AMPC

AUSTRALIAN MEAT PROCESSOR CORPORATION

Review of wastewater treatment chemicals and organic chemistry alternatives for abattoir effluent

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Executive summary

Management of wastewater from the Australian red meat processing industry is an important issue. Due to the specific characteristics of wastewater, such as irregular discharge and considerable organic and biogenic loading, it is can be difficult and costly to treat. The organic loading rate of wastewater from the red meat processing industry can be several times higher than the average domestic sewage. Also, it is well known that its high content of fat, oil and grease (FOG) is another issue that makes the treatment process much more difficult. With the increasing costs of pollution abatement and the high cost of municipal surcharges, the red meat processing industry is forced to look into more practical, more efficient and more cost-effective methods. The type and level of treatment required depends on the final usage of the treated wastewater.

The red meat processing industry in Australia comprises of around 191 sites (i.e. individual facilities) spread across around 120 businesses. The industry produces significant volumes of wastewater. An AMPC survey of 23 sites conducted in 2012 revealed that smaller plants, processing up to 1,500 tonnes of hot standard carcase weight (tHSCW) per month used on average 2.82 kL of water per tHSCW processed. The same survey revealed that larger plants mainly registered for export, processing in excess of 1,500 tHSCW per month, used on average 8.64 kL of water per tHSCW. However, the survey revealed that 61% of plants reused their wastewater to replaced potable water (in regulator-approved arrangements such as yard and stock washing, initial tripe wash, cooling applications, boiler feedwater), 7% recycled water within the same process in the plant (i.e. carcass wash systems), 69% irrigated their wastewater on site, and 30% of respondents said that their wastewater was used for off-site irrigation.

Depending on geographic location and wastewater characterisation the wastewater can require considerable treatment, involving physical, chemical and biological treatment strategies, to meet environmental standards for release. Physico-chemical methods are increasingly being used for the preliminary treatment of wastewater before its biological purification. This is due to stricter requirements with regard to the degree of purification of wastewater and the negative impact of the high loading rate and fat content on the biological process; a process contained within the 'secondary treatment' stage.

This review addresses both conventional and alternative wastewater treatment chemicals in the red meat processing industry. In addition, use of cleaning and sanitizing agents at the meat processing facilities are also addressed .The review reveals that chemical treatment has to be an integral part of the entire treatment process. There is a high interaction between physical, chemical and biological treatment processes. Chemical treatment of physically-untreated wastewater can be more costly due to higher chemical dosage required. The large solid particles in the wastewater (which can be removed easily by physical treatment) can significantly reduce the efficiency of the chemical coagulants in removing soluble and colloidal materials. For this reason, physical treatment is found to be essential and should always be carried out before a chemical treatment process. Based on the availability and performance of the physical treatment, chemical treatment efficiency may vary between 20 to 80%.

This review also shows that due to the biological characteristics of red meat processing industry wastewater, biological treatment has been used for decades as a suitable treatment process. Biological treatment processes are capable of converting the organic matter in the wastewater to compounds such as ammonia and phosphorous which can be used as fertilizers. Methane is also produced as a result of the anaerobic digestion process which is a source of energy and can offset some of the treatment plant's fuel costs if it is captured. This study shows that chemical treatment is highly efficient in removing soluble and colloidal particles from the meat processing industry wastewater. Chemical treatment has a potential either to replace or to support the biological treatment depending on the required specification of the final products and by-products. In addition, this study has revealed that there are a small number of abattoirs using chemicals for treatment of wastewater. Importantly, the chemicals in use can have a negative impact on the biological treatment and the recyclability of the by-product (sludge) generated. For these reasons alternative chemicals are suggested. Based on the literature review, these alternatives have the same efficiency of the conventional chemicals while positively impacting the subsequent biological process. For example, a combination of a main and an aid coagulant identified in this study showed to have an optimum efficiency and cost-effectiveness while having a positive impact on the biological process.

With regard to chemicals currently in use for cleaning and sanitizing (alkaline, acid and chlorine based) within red meat processing facilities, the study shows that these chemicals are hazardous. However, since these chemicals are used at low concentrations (2-5%) in the cleaning process, they have low or negligible impact on the biological process and the environment if further diluted. These chemicals can be diluted significantly to concentrations less than 0.001% by mixing with the bulk wastewater in a collection tank. Flushing these chemicals during the cleaning period directly to the biological treatment system may negatively affect microorganism activity.

Finally, this report presents more detailed practical solutions and a plan for optimising the chemical treatment process.

Based on this review a number of key recommendations have been made and include further studies into:

- Proving the performance of chemical cleaning alternatives.
- Optimizing the chemical treatment process.
- Assessing the impact of treatment chemicals (conventional and alternatives) on the biological treatment and biogas generation.
- The requirement of chemical treatment when the quality of the treated wastewater is for irrigation where physical and biological treatments are sufficient to achieve such quality.
- The level of chemical treatment when the quality of the treated wastewater is for reuse inside the plant or to be released to surface water.

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1. Introduction

The Australian red meat processing industry is a significant consumer of fresh water and producer of wastewater. The cost and regulatory restrictions around water supply and wastewater disposal therefore needs to be considered when evaluating wastewater treatment options. Water authorities in Australia have progressively implemented full cost recovery by passing the cost of water supply onto the consumers. This has caused higher water pricing over the last decade, a trend that is expected to continue which has highlighted the importance of strategies for wastewater treatment and reuse to the food manufacturing sector. Costs of wastewater disposal and limitations on discharge also need to be considered. Plants discharging treated wastewater to municipal sewerage systems face the greatest costs and limitations. Authorities currently charge on the basis of the volumetric and organic loads (BOD/COD content), and nutrients such as nitrogen and phosphorous are also expected to be introduced in the future. Authorities are in the process of formulating charging systems that will progressively increase wastewater discharge fees on a user-pay basis until full cost recovery is achieved. In addition, the quantity and the quality of solid and water wastes generate a number of environmental challenges to the red meat processing industry as part of the day-to-day running of processing plants. There is potential for odour and nuisance for neighbouring communities and pollution of surface and ground waters. In addition, there are the added chemicals to the wastewater as a result of cleaning the meat processing facilities. Chemical cleaning solutions are used for cleaning floor and wall areas as well as working tables, containers and equipment. Cleaning agents such as alkaline, acid or neutral chemical substances are used in this process. Also, surface-active agents (surfactants/detergents) are added in order to improve their dirt loosening properties. These chemicals are hazardous and may impact negatively the biological treatment process. For these reasons there is a need for responsible solids and wastewater treatment and careful disposal of putrescible organic wastes to prevent the pollution of the environment.

The objectives of this review were to address the following key questions for the Australian meat processing industry:

- What is the nature of the cleaning and wastewater chemicals in use within industry?
- Where (why and how) have they been used?
- What is their cost and efficiency?
- What is their impact if discharged to the environment?
- What are the by-products that result from using them and how can these by-products be recycled?
- What are the alternatives and how do they compare to what is available?

In order to investigate these questions, an international literature review was carried out using resources such as scientific journals/conferences publications and industry reports. The review focused on past chemicals use, chemicals currently in use and those that have potential to be used for cleaning red meat processing facilities, treatment of abattoir wastewater and enhancement of biological treatment processes. These chemicals were categorized based on their cost, efficiency, and environmental friendliness. Because chemical treatment is mostly recommended as a pre-treatment process which is followed by biological processes such as anaerobic digestion, it was important to identify chemicals that possess features such as biodegradable and non-toxic and post-treatment recyclable/reusable by-products. These features are also preferred properties for the cleaning chemicals.

Chemical treatment of the red meat processing industry wastewater is a suitable option especially when the treated water is to be utilized for reuse inside the facility or discharged to surface water. There are many kinds of inorganic metal-based coagulants on the chemical market such as aluminium sulfate (alum), ferric chloride and ferric sulfate, polyaluminium chloride (PACl) and aluminium chlorohydrate (ACH) [Al-Shaikhli, 2013]. In recent years, there has been considerable interest in the development of natural coagulants as alternatives. Using natural coagulants may result in considerable savings in chemicals and sludge handling costs. Chitosan, starch, *Moringa oleifera* and psyllium are natural-base coagulants that have been investigated for raw and wastewater treatments [Al-Shaikhli, 2013]. In this study, chemical coagulants such as ferric sulfate and chitosan were found to be efficient, low cost and environmentally friendly compared to conventional coagulants such as alum.

Finally, critical analysis of the findings of this review was performed to generate conclusions and provide recommendations with innovative and practical solutions for the industry. The outcomes of this review are aimed to enhance the current knowledge of chemical usage options within the red meat processing facility for both cleaning/sanitizing and wastewater treatment purposes. The report also addresses impact of chemical treatment on the entire wastewater treatment process and the environment. A summary of key messages obtained from the report for the industry to consider include the:

- Reassessment of the entire treatment system including physical, chemical and biological processes;
- Identification of cost-effective, more efficient, and environmentally friendly chemicals;
- Identification of chemicals that have recyclable by-products and potential reuse;
- Identification of more efficient methods for applying these chemicals;
- Identification of the impact of the chemicals currently in use on wastewater treatment system performance;

- Assessment of the influence of these alternate chemicals on secondary treatments such as anaerobic digestion process and composting;
- Identification of solutions that do not require extensive changes in the current treatment practices;
- Identification of paths for generating revenue from the chemical-treatment by-products;
- Provision of recommendations for further research if applicable.

2. Chemicals introduced to the effluent by the facility operation

Periodic cleaning and sanitation is an integral part of the red meat processing industry. Cleaning and sanitation of meat plant premises and equipment can even be considered as one of the most important activities in the meat plant because of the sensitivity of the product. Dirt and organic substances, such as fat and protein particles, need to be removed from surfaces of walls, floors, tools and equipment. Around 90% of microorganisms can be removed using conventional cleaning procedures such as brushing with the aid of water [FAO, 2014]. However, some microorganisms adhere very firmly to surfaces and cannot be removed even by deep cleaning. These microorganisms can persist and continue to multiply in tiny almost invisible layers of organic materials, so called ‘biofilms’. To remove these microorganisms, antimicrobial treatments are required such as hot pressurized water/steam and through the application of cleaning/sanitising chemicals. Sanitation also includes combating pests such as insects and rodents through chemical substances (insecticides and rodenticides).

2.1. Cleaning with chemicals

The removal of loose dirt and meat/fat residues by the dry and wet cleaning process does not mean the cleaning is complete. Sticky or encrusted layers of fat or protein will still exist and must be removed. For this purpose chemical cleaning solutions can be used and have been found to be very effective. Brushes or scrapers can be used with the aid of chemicals for dismantled equipment and for smaller surfaces. Mechanical cleaning with high pressure equipment together with cleaning chemical solutions is used for larger floor and wall areas as well as working tables, containers and equipment. In modern cleaning practices, cleaning agents are complex compositions of alkaline, acid or neutral chemical substances. Also, surface-active agents (surfactants/detergents) are added in order to improve their dirt loosening properties. Detergents are important as they keep the fat dissolved and prevent it from settling after the water temperature has decreased. Detergents may have additional cleaning components such as chlorine, silicate or phosphate. A survey carried out by the author has revealed a sample of the cleaning chemicals currently in use in the Australian red meat processing industry. Table 1 presents the different types of chemical agents in use in facility cleaning worldwide in the red meat processing industry. In practice alkaline agents are used for routine cleaning, but every few days an acid substance should be employed instead in order to remove encrusted residues and scaling. After applying chemicals to the surfaces and equipment, water will be used to remove the suspended dirt particles and fat. Foam cleaning is a relatively new cleaning method in the food industry, purposely used for larger-scale meat processing plants. Water foam containing detergents and other cleaning agents is sprayed on wetted walls, floors and surfaces of equipment. The foam sticks to the surface which allows a longer contact time with the dirt. After a sufficient impact period (minimum 15 minutes) the foam is washed down with water.

Table 1: Cleaning agents in use in red meat processing industry [FAO, 2014]

CLEANING AGENT	PURPOSE	CHEMICALS
Alkaline	Generally suitable for removing organic dirt, protein residues and fat.	Sodium hydroxide (caustic soda), sodium carbonate (soda ash), and sodium metasilicate.
Acid	Used particularly for removal of encrusted residues of dirt or protein or inorganic deposits (“scaling”).	Inorganic acids: phosphoric acid, nitric acid, sulphuric acid and hydrochloric acid. Organic acids: gluconic acid, tartaric acid, citric acid, acetic acid and sulphamic acid.
Neutral	Less effective than alkaline or acid cleaning agents, but have mild impact on skin and materials and are useful for manual cleaning of smooth surfaces without encrusted dirt.	Silicates may be used as anti-corrosive agents in alkaline detergents but will deposit on stainless steel and it is therefore important to know which materials it may be applied to.
Foam cleaning	A relatively new cleaning method, in particular for larger-scale plants.	---
Detergents	Used to improve dirt loosening properties.	Anionic, nonionic and cationic surface active agents.

Table 2 shows an example of the cleaning chemicals in used at one Australian red meat processing facility. As shown in the table, alkaline and acid agents are in common use at this site.

Table 2: Specification and status of chemicals in use at an Australian abattoir [survey carried out by the author]

NAME	CHEMICALS	USE	SUBSTANCES	HAZARDOUS AND DANGEROUS STATUS
Alkaline, TOPAX 625	Sodium Hydroxide solution	Cleaning product	Up to 3% in water. Sodium hydroxide <10%, sodium hypochlorite <10%, sodium metasilicate <10%	Classified as hazardous substance and dangerous goods

Acid, TOPAX 56	Phosphoric acid solution	Cleaning product	Up to 3% in water. (2-(2-butoxyethoxy) ethanol <10%, phosphoric acid 10-30%, isotridecyl ester <10%	Classified as hazardous substance and dangerous goods

2.2. Disinfection chemicals

The complete elimination of microorganisms can be achieved through disinfection, either by using hot water/steam or chemical disinfectants. Chemical disinfectants are preferred for disinfection in the red meat processing industry as they are easy to use and provide complete disinfection. Figure 1 shows the impact of disinfection chemicals on the meat facility surfaces. As can be seen in the figure, chemical cleaning alone cannot eliminate bacterial colonies, disinfection chemicals are required for quality clean surfaces [FAO, 2014].

