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Review

A Critical Review on Processes and Energy Profile of the Australian Meat Processing Industry

Ihsan Hamawand [1,*], Anas Ghadouni [2], Jochen Bundschuh [3], Sara Hamawand [1], Raed A. Al Juboori [4], Sayan Chakrabarty [5] and Talal Yusaf [4]

1 Hamawand for Research and Engineering Services, Toowoomba, QLD 4350, Australia; sara.ghazeibrahim@gmail.com
2 Aquatic Ecology and Ecosystem Studies Group, School of Civil, Environmental and Mining Engineering, The University of Western Australia, Crawley, WA 6009, Australia; anas.ghadouani@uwa.edu.au
3 Institute for Agriculture and the Environment, The University of Southern Queensland, Toowoomba, QLD 4350, Australia; Jochen.Bundschuh@usq.edu.au
4 Faculty of Health, Engineering and Sciences, The University of Southern Queensland, Toowoomba, QLD 4350, Australia; RaedAhmed.Mahmood@usq.edu.au (R.A.A.J.); talal.yusaf@usq.edu.au (T.Y.)
5 Institute for Resilient Regions (IRR), University of Southern Queensland, Springfield, QLD 4300, Australia; sayan.chakrabarty@usq.edu.au
* Correspondence: Ihsan.hamawand@gmail.com; Tel.: +61-4668-97659

Academic Editor: Carl-Fredrik Lindberg
Received: 28 February 2017; Accepted: 18 May 2017; Published: 20 May 2017

Abstract: This review article addresses wastewater treatment methods in the red meat processing industry. The focus is on conventional chemicals currently in use for abattoir wastewater treatment and energy related aspects. In addition, this article discusses the use of cleaning and sanitizing agents at the meat processing facilities and their effect on decision making in regard to selecting the treatment methods. This study shows that cleaning chemicals are currently used at a concentration of 2% to 3% which will further be diluted with the bulk wastewater. For example, for an abattoir that produces 3500 m^3/day wastewater and uses around 200 L (3%) acid and alkaline chemicals, the final concentration of these chemical will be around 0.00017%. For this reason, the effects of these chemicals on the treatment method and the environment are very limited. Chemical treatment is highly efficient in removing soluble and colloidal particles from the red meat processing industry wastewater. Actually, it is shown that, if chemical treatment has been applied, then biological treatment can only be included for the treatment of the solid waste by-product and/or for production of bioenergy. Chemical treatment is recommended in all cases and especially when the wastewater is required to be reused or released to water streams. This study also shows that energy consumption for chemical treatment units is insignificant while efficient compared to other physical or biological units. A combination of a main (ferric chloride) and an aid 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. In addition, the residues of these chemicals in the wastewater and the sludge have a positive or no impact on biological processes. Energy consumption from a small wastewater treatment plant (WWTP) installed to recycle wastewater for a meet facility can be around $500,000.

Keywords: wastewater treatment; cleaning agents; abattoir effluent; disinfection; energy consumption

1. Introduction

The meat processing industry is a major user of fresh water and there is an anticipation that the water use in this industry will further increase. The current trends from around the globe have shown that water consumption by meat processing industry has risen noticeably in the recent years [1]. Some other parts of the world have also witnessed an increase in meat production such as China and India due to the change in diet [2]. Considering the large populations of these countries, this implies a significant increase in meat processing wastewater produced globally. The wastewater produced from meat processing activities is more concentrated and hence its treatment is more energy intensive in comparison to municipal wastewater. Bustillo-Lecompte et al. [2] have put together a set of characteristics that describes the broad quality of meat processing wastewater as shown in Table 1.

Table 1. General characteristics of meat processing wastewater [2].

Symbols, Units	Parameter	Range	Mean
TOC (mg/L)	Total Organic Carbon	70–1200	546
BOD_5 (mg/L)	Biological Oxygen Demand	150–4635	1209
COD (mg/L)	Chemical Oxygen Demand	500–15,900	4221
TN (mg/L)	Total Nitrogen	50–841	427
TSS (mg/L)	Total Suspended Solid	270–6400	1164
pH	pH	4.90–8.10	6.95
TP (mg/L)	Total Phosphorus	25–200	50
Ortho-PO_4 (mg/L)	Orthophosphate	20–100	25
Orhto-P_2O_5 (mg/L)	-	10–80	20
K (mg/L)	Potassium	0.01–100	90
Colour (mg/L Pt scale)	-	175–400	290
Turbidity (FAU)	-	200–300	275

Taking Australia as a case study in this article, 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 the food manufacturing sector.

