provide a clear indication of the contamination between waste streams. It is unlikely that there is any commercial sense in purifying these minor sterols from waste for any industry unless high levels of phytosterols were present.

Table 12: Percent fatty acid composition of the phospholipid fraction from goat, sheep [100] and beef total lipid [101]

Fatty acid	Goat	Sheep	Beef
10:0	0.03	0.03	0.06
12:0	0.14	0.04	0.05
14:0	1.13	0.44	1.53
14:1	0.02	0.01	0.56
15:0	0.27	0.29	2.36
15:1	0.21	0.47	-
16:0	15.29	17.41	20.45
16:1	0.49	0.52	-
17:0	0.85	1.55	1.23
17:1	0.35	1.03	0.34
18:0	15.48	14.70	13.23
18:1 *trans*	0.15	0.26	0.25
18:1 *cis*	25.77	24.52	22.48

18:2 *trans*	0.10	0.06	0.12
18:2 cis	15.03	17.97	21.52
18:3ω6	0.13	0.14	0.08
18:3ω3	1.30	1.40	0.88
20:0	0.21	0.18	0.07
20:1	0.32	0.49	0.11
20:2	1.75	1.82	0.12
20:3	0.96	1.02	0.71
20:4	13.14	8.34	3.6
20:5	1.58	1.99	3.6
22:1	0.10	0.27	-
22:2	0.10	-	-
22:5	3.81	3.22	0.62
22:6	1.32	1.82	0.02

13.8 Liquid Chromatography-Mass Spectrometry (LCMS)

Over the last decade lipidomics techniques have started to become more prevalent in the lipid research literature. Lipidomics typically uses liquid chromatography mass spectrometry (LC-MS) to enable the separation of different lipid classes and species as well as give acyl chain information of the lipid species. The use of "soft" ionisation techniques such as electrospray ionisation (ESI) and atmospheric pressure chemical ionisation (APCI) enable the ionisation of the whole lipid species in its native form without the need of derivatisation and give greater detail for full lipid characterisation.

Hydrophilic Interaction liquid chromatography (HILIC) columns separate FOG by lipid class in a similar order to that obtained by silica phase TLC techniques. HILIC chromatography is particularly useful for the separation of phospholipid species, for instance the separation of sphingomyelins from phosphatidylcholines which have similar masses and fragmentation patterns. This technique also enables the simple quantification of the total number of lipid species in a class. However, HILIC columns are limited by their inability to separate species within a class and thus conducting complete identification of the lipid species is limited.

Reverse phase columns, which are more typical for LCMS, separate each species through hydrophobic interactions of the nonpolar stationary phase and the fatty acid moieties. With improving instrumentation, each lipid species can be fragmented to determine its fatty acid composition. A selection of reversed-phase HPLC columns chemistries can be used such as C8, C18 and C30 columns to obtain selective separation of lipids. Given the number of analytical columns, techniques and instruments, there is no current standardised lipidomic platform for the quick and easy quantification and structural determination of all lipid species.

A targeted lipidomics approach can also be used to analyse lipids known to be in a sample set [102, 103]. This study many lipid pathways and lipophilic molecules that have differential expression between cows with a higher feed efficiency which was determined by the average daily gain (ADG) in different tissues including adipose, liver and duodenum. Whilst application of triple quadrupole (QQQ) LCMS based targeted approach applied here was focused on the membrane lipids PC, PE, their corresponding lyso lipids and cholesterol, similar targeted approaches can be used once any metabolite or lipophilic compound is detected. The results shown in Artegoita etal. (2019) [102]

(Table 13) show higher concentrations of phospholipids containing long chain omega-3 fatty acids in the liver as compared to adipose tissue or duodenum.

Table 13: Quantification of lipid species from the major phospholipid, PC, in the liver, adipose and duodenum (results shown in mg/g) in high average daily gain beef steers. Adapted from Artegoitia et al. (2019) [102].

Phosphatidylcholine (PC)	Liver	Adipose	Duodenum
	% of total phospholipids (PL)		
16:0/16:0	31.9	14.1	10.3
16:0/18:1	6.19	3.77	1.04
16:/20:3	16.1	6.36	2.03
16:0/20:4	16.9	8.21	2.57
18:0/18:1	17.9	1.28	0.42
18:0/18:2, 18:1/18:1	5.24	1.81	0.63
18:0/20:3	7.53	2.05	0.40
18:0/20:4	10.6	3.69	0.86
18:0/22:5	15.4	1.35	1.85
18:0/22:6, 18:1/22:5	12.0	2.84	1.81
18:1/20:4, 18:0/20:5, 16:0/22:5	13.9	3.65	1.14

One advantage of lipidomics over the use of TLC and GC-FAME analysis is that other non-acyl lipid species can also be detected. Such species include the ceramides and sphingomyelin, plasmenyl and plasmanyl phospholipids which have an ether bond in the sn-1 to an alkyl or an alkenyl group, respectively, the later are called plasmalogens. Lipidomics of goat and sheep meat show that the major phospholipid in these tissues is phosphatidylcholine (PC) and between 2-5% of this can be plasmalogen PC [100]. Whilst GC-FAME analysis demonstrated that these samples predominantly were composed of the major lipids found in sheep fat (palmitic, stearic, oleic, linoleic) and the long chain PUFAs arachidonic , eicosapentaenoic (20:5ω3, EPA), docosahexaenoic acid (22:6ω3, DHA). The use of orthogonal techniques enables the discovery of other novel and perhaps valuable lipid species which may have commercial value. For instance the plasmalogens are being explored for their ability to form vesicles and may have applications in drug delivery systems [104, 105]. Also, the ceramides are of particular interest in the cosmetics industry and are used predominantly for skin creams and may be of importance in treating skin conditions [106]. Ceramides are found in cattle horns, serum, milk and likely to be found in wastewater. Studies would be required to determine the concentrations in wastewater and develop extraction techniques for these products.

An untargeted metabolomics/lipidomics approach with associated statistical/computational techniques such as principal component analysis can assist in the identification of characteristic compounds that discriminate between treatment sets. For example these techniques have been used to determining the adulteration of beef [107] with cheaper meat substitutes. Other studies have enabled the discovery of novel lipids such as the N-acyl tyrosines which have been identified in biofilms produced by bacterial growth in abattoir wastewater [108]. These N-acyl tyrosines are produced by flavobacterium species and may have useful anti-microbial properties.

13.9 Nuclear magnetic resonance (NMR) spectroscopy

NMR of lipid analysis has recently been reviewed [109]. Efimova used proton NMR in waste oil from palm oil production and municipal waste to determine the TAG content and the average chain length and number of double bonds. Nuclear magnetic resonance spectroscopy is available at different levels specificity and sensitivity and for structural elucidation or confirmation of the identity of novel compounds. At the low end, bench top NMR instruments are capable of a basic level of analysis of oil composition in samples and to determine the amount of oil in wastewater samples. At the high end, instruments require their own room and cooling with liquid helium. Phosphorus based NMR instruments are excellent for the detection and characterization of phospholipids. This technique is not useful however, for the detection of lipid classes that do not have phosphates present. ^{13}C NMR and ^{1}H NMR instruments are useful for the characterization of lipid species.

14.0 PATENT REVIEW-TECHNOLOGIES FOR SEPARATION OF FOG

14.1 Objectives

There were three main objectives:

1. To review the state of the current technologies being developed for potential use in abattoir wastewater treatment, particularly related to primary treatment for the removal and/or recovery of FOG from abattoir wastewater streams.
2. To understand which technologies, have the greatest research effort for improving FOG recovery.
3. To determine if there were any patents related to the use of ultrasound and/or megasonics for FOG demulsification and recovery.

14.2 Patent search strategy

Patent searches were focused on processes and machines for FOG separation and recovery which are or might be applied to FOG containing abattoir wastewater. These were conducted using search engines of the following databases: Google Patents ((GP) simple and advanced search) and Web of Science (Derwent Innovations index (DI)). Espacenet Patent search (ESN) was used to search international patent classification (IPC) codes obtained from relevant results from GP and DI searches using key words. The following key words were used: [wastewater], [abattoir, slaughter*, slaughter house, slaughterhouse], [fat, oil, grease, FOG, emulsion*] [separation, extraction, recovery, capture], [dissolved air flotation (DAF)], [countercurrent extraction, centrifugal countercurrent extraction], [ultrasound, megasonics]. As an example, a key word search using, dissolved air flotation and fat yielded several IPC codes, two of which are relevant and are within the classification description: Recovery of fats, fatty oils, or fatty acids from waste materials (C02F, E03F). These IPC codes could be used to drill down further to find more specific patents/IPC codes which are relevant, combined with key words or IPC codes using the advanced search function in ESN and DI. “Please note the following important comments relating to the report contents and search limitations:

1. This report generally refers to patent families rather than individual patents. A patent family is a group of patents that are related, usually by a priority document or documents, so as to relate to one invention. For example, a patent family may have related patents in Australia, the United States of America and Japan. The number of patent families is typically a better measure for most of the analytics undertaken as it removes duplicates; and

2. It is also important to note that patent information is not published in databases when a patent is first filed (i.e., at the priority date). The first publication of information for a patent may not occur for at least 18 months in most cases. Therefore, it is likely that the results for 2018 onwards do not yet include all patent applications. This data issue will be reflected in all the search results and analysis provided in this report." Hence this patent review constitute a preliminary due diligence and a more comprehensive IP landscape search may be conducted later if needed for more certainty about the status of a particular patent family of interest.

14.3 Results and discussion

The results of the of the most relevant patents are grouped in Table 14 under the same or similar technologies. The status of each patent is listed as either active, not active, pending or TBD as indicated by Google patent or Derwent Innovation data bases and a more in-depth enquire as to the current status of those TBD needs to be carried out if required. These grouping were:

1. Physicochemical coagulation/flocculation/flotation
2. Electro-coagulation/flocculation/flotation
3. Demulsification
4. Centrifugation/filtration
5. Dissolved gas flotation
6. Solvent extraction
7. Heating/pressure/settling
8. Ultrasound/megasonics

Table 14: Patents for technologies including machines and/or processes for the treatment, separation, and recovery of FOG in FOG laden abattoir wastewater

Patent No.	Date	Active	Process/ Machine	Title	Description	Assignee	Inventor(s)
				Physiochemical coagulation-flocculation/flotation			
AU-2017232158-B2	2018	Y	P+M	Water treatment system and method	Flocculation/coagulation/precipitation DAF and clarifier	Waterwerx Technology Pty Ltd	Abhyuday Bhartia et al.
CN-108911412-A	2018	TBD	P+M	A kind of slaughterhouse sewage water treatment method	Coagulation liquid/filtration/ combined process	济宁鸿润食品股份有限公司	王德定 et al.
CN109133538-A	2018	TBD	P	Processing slaughter wastewater comprises separating impurities from wastewater, stirring by multi-curved mixer, pre-treating, adding flocculant to e.g. polyaluminium chloride, carrying out nitrification and de-nitrification and refluxing	Polyaluminium chloride flocculant in DAF	HENAN HENGAN ENVIRONMENTAL TECHNOLOGY CO	CHEN X et al.
WO-2014067908-A2	2014	TBD	P+M	Device and method for obtaining at least one pure substance from biological waste or biomass	Flocculation/fat recovery	Robert Stöcklinger	Robert Stöcklinger
EP-2274243-A1	2011	Y	P	Methods for recovering tallow from wastewater	Copolymer of a tannin and cationic monomer coagulant/DAF	General Electric Company	Abdul Rafi Khwaja, Stephen R. Vasconcellos
JP-2011529525-A	2011	Pending	P	Method for removing fat, oil and grease from wastewater and method for collecting tallow	Flocculant polyacrylamide or acrylamide copolymer	ゼネラル・エレクトリック・カンパニイ	ウッド，マイケル・アール
US-2010163483-A1	2010	N	P+M	Food processing resource recovery	Hydrolysis of peptide bonds in DAF float by a lytic agent	Zentox Corporation	Michael Grady et al.
US-7771699-B2	2010	Y	P+M	Depolymerization process of conversion of organic and non-organic waste materials into useful products	Extraction/flocculation	Ab-Cwt, Llc	Terry N. Adams et al.
WO2008060631-A2	2007	TBD	P	Coagulant for use in foodstuffs wastewater treatment, comprises anionic nanoparticulate clay	Anionic nanoparticulate clay coagulant in DAF	BOC GROUP INC	
CA-2161584-C	2000	N	P	Food processing effluent rendering process and apparatus	Clay and algal derived coagulant-flocculant	Lynda C. O'carroll et al.	
US-5695647-A	1997	N	P	Methods of treating wastewater	Cellulose ester flocculant	North Carolina State University, Hoechst Celanese Corporation	Ruben G. Carbonell et al.
US-5543058-A	1996	N	P	Process for removing proteinaceous materials, fat and oils from food processing wastewater and recovering same	Lignan/halogen ion coagulant, natural polysaccharide polymer flocculant	Miller; Jack C.	Jack C. Miller
NZ260893-A	1994	TBD	P	Treatment of effluent streams containing. proteins and fats - using bentonite as coagulant, used for effluent from meat works, dairy factories, food factories etc.	Bentonite clay coagulant + flocculant in DAF	ENVIROFLO LTD	R Kovac
US-4219417-A	1980	N	P	Wastewater flotation utilizing streaming potential adjustment	Anionic polyelectrolyte flocculant	Dravo Corporation	Ernest R. Ramirez
US-3929635-A	1975	N	M	Use of polymeric quaternary ammonium betaines as water clarifiers	Polymeric quaternary ammonium betaines as flocculant-demulsifiers	Petrolite Corp	Rudolf S Buriks, Allen R Fauke
GB-172777-A	1921	N	P+M	Improvements relating to the treatment of waste organic substances	Boiling/coagulation to remove fat	Angus Maclachlan	
				Electro-coagulation/flocculation/flotation			
US-2013180857-A1	2013	N	P+M	EcoFloc Advanced Electro-coagulation Liquid Waste Treatment System and Process	Electro-coagulation	Tim Heffernan, Bruce Rea	Tim Heffernan, Bruce Rea
WO-2008077157-A1	2008	N	P+M	Electrochemical reactor and process for treating lipoid containing effluent	Electro-flotation	Ecodose Holdings (Pty) Ltd	Jochemus Johannes Smit

AMPC

CA-1084868-A	1980	N	M	Water waste treatment with periodic current reversal in production of microbubbles	Electro-flocculation	Dravo Corporation, Ernest R. Ramirez	Ernest R. Ramirez
US-4012319-A	1977	N	M	Wastewater treatment	Electro-flotation	Swift And Company	Ernest R. Ramirez
US-3479281-A	1969	N	P+M	Method and apparatus for the separation of phases by gaseous flotation	Electro-flotation	Saint Gobain Techn Nouvelles	Tivadar Kikindai, Jean Loup Burgaud
				Demulsification			
WO-2020047181-A1	2020	Y	P	Use of multiple charged ionic compounds derived from polyamines for wastewater clarification	Multiple charged ionic polyamines demulsification coagulant /flocculants	Ecolab USA Inc.	Ashish Dhawan et al.
EP-0765184-B1	1998	N	P	Novel method for treating an emulsion	Cyclodextrin demulsification	Roquette Freres SA	Serge Gosset et al.
HU-198529-B	1989	TBD	P	Process for regaining of fat or oil of animal or plant origin from watery dispersions containing protein	Emulsion breakup by settling-centrifugation	Akos Gyulai et al.	Akos Gyulai et al.
US-3673065-A	1972	N	P	Electrolytic removal of greasy matter from aqueous wastes	Electrolytic demulsification-flotation	Swift & Co	Harry T Anderson
US-3519559-A	1969	N	P	Polyglycidyl compounds as water clarifiers	Polyglycidyl compounds as demulsifiers	Baker Petrolite LLC	Patrick M Quinlan
US-2229376-A	1941	N	P	Process for dehydrating and defatting water-and oil-containing substances	Electrolyte salts as emulsion preventatives	Fauth Patent A G	Fauth Philipp Lorenz, Reichert Joseph
				Centrifugation/filtration			
EP-3426606-A1	2019	Pending	P+M	Apparatus for the treatment of wastewater containing fats, oils, and grease	Combined DAF, disk and decanter centrifuge	Physichem Ltd	Thomas Philip JAMES
US-9670429-B2	2017	Y	P+M	Separation systems for dewatering of fog and biodiesel fuel production	Filtration membranes	Smartflow Technologies, Inc.	Jason Bell et al.
DE-102011053103-A1	2012	N	P+M	Device and method for obtaining oil and / or fat from oil and / or fat-containing wastewater	Filtration and centrifugal separation	G+R Technology Group Ag	Eberhard Roquette et al.
US-2009057234-A1	2009	N	P	Method for making brown grease	Combined DAF, sludge, decanter 1 (solid/liquid), decanter 2 (water/grease)	Sf Investments, Inc.	John Noble ARMSTRONG, Cory Allen Johnson
EP-1757562-A1	2007	N	P+M	Device and process for treating residues of biogas production, manure, and sludge	Vacuum vertical lifting helix + vibration shear filter	Daniela Richter, Winfried Hitze	Daniela Richter, Winfried Hitze
CZ-7911-U1	1998	TBD	M	Apparatus for separating fats	Screen belt press filter poultry fat separation	Idea, Spol. S.R.O.	Miroslav Jirásek et al.
				Dissolved gas flotation			
US-2020131051-A1	2020	Pending	P+M	System for recovering fat, oil, and grease from wastewater	Micro air and ozone flotation bubbles distribution system	Water Environmental Technology	William Michael FIELDS et al.
WO-2019014628-A1	2019	TBD	P+M	System for recovering fat, oil, and grease from wastewater	DAF for improved removal of FOG	Water Environmental Technology	William Michael FIELDS et al.
WO-2019035999-A1	2019	TBD	M	System for resource recovery from wastewater	Multiple annular flotation zones	Water Environmental Technology	William Michael FIELDS et al.
				Solvent extraction			
WO-2018231791-A1	2018	TBD	P	Remediation of rag layer and other disposable layers in oil tanks and storage equipment	Terpene solvent and salts demulsification	Locus Oil Ip Company, Llc	Sean Farmer et al.
US-2016122686-A1	2016	N	P+M	Device and method for solubilizing, separating, removing, and reacting carboxylic acids in oils, fats, aqueous or organic solutions by means of micro-or nano emulsification	Solvent extraction of oils and fats from emulsion and membrane filtration	Ulrich Dietz	Ulrich Dietz