Modern disinfectants are mostly mixtures of different chemical substances. Combinations of disinfection chemicals (organic acids, surfactants, and peroxide compounds) may result in the elimination of a broader range of microorganisms. The exact compositions are sometimes not fully revealed by the manufacturers. In principle, as shown in table 3, the following groups of substances are used to varying degrees worldwide and in the Australian red meat processing industry [FAO, 2014; Survey carried out by the author].

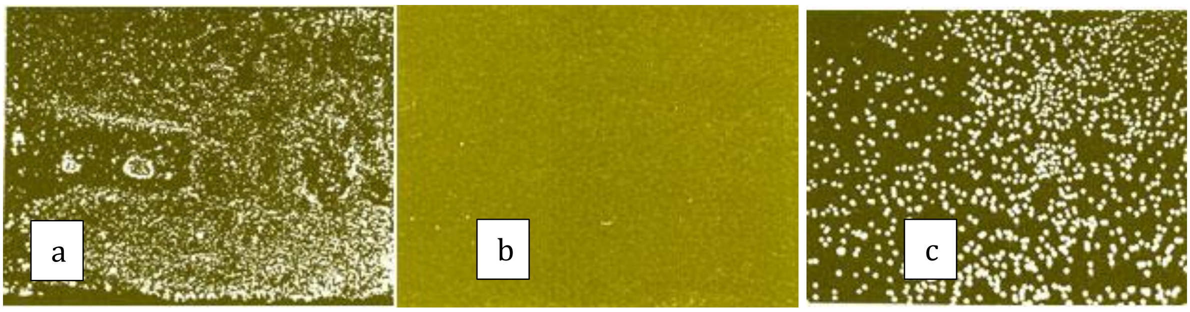

Figure 1: (a) Uncleaned (rinsed only), many bacterial colonies. (b) After chemical cleaning, reduced numbers of bacterial colonies. (c) After cleaning and disinfection, very few bacterial colonies remain [FAO, 2014].

Table 3: Available disinfectant and their usage [FAO, 2014]

DISINFECTANT	COMPOSITION	PURPOSE
Chlorine containing compounds	Na- or Ca-hypochlorite (Na/Ca O Cl), Gaseous chlorine (Cl2) (Hypochlorous acid)	Effective against a wide range of bacteria, penetrates cell walls, but has a corroding effect on equipment.
Aldehydes	Formaldedyde, Phenoles / Kresols, Alcohols, Alkalines (pH 10 or higher) (e.g. NaOH), Acids (some organic acids)	Destruction of microorganisms, may be corrosive.
Quaternary ammonium compounds (QUATS)	Amphotensids	Effect on cell walls, not corrosive, odorless, additional cleaning properties (surfactant).
Oxygen releasing substances	Peroxide compounds (H_2O_2), Per-acetic acid	Penetrate into cells, good effect on all microorganisms including spores and virus, odorless, may be corrosive at concentrations greater than 1%.

Table 4 shows an example of the sanitizing chemicals in use at one Australian red meat processing facility. As shown in the table, quaternary ammonium compounds (QUATS) and compounds containing chlorine are commonly used in industry.

Table 4: Specification and status of chemicals in use at an Australian abattoir [Survey carried out by the author]

NAME	CHEMICALS	USE	SUBSTANCES	HAZARDOUS AND DANGEROUS STATUS
SANIMAXX	----	Sanitizer	Up to 3% in water. Quaternary ammonium compound, di-c8-10-alkyldimethyl chlorides <10%, quaternary ammonium compounds, benzyl-c12-c16-alkyldimethyl, chloride <10%.	Classified as hazardous substance and not dangerous goods
XY-12	Hypochlorite solution	Sanitizer	Up to 3% in water. Sodium hypochlorite 10-30%	Classified as non hazardous substance and non dangerous goods

2.3. Environmental impact

When red meat processing industry wastewater is discharged to a water course/underground it may lead to a depletion of dissolved oxygen, odour release and sludge deposits and floating scum [Kroyer, 1995]. Red meat processing wastewater also contains nitrogen (N), typically ranging between 50 and 400 mgN/L, and so it has the potential to cause N contamination of groundwater when applied to certain areas of land in excessive amounts [Luo, et al., 2004; Hamawand, 2015]. The main sources of organic materials in wastewater include faeces, urine, blood, fat oil and grease, washings from carcasses / floors / utensils, undigested food from paunch, waste water from cooking / curing / pickling of meat and condensate from rendering of offal and other by-product processing [Hamawand, 2015]. Equally, improper disposal systems of wastes from slaughterhouses could lead to transmission of pathogens to humans [FAO, 2014]. The degree of organic loading rate in the Australian red meat processing industry is extremely high, the BOD can be as much as 4,000 mg/L. This water can be disposed on watercourses only after sufficient treatment. The minimum requirements for the discharge of dirt or wastewater into sewer and surface water can be seen in table 5, which differs from state to state. The table shows that BOD concentration for the discharged wastewater into surface water should be lower than 6 mg/L which means BOD removal of 99% [Sampson et al., 2005]. Removing 99% of the dirt in wastewater is a big and a complex challenge for the treatment plant.

Table 5: Minimum requirements for wastewater disposal to sewer and surface water in most of the Australian states [Sampson et al., 2005].

TYPE	SS	BOD_5	FOG
Sewer disposal pollutant limits	< 1000 - < 1500 mg/l	< 300 - < 3000 mg/l	<50 - < 200 mg/l
Surface water disposal pollutant limits	< 10 - < 15 mg/l	< 5 - < 10 mg/l	2 - 15 mg/l

The other source of contamination of the meat processing industry wastewater is addition of surfactants as a result of the cleaning process. Surfactants may enter the aquatic environment due to insufficient treatment of wastewater. Anionic surfactants are the major class of surfactants currently in use in detergent formulations. Surfactants can cause short term as well as long-term changes in the ecosystem; they can be harmful to humans, fish and vegetation. Subsequently, many environmental and public health regulatory authorities have fixed stringent limits for anionic detergent as standard 0.5 mg/L for drinking water and up to 1.0 mg/L for other purposes [Aboulhassan, 2006].

3. Abattoir wastewater treatment methods

Given the biological nature of the wastewater effluent from the red meat processing industry, biological treatment, specifically anaerobic digestion, tends to be the most appropriate treatment option [Johns, 1995; Hamawand, 2015]. However, this does not eliminate the need for primary physical treatment such as screening and dissolved air floatation (DAF). Provided the physical treatment is carried out efficiently to remove the bulk fat and suspended solids, biological treatment processes can then be utilized. There are circumstances where biological treatment may not be a favourable option. This is maybe due to lack of space (which is currently not the case in Australia) or the wastewater requires further treatment for specific application. In this case, chemical treatment and physical separation can be feasible options [Husband, 2014].

3.1. Physical treatments

The high concentration of fat, oil and grease in abattoir wastewater may reduce solids removal efficiency in the biological treatment system due to their insoluble nature. Fats are less dense than water, limiting the physical mass transfer from the solid to the liquid phase (diffusion). Also, the methanogenic activity may be inhibited due to the presence of long chain fatty acids [Long, 2012; Pittaway, 2011].

The physical treatment process steps involve either solely or in a combination; sedimentation, coarse screening, followed by fine screening and finally dissolved air floatation [AMPC, 2006; Lawrence, 2006]. Among physico-chemical processes, DAF system combined with coagulation process is widely used worldwide for the removal of total suspended solids (TSS), colloids, and fats from red meat processing industry wastewater [Bazrafshan et al., 2012]. Table 4 shows the performance of the different physical treatment that can be used in the red meat processing industry wastewater.

Table 6: Physical treatment methods and their performance [AMPC, 2006; Lawrence, 2006]

TREATMENT METHOD	PERFORMANCE
Coarse and Fine Screening	The first step involves coarse screening so that large particles (above 1 cm) are removed. This is important to prevent accumulation of these particles which may disrupt mechanical equipment. Primary screening can remove 5-20% BOD and 5-30% TSS.
Primary Sedimentation	Skimming and sedimentation processes are able to remove floating and sediment objects, e.g. 20 to 30 % BOD, 40 to 50 % TSS, and 50 to 60 % grease. This process is more efficient than the screening unit but this comes with high capital, operation and maintenance costs.
Dissolved Air Flotation (DAF)	Usually before anaerobic treatment, the wastewater stream is diverted to the DAF unit so that blood, fat, oil and grease constituents are reduced. A DAF system can be used to continually or periodically recover fats and protein. If the DAF process is controlled well, 30 to 35% removal of BOD, 60% removal of TSS and 80% of FOGs removal is achievable.

3.2. Chemical treatments

In general, wastewater contains particles of different sizes. The size of particles present in wastewater determines the type of treatment that required. Particles can be classified based on their sizes as dissolved (< 0.08 µm), colloidal (0.08 - 1 µm), supra-colloidal (> 1 - 100 µm) and settle-able (> 100 µm). Physical treatments such settling, screening and DAF are capable of removing particles that are visible to the naked eye. However, very fine particles of a colloidal nature (size < 1 µm) which have high stability are impossible to separate by settling or by any other means of physical treatments. These fine particles such as blood and dissolved organics are the main pollutant and contribute significantly to the high BOD in the wastewater. These particles have negative electrostatic surface charges and due to the repulsive forces between them, they are unable to aggregate and subsequently settle [Al-Shaikhli, 2013].

It is not possible to separate colloidal solids even by fine filters because they pass through any conventional filter. However, there is one way to separate these colloidal particles using chemical treatments. The separation can be achieved through addition of chemicals (called coagulants and flocculants) which enable these colloidal particles to form into flocs with settling properties [Al-Shaikhli, 2013].

Coagulation-flocculation process can be used for both wastewater treatment and also in the dewatering process of the sludge extracted from the anaerobic digestion system. These chemicals are usually added to improve the efficiency of dewatering processes and the quality of the filtrate. In many cases it is very difficult to dewater sludge using filtration even with using a filter press technique.

3.2.1. Coagulation-flocculation-sedimentation

Generally, coagulation is the process in which colloidal particles in water are clumped together into larger particles, called flocs. Coagulants have been known since early in the twentieth century and have been playing a vital role in the removal of many impurities from polluted waters. Coagulation is a process where ions of opposite charges are added to colloidal particles solution such as wastewater (refer to figure 2). The colloidal particles in wastewater are almost negatively charged which make them stable and resistant to aggregation. For this reason, cations or positively charged ions (coagulant) should be added to the solution to destabilize the particles. The process of coagulation-flocculation allows sedimentation of the colloidal particles which otherwise are very difficult to separate [Al-Shaikhli, 2013]. The aim of applying coagulation–flocculation treatment is generally to remove the colloidal matter present in the wastewater. Nutrients can also be removed during the process. The presence of phosphorus and nitrogen in the wastewater should be limited. Phosphorous can cause eutrophication of surface waters and nitrogen can reduce the levels of dissolved oxygen in water, stimulate algae growth, reduce the efficiency of disinfection (with chlorine) or affect the quality of the water for re-use [Aguilar et al., 2001].

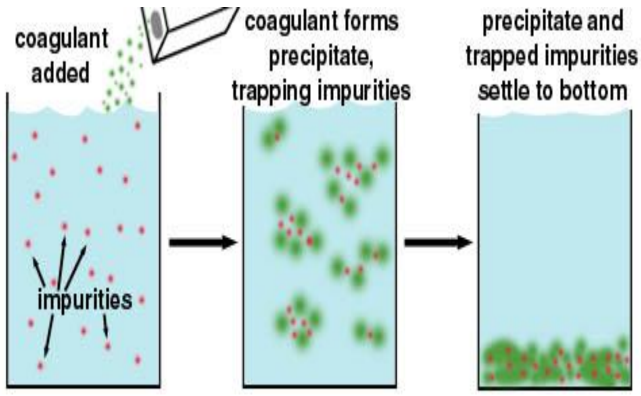

Figure 2: Coagulation/Flocculation process [Al-Shaikhli, 2013]

There are various types of coagulants in the chemical market such as inorganic metal based-coagulants. Some examples of inorganic metal coagulants are aluminium sulfate (alum), ferric chloride and ferric sulfate. Alum has been used for water purification since ancient times. Recently pre-polymerised inorganic coagulants have been used due to their availability such as polyaluminium chloride (PACl) and aluminium chlorohydrate (ACH) [Al-Shaikhli, 2013].

Recently, PACl has had more interest by the red meat processing industry because of its higher efficiency, relatively low costs compared with the traditional flocculants and is reported as most effective coagulant agents in water and wastewater treatment facilities. PACl can be used for various applications, including removal of colloids and suspended particles, organic matter, metal ions, phosphates, toxic metals and color [Bazrafshan et al., 2012].

Over the last 20 years, attempts have been made to improve the elimination of organic matter and total suspended solids (TSS) from agro-food industry wastewater and particularly those from slaughterhouses.

New coagulants, both inorganic and organic were investigated. The elimination of organic materials by coagulation process is influenced by many factors such as the conditions and the characteristics of these materials. Consequently, the removal of organic matters by coagulation varies widely between 10% and 90% [Al-Mutairi, 2006]. The effectiveness of these coagulants were found to be dependent on the composition of the wastewater, temperature, dose, the rate of mixing and the order in which coagulants and flocculants are introduced into the wastewater. Table 5 shows removal efficiencies of various coagulants, reported in a number of publications, for COD, BOD_5 and TSS at several levels of pH and doses of different coagulant aids. As can be seen from the table, three compounds: PAX-18, $Al_2(SO_4)_3$ + polyacrylamide + polyelectrolyte and $Fe_2(SO_4)_3$ + anionic polyacrylamide appear to be the most effective for COD removal, while the results obtained for the other parameters (BOD_5 and TSS) varied with pH [Arvanitoyannis and Ladas, 2008]. The coagulation/ flocculation process has been reported to be cost effective, easy to operate and energy-saving alternative treatment process [Amuda and Alada, 2006].

Table 5: Removal efficiencies of COD, BOD5 and TSS using different coagulants [Arvanitoyannis and Ladas, 2008].