Average cost of fresh water supplied to abattoirs in Australia is around \$0.75/m^3 [3]. Costs of wastewater disposal and limitations on discharge also need to be considered. Plants discharging treated wastewater to municipal sewage systems face prohibitive costs and limitations. Authorities currently charge based on the volumetric and organic loads (BOD/COD content), while nutrients such as nitrogen and phosphorous are 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. The cost of treating the effluent for disposal to sewer is \$0.5/m^3, surface water \$0.8/m^3 and for land application is \$0.3/m^3 [3]. For example, a typical abattoir in Australia that uses around 3500 m^3 of water per day will need to spend around \$2800/day (\$644,000/year; based on 230 day/year) in the case the treated wastewater is aimed to be released to water streams. In case the wastewater is aimed to be reused in the facility then the cost of treatment can be higher by many folds due to the high-water quality required. In addition, the quantity and the quality of the by-products from the treatment process (solids and liquids) generate several environmental challenges to the red meat processing industry as part of the day-to-day running of the plants. There is potential for odour and nuisance for neighbouring communities and pollution of surface and ground waters.

The other issue with the wastewater from the red meat processing industry is the use of chemicals for 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. In addition, surface-active agents (surfactants/detergents) are added to improve their dirt loosening properties [4].

Many treatment methods are currently used in red meat processing facilities, among them physical, chemical, biological and hybrid methods (a combination of two or more of the aforementioned methods). In Australia, it is found that physical treatment processes in red meat slaughterhouses involve either solely or in a combination; sedimentation, coarse screening, followed by fine screening and finally dissolved air floatation (DAF). Regarding the chemical treatments, chemical coagulants such as metal salts and/or polymers are currently being used in some abattoirs. There is 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 due to high energy consumption is preventing the industry from applying it.

Physical treatment followed by chemical treatment seems to be the most suitable option especially when the treated water is to be utilized for reuse inside the facility or discharged to surface waters. DAF combined with chemical coagulants (polymers) is currently popular and in use at many wastewater treatment plants. The chemical composition of these polymers is not declared (know-how) with claimed COD removal efficiency of 70–80%. There are many kinds of coagulants that can be used for treating meat processing wastewater: inorganic salts such as aluminium sulphate (alum), ferric chloride and ferric sulphate, polymers such as polyaluminium chloride (PACl) and aluminium chlorohydrate (ACH) and natural coagulants such as chitosan [5].

Energy accompanying meat processing wastewater treatment can be high due to variety aspects such as highly advanced treatment required for an improved effluent quality driven by stringent environmental regulations and powerful pumping associated with activities such as water recycling and sludge transferring from one stage to another [6]. In general, around 80% of energy consumption in any wastewater treatment plant is related to transporting water. Chemical treatment includes pumping and mixing, which can consume energy of around 6.5% of the total energy consumed in the treatment plant. Energy consumption for physical treatment such as sedimentation can be around 0.3% of the total. Since any unit involves some kind of pumping such as DAF, the energy consumption can increase significantly [7].

The other part of energy consideration is what can be recovered from the produced wastewater in the meat processing industry. It is known that meat processing wastewater is rich in biodegradable organic matter that can effectively be harnessed for producing energy in different forms [8]. This energy can at least offset part of the energy required for running this industry.

In this study, an extensive literature review has been carried out around various aspects of energy and treatment processes for meat processing industry with a focus on Australia as a case study. It should be noted here that part of the data presented in this article have been collected by the authors through site visits and engagement with the Australian meat processing industry stakeholders. This article sheds the light on the current practices followed in cleaning meat processing facilities and in the treatment of abattoirs wastewater. The article also includes proposing effective practices and treatment schemes for meat processing wastewater. This review is an attempt to help the Australian and global meat processing industry in decision making.