US-7638314-B2	2009	Y	P	Production of biodiesel and other valuable chemicals from wastewater treatment plant sludges	Solvent extraction of dewatered/dried sludge	Mississippi State University	Mark Zappi et al.
HU-194523-B	1988	TBD	P+M	Process and equipment for cleaning wastes mainly of poultry farms containing emulgated fat, revolving drum filter and discharge-device especially for implementation of the process	Toluene extraction of wet FOG float	Baromfitermeloek Egyesuelese	Miklos Szigeti et al.
DE-3443950-C2	1988	N	P	Patent DE3443950C2	FOG extraction using a volatile oil	Hanover Research Corp., East Hanover, N.J., Us	Charles Murray Hill et al.
CA-1167792-A	1984	N	M	Use of free bodies to increase size of dispersed phase particles	Tumbler with bitumen phase for oil extraction from wastewater	Jan Kruyer	Jan Kruyer
FR-2470629-A1	1981	N	P+M	Recovering clean water and solids from aq. solids - using fluidising oil to produce mixt. which remains pumpable after removal of water content	Extraction with low viscosity water immiscible relatively volatile light oil	Hanover Res Corp	Charles Greenfield et al.
EP14685-A	1980	N	P+M	Animal fat extraction especially from slaughterhouse waste - in static column without circulation, using super-critical gas extractant	Supercritical CO_2 extraction	HAUSSENER E (HAUS-Individual) NOVA-WERKE AG	E HAUSSENER et al.
US-3917508-A	1975	N	P+M	Process and apparatus for recovering clean water and solids from dilute aqueous solids	FOG extraction using a relatively volatile oil	Hanover Res Corp	Charles Greenfield et al.
US-3898134-A	1973	N	P+M	Process and apparatus for recovering clean water and solids from dilute, aqueous, solids containing solutions or dispersions	FOG extraction using a relatively volatile oil	Hanover Res Corp	Charles Greenfield et al.
				Heating/pressure/settling			
WO-2019053750-A1	2019	TBD	P+M	Integrated waste conversion system and method	Steam explosion, hydrolysis- saponification/biofuel production	LIFDISILLEHF.	Oddur Ingolfsson et al.
KR-101419756-B1	2014	TBD	P	Process of conversion of organic and non-organic waste materials into useful products	Heat and pressure for depolymerisation	테리 엔. 아담스	테리 엔. 아담스
FR-2929807-A1	2009	Y	P+M	Process for obtaining proteins from treatment of adipose tissues	Heat and pressure to separate wet fog from protein	Snc Cornille Snc	Denis Aignel
WO2006115422-A1	2006	TBD	P	Treating dissolved air flotation sludge, to separate fat and protein parts, comprises adjusting sludge pH to acidic pH, mixing emulsifying agent, heating, allowing to cool and stand, and removing each separated protein and fat component	DAF sludge acidification, emulsifier, heat and cool	FONTERRA COOP GROUP LTD	Hamilton R B
HU-217670-B	2000	TBD	P+M	Process and arrangement for removing of meat industrial waste and equipment for executing of the process	Heat > 100oC separates fat layer	György Sáfár	György Sáfár
CZ-427690-A3	1993	TBD	P+M	Process and apparatus for recovering solid substances containing fats and/or proteins from liquid substances containing fat, particularly from slaughterhouse sludges and/or from slaughterhouse wastewater	Heating and pressure for phase separation	Richter Gedeon Vegyeszet	Peter Ing Rudolf et al.
DD-261927-A3	1988	TBD	P+M	Device and method for separating fat from wastewater	Long basin separates FOG and sludge	Inst Gefluegelwirtschaft Merbi	Uwe Halbach et al.
				Ultrasound/megasonics			
US-9371502-B2	2016	Y	M	Vegetable oil extraction	Separation of palm oil using megasonics above 400 kHz	Commonwealth Scientific and Industrial Research Organization	Mary Ann Augustin et al.
US-9388363-B2	2016	Y	M	Ultrasonic and megasonic method for extracting palm oil	Separation of palm oil using megasonic frequency of 360 kHz	Megasonic Sweeping Incorporated	J. Michael Goodson, Lim Teong Kheng

14.3.1 Improvements to established technologies

The largest research efforts in the patented literature has been in the development of various methods of physicochemical coagulation/flocculation/flotation using a wide variety of chemicals such as polyaluminium chloride flocculant, copolymer of tannin with and cationic monomer coagulant, lytic agents for the release of FOG, anionic nanoparticulate clay coagulant, clay and algal derived coagulant-flocculant, cellulose ester flocculant, lignan/halogen ion coagulant with natural polysaccharide polymer flocculant, bentonite clay coagulant, anionic polyelectrolyte flocculant and polymeric quaternary ammonium betaines as flocculant-demulsifiers. Seven patents have expired or reached end-of-life, with 3 patents confirmed to be still active and six who's status needs to be determined.

Five patents related to Electro-coagulation/flocculation/flotation by forming microbubbles published between the years 1969-2013 are not active indicating this area of research not a growth area. Six patents have been found related to demulsification using: multiple charged ionic polyamines demulsification-coagulant/flocculants, cyclodextrin, using settling-centrifugation, electrolytic demulsification, polyglycidyl compounds, and electrolyte salts as emulsion preventatives. Only the first of these patents by Ecolab USA Inc. (2020) is active.

Six patents on centrifugation/filtration to recover FOG were found. One used a combined DAF, disk, and decanter centrifuges (2019). In the area concerned with dissolved gas floatation three recent process and machine patents have been published two in 2019 and one in 2020, all by the company, Water Environmental Technology and the patent status is pending (2020) and to be determined (2019). The main improvement is the design of multiple annular floatation zones using air or ozone floatation bubbles for an improved bubble distribution. The lack of patents around DAF indicates that this technology is already well developed.

Ten patents, of which 3 potentially active were found related to various types of solvent extraction of FOG using: terpenes and salts for demulsification (TBD, 2018), solvent extraction combined with membrane separation, solvent extraction on dewatered or dried sludge (active, 2009), toluene extraction of wet FOG float (TBD, 1988), volatile oil as a solvent for FOG, tumbler with bitumen phase for oil extraction, low viscosity water immiscible relatively volatile light oil (3 from Hanover Res Corp), supercritical CO2 extraction. Seven patents were recovered describing processes and machines using elevated temperature with/without pressure or settling to facilitate depolymerisation, and phase separation of FOG.

14.3.2 Ultrasound/megasonic demulsification

A patent search for processes using ultrasound and/or megasonic resulted in two active patents, one using a combination of an ultrasonic horn press operating at 20 kHz for extraction of oil from palm fruit and a megasonic sound waves transducer with a frequency of 360 kHz for the clarification of the oil phase emulsion (2016, Megasonic Sweeping Incorporated). The second patent (2016, Commonwealth Scientific and Research Organisation, (CSIRO)) describes the use of megasonic transducers operating at frequencies (400 kHz-2 MHz) for the demulsification, separation and recovery of oil from emulsions in palm oil mill effluent sludge.

To our knowledge these are the only two patents concerning megasonic sound waves for demulsification of wastewater streams laden with oil. Neither mention applications for recovery or separation of FOG from meat processing wastewater streams. In addition, the CSIRO patent describes frequencies in the range we are considering trialling for enhancing the separation and recovery of FOG from abattoir wastewater treatment streams. This will be the first time that megasonics will be trialled in this context for this purpose and it is anticipated that there is a strong likelihood of new IP and learnings to be gained concerning the performance and optimised conditions for separation of FOG from abattoir wastewater streams. Applications will be centred around the DAF which is the most popular primary FOG separation technology and emulsions from tricanters. High loadings of FOG tend to limit the efficiency of operation of the DAF in removing most of the FOG. The use of coagulants, salts, demulsifiers, flocculants and acids in the DAF are likely to lead to different results compared to facilities where the DAF operate without any chemical additives for the recovery of FOG for feeding back to be rendering cooker to produce tallow.

15.0 MEGASONIC TRIALS

15.1 Overview

Fat, oil, and grease (FOG) contaminated wastewater in various wastewater process-flow streams in 3 abattoirs, two in Queensland (Q1 and Q2) and one in Victoria (V2), were identified and sampled. The fat content of these streams was determined and the most relevant streams with high FOG content were subjected to a range of megasonic (MS) treatments at various temperatures with and without centrifugation under different g-force and time. The FOG separation in the MS treated samples were compared with the control (non-MS treated) samples to determine if MS treatment facilitates increased FOG separation and recovery *via* MS demulsification mechanisms. FOG separation was assessed visually, by volume measurement and/or mass measurement in separated fractions.

Of the three abattoirs investigated, Q1 and Q2 which capture FOG from wastewater for rendering and manufacture of high grade tallow were very similar and efficient at recovering most of the FOG without the use of chemical flocculants, by recycling wastewater from the rendering cooker and tallow recovery centrifuge back into the dissolved air floatation tank (DAF) in the case of Q1 and FOG float dewatering decanter, rendering decanter and tallow recovery centrifuge in the case of Q2 leaving DAF exit water with a very low FOG content (0.04-0.09%, w/w). Hence unless the DAF was overloaded, which was not the case in this study, megasonic (MS) treatment of the DAF exit wastewater proved to be of no benefit. For these two abattoirs the efficiency of the DAF can be improved by lowering the wastewater temperature to below the melting point of subcutaneous fat (29 ^{o}C) by installing cooling towers and ensuring the bubble size in the DAF is as small as possible to aid float formation. Additionally, a high-speed centrifuge can be used to capture the residual FOG emerging from the DAF.

Abattoir V2 in contrast, had several wastewater streams with high FOG contents and was the most promising abattoir for exploring the recovery of FOG using megasonic treatments. The two major streams were from the DAF sludge produced by chemical flocculation (0.6-9%) and the downstream decanter tallow sludge (33%). MS treatment on its own was not able to effectively separate the FOG from any of the FOG containing waste streams without the aid of a following centrifugation step.

MS treatment of DAF sludge at 25 ^{o}C followed by centrifugation for 3 min at 1717 g, provided clear separation of the FOG layer from a clearer water and sludge-water layer (2.5:12.5: 25 v/v/v) but there was no FOG separation seen with the control. At higher treatments (50-90 ^{o}C) there was no observable benefit of Megasonic (MS) treatment followed by centrifugation compared with centrifugation alone and the separations at 70 ^{o}C and 90 ^{o}C did not enhance the separation of FOG. Similar results were seen for the decanter tallow sludge at 25 °C and with no discernable difference in FOG separation at higher temperatures and between MS and the non-MS control. The major factor influencing the separtions of FOG being the application of centrifugation.

When the treatment temperature was fixed at 50 °C and the centrifugation force (g) and time was varied we found that MS treatment in combination when followed by centrifugation at certain parameters resulted in higher degree of FOG separation from the FOG-water emulsion leading to a denser FOG layer compared with the non-megasonic treated sample. MS followed by centrifugation at 3200 rpm (1717g) for 3 minutes separated and recovered 91% (w/w) of the FOG in the emulsion compared with a 48% separation for the non-megasonic treated sample. Centrifugation at 4000 rpm (2683 g) for 1 min resulted in similar separtions of FOG from the FOG emulsion between MS and non-MS treated samples (72% vs 68%, w/w) and centrifugation at 2000 rpm for 5min gave a slightly enhanced separation of FOG for MS over non-megasonic treated sample (67% vs 56%, w/w). These results show that MS when combined with specific centrifugation conditions such as centrifugal force and time can enhance the separation of FOG although centrifugation at higher centrifugal force and extended time with a temperature of 50 °C or higher removes an advantage of a megasonic treatment since under those condition the dominant and efficacious separation technology is centrifugation.

For the DAF sludge stream and the decanter tallow sludge, greater improvements in FOG separation and recovery may be achieved using a high-speed centrifuge. Hence, a secondary high g centrifugation may be a practical alternative solution for recovery of FOG from these fractions.

The trials conducted here were preformed a small laboratory batch scale and it is not known if MS will have a positive impact at industrial scale, but it seems unlikely from the results reported here. However, it does seem that centrifugation without the use of MS may be able to improve the FOG removal and recovery and alleviate pressure on the decanter if removed early from the DAF sludge stream before going to the decanter.

For V2, the most promising result for reducing losses of high-quality FOG from the rendering plant centrifuge wastewater due to inefficient FOG recovery was the separation effect seen in the PP3 Black pit. The PP3 Black pit contained a rich source of high-quality FOG that could easily be recovered by centrifugation for return to the render cooker prior to being lost due to mixing with the green wastewater stream for increased high-grade tallow production. This would be the earlies intervention and would greatly reduce downstream pressures on the DAF and subsequently on the decanters for the removal of FOG and hence seems to be the most logical and efficacious solution (option 1).

The FOG in the pre-PP3 black pit render centrifuge wastewater was not able to be separated by MS but we found that heating the wastewater to 55 °C and cooling to room temperature flocculated and floated the FOG to the top without the addition of any chemicals. This technique could be used with an additional DAF without flocculant addition specifically for the recovery of high-grade FOG (option 2) and /or centrifugation (option 3) to capture FOG before entering the PP3 black pit and reduce FOG lost in the DAF and decanters.

We recommended a future investigation at pilot-scale on how an early intervention at the PP3 Black pit via centrifugation at high temperature and other options mentioned above can separate and recover high-quality FOG prior to the DAF for increased tallow yield, improved efficiency of the DAF and tricanter and reduced sludge disposal and treatment costs.

16.0 METHODOLOGY

16.1 Introduction

This proof-of-concept study was conducted to explore if megasonic (MS) treatment at a laboratory bench scale (100-600 mL) could assist in the separation and recovery of fat, oil, and grease (FOG) from red meat abattoir wastewater processing streams. It follows on from the questionnaires and site visits of four relevant abattoirs, two in Queensland (Q1 and Q2) and two in Victoria (V1 and V2). V1 was deemed unsuitable for this study after the site visit since it was a new site and did not have any substantial FOG loss issues due to rendering being carried out offsite, it also did not use a DAF or decanter for FOG recovery. Milestone 1 report was completed for the discovery and scoping phase and milestone 2 report completed for the literature and patent review of technologies for abattoir wastewater treatment and FOG separation and recovery.

Before selecting the relevant wastewater streams for sampling and conducting the proof-of-concept megasonic trials, we consulted with each of the participating abattoirs to understand the issues they are facing, with the technologies they are using, for FOG separation and recovery from their wastewater streams. We then identified the most significant FOG input streams and process flows. Sampling was carried out to quantify the % FOG content in these streams to confirm the most significant process-flow stages and select the most applicable streams for megasonic intervention.

It is important here to highlight the similarities and differences between the three abattoirs participating in this study. The main technologies used for separation of FOG from wastewater in each of these abattoirs is show in Table 15. The main reasons for separation, recovery, and/or removal of FOG from wastewater containing substantial amounts of FOG and uses of the FOG are also listed. The process flow diagrams which focus on wastewater streams containing FOG and the main recovery methods are shown in Figure 58, Figure 59, and Figure 60. Section 5.1 further discuss the differences between the three abattoirs, their wastewater streams, and decisions around which streams are good applicable to megasonic treatment.

Table 15: Main technologies used for FOG separation, recovery, and removal for wastewater treatment in each of the three abattoirs Q1, Q2 (Queensland), and V2 (Victoria) highlighting main objectives, differences, and issues for DAF and Decanter use

Abattoir	Wastewater to DAF		DAF with flocculant		Decanter (3-phase, tricanter)		Reasons for FOG removal/recovery		
							Tallow production		Water treatment
	Red	Green	Yes	No	Yes	No	Yes	No	
Q1	✓			✓		✓[1]	✓		✓
Q2	✓			✓		✓[1]	✓		✓
V2	✓	✓	✓		✓			✓	✓

Issues with DAF in Q1, Q2, and V2	Issues with decanter in V2
Loss of FOG separation/recovery due to overloading, high temperature >40 oC, low dissolved gas solubility, large bubble size	Poor separation of FOG, water, solids from DAF sludge due to overloading and stable emulsion

[1]Q1 and Q2 only have non-mechanical gravity-settling decanters (Figure 58 and Figure 59)

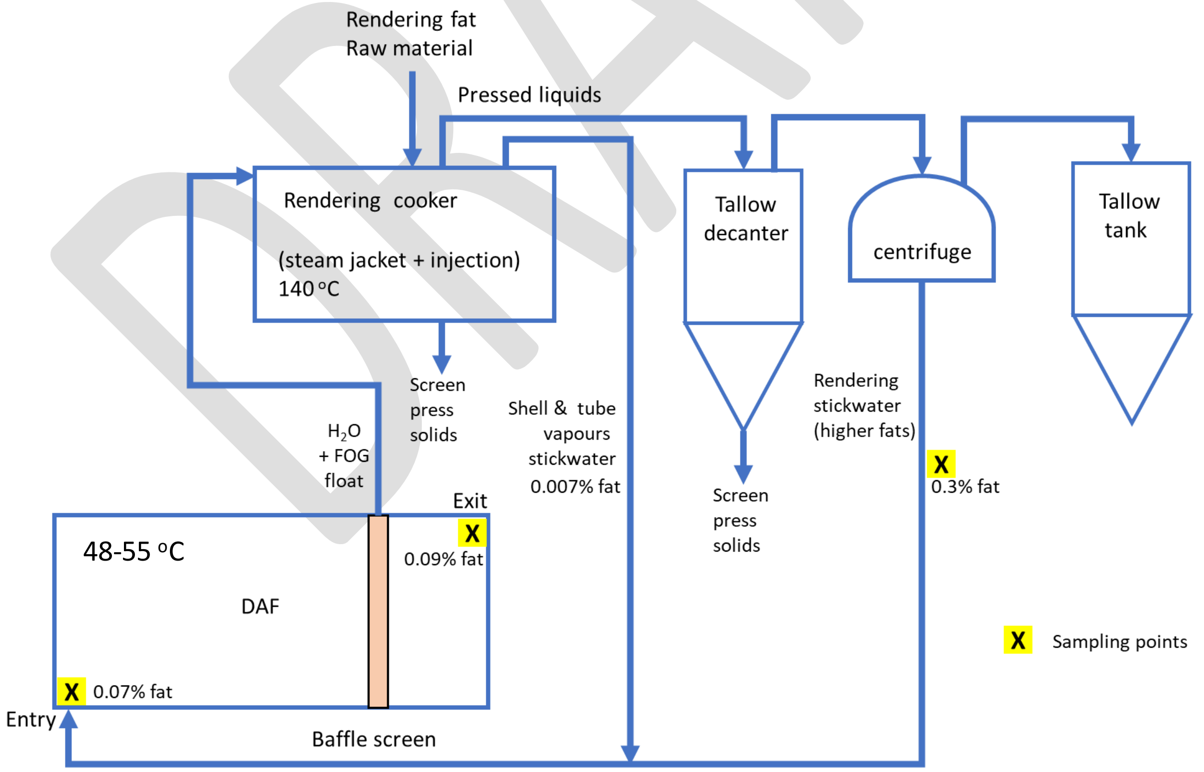

Figure 58: Process flow diagram of major FOG containing wastewater streams in Queensland abattoir Q1. The fat content of the streams was determined by CSIRO after sampling but do not reflect the mass balance as it was not possible to estimate from the survey the flow rates from the survey. Hence these values are concentrations and only indicative. The tallow decanter

performs a primary liquid tallow water separation and the centrifuge separates and removes residual water from the liquid tallow.

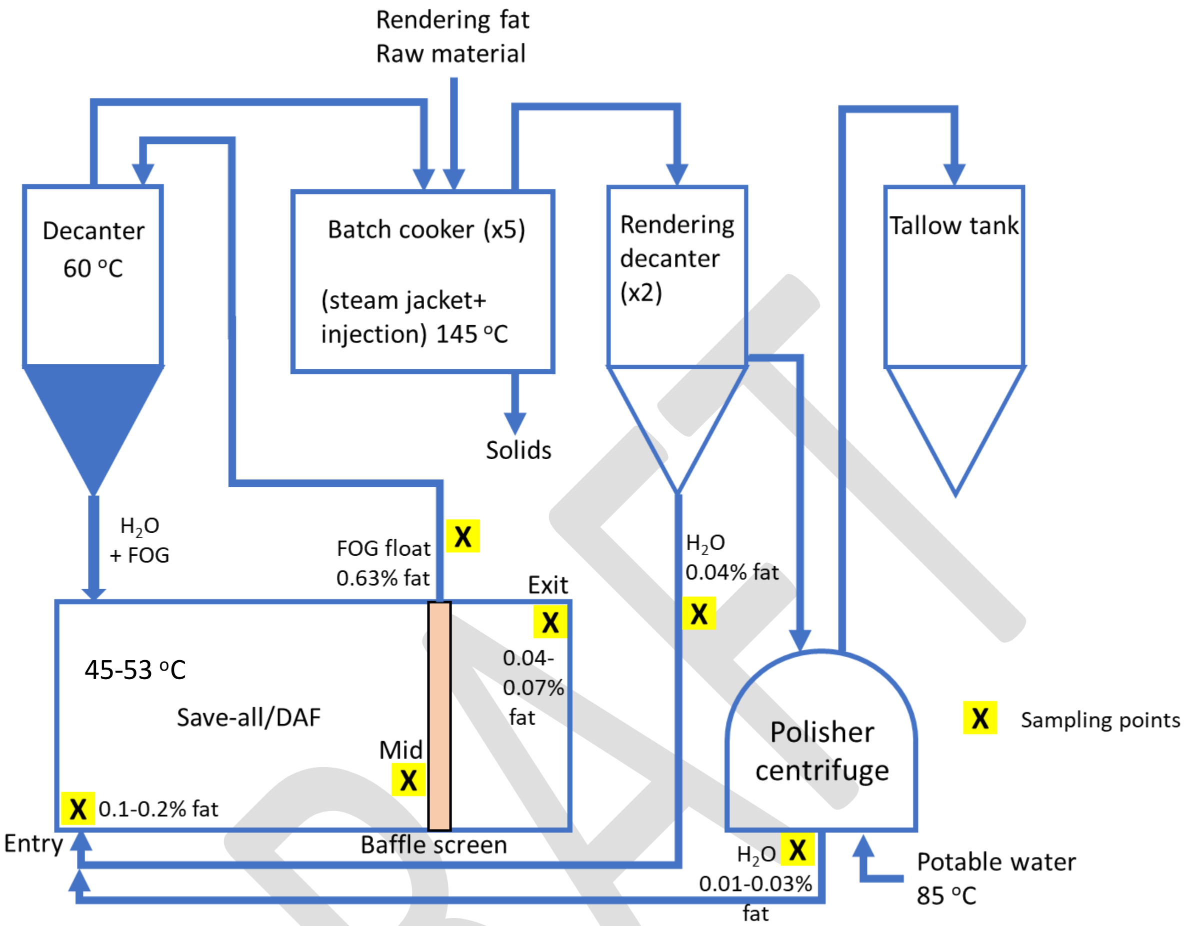

Figure 59: Process flow diagram of major FOG containing wastewater streams in Queensland abattoir Q2. The fat content of the streams was determined by CSIRO after sampling but do not reflect the mass balance as it was not possible to estimate from the survey the flow rates from the survey. Hence these values are concentrations and only indicative. Decanter going into DAF is a gravity dewatering decanter to separate FOG solid float from water while the rendering decanter separated liquid tallow from water. The polisher centrifuge further separates liquid tallow from water.