COAGULANT	COD REMOVAL EFFICIENCY (%)	BOD REMOVAL EFFICIENCY (%)	TSS REMOVAL EFFICIENCY (%)
$Al_2(SO_4)_3$ (Alum)	33.1 - 87	30 - 88	31 - 97
$Fe_2(SO_4)_3$ (ferric sulfite)	64 - 78	81 - 91	43 - 98
PAX-18	69 - 80	45 - 79	57 - 97
$Al_2(SO_4)_3$ + AP	46 - 87	62 - 90	86 - 97
$Fe_2(SO_4)_3$ + AP	59 - 90	62 - 93	81 - 98
PAX-18 + AP	69 - 80	79 - 90	88 - 98
$Al_2(SO_4)_3$ + AP polyelectrolyte	79.1	86.3	85.4

AP: anionic polyacrylamide

In a study by Aguilar et al. (2003), ferric sulfate was used with and without coagulant aids. The efficiency of coagulation varied with the waste particle size, although overall efficiency was quite considerable (87%). The use of coagulant aids improved the removal efficiency, in case of using polyvinyl alcohol the removal efficiency was around 93% and for anionic polyacrylamide was around 99%. In another study by Aguilar et al., (2001), they found that phosphorus removal of three coagulants: $Fe_2(SO_4)_3$, $Al_2(SO_4)_3$ and PAX-18 was very high, around 100% for orthophosphate and between 98.93% and 99.90% for total phosphorus. However, ammonia nitrogen removal was very low (<10%), TKN removal varied from 50% to 57% and appreciable performance was observed for albuminoid nitrogen (73.9–88.77%).

Al-Mutairi et al. (2006) investigated the use of the coagulation/flocculation process to remove organic matter from wastewater at a New Zealand slaughterhouse by adding aluminium salts and polymer compounds. The removal of COD, SS and turbidity were 3% to 20%, 98% to 99%, and 76% to 93%, respectively. The alum dosage used in this experiment was around 100–1000mg/L, with pH in the range of 4–9. When polymer was used instead, the COD and SS removals were between 9% and 43% and 95% and 96%, respectively. It was found that effluent discharge of this quality could safely be obtained at 30–70mg/L concentrations of polymer or at 100–300mg/L alum with pH in the range of 4–9.

Amuda and Lada (2006) showed that at a dose of 750 mg/L for three coagulants; alum, ferric chloride and ferric sulfate, COD removal efficiency can reach 65%, 63% and 65%, respectively.

3.2.2. Electrochemical methods

Electrochemical methods such as electro-oxidation and electro-coagulation have been introduced as a suitable treatment method for various kinds of wastewater including wastewater from abattoirs. These methods have been used successfully in the treatment of wastewater from poultry and cattle slaughterhouses and those which contain heavy metals [Bazrafshan et al., 2012]. The chemical reactions occurring in the electro-coagulation process are as follows:

$$Al \leftrightarrow Al^{3+} + 3e \quad (anode)$$

$$3H_2O + 3e \leftrightarrow \frac{3}{2}H_2 + 3OH^- \quad (cathode)$$

$$Al^{3+} + 3OH^- \leftrightarrow Al(OH)_3 \quad (bulk)$$

In the process described above Al^{3+} and OH^- ions react in the bulk solution to form aluminium hydroxide flocs. These flocs normally have large surface areas and involve in a rapid adsorption of soluble organic compounds and trapping of colloidal particles. Also, these flocs polymerize further and can be removed easily from aqueous mediums by sedimentation or/and flotation by hydrogen gas [Bazrafshan et al., 2012]. Furthermore, this process produces less sludge because it is more concentrated than that generated by normal chemical coagulation process. Electrolytic treatments are characterized by simple equipment, brief retention times and easy operation and also results in reduction of operating costs in large scale applications [Asselin et al., 2008]. The difference between chemical coagulation and electrocoagulation is the source of coagulant. In electrocoagulation, the source of the coagulant is the cat-ions produced by electrolytic dissociation of the anode metal and the activation energy applied which promotes the formation of oxides.

Internationally, in a study by Asselin et al., (2008), electrocoagulation (EC) process was tested for a poultry slaughterhouse wastewater using mild steel and aluminium electrode set in two configurations (bipolar (BP) or monopolar system). The best results were obtained by using mild steel BP electrode system operated at a current intensity of 0.3 A with a treatment time of 60 or 90 min. Under these conditions, removals of 86, 99, 50 and 82% were achieved for BOD, oil and grease, soluble COD and total COD, respectively. It has been found that EC is also efficient for de-colorization (red-colour) and clarification with removals of 89% and 90% for total suspended solids and turbidity, respectively.

3.2.3. Chemical DAF unit

Flocculants and/or coagulants may be added in the removal of targeted contaminants such as solids/fats when DAF performance is poor. This will assist in the separation of solids/fats from the water, and can greatly increase the removal efficiency of the DAF system, or allow it to effectively cope with heavier contaminant loads. DAF units can achieve COD reductions ranging from 32% up to 63% representing mostly fine and colloidal particles. This efficiency can be increased to 97% by removing part of the soluble materials if combined with chemical treatment. A wide variety of chemicals are available, a balance between cost and effectiveness is required to choose the suitable coagulant.

In a study by Masse and Masse (2000), they showed that the efficiency of a conventional DAF unit in many slaughterhouses for reduction of TCOD and SCOD is approximately 22- 35% and 0-16%, respectively. They also showed that a chemical-DAF unit can reduce TCOD and SCOD by 58 and 26%, respectively. Over 50% of the SS and 35% of the nitrogen were removed as well. However, effluent TCOD and SS concentrations were still above the maximum allowable levels for industrial wastewater discharge into municipal sewer without surcharge. The chemicals used in this process were ferric chloride coagulants.

Chemicals such as polymers and flocculants are often mixed prior to the DAF process with the aim to increase protein clumping and precipitation as well as fat flotation. Table 6 shows different DAF system performances when treating slaughterhouse wastewater [Arvanitoyannis and Ladas, 2008].

Table 6: DAF system performances for slaughterhouse wastewater [Arvanitoyannis and Ladas, 2008].

TREATMENT	COD REMOVAL EFFICIENCY, %	TSS REMOVAL EFFICIENCY, %	REFERENCE
DAF and chemicals	32–92	70–97	Karpati & Szabo (1984)
DAF at pH 4–4.5	71	78	Travers & Lovett (1985)
DAF and chemicals	38–71	37–63	Mittal (2005)
DAF with air	40	60	Travers & Lovett (1985)

3.2.4. By-Products

The by-products of the chemical treatment can be categorized into two groups. Group one: a wet solid waste which includes the solid wastes that pass through the physical treatment such as meat scraps, hair, manure, paunch, fat and semi-digested feed due to their small sizes plus most of the chemicals used in the chemical treatment. Group two: a low concentration wastewater related to organic matter and chemical residues as a result of the chemical treatment process. Most of the chemicals used in the chemical treatment process will accumulate in the by-product sludge. Typically hydrated alumina oxides and iron oxides are present in this sludge (this depends on coagulants used for the treatment). The composition and properties of these waste products depend typically on the quality of wastewater as well as on the types and doses of the chemicals used during the treatment process.

There are many studies that address the use of coagulant aids to reduce the volume of the by-product sludge. It has been found that the highest sludge volume reduction of 41.6% was achieved when anionic polyacrylamide was used as a coagulant aid together with ferric sulfate. Ferric sulfate produces the least amount of sludge for a given amount of COD (mg O_2/L) removed compared to aluminium sulfate and polyaluminium chloride. The volume of the sludge produced is around 600 mL/L when ferric sulfate is added. This diminishes up to 350 mL/L when this coagulant acts together with anionic polyacrylamide. If the weight of the sludge generated is taken into account, then ferric sulfate is a better coagulant than alum [Aguilar et al., 2003].

In the case of EC, the amount of sludge occurring during the EC process can vary from 7 to 10.24 kg/m^3 for Al electrode, and from 2.31 to 11.43 kg/m^3 for Fe electrode at various pH values, based on the operating variables [Bayramoglu et al., 2006].

3.3. Biological Treatment

Common physical-chemical treatments do not treat slaughterhouse wastewater completely. For this reason anaerobic digestion and/or enhanced sedimentation systems are crucial for the treatment of this wastewater.

3.3.1. Anaerobic Digestion Process

Anaerobic digestion is a biological process in which bacteria break down organic matter in the absence of oxygen. It is a common treatment method at the Australian red meat processing industry used for over three decades. More recently, covered anaerobic ponds have been implemented to control odours and capture methane emission which is a source of energy. The process produces biogas (a blend of methane and carbon dioxide) and a solid by-product (digestate) [Sampson, 2005]. The most common secondary treatment for abattoir wastewater is anaerobic digestion process in which its success is highly dependent on the primary physico-chemical treatment step. Increased effluent quality containing non-toxic disinfected by-products can be produced by combining physico-chemical treatments with more effective biological treatments. This has the potential to lead to the use of higher quality water for agricultural applications. [AMPC, 2006].

3.3.2. Factors affecting the efficiency of the anaerobic digestion process

3.3.2.1. High organic loading rate and FOG

Wastewaters from abattoirs are rich in biodegradable organic matter and nutrients and usually contain high level of solids, fat and protein that have low biodegradability. While high strength nature and high FOG content of abattoir wastewater can potentially produce large quantities of methane, the recalcitrant nature of these materials can result in a number of problems. Many of these problems are attributed to the high FOG and solid content of this wastewater, such as: clogging of pipes, foul odour generation, adhesion to the bacterial cell surface and reducing mass transfer efficiency, and loss of active sludge due

Figure 3: Surface of anaerobic pond receiving untreated abattoir wastewater (Churchill abattoir, 2012).

to floating [Cammarota and Freire, 2006]. FOGs and floating solids tend to accumulate on the surface of anaerobic digesters to form a recalcitrant scum layer or crust, as shown in figure 3 [UNSW-CRC, 1998; Wan et al., 2011]. When a crust forms on the surface of anaerobic pond, it will reduce the volume of the digester and the hydraulic retention time (HRT) [Edgerton, 2009]. This results in a reduction in the pond's efficiency. This crust, as reported in literature, is a mixture of fat, solids and floating sludge [Petrury and Lettinga, 1997]. Additionally, fat has a tendency to form floating aggregates and foams which may cause stratification problem due to adsorption of lipids into the biomass [Cuetos et al., 2010]. Slaughterhouses are known for their high lipid (FOG) content [Neves et al., 2009]. Also, process stability could be negatively affected by the high FOG content due to potential long chain fatty acids (LCFA) inhibition. This may lead to digestion failure due to acidification of the digester [Wan et al., 2011]. Inhibition of anaerobic digestion of slaughterhouse wastewater is also attributed to the accumulation of high levels of ammonia. Ammonia results from the degradation of the high protein content of these wastes and also to long chain fatty acids (LCFA) accumulation as consequence of lipids degradation [Cuetos et al., 2010]. Furthermore, lipids and long-chain fatty acids resulting from lipid hydrolysis can cause inhibition of methanogenic activity. Although, fat, grease and oil (FOG) counts for the highest amount of COD among the food waste industries [Nakhla et al., 2003], it is poorly biodegradable due to its low bioavailability [Petrury and Lettinga, 1997].

3.3.2.2. Cleaning chemicals

Synthetic anionic surfactants such as Linear Alkylbenzene Sulfonates (LAS) are the most widely used surfactant in cleaning activities. A study by Gavala and Ahring (2002) showed that the inhibitory effect of LAS is the main reason that anaerobic microbial enrichments on LAS have not yet succeeded. It has an inhibitory action on the acetogenic and methanogenic step of the anaerobic digestion process. They reported that the upper allowable LAS in a municipal wastewater treatment plant that employs anaerobic technology should be 14 mg LAS/gVSS^{-1}. In another study by Garcia et al., (2006), they showed that addition of LAS to the anaerobic digesters increased the biogas production at concentrations of 5 to 10 g/kg dry sludge but at higher surfactant loads it caused inhibition of the methanogenic activity. Other surfactants have been studied by Pérez-Armendáriz et al., (2010), they investigated anaerobic biodegradability and inhibitory effects on methane production of three different surfactants, two anionic: sodium lauryl sulfate (SLS) and sodium dodecylbenzene sulfonate (SDBS), and a cationic surfactant: trialkyl-methylammonium chloride (TMAC), in two different anaerobic sludges - granular and flocculent. The surfactants were tested at five different concentrations of 5, 50, 100, 250 and 500 mg/L. The SLS biodegraded at concentrations of 5, 50 and 100 mg/L with flocculent sludge and at 100 and 250 mg/L with granular sludge. However an inhibitory effect on methane production was observed in both sludges at 500 mg/L. The results indicate that TMAC was slightly degradable at 50 and 100 mg/L with the flocculent sludge, and at 100 to 500 mg/L with the granular sludge. The results also showed that SDBS was not biodegradable under anoxic conditions [Muller, 2000].

As part of the current practice, alkaline and acidic solutions are used in the cleaning process. These solutions at the end of the day will be washed out to the treatment system. The alkaline and/or acidic can have an inhibitory effect on the anaerobic digestion process. Methanogenic microorganisms are sensitive to low pH levels. The system pH should be maintained at a proper range for efficient anaerobic digestion. The generally accepted values are in the neutral range, between 6.5 and 7.6. Changes in digester operating conditions such as pH and/or introduction of toxic substances may result in imbalances in the process and accumulation of volatile fatty acids (VFA). The biogas production will decrease depending on the pH magnitude and the duration of the pH drop. In some cases the drop in pH may cease biogas production completely [Labatut and Gooch, 2014].

3.3.2.3. Water treatment chemicals

Chemical coagulants such as alum, ferrous sulfate and ferric chloride are commonly used for phosphorus and suspended/colloidal solids removal in wastewater treatment systems. The effluent wastewater from a coagulation system may contain chemicals such as alum, lime and ferrous sulfate. This may contribute to in failure or reduction in the efficiency of the following biological treatment due to the toxicity of these chemicals on microorganisms.

Many studies have reported the adverse effect of these chemicals on both plant-scale and bench-scale digesters receiving metal ion coagulants. They observed a significant decrease in volatile solids destruction, COD removal, organic nitrogen catabolism, alkalinity production, methane production and total gas production. In order to understand the effect of cations on anaerobic digestion, the role of cations in floc structure needs to be better understood. It has been proposed that there are three floc structures; iron bound organics that could be degraded by anaerobic digestion, aluminium bound fraction that resists biological degradation under aerobic and anaerobic condition and a divalent cation-bound fraction that is degraded primarily under aerobic conditions [Novak and Park, 2010].