2. Organics and Chemicals Introduced to the Effluent

The main sources of organic materials in wastewater include faeces, urine, blood, fat oil and grease, washings: carcasses/floors/utensils, undigested food, paunch, processes: cooking/curing/pickling of meat and condensate from rendering of offal and other by-products processing [9]. Periodic cleaning and sanitation is an integral part of the red meat processing industry. Cleaning and sanitation of meat plant premises and equipment can 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 [4]. 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. Wastewater Organic Loading

When red meat processing industry wastewater is discharged to a water course it may lead to a rapid depletion of dissolved oxygen which will damage aquatic lives. It is also become a biological hazardous, produces odour, results in sludge deposits and unpleasant floating scum [10]. Red meat processing wastewater also contains nitrogen (N), at concentrations typically ranging between 50 and 400 mg N/L, and so it has the potential to cause N contamination of groundwater when applied onto land in excessive amounts [9,11]. Equally, improper disposal systems of wastes from slaughterhouses could lead to transmission of pathogens to humans [4]. The degree of organic loading rate in the Australian red meat processing industry is extremely high, the Biological Oxygen Demand (BOD) can be as much as 4000 mg/L. This water can be disposed on watercourses only after adequate treatment. The minimum requirements for the discharge of dirt or wastewater into sewer and surface water, which differs from state to state is presented in Table 2. 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% in the case a wastewater with BOD of 4000 mg/L [12]. Removing 99% of the "dirt" in wastewater is a big, costly and a complex challenge for any treatment plant.

Table 2. Minimum requirements for wastewater disposal to sewer and surface water in most of the Australian states [12].

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	−15 mg/L

FOG: Fat, oil and grease; SS: Suspended solid.

2.2. Cleaning with Chemicals

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 cause short-term as well as long-term changes in the ecosystem; they are harmful to humans, fishes 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 1.0 mg/L for other purposes [13].

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 mixtures of alkaline, acid or neutral chemical substances. In addition, surface-active agents (surfactants/detergents) are added 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.

Data collected by the authors from visiting many red meat processing sites have revealed the cleaning chemicals currently in use in the Australian meat processing industry. Table 3 presents the 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 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 min), the foam is washed down with water [4].

Table 3. Cleaning agents in use in red meat processing industry [4].

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 on which materials to use.
Foam cleaning	A relatively new cleaning method, in particular for larger-scale plants.	n/a
Detergents	Used to improve dirt loosening properties.	Anionic, nonionic and cationic surface active agents.

Table 4 shows an example of the cleaning chemicals in use at one of the Australian red meat processing industry. As shown in the table alkaline and acid agents are common in this industry.

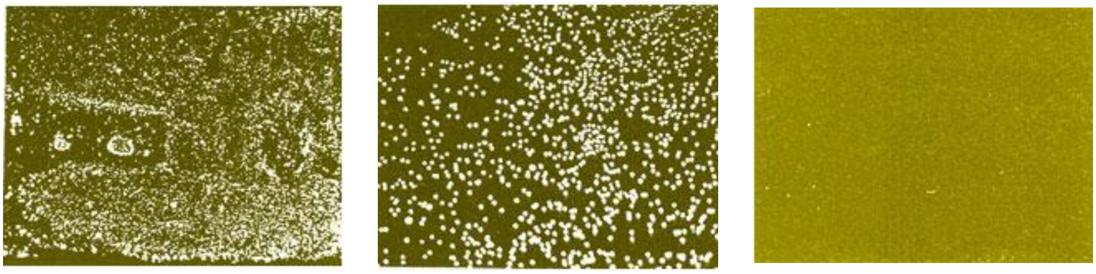
Table 4. Specification and status of chemicals in use at an Australian abattoir.

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

2.3. *Disinfecting Chemicals*

The complete elimination of microorganisms can be achieved through disinfection, using either 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 [4].

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 5, the following groups of substances are used worldwide and in the Australian red meat processing industry [4] (data collected by the author).



(**a**) (**b**) (**c**)

Figure 1. (**a**) Uncleaned (rinsed only), many bacterial colonies; (**b**) after chemical cleaning, reduced numbers of bacterial colonies; and (**c**) after cleaning and disinfection, very few bacterial colonies remain [4].

Table 5. Available disinfectant and their usage [4].

Disinfectant	Composition	Purpose
Chlorine containing compounds	Na- or Ca-hypochlorite (Na/Ca O Cl), gaseous chlorine (Cl_2) (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, odourless, 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, odourless, may be corrosive at concentrations greater than 1%

Table 6 shows an example of the sanitizing agents in use at one of the Australian red meat processing industry. As shown in the table, Quaternary ammonium compounds (QUATS) and chlorine containing compounds are common in this industry.