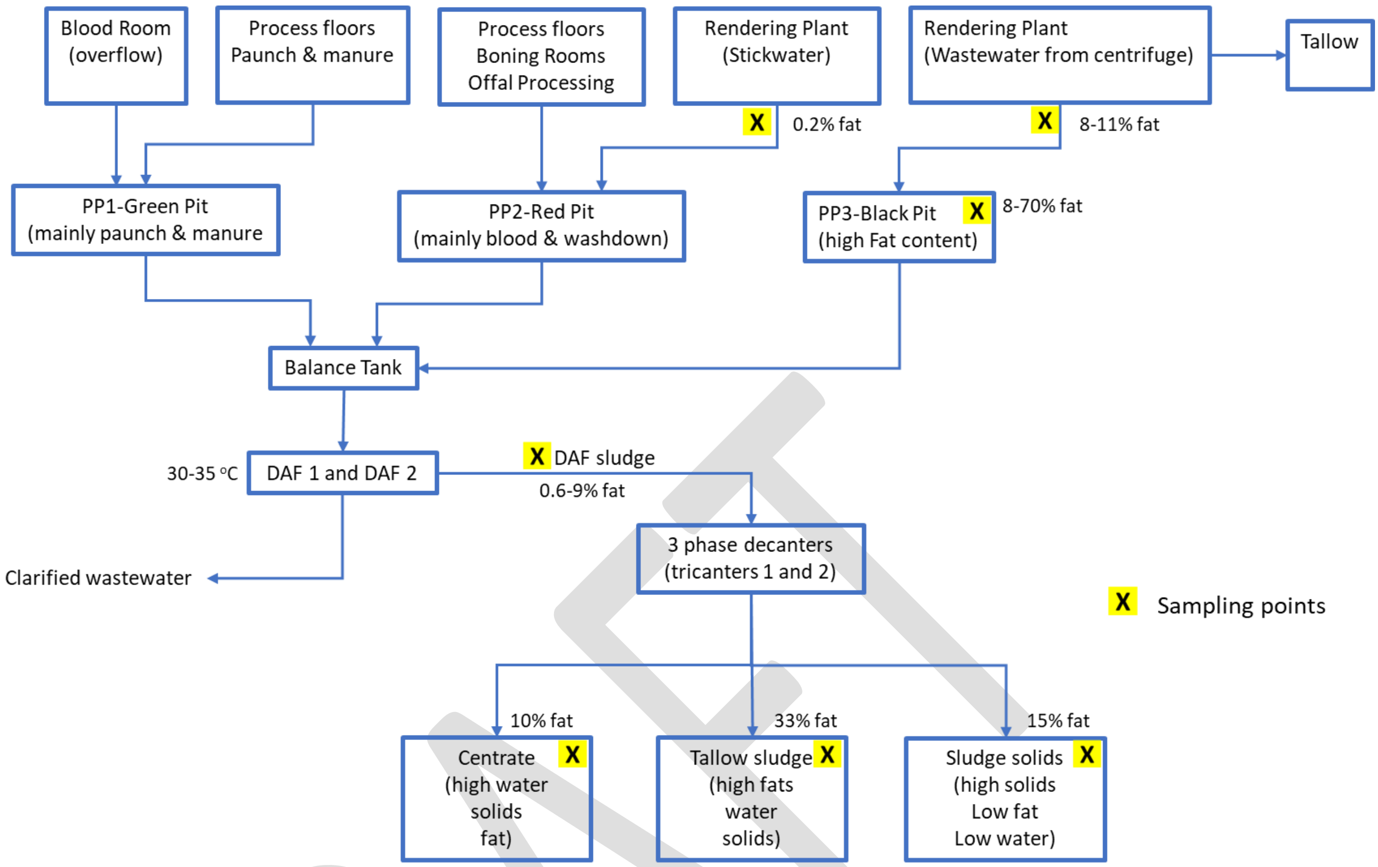

Figure 60: Process flow diagram of major FOG containing wastewater streams in Victorian abattoir V2

16.2 DAF operation and efficiency

Dissolved air floatation tanks are very popular and widely used to separate suspended solids as well as fat, oil, and grease (FOG) from industrial wastewater streams, including from abattoir processing wastewater. DAF is a very simple, scalable, and cost-effective technology for separating FOG and other suspended denser sludge solids from wastewater.

DAF works by injecting wastewater saturated with gas (usually air) under pressure in at the bottom of the tank (Figure 61). As the pressurised air-saturated wastewater is released into the wastewater in the DAF tank, the reduction in pressure releases small gas bubbles which rise through the wastewater, adhering to FOG particles making them more buoyant and helping them to float to the surface where they are concentrated. The FOG float is scrapped into a hopper and sent to the rendering cooker for tallow production (Figure 58, Figure 59, and Figure 60). The efficiency of separation depends on several variables, one of the most important is the ability to generate very small bubbles. If the bubbles become too large this will reduce the efficiency of flocculation and recovery of FOG.

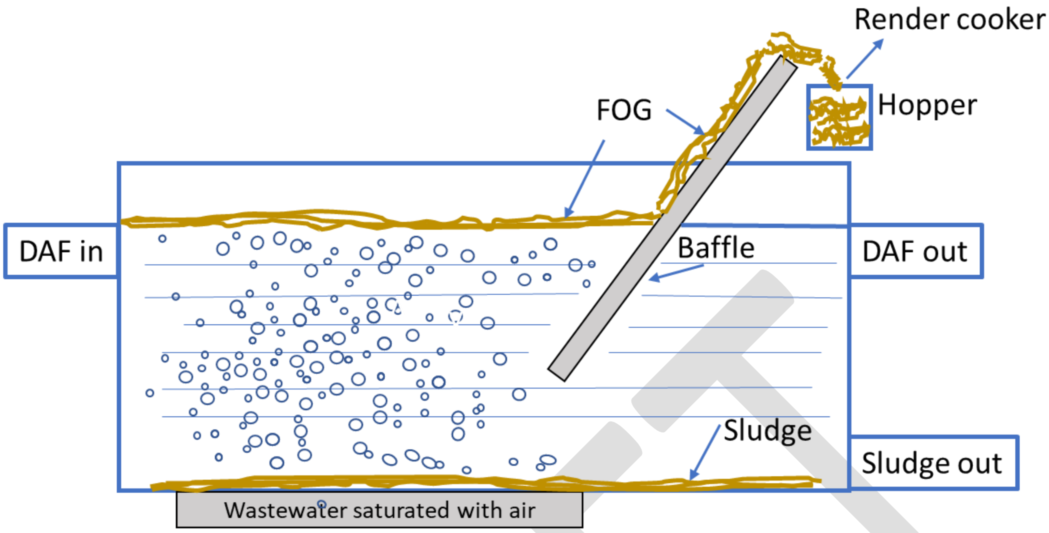

Figure 61: Diagram of dissolved air floatation (DAF) tank showing floatation of FOG float and sedimentation of sludge on bottom

Another important factor which can influence the efficiency of removal of FOG is the temperature of the wastewater within the DAF [110].

"The melting point of cattle fats varies from 29 °C for subcutaneous fat to 46 °C for intestinal fat and tallow [110, 111]; the melting point influences the degree of emulsification and FOG particle size in respective DAF units. DAF units are also ineffective at temperatures above 40 °C due to poor air solubility at these temperatures" [110, 112]. Hence it is important to keep the DAF temperature as low as possible to minimise emulsion formation through melting of the FOG and to obtain enough air solubility and keep bubble size as small as possible for optimum performance of the DAF. The DAF temperature, however, is dependent on the temperature of the incoming wastewater and ambient temperature during the day and hence may require the use of cooling towers to maintain the wastewater DAF inflow temperature withing a suitable range. In the Victorian abattoir, V2, the incoming wastewater is cooled from 40-45 °C using cooling towers to 30-35 °C and the DAF water temperature is maintained between 35-40 °C, while ideally, they would prefer to keep the DAF temperature to ~30 °C. The clarified water from the DAF, by regulation, needs to be <38 °C for output to the sewer. The temperature range in the DAF tanks in Q1 and Q2 was 48-55 °C and 45-53 °C, respectively. In discussions with the two Queensland abattoirs process engineers, they indicated that the performance of the DAF would decrease if temperature is below 45°C, and the DAF tank would then need routine downtime for cleaning. Q1 indicated issues with the bubble size being too large leading to loss in efficiency of the DAF and loss of FOG.

If the DAF is overloaded due to a high concentration of FOG and suspended solids or high temperatures, FOG could escape under the baffle as FOG particles or emulsions, respectively, in the DAF outflow (Figure 61). Both Q1 and Q2 indicated a desire to have lower DAF temperatures due to perceived loss of FOG as emulsions in the DAF wastewater outflow. DAF operations can occur with or without the addition of chemical coagulants and/or flocculants which are used to facilitate removal of combined FOG and non-FOG suspended solids (DAF sludge). Chemicals are not added to the DAF where

FOG needs to be separated from non-fat suspended solids (sediments) for tallow production. FOG for tallow production is usually recovered from the red stream which contains most of the FOG and not from the mixed red and green wastewater stream. This avoids contaminants such as pigments from the green stream which lead to a poor-quality FOG, which is very dark in colour, and which is unsuitable for tallow production. Jensen and Batstone [110] also reported that some abattoirs send only the red stream to the DAF while others combine the red and green stream before sending it to the DAF for solids and FOG separation.

16.3 Comparison between abattoirs (Q1, Q2, and V2)

Table 15 summarises the main differences between the three participating abattoirs in terms of FOG containing streams and technologies used for the separation and/or recovery of FOG as well as the main issues related to effective separation of FOG. In Q1 and Q2, dissolved air floatation is the sole technology used for the separation and recovery of high-quality FOG from the red wastewater. The captured FOG float is recycling into the rendering cooker for increased tallow production. The reduced FOG content in the wastewater improves the downstream anaerobic and aerobic treatments since excessive FOG adversely affect their operation. The DAF is operated without the addition of any chemical coagulants or flocculants. The FOG float is separated from the non-FOG sludge (which settles). The surface FOG float is removed by skimmers and removed over the baffle and the bottom sludge by bottom scrapping paddles.

The process flows of Q1 and Q2 in and around the DAF are very similar in that wastewater streams, including from tallow wash water/stickwater, are recycled back into the DAF for the capture of residual FOG for input into the render cooker and increased tallow production (Figure 58 and Figure 59). Q2 however, has an intermediate dewatering-settling decanter stage where the DAF FOG float is sent, and which separates the water by settling. The separated water containing residual FOG from the dewatering decanter is returned to the DAF while the separated FOG goes to the rendering cooker. In the case of Q1, the DAF FOG float is sent directly to the rendering cooker without an intermediate decantation step. The omission of chemicals ensures the capture of uncontaminated FOG for high-quality tallow production and the DAF also functions as a primary wastewater treatment to greatly reduce the FOG content which may hinder subsequent downstream wastewater treatment processes such as anaerobic and aerobic microbial digestion.

In contrast with Q1 and Q2, the Victorian abattoir, V2 treats the combined green and red wastewater streams, including stickwater and centrifuge wash water from the tallow rendering plant which contain residual high-quality FOG. The two wastewater streams from the rendering plant represent significant losses in tallow production once they are mixed with the green stream since they are contaminated with pigments and other organic compounds. The combined red and green stream is treated by two DAFs with the aid of a cationic polymer flocculant (Core Shell ® 71301) (Figure 60). This flocculant is very effective at flocculating both FOG and non-FOG suspended solids.

The priority in this abattoir is not the separation and recovery of high-quality FOG for recycling into the rendering cooker for increased tallow production, but rather the removal of both fat-containing and non-fat containing suspended solids for water clarification prior to disposal into the sewer. Under these conditions, the DAF sludge which floats to the top FOG and non-FOG components. The performance of DAF 1 and DAF 2 is quite different due to the different designs and the consistency of the DAF sludge from each varies from watery (DAF 1 sludge) to solid (DAF 2 sludge). For this abattoir there is no issue in the performance of the DAFs as these are very efficient at removal of most of the FOG and non-FOG suspended solids with the aid of this flocculant, leaving a clarified treated water stream fit for disposal directly into the sewer without any further treatment. The FOG, water and suspended solids laden DAF sludge is then further processed using two 3 phase decanters (tricanters) for the separation of the DAF sludge into 3 phases: the decanter water (centrate) phase, the FOG rich decanter tallow sludge phase, and a solids rich decanter sludge solids phase. While the purpose of the decanters is to dewater the sludge and clarify water (centrate) to allow the disposal of the centrate into the sewer, the other purpose is to separate and recover FOG free from water and solids and also recover solids free from FOG and water.

The effectiveness of separation in the decanters is influenced by the solids loading, throughput rate and residence time in the decanter as well as the size and g forces in the decanters. The addition of the strong cationic flocculant may affect the stability of emulsions in the sludge and hence reduce the separation of these three phases, since it was observed that storage for long periods of the centrate and tallow sludge did not result in any resolution of the emulsions, indicating that the FOG, solids, and water are tightly bound and/or the floc has a similar density to water. Hence the major issue for V2 is a poor separation of these three phases. Excessive solids were present in the centrate phase and although the centrate and tallow sludge phases were similar in appearance and are very stable emulsions, the FOG content needed to be determined. Similarly, the tallow sludge phase was assumed to contain high levels of water as well as FOG with some non-FOG solids though a more accurate determination needed to be carried out.

The excessive water in the tallow sludge as well as the poor quality of the FOG, which is highly coloured (dark green-brown) due to the presence of soluble chlorophylls and carotenoids from the green stream, meant that it could not be introduced into the rendering cooker for the manufacture of high high-quality tallow and was therefore only fit for disposal. The excessive water and high FOG load, particularly in the Tallow sludge phase meant that there were large costs associated with the disposal and treatment of this fraction due to the high volume and weight of the material that needed to be trucked away. However, the FOG in the tallow sludge is an untapped potential feedstock for potential biodiesel production and hence there may be a market demand for recovering FOG for this purpose. Hence, there was an opportunity to investigate the use of megasonics for the demulsification and recovery of FOG from the decanter tallow sludge in particular, because of the high content of FOG lost in this fraction, but also from the DAF sludge to reduce the load on the decanters and provide improved separation.

In addition, we identified the opportunity of recovering significant amounts of high-quality FOG very early in the red wastewater streams for recycling back into the tallow rendering cooker to increase tallow yield before mixing with the green stream, being contaminated and lost. These streams were from the rendering plant such as from the rendering stickwater (PP2 red pit) and rendering centrifuge wastewater pre-PP3 and PP3 black pit. If recovery of FOG from the rendering plant wastewater could be achieved, in addition to increased tallow yield, it would lead to improved water quality, and increased efficiency of separation in the DAF and decanters - due to reduced FOG load - and reduced tallow sludge disposal and treatment costs.

16.4 FOG proportions in wastewater streams

Selected wastewater samples were collected and stored refrigerated at 4 ^{o}C until needed for analysis. Fat was extracted by shaking an aliquot with hexane and the hexane layer separated by centrifugation. The fat-containing hexane layer was aspirated, and the extraction was repeated twice more with fresh hexane. The hexane extracts were combined, and the hexane was removed either by centrifugal vacuum evaporator (speed vac) or by rotary evaporation under vacuum, and the mass of fat determined by gravimetry.

In the case of determination of fat content by mass in the different layers after megasonic treatment followed by centrifugation, e.g. in FOG-rich top layer and FOG-poor lower layer, the samples were left to cool. The layers containing the FOG which solidified at room temperature were scrapped off and the fat extracted as above using hexane. Lower less hard FOG layer was either scrapped off, or if the lower layer was a liquid emulsion was aspirated into a separate tube and extracted with hexane. The bottom solid pellet was also extracted with hexane to determine the residual % fat content in this fraction.

16.5 Megasonic treatment

The selected wastewater streams were subjected to megasonic treatment with frequencies of 2 MHz (Figure 62) or 0.6 MHz (Figure 63) (power 340 W, 81.6 kJ/kg) for 20 min. Figure 64 shows a 0.6 MHz reactor for irradiation from the side rather than from below (Figure 63) [113][113][113][113].The selected wastewater sample was placed in either a 120 mL glass test tube or 400 mL beaker, depending on the volume, and suspended inside the megasonic reactor by a retort stand. For the larger volumes, we used a slow stirrer to ensure a homogeneous sample and uniform exposure to the megasonic standing waves. The megasonic reactor consisted of a rectangular stainless -steel vessel of 40 x 21 x 20 cm containing a transducer plate (16 x 16 x 3.2 cm; Sonosys, Neuenbuerg, Germany) either bolted to the side or bottom of the reactor. Transducer cooling was required for temperatures above 40 °C using recirculating cooling water through a jacket (H) around the transducer plate (G). The reactor was filled with water as a medium for the transmission of the acoustic waves. The water temperature was controlled within ± 2°C by a thermocouple controlled electrical heater (B, E). We also trialled The use of low frequency (20 kHz) ultrasound was also investigated using a Hielscher UIP1000 sonotrode (Figure 65) on selected FOG-containing wastewater samples to compare the differences between low-frequency ultrasound and high-frequency megasonic acoustic waves on FOG separation. The conditions used in the megasonic trials are shown in

Table 16. The most common megasonic conditions used were: 600 kHz (0.6 MHz), 20 min, 50 °C and subsequent centrifugation for 5 min at 3200 rpm (1717 g). Some of the samples needed to be heated to this temperature to melt the FOG and liquify the sample which was solid, particularly those high in solids and FOG such as DAF sludge and decanter tallow sludge.