In a study by Novak and Park, (2010), they found that the main effect of aluminium was reducing volatile solids destruction in the digestion process by about 2%. In contrast, they reported that as iron in sludge increases the volatile solids destruction also increases. In another study by Warman, (1975), the effect of some coagulants on the anaerobic digestion process were evaluated. Three laboratory scale continuously mixed anaerobic digesters were operated at 32 °C with a 30 day hydraulic retention time. The digesters were operated as following; number one served as a control and received sludge obtained by sedimentation of domestic sewage without the use of coagulants; number two received sludge obtained using 14 mg/l of a cationic Hercules Incorporated polymer (Hercofloc 814.2) as a coagulant; and number three received sludge obtained using 30 mg/l of ferric chloride as a primary coagulant and 1 mg/l of Hercofloc 836.2 as a coagulant aid. The results were based on the influent and the effluent values of BOD, COD, and VS and on methane production. The study reported no effect of these coagulants on the anaerobic digestion process with regards to toxicity or physical inability of anaerobic microorganisms to penetrate the flocs formed as a result of the addition of coagulants as aids for sewage sedimentation. The pH and alkalinity were consistently higher in the digesters receiving chemically coagulated sludge than in the control digester. This signified a greater buffering capacity against digester upset [Warman, 1975].

In the study by Novak and Park (2010), a mixture of primary and secondary sludge at a ratio of 1 to 1 by solid content was anaerobically digested at a constant temperature of 37^{o}C to determine the volatile solids reduction. Both sludge E and F in table 7 had very high iron contents, plant E had 8.7 mg/g TS iron and plant F had 15.42 mg/g TS iron in raw sludge. In some of these plants iron was added in the primary and/or secondary systems for the purpose of phosphorus removal. Volatile solids (VS) destruction in plants A, B, C, E, and G are in the range of 36 to 44 % as shown in Table 7. However, VS destruction in the plant D is relatively low (26.6%). Plant D did not use primary treatment and also had the lowest iron content. Plant F has the highest volatile solids removal (47.2%) and had the highest iron content. These results show that VS destruction is dependent on influent iron content since plant D had 1.87 mg/g TS of iron and plant F had 15.42 mg/g TS of iron in raw sludge. The data show that VS destruction increases as the iron content in the raw sludge increases. It is thought that one major mechanism for degradation of organics in anaerobic digesters is through the release of Iron-associated organics which are subsequently degraded [Novak and Park, 2010].

Table 7: Effect of iron content on the TS, VS, COD and N removals in an aerobic digestion process.

WWTP	TS REMOVAL (%)	VS REMOVAL (%)	COD REMOVAL (%)	ORGANIC N REMOVAL (%)	IRONCONTENT (mg/g TS)
A	30.4	39.4	52.0	26.1	39.6
B	29.7	36.7	45.4	12.6	37.4
C	27.1	42.5	62.7	44.3	41.2
D	19.9	26.6	68.0	32.1	1.87
E	32.5	43.9	65.3	41.2	8.7
F	39.4	47.2	35.9	42.4	15.42
G	31.2	37.8	49.8	50.4	38.2

3.3.3. Solid waste by-products

The anaerobic digestion process creates a large solid waste by-product. The digester should be desludged periodically to remove the sludge build-up at the bottom. Sludge can be extracted from the digester by pumping some of it to a separation unit. There are two types of digestate; the liquid and the solid types. The liquid digestate contains less than 15% DM (dry matter), while the solid digestate contains more than 15% DM. Solid Digestate is high in fibre, consisting mainly of fibrous undigested organic material (lignin and cellulose), microbial biomass, animal hair and nutrients [Marianna et al., 2012]. Digestate contains a high proportion of mineral nitrogen (N) especially in the form of ammonium. The NH_4 content of the digestate is about 60-80% of its total N content, this concentration can be higher-as much as 99% depending on the feedstock such as dairy by-products and slaughterhouse waste. Digestate has higher phosphorus (P) and potassium (K) concentrations than that of composts and they are in available forms. Heavy metal content of the feedstock usually originates from anthropogenic sources and is not degraded during AD. The primary origins of the heavy metals are animal feed additives, the food processing industry, chemical treatment (flotation sludge and fat residues) and domestic sewage. In the case of anaerobic ponds, if the organic loading rate is high and the hydraulic retention time is short, then the digestate will contain a considerable amount of undigested organic matter [Marianna et al., 2012].

There are many techniques that can be used for the purpose of solid-liquid separation such as slope screens, rotary drum thickeners and screw-press separators. The volume and the moisture content of the separated solid will vary depending on the technology used. Common solid-liquid equipment can produce digestate solids with a moisture content of 18 to 30%. Also, a combination of coagulation and filter pressing is very effective in dewatering sludge, reduction of moisture in this case is above 50%.

3.3.4. Aerobic treatment

Aerobic treatment might directly follow primary physical-chemical treatment or more typically, it might follow some form of anaerobic treatment. Anaerobic treatment alone is not able to reduce the organic matter to acceptable levels for discharge to surface water or even for animal crop irrigation. For this reason it might be followed by an aerobic treatment process. Reduction of ammonia is also a typical role of aerobic processes in the treatment of meat processing wastewaters. There are many advantages of using aerobic wastewater treatment processes; this includes low odour production, fast biological growth rate, no elevated operation temperature requirements and quick adjustments to temperature and loading rate changes. Conversely, the operating costs of aerobic systems are higher than those for anaerobic systems. This is due to the relatively high space requirements, maintenance, management and energy requirements for artificial oxygenation. Free dissolved oxygen is required for the microorganisms involved in the aerobic treatment process in order to reduce organic matter in the wastewater [Sampson, 2005].

3.4. Summary

Physical treatment is an important process of the treatment system and cannot be eliminated from the treatment plant. The efficiency of both the chemical and biological treatments is dependent on this step. For example, screening can result in 5-20% BOD removal, and 5-30% TSS removal, mostly large sized particles (organic matter) which cannot be removed by biological treatment and results in using higher dosage of coagulants when chemically treated. Skimming and sedimentation operations can result in 20 to 30 % BOD removal, 40 to 50 % TSS removal, and 50 to 60 % grease removal. In the case of an ideal dissolved air flotation process, the expectations are at least 30 to 35 % removal of the original BOD value, 60 % TSS removal and 80 % grease removal.

Regarding the use of chemical coagulants, reduction of organic matter is influenced by many factors such as the conditions and the characteristics of the wastewater. The characteristic of the wastewater can be manipulated by the physical treatment. Consequently, the removal of organic matter by coagulation varies widely between 10% and 90%. It has been shown that a combination of a main coagulant ($Fe_2(SO_4)_3$) and an aid (anionic polyacrylamide (AP)) can eliminate between 59 to 90% of the COD, 62 to 93% of the BOD and 81 to 98% of the TSS content of the wastewater. Iron-based coagulants have a positive impact on the biological process. Under the electrocoagulation (EC) process, removals of 86, 99, 50 and 82% can be achieved for BOD, oil and grease, soluble COD and total COD, respectively. It has been found that EC is also efficient for decolourization (red-colour) and clarification; removals of 89% and 90% have been achieved for total suspended solids and turbidity, respectively. However, this process comes with high operating cost due to the high consumption of electricity.

Based on the loading rate and hydraulic retention time, the degree of organic matters (OM) degradation in a typical anaerobic digester can reach 53% [Marcato et al., 2008]. Finally, due to the high operating costs of aerobic systems such as activated sludge, aerobic and facultative lagoons are more suitable options for the final stage of treatment if land is available.

4. Industrial practice and examples

The high organic loading rate (OLR) and high content of fat in abattoir wastewater can result in crust formation and low efficiency of anaerobic lagoon technology. In order for the anaerobic digester to perform effectively, efficient primary physical and/or chemical treatments are essential. In some cases, despite the presence of screening and the DAF units, the problem of crust and low efficiency of the anaerobic digester still exists. It is obvious that more efficient methods are required to reduce the OLR before the wastewater enters the biological treatment.

The temperature of the abattoir wastewater is what makes the anaerobic digestion process a suitable option. Increasing the number of physical treatment processes may significantly reduce the wastewater temperature. This may impact the biological treatment process, and for this reason chemical treatment is an option to reduce the physical treatment steps.

A brief description of the chemicals in use in thirteen Australian abattoirs is shown in Table 8. In some instances, physical or chemical wastewater treatment does not occur and the wastewater is treated using evaporation ponds. In other cases physical treatment occurs. Only a relatively small portion of abattoirs use chemicals. Just one of the abattoirs surveyed recycled a fraction of the treated water for reuse at the facility for different purposes such as washing the cattle, cleaning the feedlot and watering the gardens at the facility. Most of the abattoirs use the treated wastewater for irrigation of crops for feeding cattle inside the facility. The information in Table 8 was collected via telephone interviews with the abattoirs.

Table 8: Sample of abattoirs in Australia and their usage of chemicals [AMAL, 2014; Survey carried out by the author]

ABATTOIR	CLEANING CHEMICALS	WASTEWATER TREATMENT CHEMICALS	COMMENTS
A	Yes	No	Only one physical treatment unit (screening), then series of five anaerobic ponds and then a facultative pond
B	Yes	No	Screening, DAF, anaerobic pond and a very long serpentine pond
C	Yes	Yes, polymer for dewatering sludge	Tertiary screening, and anaerobic pond
D	Yes	NA	No treatment, just evaporation pond
E	Yes	NA	No treatment, just evaporation pond
F	Yes	NA	No treatment, just evaporation pond
G	Yes	NA	No treatment, just evaporation pond
H	Yes	Yes, polymer (zeta) in the flocculating system	Screening, flocculating tank, DAF, anaerobic pond, storage tank which then used for irrigation
I	Yes	NO	Screening, DAF, two anaerobic pond parallel, aerobic pond, settling pond, water recycled for washing (cattle and yards) and watering grass and gardens, trucks washing and feedlots, the extra water go to pond five where the water used for irrigation of crops (crops for cattle feeds only). No water leaves the plants.
J	Yes	Yes, aluminium sulfate and lime in the primary DAF and sodium hypochlorite in the tertiary DAF (pH control).	Screening, scrubbing, decanter, primary DAF, anaerobic and aerobic ponds, settling, tertiary DAF, chlorine
K	Yes	Yes, 1. Coagulant Catfloc 2. Anionic flocculant 3. pH control sulphuric acid98% sodium hydroxide 46%	In the DAF mixing tanks.
L	Yes	Only chlorine	Screening (two), anaerobic and aerobic ponds, chlorine, and then for irrigation
M	Yes	Yes, chemical DAF, ferric sulfate and anionic polymer	Shaker screening, balance tank, chemical DAF, equalizer tank, DAF aeration and then to sewage

5. Chemicals and their impact on anaerobic digestion and the environment

This section addresses the impact of cleaning/sanitizing and wastewater treatment chemicals (conventional) on both the environment and the anaerobic digestion process. Also, the aim of this section is to identify and address alternative chemicals for both the facility cleaning/sanitizing and the chemical treatment process.

5.1. Conventional Chemicals

5.1.1. Cleaning Chemicals

The inhibitory effects of cleaning/sanitizing chemicals have been reported in many studies. These chemicals have an inhibitory action on the acetogenic and methanogenic step of the anaerobic digestion process. It has been shown that addition of some of these chemicals (surfactants) in very small portions to anaerobic digesters increases biogas production (concentration of 5 to 10 g/kg dry sludge) but at higher loads it causes inhibition to the methanogenic activity [Garcia et al., 2006].

5.1.2. WWT Chemicals

5.1.2.1. Effluent effect on human health and the environment

Aluminium-based coagulants are widely used in wastewater treatment systems; however there is a concern about aluminium residuals in the treated water. These chemicals may find their way to water streams and ground water through utilizing the treated water, for example in irrigation. Aluminium may generate secondary products which can be harmful to both human health and the environment [Al-Shaikhli, 2013].

Although aluminium-based coagulants are generally known of their low effectiveness in low temperature water and effects on human health, they also produce large sludge volumes and significantly affect pH of the treated water. Also, aluminium appears to affect the anaerobic digestion process through decreasing volatile solids destruction [Novak and Park, 2010]. On the other hand, iron salt coagulants have been reported to be safer options [Al-Shaikhli, 2013]. Regarding their effect on anaerobic digestion process, it has been found that the volatile solids destruction increases as the iron content of the faded sludge increases [Novak and Park, 2010].

In a study on the toxicity of some coagulants (Al-Mutairi, 2006), adding alum at concentrations of 100 to 200 mg/L was found to slightly increase the toxicity level of slaughterhouse wastewater effluent. However, at higher concentrations of 300 to 1000 mg/L, significant residual toxicity remains in effluent wastewater, independent of the treatment process. Also, it was reported that using coagulants such as polymers contribute in making the effluents more toxic than alum even at extremely lower concentration. Cationic polymers are toxic for aquatic animals. In addition, experimental results indicated that alum and polymer have inhibitory effects to biological systems at soluble concentrations of approximately 400 and 600 mg/L and above, respectively. Furthermore, strong correlations were observed between the effluent toxicity and the coagulant (alum, polymer) concentration.

5.1.2.2. Sludge size and impact

A study undertaken by Al-Mutairi (2006) involving New Zealand slaughterhouses showed that sludge collected from the coagulation system cases where both polymer and alum were used was much more toxic than those from the effluent. Sediment samples from the polymer tests were the most toxic. In the case of alum, large amounts of waste sludge were produced and high levels of aluminium residue were found in the sludge, which raises public health concerns. In another study by Amuda and Alada (2006), a preliminary settled wastewater subjected to treatment with different dosages of alum (250, 500, 750, 1,000, 1,500 and 2,000 mg/L which is equivalent to 82, 164, 238, 319, 475 and 638 mg, respectively, of dosed aluminium). The total aluminium mass in the treated wastewater was 9.8 and 10.1 mg Al3+/1 L of wastewater, for all the dosages. The total aluminium mass in the sludge produced in each treatment dosage were 81, 165, 239, 318, 477 and 640 mg, respectively, which were very close to the amount added initially.

In general, the amount and the characteristics of the sludge produced during the coagulation/flocculation process depend on the coagulant used and the operating conditions. The study by Amuda and Alada (2006), showed that accumulated volume of wet sludge at the bottom of the jar test beakers using alum as a sole coagulant was voluminous but compacted. A maximum reduction in the volume of sludge of 54% was obtained when polymer (anionic polyacrylamide) was added as a coagulant aid. The volume of produced sludge dropped from 410 mg/L to 190 mg/L when anionic polymer was used with alum, as shown in Table 9. This finding is in accordance with that of other investigators, for example Aguilar et al., (2003). Aguilar et al., (2003) showed that the use of coagulant aids reduction in the volume of the produced sludge up to 41.6%.