Table 6. Specification and status of chemicals in use at an Australian abattoir.

Name	Sanitizing Agents	Use	Substances	Hazardous and Dangerous Status
SANIMAXX	n/a	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	Hypochlor-ite solution	Sanitizer	Up to 3% in water. Sodium hypochlorite 10–30%	Classified as non hazardous substance and non dangerous goods

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 [9,14]. However, this does not eliminate the need for primary physical treatment such as screening and diffuse air flotation (DAF). Provided the physical treatment is carried out efficiently to remove the bulk fat and suspended solids, biological treatment processes can then be utilized. This means energy consumption will be high in this case since more advanced physical treatment is required before the biological treatment. There are circumstances where biological treatment may not be a favourable option. This is may be 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 [15].

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). In addition, the methanogenic activity may be inhibited due to the presence of long chain fatty acids [16,17]. The physical treatment process steps involve either solely or in a combination; sedimentation, coarse screening, followed by fine screening and finally DAF [18,19]. Table 7 shows the performance of the different physical treatments that can be used in the red meat processing industry. In addition, the table shows energy consumption for these treatment methods. As can be seen in the table, DAF unit is more efficient but at the same consumes more energy.

Table 7. Physical treatment methods and their performance [18,19].

Treatment Method	Performance	Energy Consumption
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.	Low, no pumping is required
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.	Low, no pumping is required
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 dissolved air flotation (DAF) system can be used to continually or periodically recover fats and protein by scraping. If the dissolved air flotation process is controlled well, at least 30% to 35% removal of BOD, 60% removal of TSS and 80% of FOGs removal is achievable.	High, air pumping is required

It should be noted that physical treatment methods are mainly used as primary treatment. For further treatment of wastewater (secondary and tertiary treatments), more advanced physical treatments are employed such as the use of membrane technology. The advanced treatments of meat processing wastewater are usually applied to meet the permissible limits of the environmental legislations set by the jurisdiction where the meat processing facilities are located. Different jurisdictions around the world have different criteria of what the treated meat processing wastewater quality should be. Table 8 presents the limits of the prominent characteristics of meat processing wastewater effluent from various regions worldwide. The common membrane technologies are micro-filtration (MF), ultra-filtration (UF), nano-filtration (NF) and reverse osmosis (RO). The pore size follows the order of MF > UF > NF > RO, and the operation energy requirement for the aforementioned membrane technologies follows the reverse order of the pore size. Normally applying membrane technology in meat processing industry would incur extra energy requirements. Waeger et al. [20] reported that the energy requirement of using UF for treating anaerobic digester effluent could reach more than 36 kJ/m^3 depending on the applied pressure to obtain the desired membrane cross-flow velocity. Some studies have shown that this energy costs can be offset especially when the membrane technology is used for recycling water to be used with the meat processing unit [21].

Table 8. The standard limits of common meat processing wastewater effluent set be different jurisdictions worldwide [2].

Parameter	World Bank Standards	EU Standards	US Standards	Canadian Standards	Australian Standards
BOD (mg/L)	30	25	26	5–30	6–10
COD (mg/L)	125	125	n/a	n/a	3 × BOD
TSS (mg/L)	50	35	30	5–30	10–15
TN (mg/L)	10	10	8	1	0.1–15

3.2. Chemical Treatments

In general, wastewater contains particles of varied sizes. The size of particles present in wastewater determines the type of treatment that is 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 as settling, screening and DAF can remove 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 except by membrane technology. 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 [5]. It is not possible to separate colloidal solids even by fine filters because they pass through any conventional filter (non-membrane). 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 [5]. Coagulation-flocculation process can be used for both wastewater treatment and 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 20th 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 [5]. 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 [22].

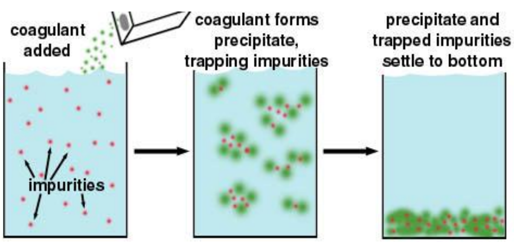


Figure 2. Coagulation/flocculation process [5].