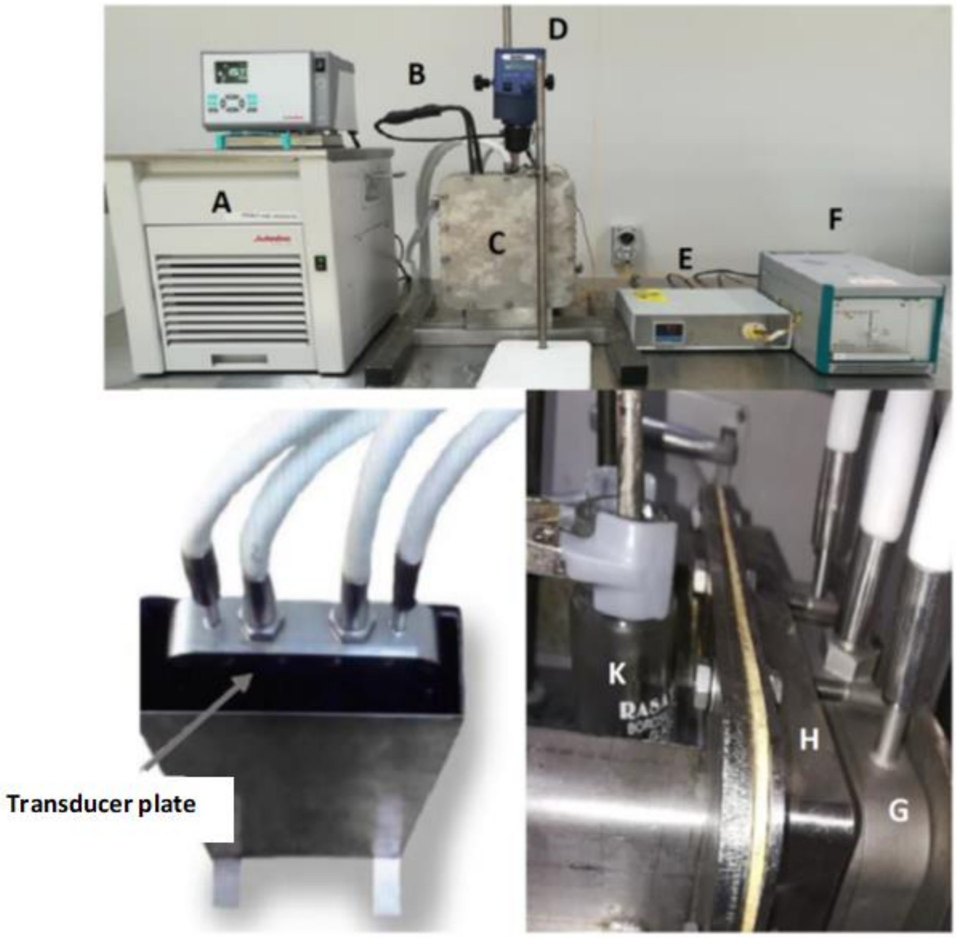

Figure 62: Experimental setup for megasonic treatment using a 2 MHz transducer array (SONOSYS®) vertically bolted for transmission from the side., A: cooling system; B: electrical heater; C: megasonic reactor, D: electrical stirrer; E: temperature control; F: generator; G: transducer array plate; H: cooling jacket; K: glass tube

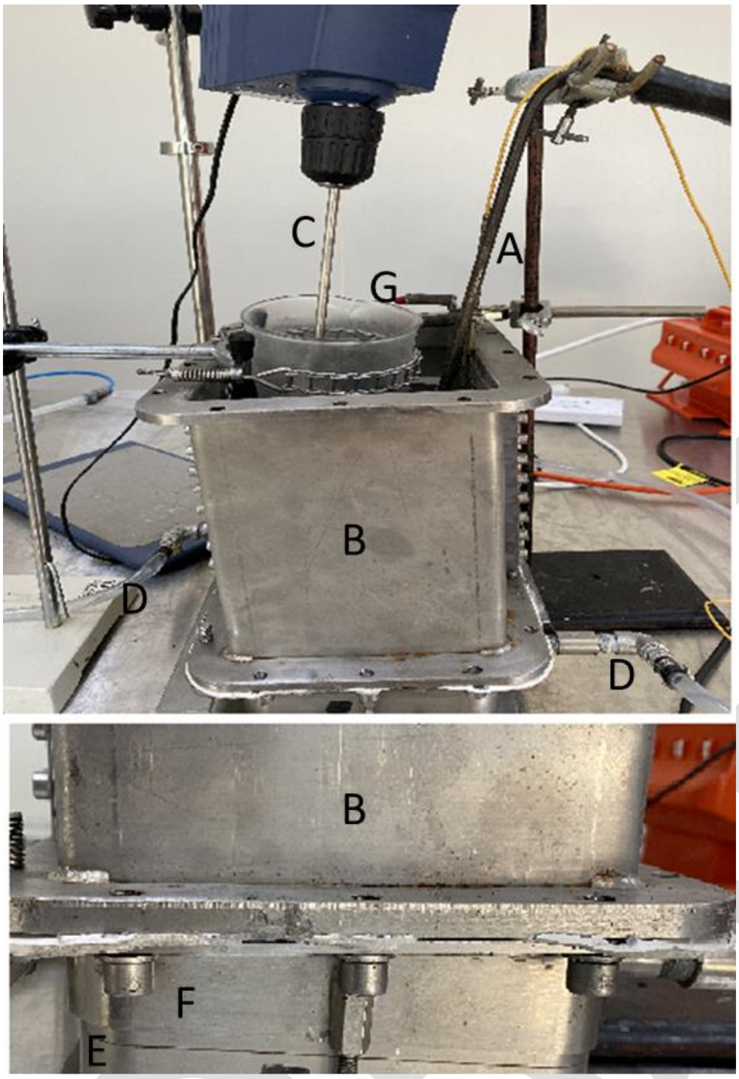

Figure 63: Experimental setup for megasonic treatment using a 600 kHz transducer array (SONOSYS®) mounted on the bottom for transmission from the bottom., A: electrical heater; B: megasonic reactor; C: electrical stirrer D: cooling hoses; E: transducer array plate; F: cooling jacket; G: glass tube

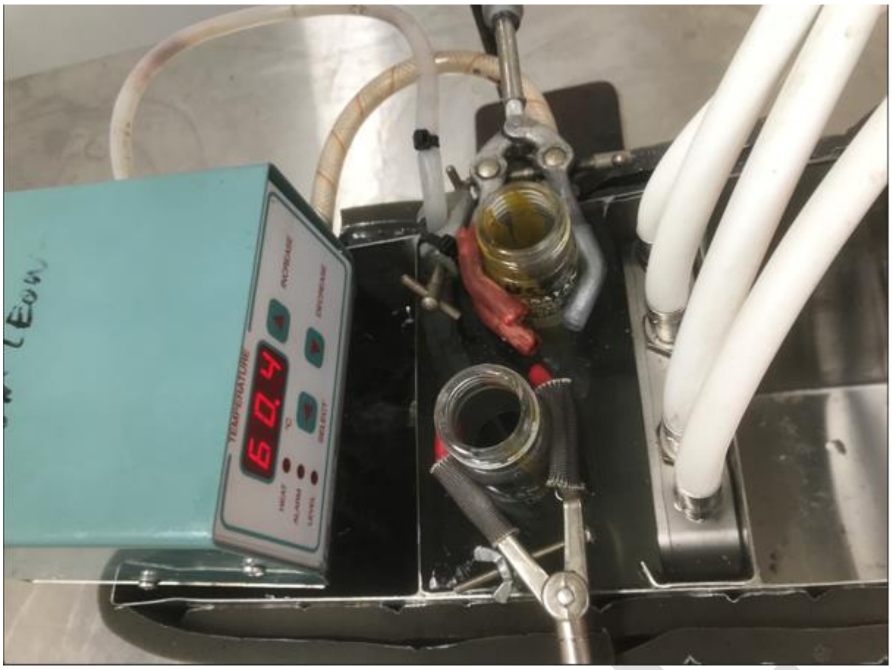

Figure 64: 600 kHz megasonic reactor with horizontal irradiation from transducer array (SONOSYS®) with a recirculating bath temperature control

Figure 65: 20 kHz ultrasound sonication sonotrode (Heischer UIP1000) for mid temperatures up to 65 ^{o}C

16.6 Experimental conditions

The parameters tested to determine the best conditions for fat separation from the wastewater steams of the abattoir V2 are shown in Table 16.

16.7 The effect of megasonic frequencies

It was expected that 600 kHz and 2 MHz frequencies may be effective in enhancing the rate or degree of separation of FOG. Therefore, some preliminary trials were conducted using megasonics with high frequency of 600 kHz or 2 MHz but there was no discernable difference in FOG separation between 600 kHz and 2 MHz treatments alone or after centrifugation and therefore all further experiments were conducted at a frequency of 600 kHz irradiating from the bottom except for a few experiments where irradiation from the side was used.

A short low frequency (20 kHz) ultrasound pretreatment was trialed to homogenise the sample prior to high frequency megasonic treatment (Table 16). This pretreatment, however, was counterproductive since it formed a stable paste-like emulsion which was difficult to separate by subsequent high frequency megasonics treatment and centrifugation. Therefore, low frequency pretreatment was not used in subsequent trials.

Table 16: Treatment condition of the various megasonic trials for each wastewater stream from the V2 abattoir

Wastewater stream	Treatment temperature (°C)	Megasonics (MS, 20 min)		Ultrasound (US, 1-2 min)	US (1 min) + MS (20 min)	Centrifugation
		MS 1 2 MHz	MS 2 600 kHz	US 20 kHz		
Pre-PP3 black pit rendering centrifuge wastewater	25/55		✓			3200 rpm (1717g) 5/12 min
PP3 black pit	25/50/60/ 70/90	✓	✓	✓	✓	3200 rpm (1717g) 5 min
PP2 Red pit rendering stickwater	50/60	✓	✓	✓		3200 rpm (1717g) 5 min
DAF 1, 2 sludge	25/50/60/ 70/90	✓	✓	✓	✓	3200 rpm (1717g) 5 min
Decanter tallow sludge (DTS)	25/50/60/ 70/90		✓			3200 rpm (1717g) 3, 5 min
	50		✓			4000 rpm (2683g) 1, 2min
	50		✓			2000 rpm (671 g) 5 min
Decanter centrate	50		✓			3200 rpm (1717 g) 12 min
Decanter sludge solids	50/60/70/90	✓	✓	✓	✓	3200 rpm (1717 g) 5 min

17.0 RESULTS AND DISCUSSION

17.1 FOG content of various wastewater streams

Table 17, Table 18 and Table 19 shows the fat content of different streams sampled from the Queensland abattoirs Q1 and Q2 and the Victorian abattoir V2, respectively.

Table 17: Fat content of major wastewater streams in Abattoir Q1

Wastewater stream	Fat (%)
Tallow rendering centrifuge stickwater	0.3
Rendering top of cooker shell & tube vapour stickwater	0.007
DAF entry	0.07
DAF exit	0.09
WAS	0.004

% = g/100mL refer to Figure 58 for process flow diagram. WAS=waste activated sludge water after covered anaerobic lagoon (CAL), biological nutrient removal (BNR) and clarifier

Table 18: Fat content of major wastewater streams in Abattoir Q2

Wastewater stream	Fat (%)
DAF entry	0.10-0.19
DAF exit	0.04-0.07
Dewatering gravity decanter entry	0.63
Rendering decanter exit	0.05
Polisher exit	0.01-0.03

% = g/100mL refer to Figure 59 for process flow diagram

Table 19: Fat content of major wastewater stream in Abattoir V2

Wastewater stream	Fat (%)
Rendering centrifuge wastewater pre-black pit (PP3)	8.0-11.0
Rendering wash water black pit (PP3)	8.0-70.0
Rendering stickwater (PP2)	0.2
DAF 1 sludge (exit)	9.1
DAF 2 sludge (exit)	0.6
Decanter sludge solid	15.5
Decanter tallow sludge	33.7
Decanter centrate	10.0

% = g/100mL refer to Figure 60 for process flow diagram

A summary of the results for FOG separation by megasonics alone and combined with centrifugation is show in Table 20. Detailed discussion of the results is in the following sections

Table 20: Summary of results for separation of FOG from the key FOG containing wastewater streams with megasonic and non-megasonic treatment under different conditions with and without a subsequent centrifugation treatment

Waste stream	Temp (°C)	FOG separation without centrifugation (%)		Centrifugation conditions	FOG separation after centrifugation (%)[1]		Figure
		No MS	MS[2]		No MS	MS	
DAF	25	ns[3]	ns	3200 rpm, 5min	0	100	Figure 66
	50-90	ns	ns	3200 rpm, 5min	100	100	
DTS[4]	25	ns	ns	3200 rpm, 5min	23	64	Figure 67
	50-90	ns	ns	3200 rpm, 5min	70	70	
DTS	50	ns	ns	3200 rpm, 3min	48[5]	91[5]	Figure 74
				4000 rpm, 1min	68[5]	72[5]	
				2000 rpm, 5min	56[5]	67[5]	
				4000 rpm, 2min	56	63	
PP3 black pit	50-90	100	100	-	-	-	Figure 75
Pre-PP3 black pit rendering centrifuge wastewater	20	ns	ns	3200 rpm, 3min	100	100	Figure 76
	25-RT[6]	ns	20[7]	-	-	-	Figure 77
	55-RT[6]	50[7]	50[7]	-	-	-	
PP2 red pit rendering stickwater	50	ns	ns	3200 rpm, 5min	100	100	Figure 79
Decanter centrate	50	ns	ns	3200 rpm, 12min	Low levels[8]	Low levels	Figure 70
Decanter sludge solids	60	ns	ns	3200 rpm, 5min	Low levels[8]	Low levels	Figure 71

[1]The % of FOG layer separation after centrifugation is based on the height of the FOG layer as a fraction of the sum of height of fat and emulsion layers; [2]600 kHz for 20 min MS treatment was used; [3]ns= no separation; [4]DTS=decanter tallow sludge; [5]determined by extracting and weighing the FOG in the top layer as a fraction of the total FOG and emulsion layer; [6]heating followed by slow cooling to room temperature; [7]% of water separated from FOG emulsion; [8]most of the suspended solids are non-FOG, and FOG is of a very low proportion of this stream; 3200 rpm (1717g), 2000 rpm (671g), 4000 rpm (2683g).

For Q1 and Q2 only the red wastewater streams enter the DAF for recovery of high-quality FOG for the rendering cooker for tallow production. The wastewater process flowcharts for Q1 and Q2 (Figure 58 and Figure 59, respectively), are similar. For Q1, the main input of wastewater containing FOG entering the DAF on a % w/v basis, comes from the tallow rendering centrifuge stickwater (0.3% FOG) with a small contribution from the render cooker shell and tube vapour stickwater (0.007% FOG). Due to the volumetric dilution effect of these streams mixing and entering the DAF the concentration of FOG in the DAF is very low (0.07%). Due to the high temperature in the DAF it is likely that some FOG melts and is lost as a dilute emulsion in the DAF outflow stream (0.09% FOG) hence the FOG content in the DAF water remains at 0.07-0.09%.

In the case of Q2, the main inputs of FOG into the DAF come from the rendering decanter (0.04%) and rendering polishing centrifuge wastewater (0.01-0.03%). Q1 and Q2 are very similar but with two slight differences, one being that in Q2 the DAF FOG float goes into a decanter gravity settling dewatering tank in which the water is recycled back into the DAF and the dewatered FOG goes to the render cooker, but for Q1 the FOG float goes directly to the render cooker. The other difference is that for Q1 the pressed liquids (FOG and water) go to the centrifuge for separation of tallow and the water recycled back to the DAF, while for Q2 after rendering there is an intermediate rendering decanter settling tank as well as the polishing centrifuge and wastewater from both are returned back to the DAF to recover residual FOG.

In both Q1 and Q2 the FOG recovery using the DAF is very efficient, especially when the wastewater from the rendering cooker and rendering centrifuge wastewater is recycled back to the DAF. In some instances where the DAF is overloaded when the plant is operating at full capacity and trying to recover FOG from wastewater with high FOG and solids loading, and if the DAF temperature is too high, FOG can pass through the DAF and be lost in the covered anaerobic lagoon (CAL) /aerobic-anaerobic dams where FOG crusts can form potentially hindering the biological digestion of nutrients. During this study and at the time of sampling, the DAF tanks in both Q1 and Q2 were functioning well and did not experience large losses of FOG in the DAF outflow. We trialed the use megasonics to see if it could recover additional FOG from the DAF entry/exit after thorough mixing but observed no measurable difference compared with the non-MS treated samples. We concluded that due to the very low FOG content in the bulk water entering and exiting the DAF and lack of emulsions containing high FOG content from both Q1 and Q2 DAF entry/exits under non-overloaded conditions, the application of megasonics was not feasible under non-overload low FOG conditions.

For the Victorian abattoir V2, however, there were several streams with significant to high FOG content where megasonic treatments could be more feasible. These were: the rendering centrifuge wastewater pre-black pit (PP3) (8.0-11.0%), rendering wastewater PP3 black pit (8.0-70.0%), DAF sludge (0.6-9.0%) and the three streams from the decanters: tallow sludge (33.7%), centrate (10.0%) and sludge solids (15.5%). Hence, the megasonic trials were conducted on these streams to see if megasonics could assist in the separation and recovery of FOG.

17.2 The effect of megasonics and temperature on FOG separation

17.2.1 DAF sludge from V2

We focused on the DAF sludge stream because if FOG could be effectively separated and recovered from the DAF sludge this would alleviate the load on the decanters and assist with more efficient and better separation of water (centrate), FOG, and solids. We also focused on the decanter tallow sludge stream as this contained the highest FOG content and had the highest potential for FOG recovery since megasonics was able to successfully separated FOG from as grease trap FOG emulsion (unpublished results CSIRO Internal Report, 2018).

The effect of megasonic treatment temperature on the fat separation from the DAF sludge from the Victorian abattoir, V2 was investigated to determine which temperature provided the best separation. Megasonics alone did not produce any separation of FOG (results not shown) but a following centrifugation step allowed the FOG layer to be separated from the water and non-FOG sediment. The results are shown in Figure 66. At 50, 70 and 90 °C there was no observable difference in the separation of fat between the control (non-megasonic treated) and megasonic treated sample. The addition of the cationic flocculant may have resulted in strong bonding between the fat, water, and solids forming a stable emulsion which the MS treatment could not overcome without centrifugation, although we were not able to test this hypothesis since we could not obtain a sample without added flocculant. However, centrifugation was able to effectively separate to a substantial degree the fat, water, and solids in most samples

Figure 66: DAF 1 sludge sample, control (A), megasonic (MS) treatment (B) at 25 ^{o}C; control (C), MS treatment (D) at 50 ^{o}C; control (E), MS treatment (F) at 70 ^{o}C; control (G), MS treatment (H) at 90 ^{o}C with 600 kHz from the bottom for 20 min followed by centrifugation at 3200 rpm (1717 g) for 5 min.), particularly at temperatures of 50 ^{o}C or higher, due to reduced viscosity at higher temperatures and overcoming any bonding forces caused by the flocculant. This indicated that the centrifugal force was stronger than the effect of MS and was the dominant force facilitating separation.

At 25 °C, however, the megasonic treated sample with the assistance of a subsequent centrifugation provided complete separation of the FOG (top phase), compared with the control (non-megasonic treated) sample which did not, indicating that at lower temperatures MS might have a beneficial effect in increasing the rate and degree of separation. But at 50 °C a clearer separation of the dark FOG layer over an emulsion layer was obtained, this could be due to the temperature being above the melting point range of tallow (>46 °C). Similar separations to those seen at 50 °C were observed at the higher temperatures of 70-90 °C. Overall, however, there was no apparent difference in the separation of FOG between the megasonic and non-megasonic treated control at 50-90 °C showing that centrifugation under these conditions is the dominant force for separation, but megasonic treatment may have an advantage at lower temperatures. Further research is needed to confirm this hypothesis at temperatures lower than 50 °C, particularly in the range of 30-40 °C since at the abattoir V2 the wastewater is cooled by the cooling towers from 40-45 °C to 30 °C for entry into the DAF where it is controlled to 30-35 °C (up to 40 °C in the Summer).

A primary centrifugation step of the DAF sludge from V2 with or without MS treatment might be able to separate and recover the FOG from the DAF sludge before entry to the decanters, thereby reducing the FOG load and enhancing the separation of residual FOG, water, and solids in the decanters Further work is required at a pilot scale to test this hypothesis with centrifuges like those used in the industry. In the case of DAF outflow water from Q1 and Q2 under high FOG loads, a centrifuge could also be used to capture any liquified FOG, if temperatures exceed the melting temperature, which may otherwise be lost.