The other issue with using alum as a coagulant agent is the decrease in effluent pH, while polymers have no effect on pH. The reduction in pH may contribute to the death of microorganisms present in the biological reactor when carried out after chemical treatment [Al-Mutairi, 2006].

Table 9: Volumes of sludge produced during coagulation/flocculation with alum and polymer [Aguilar et al., 2003].

COAGULANT TYPE AND DOSE	VOLUME OF SLUDGE (mL/L)
Alum (200 mg/L)	410
Alum:polymer (200:5 mg/L)	330
Alum:polymer (200:10 mg/L)	265
Alum:polymer (200:20 mg/L)	190

5.2. Environmentally safe chemical alternatives

5.2.1. Cleaning chemicals

There is a wide range of cleaning products available on the market; most of these chemicals are toxic. Abattoirs use these chemicals for a variety of cleaning and sanitising purposes. In some cases, highly contaminated areas with sticky materials such as faeces, blood, urine, grease, and fat are difficult to clean even with a high corrosive substance such as sodium hydroxide. Increasingly, biotechnological cleaning and sanitising agents are becoming available on the market. These alternatives are proven to be as effective as conventional cleaning chemicals. These alternatives make cleaning of such areas more time efficient. They are also safer and use less energy since hot water is not required [Pagan, et al., 2002].

Plant-based cleaning compounds contain naturally occurring plant-based substances such as ester alcohols which are readily biodegradable and non-toxic. These plant-based cleaning compounds are efficient in repelling organic wastes from surfaces. They are a good option to replace chemical cleaning because they are biodegradable therefore they are compatible with biological wastewater treatment systems [FAO, 2014].

Another option is biotechnology-based cleaning agents which contain naturally occurring enzymes or microorganisms. They are less harmful to the environment, can be used at lower temperatures than conventional chemicals and are non-corrosive [FAO, 2014]. Detergents with enzymes are typically mild, noncorrosive, and safe to handle. Enzymes offer a cost-effective alternative by working effectively at low wash temperatures and mild pH, enabling reduce in; water usage, raw materials, and energy. While it improving the cleaning efficiency and extending the lifetime of equipment and textile [Novozymes, 2014].

Enzymes offer superior cleaning due to their targeted catalytic action mode. Due to the diversity of soils, five different enzyme types can be added together to formulate a strong cleaning agent. These enzymes are:

- Protease: degrades proteins such as those present in blood;

- Amylase: breaks down polysaccharides present in food stains;
- Cellulase: degrades cellulose present in undigested food;
- Lipase: degrades soils and fats present in dairy and meat processing equipment;
- Mannanase: degrades mannan/guar gum, a commonly used food thickener, which is difficult to remove.

Industrial food and beverage processing generates specific cleaning challenges, where enzymes prove their worth by speeding up and improving cleaning performance and maximizing equipment utilization. A company entitled Novozymes offers a full range of proteases, amylases, lipases, cellulases, and other enzymes that act on food residues for cleaning in food and beverage processing plants [Novozymes, 2014]. They claim the following:

- Improved cleaning by targeting specific soils causing cleaning challenges in food processing units;
- Saving costs by increasing system efficiency, reducing the downtime for cleaning in place, and ensuring higher productivity.

5.2.2. Treatment chemicals

5.2.2.1. Coagulant chemicals

In recent years, there has been considerable interest in the development of natural coagulants, shown in Table 10. Using natural coagulants may result in considerable savings in chemicals and sludge handling costs. Chitosan, starch, *Moringa oleifera* and psyllium are natural-base coagulants that have been investigated for raw and wastewater treatments [Al-Shaikhli, 2013]. These coagulants have not been tested for treating abattoir wastewater in Australia.

In a study by Chuentongaram (2004), ferric chloride and chitosan were used as sole coagulants and as a mixture for treating slaughterhouse wastewater. Results showed that coagulation of slaughterhouse wastewater using ferric chloride or chitosan alone at pH 5 can achieve COD removal of 48.4% and 30.5%, respectively. The doses of ferric chloride and chitosan applied were 160 mg/L and 10 mg/L, respectively. Higher removal was achieved with ferric chloride for turbidity and SS of 97.77% and 97.39%, respectively. For chitosan the removals were around 93.28% and 92.19%, respectively. With regards to combination of ferric chloride and chitosan, the optimum ratio of the two coagulations was 1:16 with removal efficiencies of COD, turbidity, and SS, being around 53.7%, 93.7%, and 92.2%, respectively [Chuentongaram 2004].

Morales Avelino et al., (2009) studied both the solution and the suspension of grinded and soaked seeds of *Moringa oleifera* Lam, in reducing turbidity of wastewater from a slaughterhouse. The results showed

82% of absorbency reduction for the wastewater from the pond. In relation to the coagulant dose (seeds suspension), 25 g/L can achieve up to 78% of turbidity reduction. In a study by Lagasi et al., (2014), *Moringa oleifera* was used as a coagulant to treat abattoir wastewater and found to be effective. In this study, a comparison was made using *Moringa oleifera* extracts in its ordinary state and after extracting the oil content. Significant turbidity reduction from 218.4NTU to 42NTU (reduction 80.8%) was observed when de-oiled *Moringa* was used. The ordinary *Moringa* reduced turbidity from 218.4NTU to 68NTU (reduction 68.9%).

Given the findings above, natural coagulants such as chitosan and *Moringa oleifera* extracts appear to be good alternatives to the chemical coagulants.

Table 10: Natural coagulants advantages and disadvantages

SOME NATURAL COAGULANTS	CHEMICALS	ADVANTAGES	DISADVANTAGES
Natural polymers	Sodium alginate	Can be effective when used with alum	Less efficient than synthetic polymers
	Chitosan	Inexpensive additives for increasing settling velocity, and reducing coagulant dosage	
	Starch		
	Moringa oleifera		
	Psyllium		

Another natural coagulant is Tannin, which is a naturally sourced compound that is environmentally safe. Khwaja and Vasconcellos (2011) reported a method for recovering tallow from meat processing wastewater in the US. The method involves adding a coagulant mixture including tannin to the wastewater to agglomerate suspended fat, oil and grease particles. For example, a coagulant composition was prepared by mixing 200 ppm tannin-PolyMADAME, 29 ppm of a 10/90 methyl chloride quaternary salt of dimethylaminoethyl acrylate/acrylamide copolymer and 19 ppm of a 39/61 acrylic acid/acrylamide copolymer. The coagulant composition was added to beef wastewater that was flowing through a 50 gallon per minute (gpm) Entrapped Air Flotation (EAF) unit. The results are shown in table 11, the reduction in each of BOD_5, TSS and FOG are around 73% and greater.

Table 11: Field trial results for tannin-based coagulant tested on beef processing wastewater

PARAMETERS	INFLUENT, mg/L	REDUCTION, %
BOD5	3425	73
TSS	1230	76
FOG	1090	74
TKN	220	45
TP	64	27

5.2.2.2. Anaerobic digestion enhancement chemicals and substrates

There is little information reported on chemicals that can be used to enhance the performance of biological processes. For abattoir wastewater, fats are shown to be the main problem due to their low solubility. Some literature relates the enhancement in the biological treatment to the better management of the fats in the wastewater treatment plant. FOG is highly resistant to biodegradation and contributes to high COD levels in abattoir wastewater. Anaerobic treatment alone is not efficient at eliminating FOG. The use of a surfactant may enable the enhancement of anaerobic biodegradability of meat processing wastewater by solubilizing the fat, oil and grease [Nakhla *et al.* 2003]. Biodegradable surfactants are more favourable than chemical surfactants because the later may cause toxication toward the microbial colonies in the digester. Nakhla *et al.* (2003) tested the impact of a biosurfactant (BOD-balance), derived from cactus, on the treatment of FOG-rich rendering wastewater. The reduction of FOG concentration to <800 mg/L increased total and soluble COD degradation rates by 106%. Results from the full-scale mesophilic anaerobic digestion system indicated that the addition of biosurfactant at doses of 130–200 mg/L can decrease FOG concentration from 66,300 to 10,200 mg/L over a 2-month-period.

In a study by Masse et al., (2001), sodium hydroxide and three commercial lipases of plant, microbial and animal origins were tested. In regards to NaOH addition, the study does not recommend NaOH hydrolysis pre-treatment for fat particles due to the high dose of NaOH required which increases pH and alkaline. Recently, enzymatic products are becoming more available commercially. The first enzyme is a pork pancreatic lipase called pancreatic lipase 250 (PL-250, Genencor International, Rochester, NY). Pancreatic lipase 250 is claimed to be efficient for hydrolysing triglycerides containing LCFAs with more than 12 carbons, such as those in animal fat. The second enzyme is a bacterial lipase extracted from *Rhizomucor miehei* called lipase G-1000 (LG-1000, Genencor International, Rochester, NY). Lipase G-1000 is reported to hydrolyse natural fats, such as oils, beef tallow, butter fats and lard oil, with a preference for shorter chain fatty acids (< 12 carbons). The third enzyme is a plant lipase called EcoSystem Plus (ESP, Neozyme International, Newport Beach, CA). Neozyme claims that ESP effectively breaks down fat particles in aerobic or anaerobic environments. This study concluded that PL-250 is the best pre-treatment to hydrolyse fat particles. Also, the tests showed that pancreatic lipase is more efficient with beef fat than pork fat, possibly because beef fat contains less polyunsaturated fatty acids than pork fat [Masse et al., 2001]. These enzymes increase soluble COD in the wastewater, for example, in samples receiving 500 and 3500 mg/l of LG-1000, the SCOD increased by 6% and 27%, respectively.

In a study by Jeganathan et al., (2007), a preliminary anaerobic digestion experiment was carried out to confirm the biodegradability of wastewater pre-treated by immobilized lipase. The COD and O&G reduction were 49 and 45% without pre-treatment and 65 and 64% with pre-treatment, respectively. The maximum growth rate of the pre-treated wastewater (0.17 d^{-1}) was 3.4 folds higher than that of raw wastewater (0.05 d^{-1}).

Some cleaning chemicals are beneficial in the anaerobic digester, if present at low concentrations. Many commercial chemical surfactants include sodium lauryl sulfate (SLS). It has been reported that surfactants such as sodium lauryl sulfate (SLS) at low concentrations contributes enhances biogas production. This is attributed to an increase in the bioavailability and subsequent biodegradation of organic pollutants associated with the sludge, promoted by the surfactant adsorption at the solid/liquid interface [Pérez-Armendáriz et al., 2010].

5.3. Summary

Conventional cleaning/sanitizing chemicals can be hazardous and have an inhibitory action on the acetogenic and methanogenic steps of the anaerobic digestion process. Plant-based cleaning compounds can be efficient and have the potential to replace cleaning chemicals because they are biodegradable. However, there is lack of research and industrial-scale tests for these natural chemicals.

Studies using conventional coagulants have revealed that alum-based and some polymer coagulants are toxic to the microorganisms in the biological system. In recent years, there has been considerable interest in the development of natural coagulants such as chitosan, starch, *moringa oleifera* and psyllium. These coagulants have not been tested in the treatment of abattoir wastewater in Australia. However, literature has shown that, some of these natural coagulants are good alternatives to conventional chemical coagulants such as alum. Also, literature has shown that iron-based coagulants have a positive impact on the biological treatment by enhancing its biogas production.

To conclude, it is recommended to use iron-based coagulants as the main coagulants with a natural coagulant as an aid. This will produce better results than using alum or any other chemical product that may cause health or environmental problems. It is not only more efficient but also it reduces the amount of sludge produced and its toxicity.

6. Chemical-Free Cleaning and Wastewater Treatment Alternatives

6.1. Facility cleaning

6.1.1. Heat/steam

In many cases steam is a very good choice for disinfection but it may be impractical due to many reasons. Generating steam is an expensive process. It causes materials to deteriorate and equipment to distort. It takes considerable time to heat and cool the equipment. It may cause baking-on of food and other residues. It reduces visibility in the working environment thus reducing the effectiveness of the sanitizing procedures. It also associated with condensation problems. Insufficient heating may result in the incubation of microorganisms in inaccessible parts of the machines and the equipment [FAO, 2014].

6.1.2. Ozone

Another method of cleaning and sanitation which is chemical free and does not end up in the wastewater stream is Ozone (O_3). Ozone is an extremely powerful and effective natural disinfecting agent. It can be generated with an ozone generator that converts oxygen from the air into ozone using electricity and ultra-violet (UV) light. Ozone avoids the use of sanitising chemicals and any unused ozone naturally decays back to oxygen in a few hours [FAO, 2014]. Ozone can be simultaneously applied at any time during processing on the product and equipment because it is an approved food additive. It can eliminate biofilm and significantly reduce fats, oils and grease on all surfaces. This can reduce downtime for cleaning as well as provide further protection from cross-contamination in the processing line [MPMP, 2014].

Ozone disinfection can be applied at multiple points in meat processing, including:

- Carcass sanitation;
- Direct contact meat sanitation at all cut points;
- Post-lethality sanitation on RTE meat products;

- Surface sanitation on food-contact and non-food-contact surfaces;
- Process equipment, e.g. knives, cutters, conveyors, automated cutting equipment saws and gloves.

There are many advantages for using ozone in meat processing sanitation. Compared with traditional disinfectants used in meat processing such as chlorine, peroxyacetic acid, acidified sodium chlorite, hydrogen peroxide and quaternary ammonia, ozone is more favourable. It has a broader spectrum of efficacy and unlike other disinfectants; ozone will penetrate and destroy biofilm. Also, ozone does not leave harmful by-products and requires no rinsing. In addition, it has been approved by USDA, FDA, EPA and USDA-Organic [MPMP, 2014].

6.1.3. Hydrogen peroxide

Hydrogen peroxide is a chemical compound with the formula H_2O_2, it is a colourless liquid in its pure form and slightly more viscous than water. For safety reasons it is normally encountered as an aqueous solution, also colourless. Hydrogen peroxide is a strong oxidizer and is used as a bleaching agent and disinfectant. Hydrogen peroxide is thermodynamically unstable and decomposes to form water and oxygen, as shown in the following equation:

$$2\ H_2O_2 \rightarrow 2\ H_2O + O_2$$

A mixture of hydrogen peroxide and acetic acid (peracetic acid), is effective against bacteria, spores, yeasts, molds and viruses and it is non-corrosive [FAO, 2014].