There are several types of coagulants in the chemical market such as inorganic metal based-coagulants. Some examples of inorganic metal coagulants are aluminium sulphate (alum), ferric chloride and ferric sulphate. Aluminium sulphate (alum) has been used for water purification since ancient times. However, some studies showed that using alum for abattoir wastewater treatment produces higher amount of sludge in comparison to ferrous sulphate and an anionic polyelectrolyte [23]. The addition of coagulant aids such as silica and activated carbon can help reducing sludge volume [24].

Recently pre-polymerised inorganic coagulants have been used due to their availability such as polyaluminium chloride (PACl) and aluminium chlorohydrate (ACH) [5].

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 colour [25].

Over the last 20 years, there were attempts 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% [26]. The effectiveness of these coagulants was found to be dependent on the composition of the wastewater, temperature, dose, rate of mixing and order in which coagulants and flocculants are introduced into the wastewater. Table 9 shows removal efficiencies of various coagulants, reported in several 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 [27]. The coagulation/flocculation process has been reported to be cost effective, easy to operate and energy-saving alternative treatment process [28].

Table 9. Removal efficiencies of COD, BOD_5 and TSS using different coagulants [27].

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 sulphite)	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. [29], ferric sulphate 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 it was around 99%. In another study by Aguilar et al. [22], 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. [26] investigated the use of the coagulation/flocculation process to remove organic matter from red meat slaughterhouse wastewater 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 100–1000 mg/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 30–70 mg/L concentrations of polymer or at 100–300 mg/L alum with pH in the range of 4–9. Amuda and Lada [28] showed that at a dose of 750 mg/L, for three coagulants, alum, ferric chloride and ferric sulphate, COD removal efficiency can reach 65%, 63% and 65%, respectively.

One of the major problems of using coagulation is the sludge produced from this process that carries some hazardous metals such as Al. Therefore, some researchers have advocated the use of natural coagulants that can be less harmful to the environment and human health. One of the commonly used natural coagulants for wastewater treatment is chitosan [30]. Chitosan is a natural polymer produced from treating one form of seafood waste (shrimp shells) with alkaline substances. Ahmad et al. [31] compared the effectiveness of chitosan as a coagulant to traditional alum and poly-aluminium coagulant (PAC) for treating oily wastewater, and they found that chitosan required lower dosage, less mixing time and less sedimentation time as opposed to the other studied coagulants. This reflects the potency of chitosan as a promising eco-friendly coagulant for meat processing wastewater treatment.

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. The important part of the system is the reactor where the agglomeration of organics, metals and even pathogens happens due to the reaction with the released M^{+3} from the sacrificial electrodes. These electrodes are normally made of Al, Fe, Pt, SnO_2 and TiO_2 with Al and Fe being the most popular ones. These methods have been used successfully in the treatment of wastewater from poultry and cattle slaughterhouses and those which contain heavy metals [25]. The chemical reactions occurring in the electro-coagulation process are as follows:

$$\mathrm{Al} \leftrightarrow [\mathrm{Al}]^{3+} + 3\mathrm{e}\ (\text{anode}) \quad (1)$$

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

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

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 this is especially the case with neutral to alkaline pH range [32]. In addition, these flocs polymerize further and can be removed easily from aqueous mediums by sedimentation or/and flotation by hydrogen gas [25]. At acidic pH range <5, the positively charged Al species are prevalent and hence the scavenging of organic materials happens through charge neutralisation. Alum coagulation mechanisms are equally valid for chemical- and electro-coagulations. Furthermore, this process produces less sludge because it is more concentrated than that generated by normal chemical coagulation processes. Electrolytic treatments are characterized by simple equipment, brief retention times and easy operation and also result in reduction of operating costs in large-scale applications [33]. The difference between chemical coagulation and electrocoagulation is the source of coagulant. In electrocoagulation, the source of the coagulant is the cations produced by electrolytic dissociation of the anode metal and the activation energy applied which promotes the formation of oxides.

In a study by Asselin et al. [33], 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 between 60 and 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-colourization (red colour) and clarification with removals of 89% and 90% for total suspended solids and turbidity, respectively. Another study conducted by Kobya et al. [34] on the use of electro-coagulation for treating poultry slaughterhouse wastewaters showed that the maximum COD removal was achieved with Al electrodes while the maximum removal of oil and grease was achieved with Fe electrode.

Cost-effectiveness analyses for the use of electro-coagulation for reducing COD in meat processing wastewater considering operation and maintenance, electrode depreciation and sludge handling revealed that Fe electrode was more feasible than Al electrode (nearly 50% less cost) [35].