At V2, the DAF sludge is heated by steam injection to 95 °C with mixing in the sludge tank to liquefy the DAF sludge composite for separation in the two, three-phase decanters. Recovery of the FOG by a prior centrifugation at a lower temperature immediately from the DAF may omit the need for the steam injection and save energy and reduce processing, disposal, and downstream treatment costs. The poor quality of the fat, in the DAF sludge, contaminated by mixing with the green stream, makes it unsuitable for it to be added to the rendering plant for tallow production, however, recovery of this low low-grade fat could be utilised as a feedstock by a biodiesel producer and, therefore, could be a useful value-add coproduct. However, it would be preferable if the high-grade FOG could be recovered from the rendering plant stickwater (which goes to the PP2 red pit) and the rendering centrifuge wastewater (which goes to the PP3 black pit), prior to being mixed and contaminated with the green stream, as this would increase the yield of the higher value, high-grade tallow main co-product.

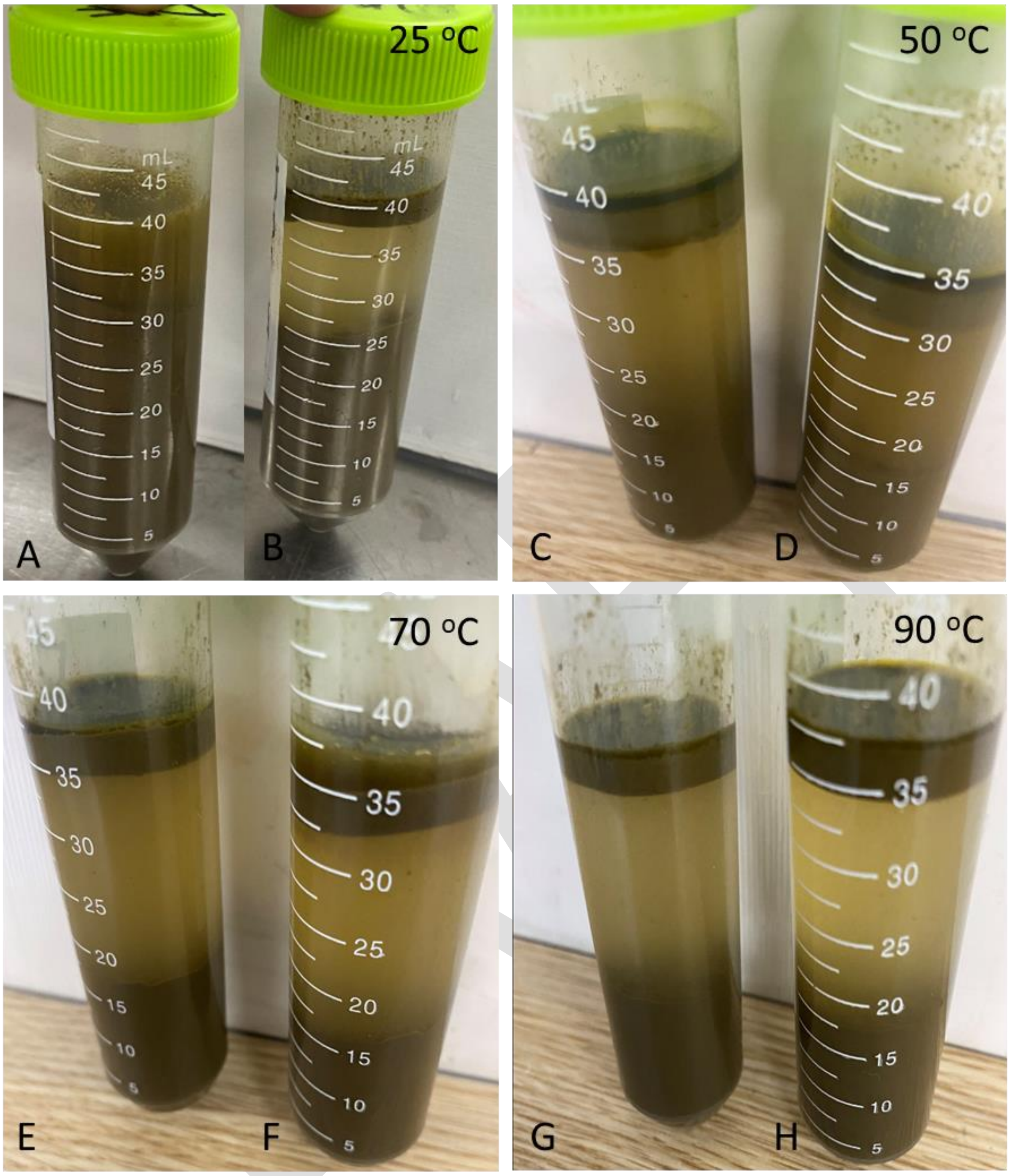

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Figure 66: DAF 1 sludge sample, control (A), megasonic (MS) treatment (B) at 25 °C; control (C), MS treatment (D) at 50 °C; control (E), MS treatment (F) at 70 °C; control (G), MS treatment (H) at 90 °C with 600 kHz from the bottom for 20 min followed by centrifugation at 3200 rpm (1717 g) for 5 min.

Accomplishing this would increase tallow production and at the same time reduce FOG loading on the DAF and subsequently on the decanters, and hence increase the efficiency of separation of the decanters and reduce costs for sludge removal and further downstream treatment and disposal.

In addition, the reduced fat content in the sludge solids could enable its use as a nitrogen-rich fertiliser providing extra revenues from this coproduct.

17.2.2 Decanter Tallow Sludge from V2

Figure 67 shows the effect of temperature and megasonic treatment on fat separation from the decanter tallow sludge sample for the same temperature range (25-90 °C). At 50 °C and above for megasonic and non-megasonic control, good separations of a dark FOG-rich top layer from the emulsion was achieved after centrifugation, leaving a small amount of emulsion (lighter colour) at the interface between FOG and water. Water and non-FOG sediment were also well separated from the FOG top layer. As in the DAF sludge sample, there was no noticeable difference in separation of FOG between the megasonic and non-MS treated sample at temperature of 50 ^{o}C and higher. At 25 ^{o}C, however, based on measurement of FOG height as a fraction of the total FOG-emulsion height the MS treated sample separated 64% FOG from FOG emulsion compared with 23% separation for the non-MS control sample. The megasonic treated decanter tallow sludge separation compared with the non-megasonic treated sample increased in temperature to 35 ^{o}C during the treatment due to heat generated by the transducer as a result of the dissipation of acoustic energy, whereas the control sample in a separate heating bath did not. This may have affected the results since, upon centrifugation the control sample may have cooled more than the MS treated sample, increasing the viscosity, and reducing the rate of separation compared with the megasonic treated sample. This is likely and so further research is required to validate this observation. Under these conditions, the sedimentation of the layers in the control and MS treated sample at 50 °C or higher is very similar, resulting in similar FOG separation with no discernible difference or advantage of a MS treatment. Heating at 90 ^{o}C followed by centrifugation produced the smallest amount of emulsion layer (~5 mL from 40 mL) compared to 50 ^{o}C and 70 ^{o}C. The main conclusion is that the three phase decanter does not effectively separated all FOG, water and non-FOG solids possibly due to the binding effect of the flocculant, and operation conditions such as FOG, and non-FOG loading, g force and residence time. A secondary centrifugation step of the fat-rich decanter tallow sludge phase may, under the right conditions, recover most of the fat and at the same time separate and remove water and solids as shown here on a small laboratory scale. Separation and recovery of large volumes of the fat fraction from this stream presents a value-add opportunity for creating a FOG feedstock for biodiesel production or for other low-grade tallow, detergent, and glycerol co-products or raw material feedstocks as well as reducing the FOG content in this fraction which will save on further treatment costs prior to disposal.

Further research can be conducted at a pilot-scale using a continuous flow plate centrifuge to determine the efficacy and feasibility of a secondary centrifugation for the separation and recovery of FOG from the tallow sludge fraction since this proof of concept study was carried out on a small laboratory bench-scale batch centrifuge. In the olive oil processing industry, decanters are used to separate liquids from solids and the liquids are subsequently separated into an oil and water phase using high-speed disk centrifuges. High-speed, high g-force disk centrifuges, however, are limited to processing liquids with a solids content of not more than 10% (w/w) to avoid overloading and loss of separation efficiency. Hence, a similar option as to that used in the olive oil processing industry for the recovery of fat (~50% v/v) from the decanter tallow sludge fraction could be investigated where the three-phase decanter, rather than attempting to separate three phases, is optimised to separate sludge solids from liquids in a first stage separation of either DAF sludge or decanter tallow sludge followed by a second stage disk centrifugation for separation and recovery of fat from the fat-water emulsion.

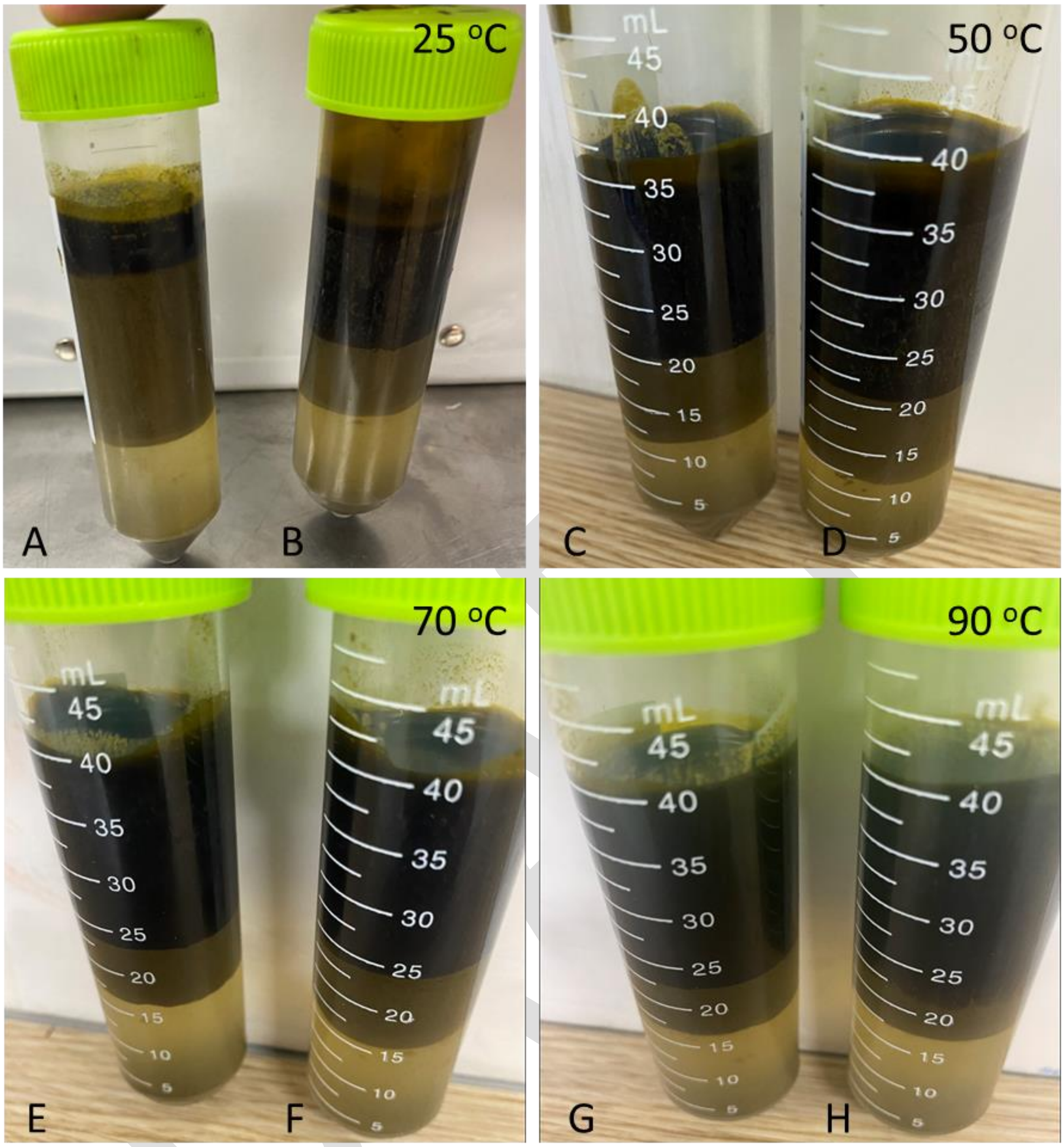

Figure 67: Decanter tallow sludge sample, control treatment (A), (B) megasonic (MS) at 25 °C; control (C), MS treatment (D) at 50 °C; control (E), MS treatment (F) at 70 °C; control (G), MS treatment (H) at 90 °C with 600 kHz for 20 min followed by centrifugation at 3200 rpm, 1717g for 5 min.

17.3 Effect of megasonics and centrifugation

17.3.1 DAF sludge from V2

The DAF sludge from DAF 1 and DAF 2 from abattoir V2 was subjected to megasonic (MS) treatment at 60 °C for 20 min with irradiation horizontally from the side - as opposed to MS treatment from the bottom - using a 600 kHz transducer array to see if the orientation of acoustic stationary standing waves made any observable difference to FOG separation without subsequent centrifugation. The results are shown in Figure 68. For DAF 1 sludge after MS treatment the sludge expanded in volume (right) compared to the non-MS heated control sample (left). The sludge settled and allowed some water separation on the top of both the control and MS treated samples but more so for the control showing that the sludge had a higher density than water, however, there was no visible separation of FOG on the surface of the water layer indicating that the cationic flocculant tightly bound up the FOG in the sludge matrix. MS treatment on its own could not overcome the strong binding forces without a subsequent centrifugation as seen previously. Upon closer inspection, the sludge in the MS treated sample, appeared slightly disrupted but insufficiently to cause the release and separation of the FOG.

In the case of the sludge from DAF 2 there was a greater degree of disruption of the sludge compared with DAF 1 sample, which allowed some water to separate and collect in pockets. Some sediment settled and water pooled above it, but the bulk of the sludge floated above the water indicating it was less dense than water or had some buoyancy associated with it, perhaps due to a higher FOG content in that sample. These effects were not seen in the MS treatment vertically from below suggesting that more of the material is exposed to the acoustic wave when irradiated horizontally from the side. As with DAF 1 sludge - despite differences in characteristics and response of DAF 1 and DAF 2 sludge, compared to MS treatment – for the DAF 2 sludge sample, there was no visible separation of FOG on the surface either. We hypothesise that the cationic flocculant may be hindering the release of FOG from the sludge since it has a high activity for binding FOG and non-FOG suspended solids. The main conclusion is that MS treatment on its own is ineffective for the separation of fat from DAF sludge, whether the sample is irradiated from the bottom or the side, without the use of a subsequent centrifugation process.

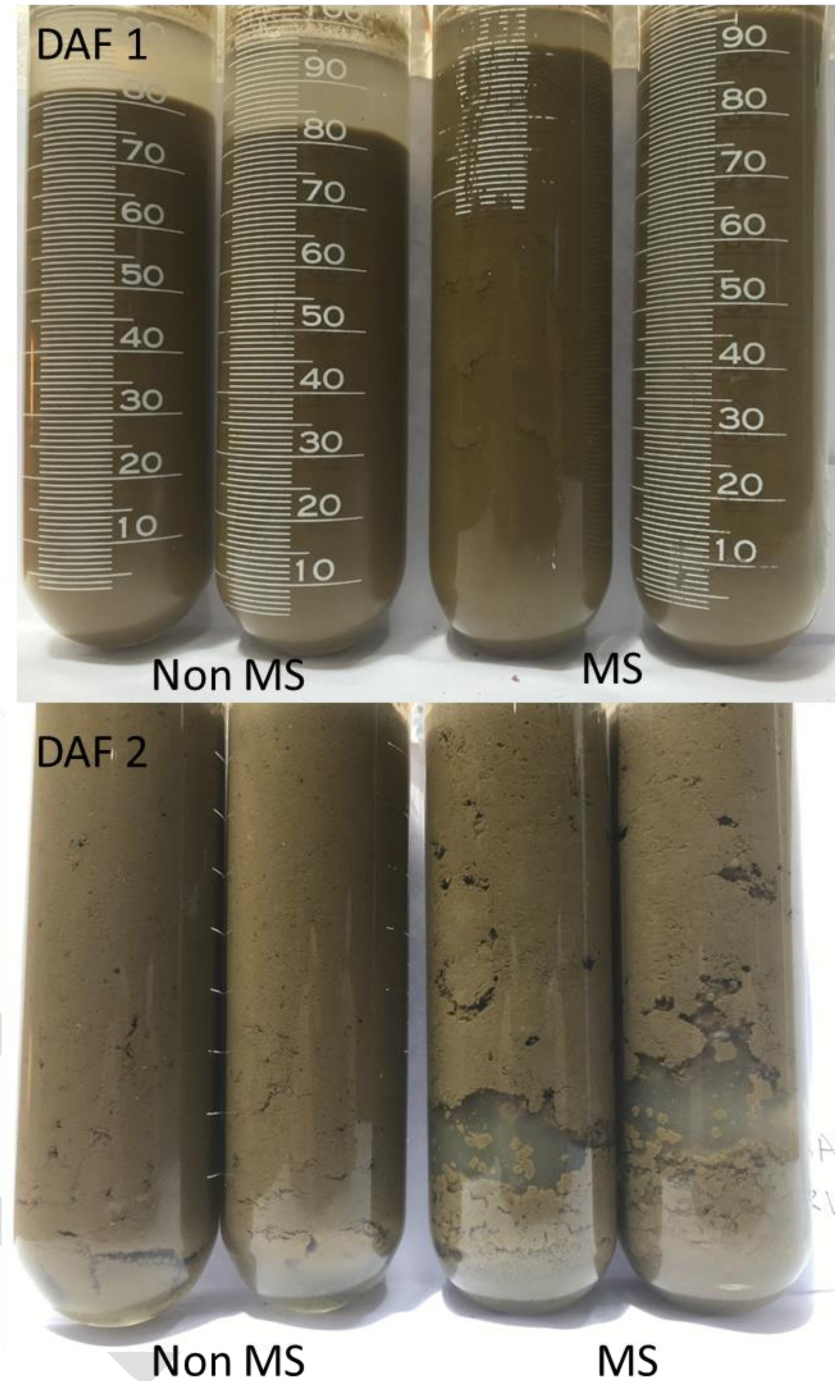

Figure 68: DAF sludge from DAF 1 and DAF 2 subjected to megasonic treatment at 60 °C for 20 min with side on irradiation using 600 kHz transducer array

When DAF 1 sludge was MS treated and centrifuged it could be seen that a small (~2.5 mL) distinct non-uniform dark band of FOG separated on the surface, but was more diffuse in the non-MS treated sample (Figure 69), indicating that MS treatment may have enhanced the concentration of the FOG. In the MS treated sample, some partially separated dark dark-coloured FOG pockets could be seen in the emulsion layer (indicated by the arrow) which presumably are in the process of coalescence and rising to the top. Extending the time of centrifugation may facilitate a more complete separation.

Both non-MS and MS treated samples effectively separated the non-FOG light brown sediment to a similar degree (~22.5 mL). This showed that centrifugation is the overriding factor with no noticeable advantage of MS in separating the non-FOG sediment from the DAF sludge. MS treatment may slightly enhance the concentration and separation of FOG from the liquid phase after centrifugation, but it was difficult to quantify any differences due to the small amount of fat in this sample and any such differences appear to be small. Furthermore, it is not known if this effect would be seen at an industrial scale and would justify the added expense of a MS treatment on the DAF sludge prior to the decanter separation. From the laboratory small scale trials, it appears that it may be more economical to explore the efficacy of using a high centrifugal force plate centrifuge to recover FOG from the either the DAF sludge, after an initial solids removal using a decanter or from the decanter FOG-rich tallow sludge., Since decanters are well suited for the separation of solids from samples with a high solids loading (>10%, w/w), while plate centrifuges are easily clogged by samples with high solids loading (>10%, w/w) it is more logical to use a plate centrifuge to recover the FOG from the tallow sludge phase which has had a high proportion of sludge solids removed.