6.2. Waste Water Treatments

All the physical processes such as coarse and fine screening, primary sedimentation and diffuse air flotation, addressed in the previous sections are chemically free. Physical processes are frequently used in waste water treatment as they are effective in removing insoluble BOD and COD.

6.3. Anaerobic Digestion Enhancement

Co-digestion is the least expensive and easiest method of optimization carbon to nitrogen (C:N) ratio of a feedstock. Wastes with low C:N are accompanied with high release of ammonia as much as 4,289 mg/L. The highest digestion efficiency is associated with wastes that have low concentration of ammonia and alkalinity, below, 1,736 and 8,970 mg/L respectively [Shanmugam and Horan, 2009a]. In a study by Shanmugam and Horan (2009a), they showed that blended wastewater from leather industry with municipal solid waste helped in reducing ammonia concentration and maximizing biogas production. The cumulative biogas yield increased from 560 mL using leather wastewater fraction alone, to 6,518 mL with optimum blend. Co-digestion has been proven to be able to overcome the LFA (Long Fatty Acid) inhibition and biomass floating issues by many researchers [Long et al., 2012]. Co-digestion is highly recommended to be applied in wastes with high Fat, Oil and Grease (FOG) content such as wastewater from red meat processing industry. This is due to low degradability of FOG and potential of Long-Faty-Acid (LFA) inhibition [Chen et al., 2008].

Co-digestion using different substrates can help in minimizing the effect of the inhibitory compounds in an anaerobic process. It also contributes to improving the stability of digestion of the poorly digestible wastes such as fat or protein and the performance of the process overall [Buendia et al., 2009]. Co-digestion can offer several benefits such as operational advantages, improve nutrient balance, co-substrate handling and fluid dynamics. Also, it may enhance the process economics through higher biogas yields and additional income from a better quality digestate [Hamawand, 2015].

6.4. Summary

Chemical-free methods for cleaning and sanitizing meat processing facilities have not been widely researched. Adopting chemical free methods is not an easy task due to the sensitivity of the subject. Failures in facility hygiene, will contribute to quality losses and deterioration of the final products. Further research is required to identify a chemical-free method that is comparable to the current practice.

In regards to the chemical-free wastewater treatment, most of the abattoirs in Australia are currently using a combination of physical and biological treatments. The physical treatments in use are simple and inefficient to reduce the high organic loading rate of the wastewater.

In order to free the treatment process from chemical usage, more extensive and efficient physical and biological processes will be required. Though, this will not be sufficient to raise the quality of the treated wastewater to the level where it is suitable for surface water disposal.

There is little information reported on chemicals that can be used to enhance the performance of biological processes. As recommended by literature, co-digestion may be the least expensive and easiest method of optimization carbon to nitrogen (C:N) ratio of a feedstock (included in the “Chemical Free” section).

7. Utilization of By-Products

7.1. Utilization of Physical Treatment By-Products

When a plant has sufficient land available and is not located adjacent to a sensitive population, the wastes can be treated on-site to produce useful and saleable by-products. Much of the solid waste produced from the physical treatment units is organic and is suitable for land based disposal after treatment. Another way of utilizing this waste, which is mostly pieces of meat and fat, is by recycling it to the rendering room.

The other solid waste is the cattle paunch which is a major source of solid waste from meat processing plants. Drying and then dumping of paunch has been promoted for many years and is now gaining wider acceptance in Australia [AMPC, 2006]. Paunch can also be used as a fuel in the boilers similar to sugar cane by-products (bagasse) after drying it to suitable moisture content [Gilberd, and Sheehan, 2013]. The organic waste solids are very suitable for biological treatment (for example for composting) to produce stable, useful products. Composting is the most accepted method for treating and recycling nutrients present in all organic wastes from meat processing. Several techniques may be utilised but all produce a stable final material that can be sold as a soil conditioner or ingredient in a potting mix. However, the value of the compost may not fully recover the cost of production [AMPC, 2006].

7.2. Utilization of Chemical Treatment By-Products

Chemical treatment systems create large solid waste by-products which will be concentrated with chemical coagulants. This added chemical makes this waste non-suitable for further treatment, in case of using metal-based coagulants such as alum composting and soil applications may not be applicable. Other disposal means may be required which may increase the cost of waste management.

Sludge that has been treated with biodegradable coagulants such as chitosan could be disposed in landfill, or else used in land reclamation, composting and soil conditioning. Land application and use of sludge for soil conditioning appear to be the most acceptable application. Sludge, should be regarded as a valuable commodity and for it to serve its useful purposes it must be safe to use [Ize-Iyamu et al., 2011].

7.3. Utilization of Biological Treatment By-Products

Digestate resulting from an anaerobic digestion process has the potential to be used as a bio-fertiliser. The quality of the digestate is essential if required to replace mineral fertilisers for crop production. The features of high quality digestate are nutrient content, pH, free of inorganic impurities, sanitized and safe in regard to pathological and chemical contents. The digestion process cannot degrade all the organic compounds in the feedstock which may require excluding any feedstock that may have potential to contaminate the digestate [Erden et al., 2010].

The digestate can also be sold as a dried fertilizer which reduces the potential of any pathogenic problems. Also, drying will result in reducing the weight of the fertilizer and increase its shelf life [Polprasert et al., 1992; Qi et al., 1993].

7.4. Summary

There is potential for the by-products from the physical, chemical and biological processes to be used to generate revenue for the meat processing plant. These by-products should first go through some treatment processes to eliminate biological hazards. When chemicals are used in the treatment process such as in the coagulation system, then these chemicals will end up in the by-product. For this reason, chemicals should be used wisely, biodegradable chemicals are highly recommended.

Most of the by-products collected from the physical treatment can be recycled to the rendering room, except for the paunch which either should go through a composting process for soil conditioning purpose or used for energy purpose after drying. By-products from chemical treatments can be used as soil fertilizers in case of applying biodegradable coagulants otherwise it will be another waste that should be managed separately. Biological treatment by-products (solid and water) are very suitable for agricultural application. The quality of these by-products depends on the efficiency of the biological process; more efficient biological degradation means better quality by-products.

8. Findings of the Survey - Australia

The physical treatment process used in red meat slaughterhouses in Australia typically involves a combination of sedimentation and coarse screening, followed by fine screening and finally dissolved air floatation (DAF). Among physico-chemical processes, DAF is widely used in Australia and in some cases DAF combined with a coagulation process. These are important processes for the removal of total suspended solids (TSS), colloids, and fats from red meat processing industry wastewater.

Aluminium salts and polymer compounds have been investigated in a chemical coagulation process of the Australian red meat slaughterhouse wastewater. DAF combined with chemicals (polymers) is currently in use at some wastewater treatment plants. The chemical composition of these polymers is not declared (knowhow) with claimed COD removal efficiency of 70-80%.

The survey has also showed no usage of electro-coagulation in the red meat processing industry in Australia. Despite its high efficiency, it seems that the cost associated with this process is preventing the industry from applying it.

In recent years, there has been considerable interest in the development of natural coagulants. Using natural coagulants may result in considerable savings in chemicals and sludge handling costs. Chitosan, starch, *Moringa oleifera* and psyllium are natural-base coagulants that have been investigated internationally for raw and wastewater treatments. These coagulants have not yet been tested for treating abattoir wastewater in Australia.

The survey revealed that cleaning chemicals are used at concentration of 2 to 3% and are further diluted with the bulk wastewater. For this reason, these chemicals have a very low effect on the anaerobic digestion process and the environment.

9. Cost Benefit Analysis

Abattoirs can significantly reduce waste management expense and increase revenue generation by recovering as much solid waste as possible from the wastewater and then converting these wastes to useful products. High recovery of the solid wastes results in high reduction of the wastewater organic loading rate which may positively impact the biological process. Additionally, efficient biological process may result in better quality and more sanitized by-products and lower maintenance costs. However, comprehensive solid waste recovery is best achieved with the addition of chemicals. In this case the cost of these chemicals should be considered in the total cost analysis of the treatment plant.

9.1. Cost of Conventional and Alternative Cleaning Methods

Table 12 shows costs of cleaning and sanitizing chemicals in the international market (China). The usage of these chemicals depends on the size of the red meat processing facility. The following analysis has been done based on some case studies from table 8; case A (produce 1 ML wastewater) and case B (produce 3.5 ML wastewater). In case of abattoir A, the usage amount is around 39-52 t/year (150-200 L/day) and in case of abattoir B it is around 50-78 t/year (250-300 L/day). Most of these chemicals can be bought at a price of 300 to 3,000 AUD per tonne (does not include delivery cost) depend on the quality and the quantity.

Plant-based and other options such as biotechnology-based cleaning compounds contain natural substances which are readily biodegradable and non-toxic. They can be a good option to replace cleaning chemicals. Biotechnology-based cleaning agents offer a cost-saving alternative by working effectively at low wash temperatures and mild pH. This will enable reduction in usage of water, raw materials and energy while improving cleaning efficiency as well as extending the lifetime of the equipment and textile [Novozymes, 2014]. Table 12 also shows costs of natural products that can be used in cleaning and sanitizing the red meat processing plant. The main issue with these natural based chemicals is the higher price compared to the conventional chemicals. In addition, these natural chemicals have not been tried on industrial scales yet.

Table 12: Conventional cleaning and sanitizing agents [Alibaba, 2014].

NAMES	CHEMICALS	PRICE AUD/t*
Chemical-base		
Acid, TOPAX 56	Phosphoric acid solution	700-800
Alkaline, TOPAX 625	Caustic alkaline liquid, sodium hydroxide	350-365
RESI-QUAT, SANIMAXX	Quaternary Ammonium Compound	1,000-1,700
Hypochlor	Sodium Hypochlorite	300-500
Chlortan 16	Chlorinated detergent	900-1,100
Eclipse	Liquid antibacterial hand cleanser	1,000-3,000
Detergent	General purpose	1,000-5,000
Plant-base		
Plant-based cleaning	Ester alcohols	1,000-4,000
Enzymes or microorganisms	Protease	800-2,500
	Amylase	900-950
	Lipase	10,000-50,000
	Mannanase	1,000-3,000
Enzyme cleaning detergents	General	740-1,240

*based on 1 USD = 1AUD

9.2. Cost of Treatment Chemicals

9.2.1. Cost of conventional chemical treatment (coagulation)

The chemical market offers a variety of coagulants for water treatment. Table 13 shows some of these chemicals and their prices. As can be seen in the table, alum is the cheapest coagulant available in the market. However, the price should not be the only parameter considered when selecting a coagulant. Other parameters such as efficiency, sludge volume, toxicity and its impact on the biological treatment process (if available) should also be considered.

Table 13: Market price for some conventional chemical coagulants [Alibaba, 2014]

CHEMICAL COAGULANT	AUD/t
Aluminium sulfate (Alum)	148-150
Polyaluminium chloride (PAC)	275-285
Aluminium chlorohydrate (ACH)	500-600
Polyaluminium chloride organic	450-455
Ferric chloride	250-350
Ferric sulfate	250-350
Polyferric sulfate	180-250
Anionic polyacrylamide	1,800-2,200

*based on 1 USD = 1AUD

In this report, it has been shown that iron-based coagulants are not only efficient as much as aluminium-based coagulants but also have a positive impact on the biological treatment process. Also, reported that a dose of 750 mg/L for three coagulants; alum, ferric chloride and ferric sulfate can achieve COD removal efficiencies of 65%, 63% and 65%, respectively [Amuda and Lada, 2006]. Based on these results, the amount of chemicals required and their costs are calculated and presented in table 14. The price of these chemicals is estimated based on suppliers from china as they are the cheapest [Alibaba, 2014].

Table 14: Amount of chemicals required and their costs [Alibaba, 2014].

CHEMICALS	DOSE, mg/L	DOSE, kg/m^3	COST, AUD/t	COST, AUD/m^3
Alum	750	0.75	150	0.11
Ferric chloride	750	0.75	250	0.19
Ferric sulfate	750	0.75	250	0.19

For example, in case of abattoir B (table 8), approximately 3500 m^3/day of fresh water is used. The total cost of using chemicals at the wastewater treatment plant per annum will be around 80,000 AUD in case of using alum and 138,000 AUD in case of using Iron-based coagulant, see table 15. These figures are based on 260 days of operation per annum and 2,800 m^3/day of treated wastewater (assume 80% of the fresh water converts to wastewater). The amount of alum and iron-based coagulants is the same which is approximately 2,100 kg/day (546 t /year). The 60,000 USD extra costs every year when using Iron-based chemicals can be compensated with the useful use of the sludge and the positive impact of iron on biogas generation at the biological process. In case of using alum the sludge will be another hazardous waste which needs separate management.

Table 15: Cost analysis per annum for chemical usage at abattoirs A and B

CHEMICALS	t /YEAR	AUD/YEAR	SLUDGE, t /YEAR*
Alum	546	80,080	546
Ferric chloride	546	138,320	546
Ferric sulfate	546	138,320	546

*Based on the amount of coagulants only

Another example is abattoir M (table 8) where chemicals are used in the wastewater treatment plant. The plant uses chemicals such as ferric sulfate and anionic polymer in the chemical DAF system. This plant is treating only part of the wastewater which is around 400 kL out of total of 1,500 kL. The treated wastewater is then mixed with the remaining wastewater in order to dilute its concentration to acceptable levels for releasing into the sewage system. Table 16 shows the chemicals in use at the plant and the cost of these chemicals annually as reported by the manager at the plant. This plant is using a coagulant dose of 375 mg/L which is half of that recommended by the literature (750 mg/L).

Table 16: Chemical usage and costs at abattoir M (table 8)

CHEMICALS	WW TREATED	DOSE, kg/m^3	USAGE, kg/day	USAGE, t /day	COST, AUD/ t	COST, AUD/m^3	COST, AUD/year	WET SLUDGE, t /day
Ferric sulfate	400 m^3/day	0.375	150	39	900	0.34	35,100	60
Anionic polymer		0.0125	5	1.3	5,500	0.069	7,150	
Total			155	40.3		0.41	42,250	60

9.2.2. Cost of alternative chemical treatments (coagulation-flocculation)

As can be seen in table 17, chitosan is the cheapest coagulant among the other plant-based chemicals. Its efficiency is comparable to the metal based coagulants such as alum and ferric sulfate. The coagulants psyllium and *Moringa oleifera* are mostly used as an aid to the metal based chemicals because of their low efficiency.