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 reduction 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. 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 [25].

A study by Masse and Masse [36] showed that the efficiency of a conventional DAF unit, used in many slaughterhouses for reduction of TCOD and SCOD, is approximately 22–35% and 0–16%, respectively. These authors 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.

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 10 shows the performance of different DAF systems when treating slaughterhouse wastewater [27].

Table 10. DAF system performances for slaughterhouse wastewater [27].

Treatment	COD Removal Efficiency (%)	TSS Removal Efficiency (%)	Reference
DAF and chemicals	32–92	70–97	[37]
DAF at pH 4–4.5	71	78	[38]
DAF and chemicals	38–71	37–63	[24]
DAF with air	40	60	[38]

3.2.4. By-Products

The by-products of the chemical treatment can be categorized into two groups: (1) 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; and (2) 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.

Many studies 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 sulphate. Ferric sulphate produces the least amount of sludge for a given amount of COD (mg O_2/L) removed compared to aluminium sulphate and polyaluminium chloride. The volume of the sludge produced is around 600 mL/L when ferric sulphate 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 considered, then ferric sulphate is a better coagulant than alum [29]. In the case of EC, the amount of sludge generated 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 [35].

3.3. Biological Treatment

3.3.1. Anaerobic Digestion Process

Anaerobic digestion, a chemical/biological process, takes place in the absence of oxygen, in which organic matter is broken down by microorganisms. This process results in the generation of carbon dioxide (CO_2) and methane (CH_4). It is a common treatment method at the Australian red meat processing industry used for over three decades. This treatment method is known by its high efficiency in removing COD, potential production of biogas and lower sludge produced in comparison to the aerobic digestion (by 5–20%) [2]. However, the effluent quality of the anaerobic digestion does not normally comply with the legislative requirements [2]. The energy consumption for anaerobic processes mainly related to fluid pumping. Bustillo-Lecompte et al. [2] proposed the following equation for estimating electrical energy consumption in anaerobic process:

$$E = Q \times \rho \times g \times h / 1000 \times \eta \times t \quad (4)$$

where E (J) is the electrical energy, Q is the flow rate (m^3/s), ρ is the density of the wastewater (kg/m^3), g is gravity (m/s^2), h is the head (m), η is the pump efficiency (%), and t is the residence time (s).

The anaerobic digestion can be found in various configurations such as anaerobic baffled reactor (ABR), anaerobic filter (AF), anaerobic lagoon (AL) up-flow an aerobic sludge blanket (UASB) and anaerobic sequencing batch reactor (SBR). More recently, covered anaerobic ponds (one of AL form) 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) [12]. The success of the anaerobic digestion process is highly dependent on the primary physico-chemical treatment step [18]. The advantage of AL is high removal of COD, BOD and TSS [24], however it is influenced by the weather conditions and requires highly durable covers [2].

Factors affecting the efficiency of the Anaerobic Digestion Process:

(1) High Organic Loading Rate and FOG

Wastewaters from abattoirs are rich in biodegradable organic matter and nutrients and usually contain elevated level of solids, fat and protein that have low biodegradability. The high organic loading rate to anaerobic digester may lead to form a solid crust on the surface of anaerobic pond, this will reduce the volume of the digester and the hydraulic retention time (HRT) [39]. This results in a reduction in the pond's efficiency. As reported in the literature, the crust is a mixture of fat, solids and floating sludge [40]. Additionally, fat tends to form floating aggregates and foams which may cause stratification problem due to adsorption of lipids into the biomass [41]. Slaughterhouses are known for their high lipid (FOG) content [42]. In addition, 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 [43]. Inhibition of anaerobic digestion of slaughterhouse wastewater is also attributed to the accumulation of elevated levels of ammonia. Ammonia results from the degradation of the high protein content of these wastes and to long chain fatty acids (LCFA) accumulation as consequence of lipids degradation [41]. 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 [44], it is poorly biodegradable due to its low bioavailability [40].

(2) Cleaning Chemicals Effect on Biological Process

Synthetic anionic surfactants such as Linear Alkylbenzene Sulphonates (LAS) are the most widely used surfactant in cleaning activities. A study by Gavala and Ahring [45] 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. In another study by Garcia et al. [46], 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. [47], they investigated anaerobic biodegradability and inhibitory effects on methane production of three different surfactants, two anionic: sodium lauryl sulphate (SLS) and sodium dodecylbenzene sulphonate (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: 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 sludge 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 [48].