After discussions with the abattoir, due to overloading and high throughput flowrate used, the full separation potential between water, FOG and solids is compromised hence another option is to explore optimising the three-phase decanter parameters such as load, flowrate (residence time).. There is also the possibility that the high temperature in the decanter (95 ^{o}C) after steam injection in the sludge tank used to liquify the DAF sludge and the use of the cationic flocculant may also impede the separation due to stable sludge-emulsion formation, though the effect of temperature has not been studied. By comparison, in the olive oil processing industry, two-phase decanters are used to achieve an initial separation of the solids (pomace) from the liquid (water and oil). The liquid phase that emerging from the decanters is then put through a high centrifugal force plate centrifuge for separation and recovery of the oil from the water. This approach is worthy of consideration as an option for a more complete recovery of lost FOG in the tallow sludge phase.

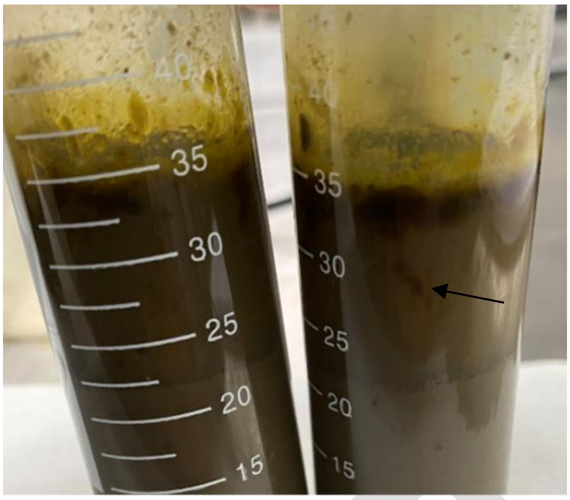

Figure 69: DAF 1 sludge centrifuged after MS treatment (600 kHz, 20 min, 50 °C) and centrifuge at 3200 rpm, 1717 g for 5 min. Arrow show partially coalesced FOG region in the process of rising to the surface. A partially coalesced FOG pocket is indicated by the arrow

17.3.2 Decanter centrate from V2

The decanter centrate is the aqueous phase that flows into the sewer, which should contain no or minimal fat and solids loading within acceptable levels. However, from observation and discussion with the abattoir wastewater management team it has a high suspended solids content. From the fat analysis, a fat content of ~10% fat (w/w) was determined. A non-MS and MS treatment using 600 kHz irradiation from the bottom at 50 °C with stirring for 20 min on a larger 500 mL sample was performed. We observed no visible separation of FOG or settling of non-FOG sediment after the treatments (Figure 70 left) or even after prolonged standing (data not shown). After non-MS and MS treatment centrifugation at 3200 rpm (1717 g, 12 min) (Figure 70) did separate a high proportion (~30 % v/v) of very fine bottom non-FOG containing sediment, though an emulsion and/or suspended fine solids still was still present above this layer, indicating that higher centrifugal force with longer treatment time is probably required to achieve a greater degree of separation and that this steam contained very little FOG. These observations show that although a much better separation can be gained by a second centrifugation, complete separation may be more challenging to achieve on scale up to industrial scale without adequate centrifugation conditions. Only small amounts of particulate FOG were seen on the surface, indicating that it could be quite difficult and unrealistic to recover the small proportion of FOG from this fraction since most of the FOG is being concentrated in the tallow sludge phase. The main advantage of an additional centrifugation with a second decanter/centrifuge pass of this fraction could be used to dramatically reduce the solids loading and improve the water quality to the sewer system; however, but not primarily to recover large amounts of FOG.

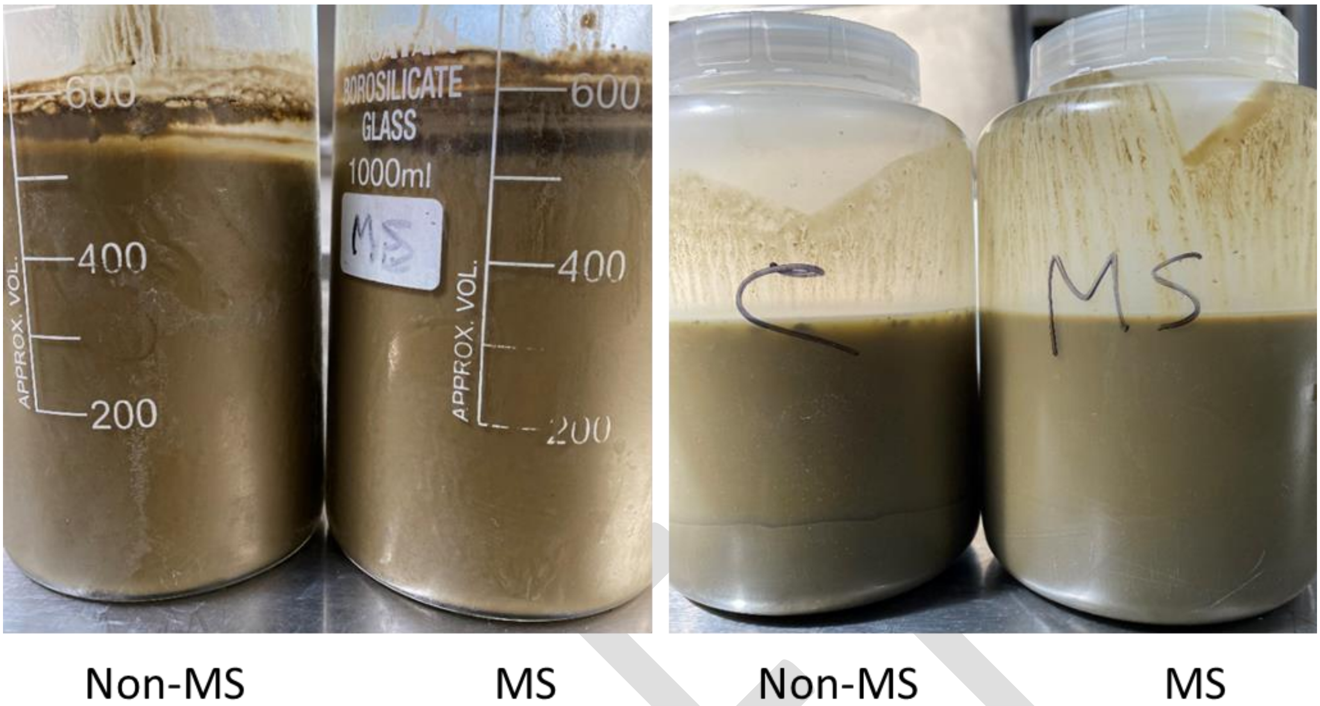

Figure 70: Decanter centrate without and with MS treatment (600 kHz from the bottom, 20 min, 50 °C) with mixing, before (left) and after centrifugation (right, 3200 rpm, 1717 g, 12 min)

17.3.3 Decanter sludge solids from V2

The decanter sludge solids phase has been disposed with an additional expense for removal for offsite composting in the past, although it is assumed that residual FOG has prevented its use due to bacterial growth and the formation of offensive odours. From the fat quantification by hexane extraction a level of ~15% (w/w) was determined. A portion of sludge solids (60 g) was suspended in 300 mL water (Figure 71) to facilitate non-MS and MS treatment, since megasonic fat separation is carried out in the liquid phase through the formation of stationary standing waves. We used 600 kHz irradiation from the bottom at 60 °C with stirring for 20 min. Only after centrifugation of both the non-MS and MS treated sample for 12 min at 3200 rpm (1717 g) (Figure 71) did we observe the separation of a very small amount of yellow fat (oil) droplets which floated on or near the surface of the water or stuck on the plastic walls of the centrifuge tube. There appeared to be no dramatic difference between the non-MS and MS treated sample, apart from the formation of a yellow opaque water or oil emulsion or the release of smaller non-coalesced oil droplets which could be suspended or stuck on the inside wall of the plastic centrifuge tube in the case of the MS treated sample. This observation could be significant and may be showing enhanced oil removal due to MS treatment but further carefully controlled trials would need to be carried out using different ratios of solid to water, to accurately quantify any differences between non-MS and MS treatment, and to see if MS enhances separation and recovery of the residual FOG. However, the results here show that simple heating at 60 °C with mixing without MS treatment can separate and recover residual FOG. The amount of FOG in this fraction is very small compared with the amount in the decanter tallow sludge. Hence, the extra expense to recover FOG from this fraction is not justified. However, the recovery of FOG from the tallow sludge phase, due to the high FOG content, is justified since there is value proposition in recovering low-grade FOG from this stream which is suitable a feedstock for biodiesel manufacturers.

Figure 71: Decanter sludge solids diluted with water (5:1 v/w, left), without MS and with MS treatment (600 kHz, 20 min, 60 °C) with mixing, after centrifugation (right, 3200 rpm, 1717 g, 5 min)

17.3.4 Decanter tallow sludge (DTS)

The decanter tallow sludge (DTS) from abattoir V2 was subjected to megasonic (MS) treatment at 60 °C for 20 min with horizontal irradiation from the side using 600 kHz transducer array without stirring and subsequent centrifugation to see if side-on irradiation was able to separate FOG without centrifugation. The results are shown in Figure 72. There were no significant differences in the separation of FOG between the non-MS and MS treated samples. MS treatment, however, separated and coalesced some small amount of FOG resulting in small regions of dark FOG trapped within the sludge matrix not fully coalesced as well as some bottom sediment, assumed to be fat depleted proteinaceous material, similar to the DAF 2 MS treated sludge sample (Figure 68). The non-MS heated sample did not produce these effects but only separated some water at the bottom of the tube indicating that the unaffected sludge is less dense than water, likely due lower-density emulsified FOG which makes it buoyant. The partial coalescence of FOG and sinking of sediment suggests that the MS treatment may have partially disrupted the bonding between the FOG and non-FOG sludge resulting in the release of some FOG and FOG-depleted sludge. The partial separation also allowed some water separation on top of the non-FOG bottom sludge.

Although there was some disruption of the tallow sludge matrix, the separation was minor without the aid of a subsequent centrifugation step, hence MS treatment alone is ineffective for the complete liberation of FOG from the tallow sludge matrix with no visible separation of FOG on the surface. These observations support the hypothesis that the cationic flocculant is likely hindering the release of FOG, proteinaceous sediment, and water from the sludge without a subsequent centrifugation step.

Figure 72: Decanter tallow sludge from abattoir V2 subjected to megasonic treatment at 60 °C for 20 min with side on irradiation using 600 kHz transducer array

A megasonic treatment of the decanter tallow sludge (DTS) was trialled at a larger scale (500 mL) with a 600 kHz transducer array from the bottom for 40 min at 50 °C with mixing to ensure a homogeneous sample consistency and uniform exposure of the sample to the acoustic standing waves. An ultrasound (US) treatment using 20 kHz for 3 min at 50 °C, was also carried out to explore if low-frequency acoustic waves are beneficial for FOG separation. The samples were then left standing for 30 min and then centrifuged for 9 min at 3200 rpm (1717 g) (Figure 73 A and B, respectively). There was no evidence of any separation for the non-MS and MS treatment without centrifugation, however, upon standing for 30 min it appeared that the MS treated DTS may have released slightly more water than the non-MS heated sample, although there was no sediment separation on the bottom or FOG separation on the surface of the sludge in either sample. The ultrasound (20 kHz) treated sample formed a viscous stable emulsion which did not separate any substantial volume of water or FOG but formed a thick paste on cooling to room temperature and hence did not perform as well as the megasonic treatment.

Centrifugation of both non-MS and MS treated samples (Figure 73B) provided a high degree of separation between non-FOG proteinaceous sediment (bottom), a water layer (middle) and FOG-emulsion (top). Upon closer inspection of the FOG-emulsion (light brown) layer, it could be seen that the MS treated sample showed a greater degree of disruption - albeit incomplete - of the emulsion phase, resulting in the release of more dark coloured FOG where it coalesced and pooled unevenly at the top, while, in the case of the non-MS treated sample the dark FOG layer was trapped in-between two emulsion layers. For a clearer, quantification of differences in separation and recovery of FOG from DTS see the section on the effect of MS with centrifugation parameters performed on a smaller scale. Ultrasound (US) treatment followed by centrifugation resulted in the poorest separation indicating that low low-frequency US treatment was counterproductive in the breaking of the tallow sludge emulsion and hence separation and recovery of FOG, but rather formed a stable emulsion.

Therefore, US is not recommended for use for the separation and recovery of FOG from the decanter tallow sludge.

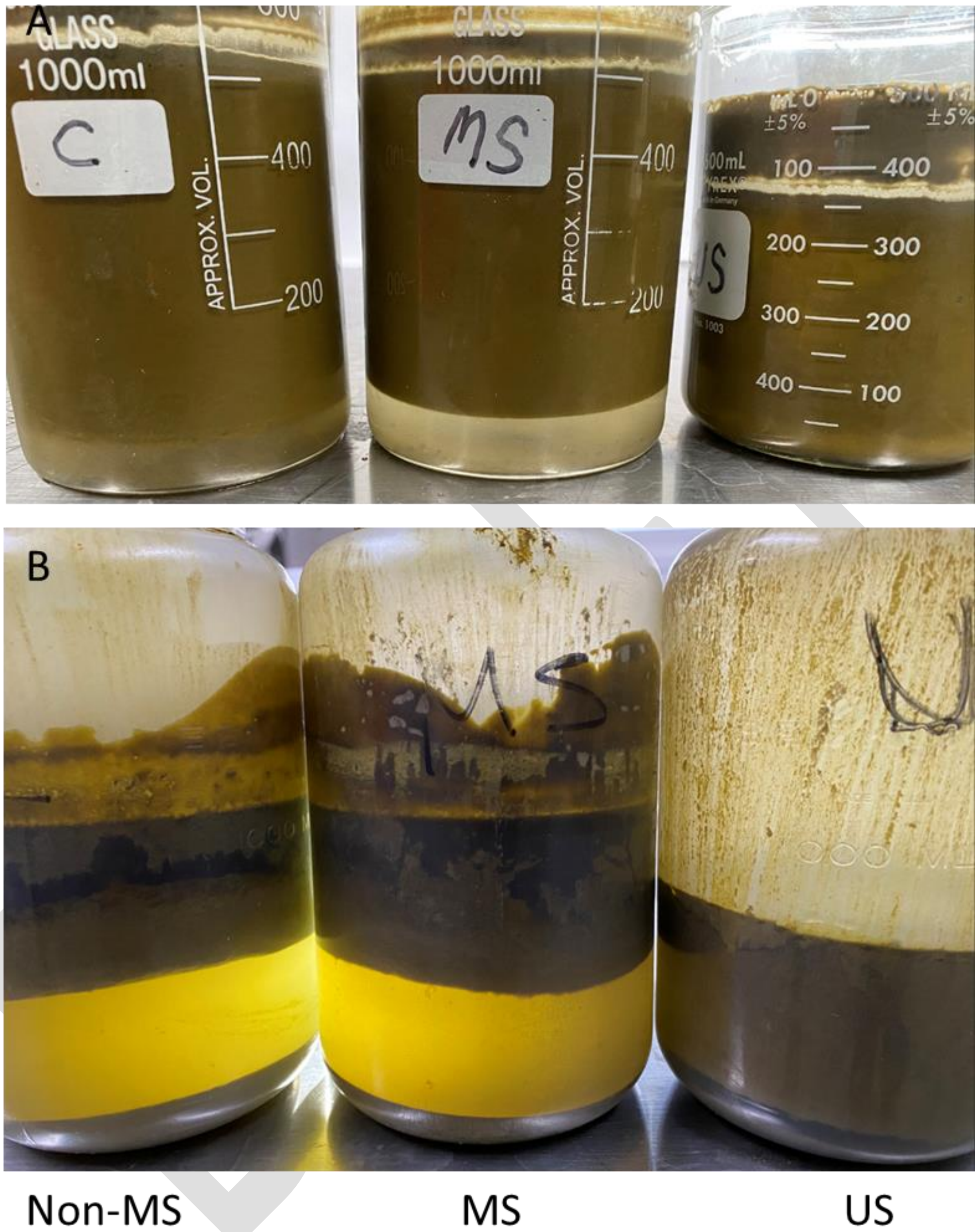

Figure 73: Decanter tallow sludge non-MS heated control, MS treated at 600 kHz from the bottom, 50 ºC, 40 min with mixing and ultrasound treated using 20 kHz, 50 ºC, 3 min, Standing for 30 min (A) and centrifugation for 12 min at 3200 rpm, 1717g (B)

17.4 Effect of centrifugation in decanter tallow sludge from V2

For V2 it was evident that centrifugation was the overriding and dominant force that enabled the separation of FOG, water, and solids, from the decanter tallow sludge phase and made it easier to semi-quantify differences in separation of the FOG/FOG emulsion/water and solid phase. The effect of centrifugation parameters (centrifugal force, g) and residence time on FOG separation was investigated using the following conditions: (5 min @ 2000 rpm (671 g), 3 min @ 3200 rpm (1717 g) and 1 min and 2 min @ 4000 rpm (2683 g).

After centrifugation, the tubes were cooled to room temperature causing the FOG top layers to solidify. This allowed us to scrape off each FOG, FOG emulsion layer, extract the FOG in hexane, centrifuge and weigh the separated FOG after evaporation of the hexane. This was a more precise method than measuring the volume or height of the layer since we could not accurately determine the FOG content visually could not be accurately determined due to the variable concentration of FOG in these layers. The results are shown in Figure 74. All MS treated samples showed a higher FOG content in the dark top layer. The difference was greatest after centrifugation at 3200 rpm (1717 g) for 3 min. Centrifugation of the MS treated sample for 3 min at 3200 rpm (1717 g) gave the highest fat separation compared with the non-MS treated sample (91% vs and 45%, respectively). The advantage of MS was less if centrifuged at 2000 rpm (671 g) for 5 min (67% vs and 56%, for MS vs and non-MS treated sample, respectively) and even less after centrifuging at 4000 rpm (2683 g) for 1 min (72% andvs 68%, for MS vs and non-MS treated sample, respectively). These results indicate that at higher centrifugal force the effect of MS is diminished. Likewise, at lower centrifugal force (2000 rpm (671 g) with extended centrifugation of 5 min, the improved separation due to MS treatment is reduced.

These observations suggest that the improvement in FOG separation and recovery is only observable in a narrow window of centrifugal force and centrifugation time. It is not known what effect MS treatments might have under industrial centrifugal forces and residence time under continuous flow conditions. It may be that MS could provide some improvement in separation efficiency. However, pilot pilot-scale trials need to be conducted simulating industrial centrifugation conditions to determine if megasonic treatments result in any enhanced separation and recovery of FOG.