Table 17: Alternative organic coagulants

CHEMICAL COAGULANTS	AUD/ t
Chitosan	1,500-1,800/metric t
Psyllium husk powder	3,000-6,000/ t
Moringa oleifera	4,000-6,000/ t
Sodium Alginate	1,000-8,000 / t

*based on 1 USD = 1AUD

As reported in previous sections of this report, a combination of ferric chloride and chitosan can achieve at the optimum ratio of the two coagulations of 16:1 removal efficiencies of COD, turbidity, and SS of 53.7%, 93.73%, and 92.14%, respectively [Chuentongaram 2004].

In case of abattoir B (table 8), table 18 shows the amount of coagulants required and the total cost of the combined chemicals. The total cost of using this combination (ferric chloride and chitosan) at the wastewater treatment plant per annum will be around 40,000 AUD. The figures in the table are based on 260 days of operation per annum and 2800 m^3/day of wastewater treated. The amount of ferric chloride and chitosan coagulants required will be around 448 kg/day (116 t /year) and 28 kg/day (7.3 t /year), respectively. The saving is obvious when chitosan is used in a combination with ferric chloride; it is half the cost of using alum. Also, the weight of sludge produced in case of this combination is around 123 tonne. Compared to alum which is around 546 tonne, the sludge produced by this combination is less by 77%.

Table 18: Amount of ferric chloride and chitosan required and their costs

CHEMICALS	DOSE, mg/L	DOSE, kg/m^3	COST, AUD/ t	COST, AUD/m^3	t / YEAR	COST, AUD/ YEAR	SLUDGE, t/ YEAR*
Ferric chloride	160	0.16	250	0.04	116	29,120	116
Chitosan	10	0.01	1,500	0.015	7.3	10,920	7.3
Total				0.055	123.3	40,040	123.3

*Based on the amount of coagulants only

9.2.3. Cost of electrochemical treatment

Asselin et al., (2008), estimated the total cost of electrochemical (EC) coagulation operated under optimal conditions to be around 0.71 AUD $ per cubic meter of treated red meat slaughterhouse effluent. This cost includes energy and electrode consumptions (mild steel), chemicals and sludge disposal. Table 19 shows a comparison between the raw effluent with the treated effluent using EC. The removal efficiency of this process is around 99%, 82% and 89% for O&G, COD and TSS, respectively. The costs of the consumed materials are estimated as following; energy consumed at a cost of 0.06 AUD kWh^{-1}, the cationic polymer (LPM 9511) consumed at a cost of 5 AUD kg^{-1}, and the electrolyte (Na_2SO4) consumed at a cost of 1.77 AUD kg^{-1}, the mild steel electrode consumed at a cost of 228 AUD t^{-1} whereas a cost of 1,596 AUD t^{-1} was considered for aluminium electrode. The disposal costs for the residual sludge, considered as non-hazardous materials, including transportation and charges for waste disposal were evaluated at 60 AUD $ t^{-1} of dry residue (did not include the cost of drying the sludge). The total cost was evaluated in terms of United States dollars spent per cubic meter of treated effluent of 0.71 AUD/m^3.

Table 19: Efficiency and cost of EC treatment system using mild steel electrode (reaction time = 60 min) [Asselin et al., 2008].

PARAMETERS	WASTEWATER		REMOVAL
	RAW EFFLUENT	TREATED EFFLUENT	%
Current intensity imposed (A)	--	0.3 ± 0.0	--
Electrical conductivity (µS cm^{-1})	473 ± 14	385 ± 45	--
pH	6.15–6.46	8.35–9.13	--
Energy consumption (kW h m^{-3})	--	4.19 ± 0.12	--
Electrode consumption (kg m^{-3})	--	1.29 ± 0.00	--
Sludge production (kg m^{-3})	--	1.98 ± 0.12	--
Polymer (kg m^{-3})	--	0.01 ± 0.00	--
Oil and grease (mg l^{-1})	853 ± 119	13 ± 4	99 ± 1
BOD (mg l^{-1})	2,930 ± 210	420 ± 20	86 ± 2
Soluble COD (mg l^{-1})	1,270 ± 30	634 ± 56	50 ± 4
Total COD (mg l^{-1})	3,340 ± 180	605 ± 21	82 ± 2
Total suspended solids (mg l^{-1})	1,560 ± 880	152 ± 45	89 ± 4
Total solids (mg l^{-1})	2,380 ± 380	841 ± 100	64 ± 6
Turbidity (NTU)	977 ± 83	102 ± 37	90 ± 4
Electrical energy cost (AUD m^{-3})	--	0.25 ± 0.01	--
Electrode cons. cost (AUD m^{-3})	--	0.29 ± 0.00	--
Polymer cost (AUD m^{-3})	--	0.05 ± 0.00	--
Sludge disposal cost (AUD m^{-3})	--	0.12 ± 0.01	--
Total operating cost (AUD m^{-3})	--	0.71 ± 0.01	--

*based on 1 USD = 1AUD

In another study by Bayramoglu et al., (2006), electrocoagulation (EC) process is assessed by carrying out an economic analysis for the treatment of a slaughterhouse wastewater. Various direct and indirect costs have been considered in the calculation of the total cost, these include; electrical, sacrificial electrodes (iron and aluminium), labour, sludge handling, maintenance and depreciation costs. Aluminium electrode performed better in COD removal with a removal efficiency of 93% (at pH 3 and current density of 150 A/m^2) and iron electrode was more successful in removing oil and grease with 98% efficiency (irrespective of the initial pH) in 25 min. From economic point of view, iron electrode is preferable because its total operating cost is nearly half that of aluminium electrode. The total operating cost for iron electrode is between 0.3 and 0.4 AUD/m^3 [Bayramoglu et al., 2006, Kobya et al., 2006]. Again, if abattoir B (table 8) is taken as an example, based on these figures, table 20 shows that the minimum cost for treating the wastewater at abattoir B can be around 250K AUD per annum for using this technology. This technique is significantly expensive when compared to the chemical coagulation.

Table 20: Minimum operation costs per year for alum and iron electrode

ELECTRODE	TOTAL OPERATIION COST, AUD/m^3	COST, AUD/YEAR
Aluminium	0.7	509,600
Iron	0.35	254,800

9.2.4. Summary

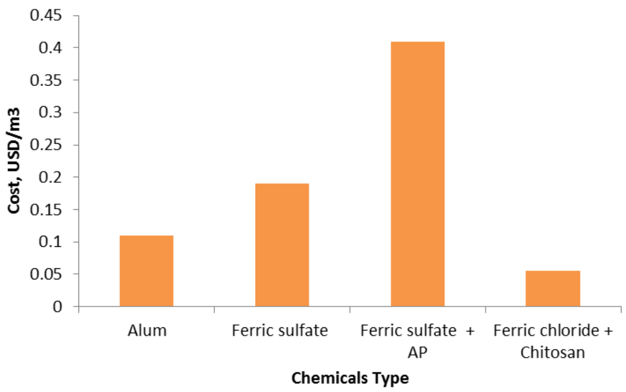

Figure 4: Chemical coagulant prices on the international market

To summarize the findings of this section, table 21 was constructed to include most of the coagulants that have potential to be used in treating wastewater from the red meat processing industry. Ferric chloride in a combination with chitosan has the lowest cost per meter cubic treated, see figure 4. In addition, it has a positive impact on the biological process and biogas production. The amount of sludge produced with this combination is less by 56% than the combination of ferric sulfate and anionic polymer.

Table 21: Coagulants that have potential to be used in treating wastewater from the red meat processing industry

CHEMICALS	Dose kg/m3	Cost AUD/m3	SLUDGE, kg/m3	Efficiency COD % removal	Impact
Alum	0.75	0.11	0.75	65	Alzheimer disease, rise wastewater pH, negative impact on the AD and high sludge volume
Ferric sulfate	0.75	0.19	0.75	65	Positive impact on the AD
Ferric sulfate + Anionic polymer (AP)	0.375	0.34*	0.375	46-87	Polymer has toxic impact on AD, low sludge volume
	0.012	0.069*	0.012		
Ferric chloride + Chitosan	0.16	0.04	0.16	53.7	Positive impact on the AD, low sludge volume
	0.01	0.015	0.01		

*based on 1 AUD = 1 USD

9.3. Cost of Enhancement Chemicals for Biological Treatment

In a previous section of this report, it has been shown that bio-surfactants and enzymes are the main chemicals that have been reported in literature for enhancing the performance of biological processes. In regards to surfactants, a study by Nakhla et al., (2003) showed that the use of a bio-surfactant may enable the enhancement of anaerobic biodegradability of meat processing wastewater by solubilizing and improving the biodegradability of the fat, oil and grease and increasing the biogas production. Chemical surfactants have been neglected because of their inhibition/intoxication impact toward microorganisms in biological digesters. A bio-surfactant titled 'BOD-balance' was tested for the treatment of FOG-rich rendering wastewater. At a dose of 130 to 200 mg/L, there was an indication of reduction in FOG concentration from 66,300 to 10,200 mg/L over a 2-month-period. With regards to lipase such as lipase G-1000 (LG-1000), this enzyme was tested at a dose of 3,500 mg/L, it helped to increase the SCOD in the wastewater by 27% [Masse et al., 2001].

Based on 200 mg/L dose of bio-surfactant required and wastewater production at abattoir B (table 8), the amount of bio-surfactant required will be around 145 tonne per annum which cost around 94,600 AUD/year, as shown in table 22. In case of lipase, the minimum cost of using lipase G-1000 for abattoir B can reach a significant number of 364,000 AUD/year.

Table 22: **Costs of using Bio-surfactant and Lipase**

CHEMICALS	DOSE, mg/L	t /YEAR	PRICE, AUD/ t	COST, AUD/YEAR - MINIMUM
Bio-surfactant	130–200 mg/l	94.6-145.6	10,000-100,000	94,600
Lipase	500-3,500 mg/l	364-2,548	10,000-50,000	364,000

*based on 1 AUD = 1 USD

It is obvious that using these alternatives for enhancing the performance of the biological process are not feasible economically. Adding co-digestion substrates/wastes to the anaerobic digester may be the cheapest way to enhance its performance. Preferably wastes produced at the location of the abattoir such as manure, or wastes from the neighbouring farms such as waste vegetables and/or fruits [Hamawand, 2015].

9.4. Cost of Chemical-Free Methods

9.4.1. Chemical-free cleaning

Chemical-free cleaning and sanitizing method are a good alternative due to their high efficiency and absence of toxic chemicals in the process. However, lack of research in this field including industrial-scale tests for these methods and due to the sensitivity of the subject have created a resistance to apply these techniques. Table 23 shows some of these chemical-free methods and their capital and operational costs.

Table 23: Chemical-free cleaning and sanitizing methods

NAME	PRICE	CAPITAL INVESTMENT
Heat steam	Electricity, 28 ct/kwh	10,000-21,000 (1-10 t/hr)
Ozone	Electricity, 28 ct/kwh	350,000-435,000 (20 kg/hr)
Hydrogen peroxide (35-50 %)	400-550 AUD/t	---

9.4.2. Chemical-free treatment

Chemical-free wastewater treatment in the red meat processing industry includes the following; screening, settling tank, DAF, low rate anaerobic and aerobic processes. Most of these processes have low capital and operation costs; however they are only capable to treat abattoir wastewaters to a quality acceptable for irrigation for animal feed crops. They are widely used in wastewater treatment of the red meat processing industry in Australia and have been associated with many difficulties due to low/no maintenance. Table 24 shows some of these methods and the type and cost of energy used in driving them.

Table 24: Chemical-free treatment methods energy consumption

NAME	ENERGY TYPE	ENERGY USAGE
Screening	Electricity	Low
DAF	Electricity	high
Anaerobic pond	Electricity	Low
Aerobic pond	Electricity	High

9.5. Summary

The analysis above indicates that alternative cleaning and sanitizing agents are more expensive than the conventional chemicals. Also, this subject is sensitive because it relates directly to human health. Due to the requirements of keeping hygiene standards at the red meat processing facilities and lack of research related to using alternative cleaning chemicals, the industry may be uncomfortable with trying these chemicals.

With regards to wastewater treatment chemicals, a combination of ferric chloride (main coagulant) and chitosan (aid) is the optimum solution when it comes to cost and sludge volume. Although the removal efficiency of this combination is slightly lower than alum (see figure 5), these chemicals have a positive impact on the biological process.

With regards to enhancing the efficiency of the biological process, co-digestion by adding vegetable and fruit wastes produced at or close to the wastewater treatment plant is a much cheaper solution than adding chemicals.

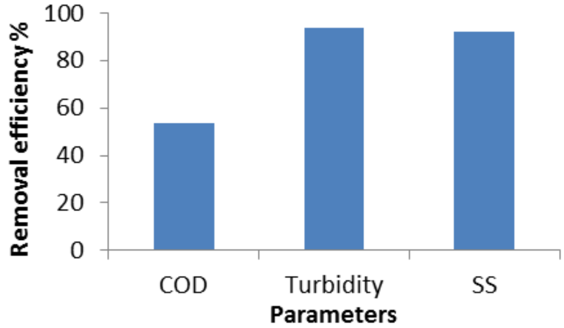

Figure 5: Removal efficiency of the combination of ferric chloride and chitosan

With regards to the chemical-free treatment methods such as screening and anaerobic digestion processes, these methods have the lowest operation cost due to low energy consumption. Both DAF and aerobic process consume higher energy due to the operational requirement of constant air injection.

When the effluent wastewater is aimed to be reused or released to surface streams, chemical treatment is the cheapest and fastest method to reach this goal.

10. Optimal and Practical Solutions

Before discussing optimal and/or practical solutions for the treatment of red meat processing industry wastewater, the efficiency of the treatment plant should be addressed. The following steps should be applied to enhance the plant efficiency:

- Optimize fresh water usage;
- Improve separation of blood from the wastewater system;
- Removal of solid waste from production area floors before wet cleaning;
- Installation of sludge trap and fat separator.