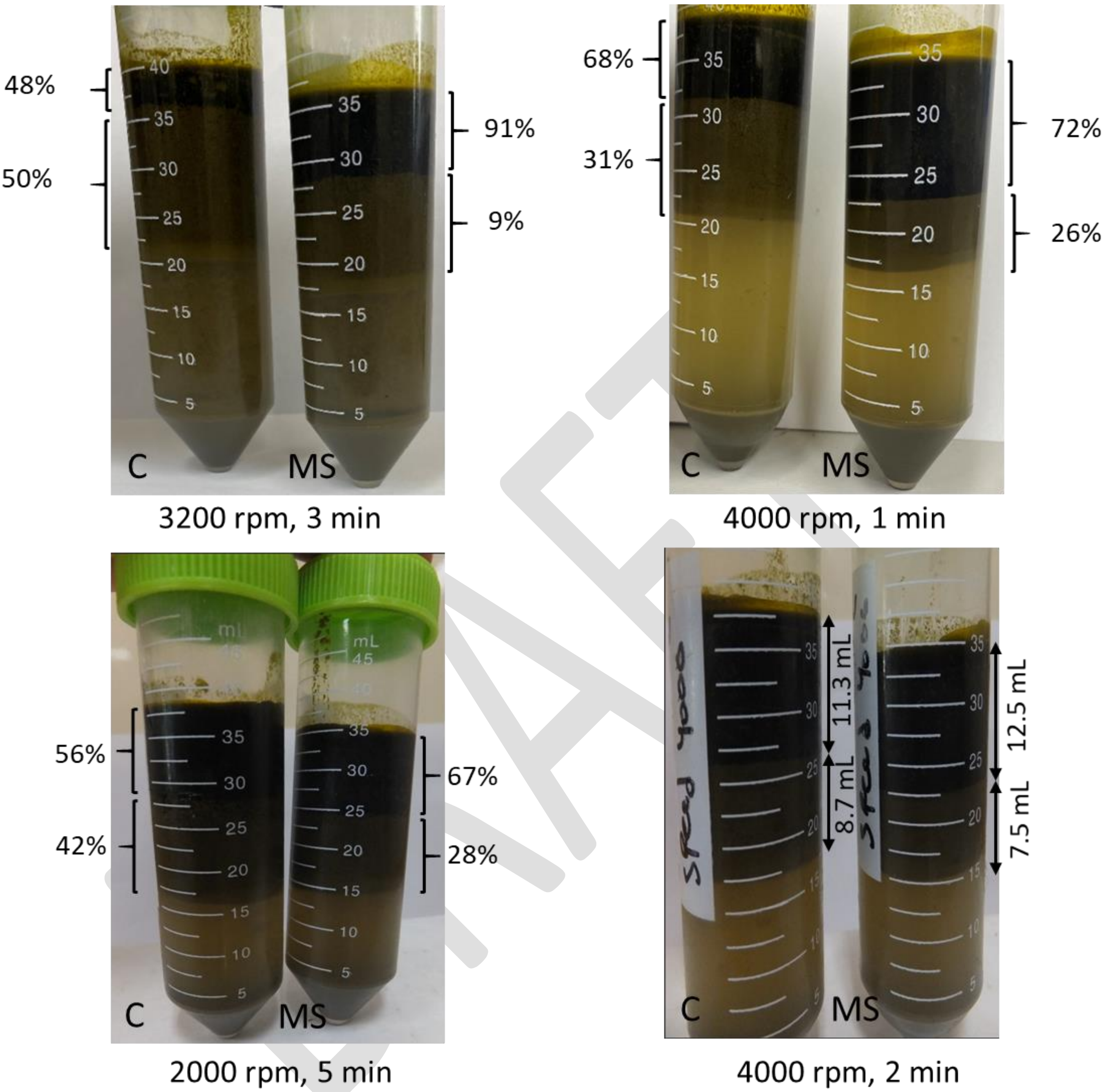

Figure 74: Control (C) and megasonic treated (MS) decanter tallow sludge using 600 kHz for 20 min at 50 ºC with subsequent centrifugation at 2000 (671 g), 3200 (1717 g) and 4000 rpm (2683 g) for 5min, 3min, 1min and, 2min, respectively

17.5 PP3 Black pit from V2

The PP3 black pit is upstream from the DAF and balance tank (Figure 60) before the mixing of the red and green streams. The PP3 black pit receives the wastewater containing residual high-quality FOG from the tallow rendering centrifuge wastewater. Samples were collected from the surface of the pit containing very hot liquid at temperatures of ~80-95 °C. As can be seen, the sample is very rich and almost exclusively FOG, which is a uniform liquid phase when heated to 50 °C (Figure 75A), but at room temperature will solidify. The sample was readily separated into a liquid FOG top layer (red) and a clear water bottom layer upon standing for 15 min after the samples were shaken to ensure homogeneity. Likewise, when we mixed the melted FOG was mixed with hot water, the FOG and water spontaneously and completely separated with a distinct boundary without any need for centrifugation. This indicated to us that FOG from this phase is of high quality. There was no difference in separation between the non-MS heated sample and the MS treated sample (Figure 75B and Figure 75C, respectively), and hence there is no point in applying a MS treatment to the surface sample from the PP3 black pit.

The FOG content determined by hexane extraction confirmed the sample was very rich high in FOG with a concentration of approximately containing ~ 70% (w/w). However, it is questioned if this very high concentration of FOG was the same as that coming into the PP3 black pit directly from the tallow rendering centrifuge wastewater. Discussions with the wastewater treatment manager confirmed our the hypothesis that this high concentration is not the same as that coming from the tallow rendering centrifuge wastewater. The sample was collected from the surface and hence is most likely not homogeneous with the bulk liquid in the PP3 black pit, since the liquid in the black pit is not mixed. It was not possible to ensure homogeneity of the sample with the bulk liquid in the black pit due to the high temperatures, lack of mixing and sampling difficulties.

We hypothesizeIt is hypothesised that it is highly likely that the black pit is acting as a separation chamber which at high temperature and with enough residence time facilitates the separation and clarification of a non-emulsified liquid FOG layer. The residence time and throughput in the PP3 black pit is not known and further work is required to better understand this phenomenon and how it may be exploited to capture this the FOG.

The PP3 black pit wastewater may be the highest contributor to FOG in the downstream wastewater. Unfortunately, this high high-quality FOG, which is a major FOG input stream, is not recovered from the PP3 black pit for return to the rendering plant for increased high high-quality tallow production but rather is lost as it proceeds to the balance tank where it is then combined with the green stream wastewater making recovery from the downstream wastewater more difficult. The combined streams then proceed to the DAF and FOG is removed with the DAF sludge. Any FOG separated from the DAF sludge by the decanters as the tallow sludge fraction is of poor quality since it is contaminated with highly coloured pigments from the green stream and contains excessive amounts of water. Due to its poor quality, it is discarded, resulting in lost revenue due to a decrease in tallow production and increased disposal costs for offsite treatment of the tallow sludge. Recovery of the high-quality FOG from or prior to the PP3 back pit would result in increased tallow production and at the same time reduce the FOG load on the DAF 1 and 2 and decanters 1 and 2, and hence increase the separation efficiency of the decanters.

From these observations, we were prompted to also investigate the pre-PP3 black pit stream and the PP2 red pit stream. A closer examination of the PP3 black pit is needed to better understand the mechanism of separation of FOG. There is a possibility that centrifugation could be a cost-effective option for effectively and efficiently recovering most of the FOG in the PP3 black pit for high high-quality tallow production. In the following section, we examine the pre-PP3 rendering centrifuge wastewater stream as well as the PP2 red stream rendering stickwater since it makes sense to attempt to recover FOG from a point as early as possible before dilution and mixing with other streams.

Figure 75: PP3 black pit (from rendering centrifuge wastewater) FOG taken from the surface of the pit (A), heated non-MS control (B) and MS treated sample (C, 55 °C, 600 kHz, 20 min)

17.6 Pre-PP3 rendering centrifuge wastewater from V2

17.6.1 Effect of MS with centrifugation

The rendering centrifuge wastewater which flows into the PP3 black pit was subjected to Megasonic and non-MS treatment with a subsequent centrifugation step to see MS combined with centrifugation could enhance the separation and recovery of the FOG. Figure 76 shows, on a small scale, three samples of the pre-PP3 black pit stream. Fine suspended particles of FOG are (left), have some buoyancy, however, the flocks are quite fragile and rather than sticking together are easily disturbed and dispersed. The first tube shows some separation of water (bottom) and tube 3 shows some yellow oil on the surface. After centrifugation at room temperature without any application of MS, high-quality FOG particles float and are compacted at the top while the denser non-FOG (presumed protein) particles are settled at the bottom with a clear water layer in the middle. Some settling of non-FOG particles occurs without centrifugation (left), indicating that separation using centrifugation is likely to be quite efficient and easily achieved. This is confirmed in the pictures to the right.

There is some variability in the amount of FOG in each sample, however, it is clear that centrifugation is an effective technology for the separation and recovery of the residual high-quality FOG in this wastewater stream which could lead to increased tallow production and reduce the FOG load on the DAFs and decanters. There is a lack of red-brown pigmentation in the FOG as seen in FOG from the PP3 black pit due to mixing with the red stream. This indicates the importance of capturing FOG prior to entry into the black pit for recovery of untainted high-quality FOG for increased tallow production. This, in turn, could potentially enhance their separation performance. Therefore, the use of centrifugation for separation and recovery from the pre-PP3 steam is worth exploring in larger pilot-scale trials to see if it can deliver the same separation and recovery performance. Another option which could work is the use of DAF without the use of flocculants and should be considered also as this is an effective and simple and widely used method successfully used in Q1 and Q2.

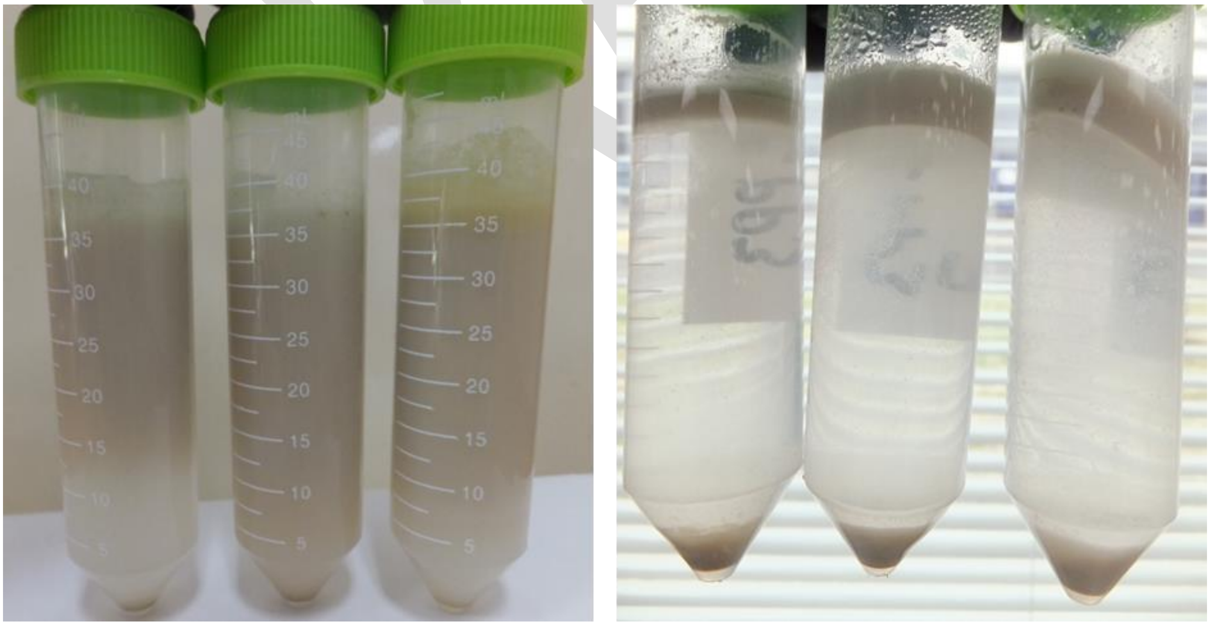

Figure 76: Three samples from the pre-PP3 black pit originating from the tallow rendering centrifuge wastewater without heating (left) and after centrifugation at room temperature (3200 rpm, 1717 g for 3 min) (right).

17.6.2 Effect of heating and cooling of pre-PP3 from V2

Based on the successful results of centrifugation on a small scale (Figure 76), it was we decided to examine the effect of megasonic (MS) treatment and heating-cooling at a larger scale (600 mL) on the separation of FOG from pre-PP3 rendering centrifuge wastewater. Figure 77 shows the results of MS treatment using irradiation from below (600 kHz, 20 min with mixing, at 55 °C). It can be seen that MS treatment alone at 50 °C did not separate the FOG (A), although, upon cooling for 45 min, approximately 300 mL water was separated with the FOG flocculating and floating to the top for both the non-MS and MS treated sample (B). When the same experiment was conducted at 25 °C, no noticeable difference was observed (C). Upon standing for 2 hours, more water (~150 mL) was separated in the MS treated sample than the non-MS treated sample (D). When the experiment was conducted at the higher temperature of 50 °C, a better flocculation of FOG and separation of water (~300 mL) occurred compared to 25 °C but only after cooling for 45 min to room temperature. Although MS treatment showed a benefit at 25 °C, it was less than non-MS treatment at 50 °C. Hence, it seems that heating at higher temperatures combined with a subsequent cooling were the key factors responsible for enhanced flocculation and floatation.

This protocol could be used to facilitate the concentration, separation, and recovery of FOG. Further investigations could be carried out to optimise the separation conditions. Flocculation and floatation occurred without the addition of chemicals or injection of dissolved air for floatation (DAF). This observation lends support for the use of DAF with optimised temperature as an efficient option for the separation and recovery of FOG from the pre-PP3 stream.

Interestingly when the heated and cooled samples were centrifuged (Figure 78), the sediment settled at the bottom and fat particles collected at the surface;, however, the water layer was not as clear as when performed on a small scale (Figure 76), indicating that centrifugation parameters such as centrifugal force and residence time need to be adjusted to achieve a similarly clean separation. However, it may not be necessary to separate the FOG float from non-FOG sediment ifn (??) a DAF if the FOG float is sent to the rendering cooker; but the overriding objective is the dewatering of the FOG float since excessive water will require more energy to heat in the rendering cooker.

Time did not permit investigation at higher temperatures;, however, the temperature of the centrifuge wastewater is likely to be around 80-95 °C, so further trials in this temperature range could give different results and may be an important factor that may affect the separation of FOG in the PP3 black pit causing melting and coalescence of FOG particles into a uniform oil phase. At 50 °C, there is no visible effect of MS as there was at a lower temperature of 25 °C, which, however, but is not as beneficial efficient as centrifugation. Therefore, MS is not recommended as an option for the recovery of FOG from pre-PP3 or PP3 black pit wastewater. The effect of temperature and heating-cooling regimes could be explored using an experimental reactor-settling tank to model what is occurring in the PP3 black pit for the optimised separation and recovery of FOG using centrifugation (option A), or the FOG could be intercepted prior to the PP3 black pit with DAF (option B) and/or secondary centrifugation (option C).

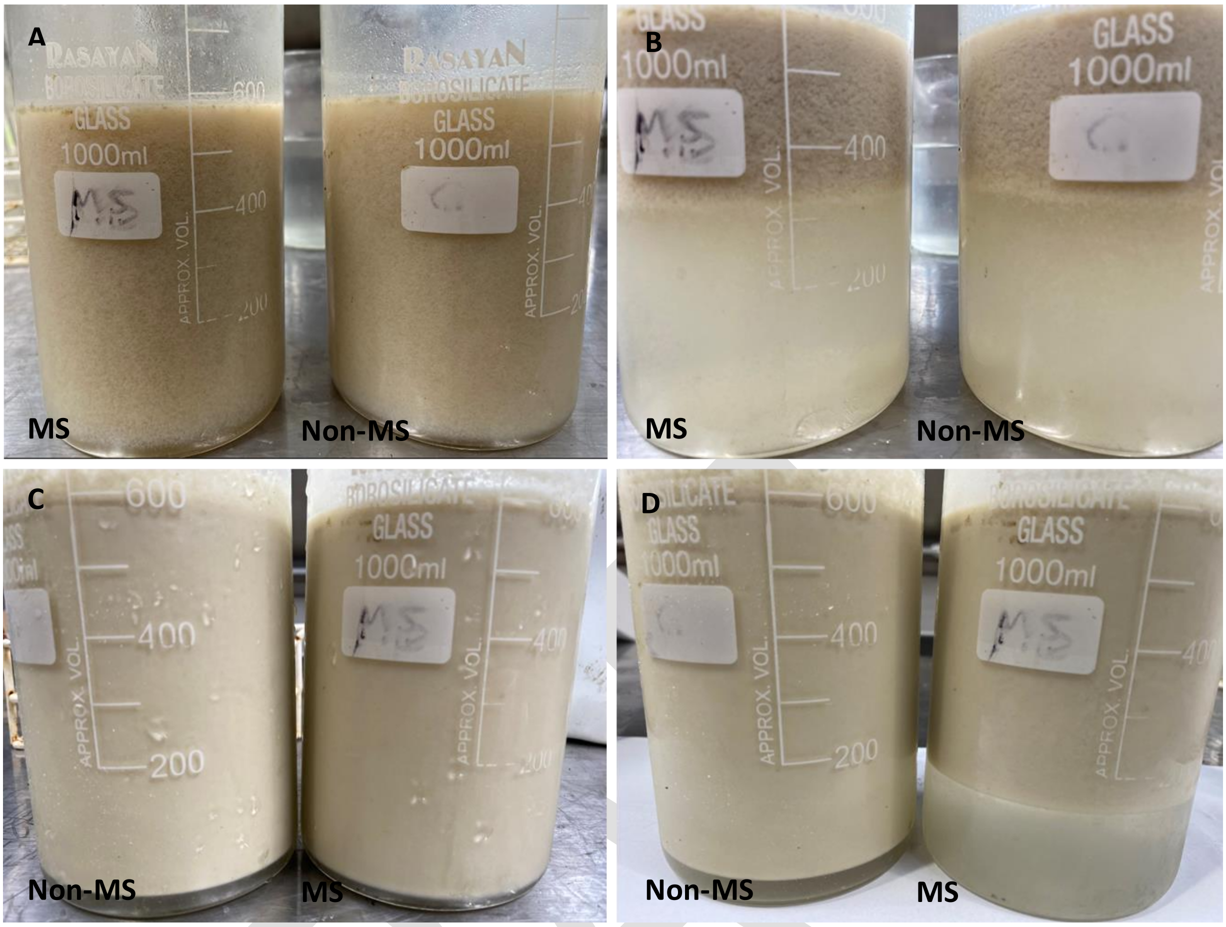

Figure 77: Pre-PP3 black pit, rendering centrifuge wastewater, heated at 55 ºC with and without MS (600 kHz from the bottom, 20 min with mixing) (A), after 45 min cooling (B), heated at 25 ºC with and without MS (600 kHz from the bottom, 20 min with mixing) (C) and standing at room temperature for 2 hrs (D)

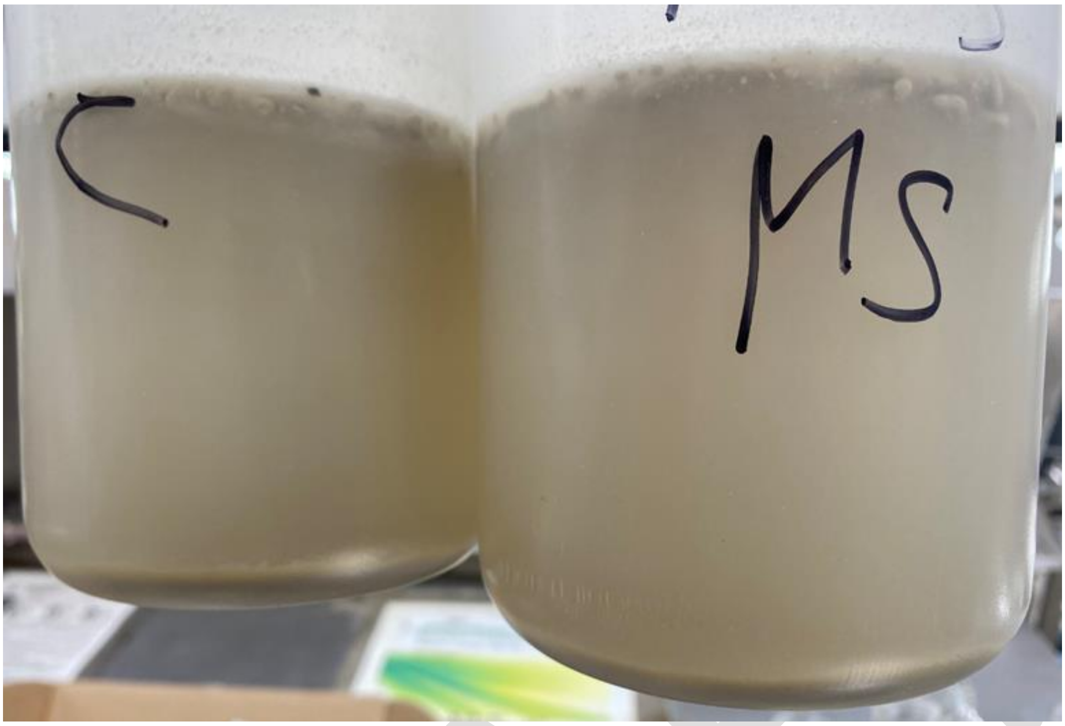

Figure 78: pre-PP3 black pit rendering centrifuge wastewater without and with MS treatment (600 kHz, from the bottom at 50 °C for 20 min with mixing) after cooling for 45 min (refer to Figure 77B) after centrifuging at 3200 rpm, 1717 g, 12 min

17.7 PP2 Red pit rendering stickwater

FOG in the PP2 Red pit wastewater stream originates from both the rendering stickwater and is added and diluted with blood from the washdown water from the process floors, boning rooms and offal processing (Figure 60). After MS and non-MS treatment, there was no observable separation of FOG or sediment (Figure 79). However, after centrifugation of both the MS and non-MS treated samples, a small layer of FOG was separated from the water and bottom non-FOG sediment (Figure 76) similar to that seen in the pre-PP3 sample. The proportion of FOG in the PP2 samples, however, was lower compared with that in the pre-PP3 sample, consistent with the lower % FOG determined by hexane extraction and gravimetry (0.2% w/w) and 8-11% (w/w), respectively (Table 19). Although the proportion of FOG in the PP2 stream is lower than that in the pre-PP3 stream, it is still significant in terms of the large volumes of water that are processed. The PP2 samples also had a higher amount of sediment compared to the pre-PP3 samples.

The capture of the FOG from the PP2 rendering stickwater prior to going to the red pit and mixing with the green stream by centrifugation may also be profitable as it may contribute to an increase in tallow yield. The higher proportion of non-FOG sediment in the PP2 wastewater compared with the pre-PP3 wastewater (Figure 76) suggests that an added benefit of secondary centrifugation at this stage is the reduction of the non-FOG sludge load on the DAF and subsequently the decanters. Ultrasound treatment at 20 kHz produced a very stable emulsion like in previous trials which centrifugation could not easily break, therefore the use of low frequency ultrasound at is not recommended.

Figure 79: PP2 red pit rendering stickwater with megasonic (MS) treatment (600 kHz, 50 °C, 20 min) and non-MS treatment (left) and MS and ultrasound treatment (US, 20 kHz, 50 °C, 2 min) and non-MS treatment after centrifugation, 3200 rpm, 1717g, 5 min (right)

18.0 CONCLUSIONS/ RECOMMENDATIONS

Milestone 2: Large losses of FOG occur in the DAF in the two Queensland abattoirs and in the decanters of one Victorian abattoir. Loss of FOG separation and recovery in the DAF reduces the yield of high value tallow in the two Queensland abattoirs, especially when the DAF is operated under high load, at high temperature with short residence times. In the Victorian abattoir which uses a DAF with chemical coagulant-flocculant, most of the FOG is recovered as a sludge which is then separated in the three-phase decanter (tricanter). However, after heating the sludge to 95 °C using steam injection prior to entering into the decanter and emulsion is formed and when processed in the decanter under high load, high temperature and short residence time, poor separation of the water, FOG and solids phase occurs due to unresolved emulsions, and so potentially valuable FOG is lost. The water phase contains large amounts of FOG and the FOG sludge phase contains excessive amounts of water. The solids phase is likely to contain water and FOG sludge.

From the literature and patent searches and to the best of our knowledge, megasonics have not yet been applied to FOG separation and recovery from abattoir wastewater streams. Due to the demonstrated effect of megasonics in demulsification and recovery of palm oil from emulsions in palm oil processing wastewater streams as shown in the two megasonics patents, this technology is promising for application in abattoir wastewater treatment. Notwithstanding the other optional technologies which are currently being used or being improved as shown in the patent review. It is not known how effective megasonics with be at resolving emulsions in abattoir wastewater and how it will compare against currently applied technologies. One of the advantages of megasonics is that it can be operated with or without chemical coagulants and flocculants. We therefore recommend proceeding to stage 3 of this project involving laboratory scale megasonic proof-of-concept trials with samples around the DAF from the two Queensland abattoirs. For the Victorian abattoir we recommend sampling each of the three phases of the decanter (tricanter): the FOG sludge phase, water phase and sludge solids phase as well as the inflow to the decanter. This Victorian abattoir is very interested in improving the very poor separation in each of these phases due to the loss in FOG and the expense of further treatment and/or disposal costs. The two other Queensland abattoirs are also interested in increasing the recovery of FOG from the DAF.

Milestone 3:

Q1 and Q2

From the sampling of wastewater flowing into and out of the DAF in the two Queensland abattoirs, Q1 and Q2, it was evident that the residual FOG content was very low and below the efficacy of megasonic treatment to recover such low quantities of FOG. It was therefore not applicable for megasonic treatment to be trialled on such samples, so long as the DAF tanks were operating efficiently, within optimal temperature ranges, and not overloaded. These observations were contrary to our expectations based on the answers to the survey questionnaires and site visits since it was reported that significant losses of FOG as emulsions were an issue particularly if the DAF was overloaded, or operated at higher than optimal temperatures, or in need of maintenance due to large bubble size in the tank. These adverse occurrences did not occur during the time of this study. The recycling of wastewater from the rendering process back into the DAF allows the recovery of residual FOG which would otherwise be lost, making these systems quite effective and efficient. Based on these observations, we do not recommend any further study with Q1 or Q2 using megasonics for the recovery of FOG from wastewater steams.

V2

In the case of the Victorian abattoir, V2, there were several potential intervention points that contained significant amounts of FOG which is discarded. The major ones included:

- DAF sludge
- Decanter tallow sludge (DTS), which contained the highest FOG content

The decanter centrate and decanter solids contained smaller amounts of FOG and so are therefore less important since it would potentially be more costly to try and recover the much smaller proportions of FOG.

- Megasonic treatment of the DAF sludge and decanter tallow sludge at 50 °C or higher did not improve the separation and recovery of FOG compared with the non-MS heated sample, without the aid of a subsequent centrifugation step.
- Centrifugation after MS treatment was able to separate FOG, water and solids to a similar extent as the control, however, at 25 °C the FOG was separated after MS treatment compared with the control for the DAF sludge and DTS samples.
- Centrifugation of the MS treated DTS sample at 1717 g for 3min produced a more concentrated FOG top layer, but the increase was less pronounced at other conditions (5 min at 671 g and 1-2min at 2683 g).

The DAF and DTS samples contained poor quality FOG due to contamination from the green stream; therefore, so FOG recovered from these streams cannot be used to make high-grade tallow but could be used as a feedstock for biodiesel manufacturers.

The pre-DAF streams, namely,

- PP3 black pit and pre-PP3 rendering centrifuge wastewater
- PP2 red pit rendering stickwater

contain significant amounts of high-grade FOG, particularly, the PP3 black pit and pre-PP3 rendering centrifuge wastewater stream which is rich in FOG. This FOG could be captured prior to mixing with the green stream and is the preferred option since the recovered high-grade FOG could be fed back into the render cooker. This would lead to increased high-quality tallow yields, decreased FOG loads on the two DAFs and the two decanters, thereby increasing the separation performance of the decanters and reducing offsite sludge disposal and treatment cost to treat or remove excessive FOG from the decanter tallow sludge stream.

Megasonic treatment of these streams did not improve FOG recovery; however, centrifugation was very effective at the separation of and recovery of high-grade FOG, as well as the sediment from the PP3, pre-PP3, and PP2 wastewater. The surface samples from the PP3 black pit contained almost exclusively FOG and we it is hypothesised that the black pit at 80-95 °C, could be acting as a separator. The most promising result of this study was the finding that simple heating and cooling of the pre-PP3 sample alone, without centrifugation or megasonic treatment, was able to flocculate and float the FOG from the pre-PP3 stream. This result strongly suggests that the FOG can be effectively separated by using a DAF without added flocculants as in Q1 and Q2, or alternatively separated by high speed disk centrifugation.

The proposal for milestone 4 was to produce a drawing of a megasonic reactor based on the assumed benefit of megasonic treatment. Since MS did not work as intended, and in light of the promising results for the potential recovery of high-grade FOG, currently being lost from PP3, and pre-PP3, for increased tallow production, we seek a discussion with AMPC to consider a change in Milestone 4 and a proposal to investigate options for FOG separation and recovery in the PP3 black pit and pre-PP3 rendering centrifuge wastewater. We propose two options for discussion:

Option 1.

Pilot Pilot-scale centrifugation trials on PP3 black pit, pre-PP3 rendering centrifuge wastewater and PP2 stickwater

Option 2.

Small-scale simulated DAF trials for pre-PP3 and PP2 streams.

Other abattoirs that use a similar processes to those of the Victorian abattoir, V2 may also be encountering similar issues and loosing large quantities of high-grade FOG in the DAF sludge and decanter tallow sludge and could, therefore, could benefit from the findings of this study. Furthermore, they could benefit from further research targeted at interception and recovery of high-grade FOG streams from the rendering wastewater (PP2 and pre-PP3). Heating and cooling could be explored to increase the effectiveness of floatation and separation of the FOG in a small-scale DAF without the use of flocculants as seen here on a small bench scale. In addition to increasing the tallow yield, it could significantly reduce the amount of FOG mixing with the green stream and going to the DAF and/or decanters.

19.0 APPENDICES

19.1 Appendix 1 – Process Flow Diagrams

Process flow diagrams for abattoir V1, Q1 and V2 are shown below

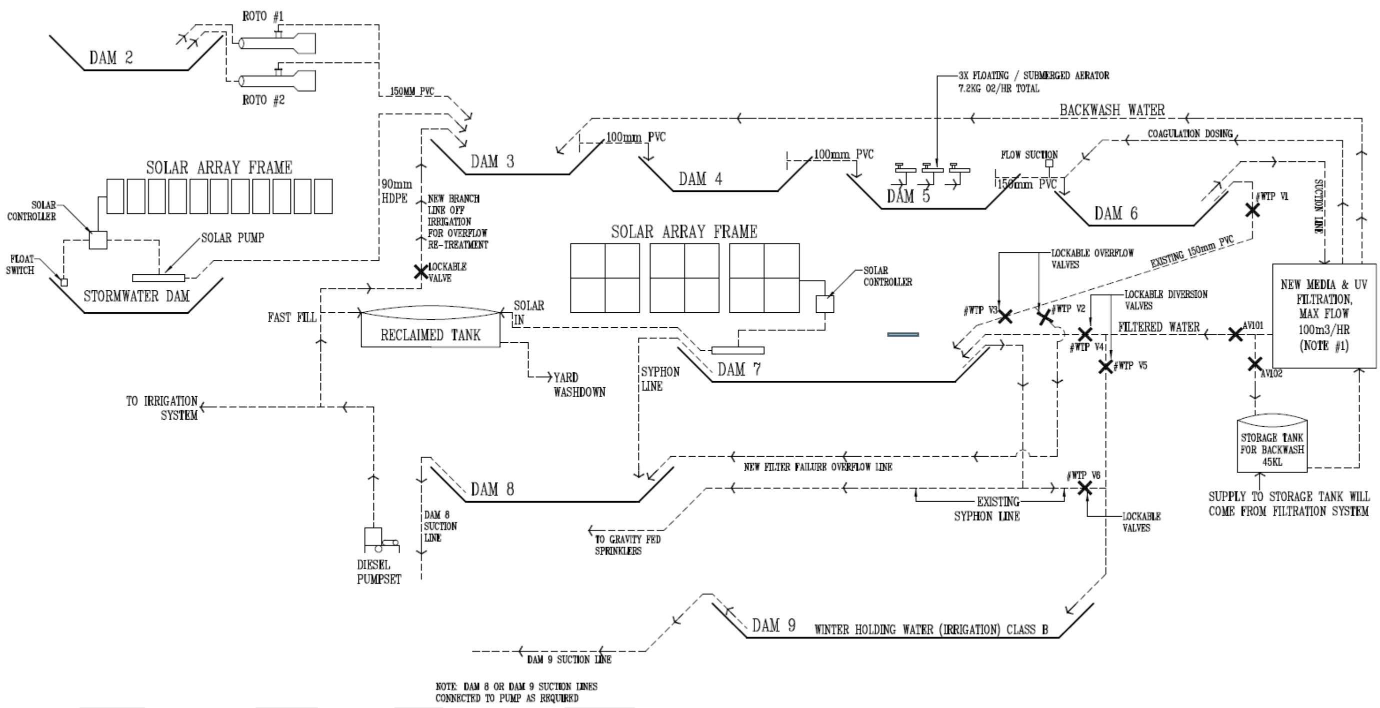

Figure 1. Detailed process flow diagram for abattoir V1

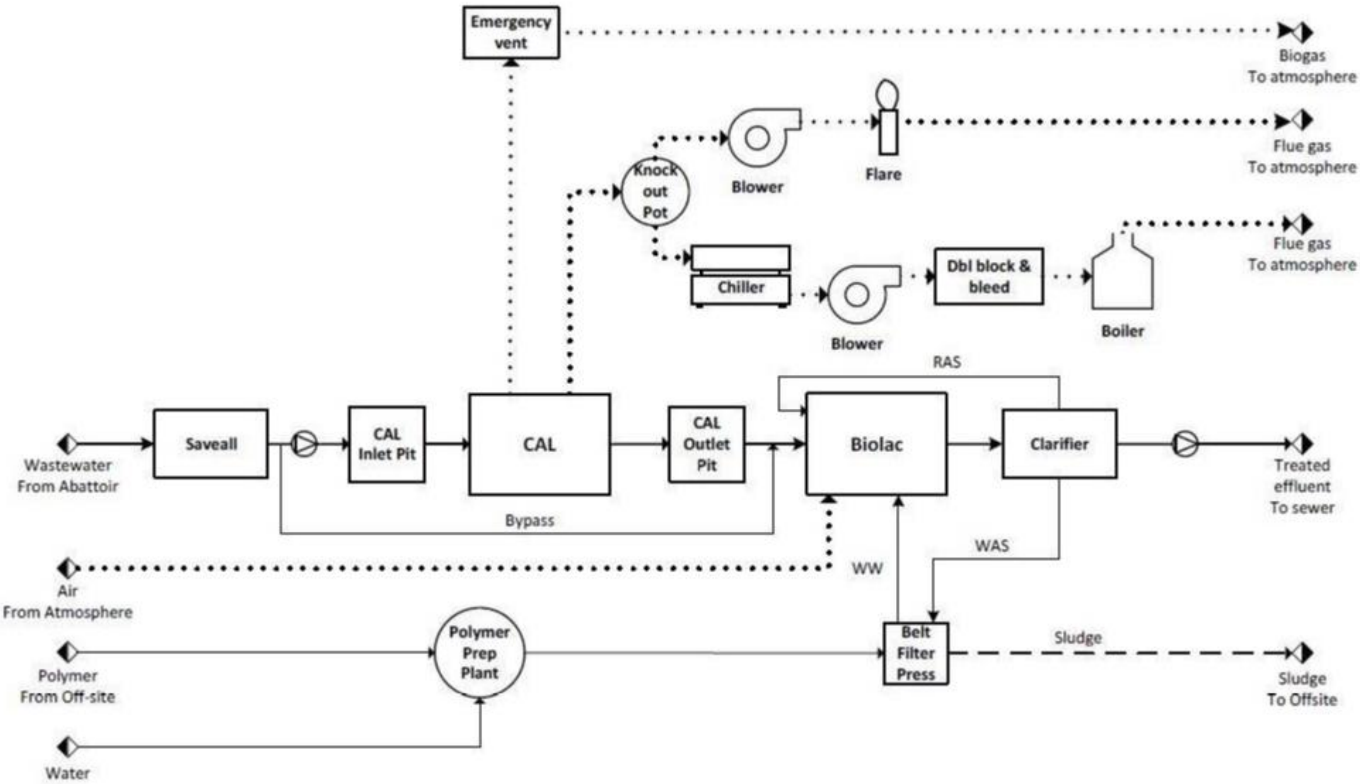

Figure 2. Detailed process flow diagram for abattoir Q1

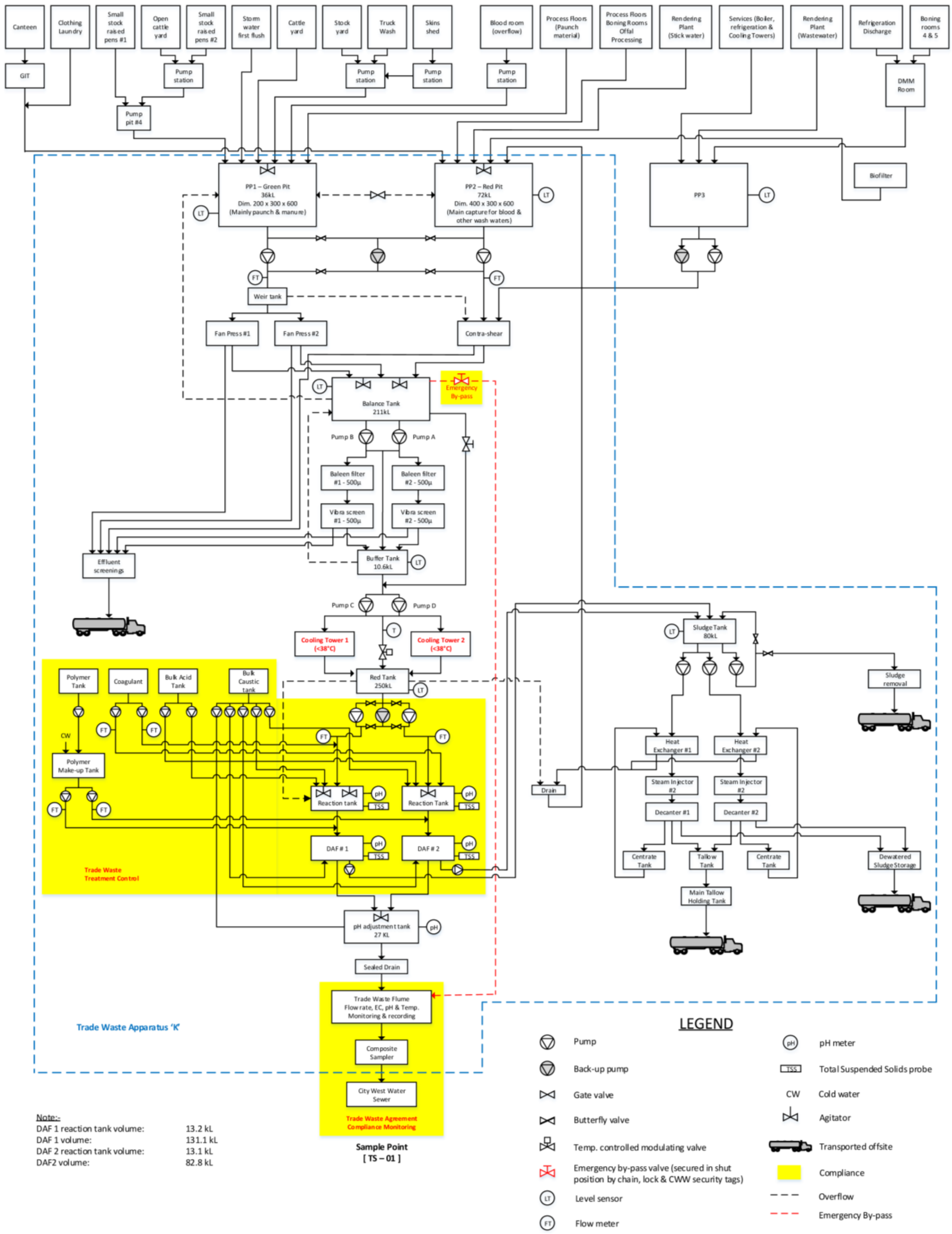

Figure 3. Detailed process flow diagram for abattoir V2

AMPC

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