These steps, if applied, will reduce the amount of water consumed and wastewater produced which will positively impact the expenses of the plant. Also, it will reduce sludge production in the physical, chemical and biological treatment processes which means less cost to handle these by-products. By applying these steps and combining them with an optimal treatment process, the financial and the environmental benefits will be improved.

10.1. Chemicals Recommended for the Facility Cleaning

Due to sensitivity of this subject and lack of adequate research in the field of alternative chemicals/methods for cleaning and sanitizing red meat processing facilities, it is not recommended to change the current practice. The current cleaning and sanitizing practices have been proven to be effective. However, enzymes and ozone have the potential to replace the dangerous and hazardous chemicals currently in use after extensive tests to ensure their effectiveness. The main issue with using enzymes is the price of these materials which make them less attractive for the industry.

10.2. Chemicals Recommended for Wastewater Treatment

The current study shows that chemical coagulants might be required in the treatment of red meat processing industry wastewater to reach a quality suitable for reuse or dispose to surface water streams. The chemical treatment unit can be added either at the final stage of the treatment process in order to produce water that is suitable for surface water disposal or at the start of the process to assist other units in the treatment plant to perform more efficiently, such as the biological process.

A combination of a main and an aid coagulant is recommended due to its high efficiency, low cost and small sludge size produced. Coagulant aids are inexpensive additives which help increase settling velocity and reduce coagulant dosage. As identified in the previous sections, iron-based coagulant in a combination with chitosan is more favourable when it comes to the price per cubic meter treated (0.055 AUD/m^3) compare to alum (0.11 AUD/m^3). Also, the amount of sludge produced is 77% less than that produced by alum. The efficiency of this combination is around 53.7% COD removal, which is lower only by 10% than alum. Moreover, the residue of this combination in the wastewater has a positive impact on the biological treatment processes.

Using chemicals for enhancing the biological treatment process, may not be applicable due to the high price of these chemicals and low performance. Co-digestion with waste from fruits and/or vegetables is a better option due to its low cost, especially if this waste is produced at or nearby the location of the digester. Some of the co-digestion materials can be grown onsite, irrigated with the treated wastewater. Co-digestion may also contribute in enhancing the production of biogas which results in generating more revenue.

10.3. Optimal and practical treatment design

Low cost, efficient treatment and environmentally friendly by-products can be a definition for an optimum treatment solution for any wastewater. Based on the current information provided in this study, the optimal treatment process can be categorized into different scenarios based on the required outcomes. To identify these scenarios, it is important to start with analysing the units in the treatment system.

The physical treatment units are very important parts and cannot be eliminated from the treatment process. A settling tank after screening would be ideal for mixing and controlling the composition and flow rate of the influent. This will dilute the cleaning chemicals to low concentration which will eliminate their impact on the biological, physical and chemical treatment processes. Screening and settling can achieve around 90% removal for the coarse particles which are separated by gravity.

The insoluble and the fine colloidal particles can be removed by other treatment processes. The DAF unit can be an integral part to the physical treatment where fine particles, including fat, oil and grease can be removed. DAF units can achieve COD reductions ranging from 32% up to 63% of mostly fine and colloidal particles. This efficiency can be increased to 97% by adding chemical coagulants which remove a large portion of the soluble materials. The chemical recommended for the coagulation/flocculation step are a combination of ferric chloride and chitosan. Chemical treatment using this combination has been addressed in previous sections of this report as the optimum treatment method. This chemical combination has lower cost and comparable efficiency compared to alum. Also, the residuals of these chemicals in the wastewater and sludge have positive impact on the biological processes (anaerobic digestion and composting).

Figure 6, in scenario one, chemical DAF is recommended to eliminate problems associated with crust formation at the biological stage. This scenario will be able to refine the wastewater to a level where it is suitable for irrigation of animal feed crops. This is because of the low efficiency of anaerobic digestion process. The degree of organic matter degradation in a typical anaerobic pond typical anaerobic digester can reach 53% [Marcato et al., 2008]. Effluent wastewater from the biological treatment will be loaded with other soluble organic matter as a result of the biological reactions such as phosphors and ammonia which makes it suitable for irrigation. It is recommended to manipulate the physico-chemical treatment efficiency in order to reduce the organic loading rate of the wastewater to acceptable range for anaerobic digestion process which is around 0.05 to 0.08 kg BOD/m3day (low rate anaerobic digesters such as ponds).

Figure 6, in scenario two, chemical treatment can be installed at a last stage of the treatment system after the biological treatment. At this stage most of the wastewater content is in forms of soluble and/or colloidal particles which are appropriate for chemical treatment. By controlling the chemical dosage and the pH of the wastewater, the treated water can reach a specification suitable for surface water release or recycled for specific use in the plant. Because discharging wastewater directly into surface water requires sterilisation with chlorinated chemicals, a sterilization unit can be added at the end of the treatment system [SMP, 2014]. In this scenario, the biological treatment is not essential. The biological process can be removed from the treatment system, however this may increase the dose of the chemical coagulants. Additionally, the treatment plant will lose the opportunity of generating energy and producing agricultural fertilizer. In case of using chemical treatment, biological process will be a flexible choice.

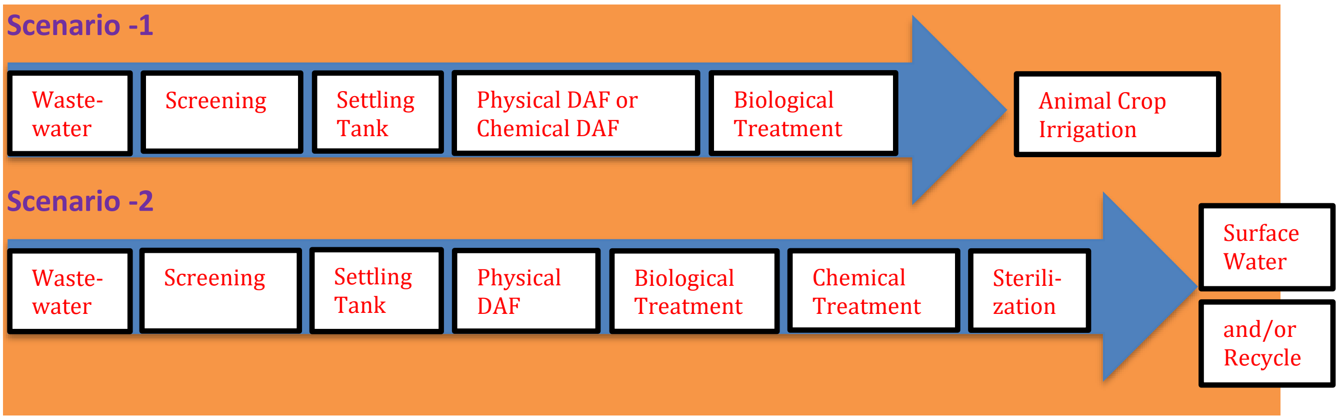

Figure 6: Block diagram for different scenarios for meat industry wastewater treatments

11. Gaps in Research

Based on an extensive literature review carried out in this field, more research needs to be carried out in the following areas:

- Effect of cleaning chemicals on the chemical and biological treatments and subsequent biogas generation if this is being captured;
- Use of alternative chemicals and chemical combinations in abattoir wastewater treatment;
- Uncertainty about the factors that affect the wide range efficiency (from 30 to 90%) for the chemical treatment;
- Effect of physical treatments on the performance of the chemical treatment;
- The relationship between the number of physical treatment steps and wastewater temperature;
- Cost benefit analysis studies for conventional and alternative chemicals.

12. Conclusions and Recommendations

12.1. Conclusions

The following points are the main conclusions from this study;

- Conventional cleaning chemicals have been used in cleaning and sanitizing facilities in the meat processing industry for decades. They are applied at low concentrations and quantities:
  - Concentration: 3% - 5%.
  - Quantity: 0.1 – 0.25 L/1KL wastewater.
- Alternative cleaning chemicals presented in this study are apparently capable to replace conventional chemicals and have positive impact on the biological treatment stage, however they are expensive.
- Releasing conventional cleaning chemicals to the biological treatment system at high concentration may create dead zones inside the digester.
- Wastewater treatment chemicals (conventional and alternative) are capable of reducing the nutrient content of abattoir wastewaters to acceptable levels, suitable for releasing to sewage systems and/or surface water streams.
- A combination of a main and an aid coagulant has shown to be efficient and cost-effective in treating abattoir wastewater. Coagulant aids are capable of reducing the amount of chemicals required and the sludge produced.
- In order for the chemical treatment to be efficient, physical treatment is an important stage of the treatment system which cannot be eliminated. The efficiency of the biological treatment dependents on this stage as well.
- Given the biological nature of the wastewater effluent from the red meat processing industry, biological treatment, specifically anaerobic digestion process, seems to be an appropriate option of treatment. Low rate anaerobic ponds are preferred across the industry due to the low capital and operation costs.
- The by-product of the chemical treatment when alternative chemicals are used shows better potential to be used in other applications. This is due to its higher degradability and lower toxicity to both the biological process and soil applications.
- Effect of chemical treatment on biogas generation potential in the anaerobic digestion unit is unknown.
- Effect of physical treatments on the efficiency of the chemical treatment and the wastewater temperature is unknown.

12.2. Recommendations

The recommendations from this study include the following:

- In order to reduce/eliminate the impact of the conventional cleaning chemicals on the biological treatment processes and the environment, it is recommended to dilute these chemicals in the bulk wastewater before feeding it to the treatment plant. This can be done by adding a storage tank at the beginning of the treatment plant to collect the entire wastewater produced in one day in this tank. This will enable diluting these chemicals with the entire wastewater and stabilize wastewater feeding rate to the treatment plant.
- Alternative chemicals are not recommended for the purpose of cleaning and sanitizing the red meat processing facility until further research is undertaken into these alternatives. Also, the higher price of these alternatives compared to conventional chemicals has added another barrier for adoption.
- Alternative environmentally safe chemicals for treating the wastewater are recommended due to their high performance and cost-effectiveness which is comparable to conventional chemicals such as alum. A combination of a main (ferric chloride) and an aid (chitosan) coagulant has shown to be efficient and cost-effective in treating abattoir wastewater. The cost of using this combination per cubic meter wastewater treated is 0.055 USD/m^3 compared to 0.11 USD/m^3 for alum and the amount of sludge produced is 77% less than that produced by alum. Also, the residues of these chemicals in the wastewater and the sludge have a positive or no impact on biological processes.
- Chemical treatment may not be recommended when the quality of the treated wastewater is for irrigation for animal crops. Physical and biological treatments are sufficient to achieve such quality.
- Chemical treatment is highly recommended when the quality of the treated wastewater is for reuse inside the plant or to be released to surface water. To achieve this quality, another unit should be added to the treatment plant which is sanitizing the final product via UV light.
- Chemical treatment can replace the biological treatment, however it is not recommended because anaerobic digestion can be a source of energy which can offset some of the plant expenses.
- A long sequence of physical treatment processes is not recommended when the treatment plant includes an anaerobic digestion process. This will reduce the temperature of the wastewater and as a result the efficiency of the digestion process.
- Screening plus a settling tank with addition of chemical coagulants is recommended to reduce the number of physical treatment and as a result reduce the maintenance service.

13. Future Research

Based on the conclusions and recommendations made in the previous section, the following list of further work is recommended.

13.1. Cleaning chemicals

Further research is required to evaluate the efficiency of alternative chemicals and chemical-free methods which have potential to be used for cleaning and sanitizing the meat processing facility. This can be done through lab-scale biological tests for selected locations in the red meat processing facilities (after it has been cleaned by alternative chemicals). The following questions can be the focus of this study:

- What is the optimum dosage of these chemical?
- What is the best combination?
- What standard of hygiene is achievable?

13.2. Wastewater treatment chemicals

The alternative chemicals recommended in this study for treatment of abattoir wastewater require further investigations in order to identify the optimum and the most effective chemicals and/or combination of chemicals. This can be done through long-term multiple projects where both the conventional and alternative chemicals are tested at a lab-scale level. The following projects are required:

Project I: Optimization of chemical treatment method

Stage I:

Carry out a laboratory-scale prove of concept test to identify the optimum conditions for the chemical treatment process. This can be done by conducting jar tests in order to analyse the performance, impact and cost-effective of the chemical coagulants. In addition, effect of the physical treatment and wastewater temperature on the chemical treatment should be considered. At a later stage, industrial-scale tests should be carried out to study the efficiency of these chemicals in a practical situation.

Stage II:

Carry out anaerobic digestion experiments for the treated water to study the effect of the chemical treatment step on the biological activity and wastewater temperature and subsequent biogas generation. Also, study the potential of using the by-products of the chemical treatment as a co-digestion material, which may require pre-treatment, for enhancing biogas production from centralized anaerobic digesters.

Project II: Test chemical treatment sludge for composting and soil conditioning

The solid by-product of the chemical treatment process, specifically when using the recommended chemicals of this study, requires further research to evaluate its suitability for composting and later for soil conditioning.

Abbreviations

SYMBOL	DESCRIPTION
FOG	Fat, oil and grease
OLR	Organic loading rate
LCEF	Long chain fatty acids
DAF	Diffuse/dissolve air floatation
AMPC	Australian Meat Processing Corporation
NCEA	National Centre for Engineering in Agriculture
USQ	University of Southern Queensland
HSCW	Hot standard carcase weight
COD	Chemical oxygen demand
BOD	Biochemical oxygen demand
TSS	Total suspended solid
HRT	Hydraulic retention time
VSS	Volatile suspended solid
TKN	Total Kjeldahl Nitrogen
TDS	Total dissolved solids
TP	Total Phosphorous
PACI	Polyaluminium chloride
Alum	Aluminium sulfate
ACH	Aluminium chlorohydrate
EC	Electrocoagulation
UASB	Upflow anaerobic sludge blanket
OM	Organic matter
LAS	Alkylbenzene Sulfonates
SLS	Sodium lauryl sulfate
TMAC	Trialkyl-methylammonium chloride
AE	Alcohol ethoxylates
DM	Dry matter
K	potassium
AD	Anaerobic digestion
SRT	Solid retention time
AP	Anionic polyacrylamide
NH4-N	Ammonium nitrogen
NaOH	Sodium hydroxide
SLS	Sodium lauryl sulfate
C:N	Carbon to nitrogen ratio
UV	ultra-violet
CaCO3	Coliseum carbonate
t	tonne
EAF	Entrapped air flotation

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