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 wastewater 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 [49].

(3) Water Treatment Chemicals Effect on Biological Process

Chemical coagulants such as alum, ferrous sulphate 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 sulphate. This may contribute 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. Significant decrease in volatile solids destruction, COD removal, organic nitrogen catabolism, alkalinity production, methane production and total gas production was observed. 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 [50].

In a study by Novak and Park [50], 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 [51], the effects 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 [51].

In the study by Novak and Park [50], 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 °C to determine the volatile solids reduction. Both sludge E and F in Table 11 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 11. However, VS destruction in plant D is relatively low (26.6%). Plant D did not use primary treatment and 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 [50].

Table 11. Effect of iron content on the TS, VS, COD and N removals in an aerobic digestion process [50].

WWTP	TS Removal (%)	VS Removal (%)	COD Removal (%)	Organic N Removal (%)	Iron Content (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

(4) Solid Waste by-Products

Anaerobic digestion (AD) 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 [52]. 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 [52].

Many techniques 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 solid content of 18% to 30%. In addition, a combination of coagulation and filter pressing is very effective in dewatering sludge; reduction of moisture in this case is above 50%.

3.3.2. 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 consumption and 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, 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 [12]. The power requirements for aerobic process mainly come from the air blower. This power figure can be determined using the formula below [53]:

$$P = (q_{air} \times R \times T)/8.41 \times \eta \times [(P_{out}/P_{in})^{0.283} - 1] \quad (5)$$

where P (kW) is the power required for the air blower, q_{air} is the air flowrate (m^3/s), R is the gas constant (8.314 kJ/kmol.K), T is the temperature (K), η is the efficiency of the blower (%) and P_{in} and P_{out} are the in- and out-let pressures (atm), respectively.

The typical configurations of aerobic system include activated sludge (AS), rotating biological contactors (RBCs) and aerobic Sequencing batch reactors (SBRs) [2]. AS is applied for converting soluble and insoluble organic matter and bacteria to agglomerates that can settle in the clarifier that follows this process. AS is relatively cost-effective methods for treating meat processing wastewater as opposed to other biological treatments. RBC mechanism in treating wastewater is by bringing the wastewater in contact with biological media for metabolizing its organic content [24]. It was reported that RBC was less efficient that AS in treating meat processing wastewater [14]. Aerobic SBR consists effectively of 4 stages: filling, reaction, settling and decanting [2]. The first stage involves feeding the reactor with wastewater with mechanical mixing in absence of air. The air is introduced in the second stage where the reactions occur. In the third stage the aerated wastewater is given a time for TSS to settle and finally the supernatant is discharged in the fourth stage. Although some studies have demonstrated high nutrients and COD removal using aerobic SBR [54,55], judging from the mixing and fluid transport requirements one can infer that this process is an energy intensive one.

3.4. Combined Processes for Producing High Quality Effluent

A combination of treatment processes is inevitable for meat processing wastewater treatment to achieve a satisfactory quality of the final product especially this type of wastewater contains various contaminants (organic, inorganic, toxic and microbial contaminants). Combined process for treating wastewater have also been found as a cost-effective approach for such application [2]. The level of complication of the combined treatment systems depends on the purpose of the treatment (recycling or discharge back to the natural aquatic systems) and the energy balance of the system (consumption/production). In general, there are four possible combinations of processes for treating wastewater: (1) Physical–biological; (2) Physical–chemical; (3) Chemical–biological; and (4) Physical–chemical–biological [8]. In some cases, advanced oxidation processes (AOP) is used along with these combinations to increase the biodegradability of organic materials [2]. AOP are powerful oxidation techniques that rely on the generation of hydroxyl radicals ($^{\bullet}OH$) which is regarded as one of the strongest oxidants due to its high oxidation potential (2.8 V) [56].

The physical–biological combination is for removing suspended solids, oil and grease, organic and inorganic contaminants. The combination of processes does not necessary mean multi-unit operation, it could only be a single unit that combines the concepts of both treatments physical and biological. Membrane bio-reactor (MBR) is a good example for such combination. MBR has the advantages of handling high volumetric organic loading rates [57], good separation of bacteria and suspended solids which make the produced water quality attractive for recycling [58] and complete and stable nitrification [54]. There are many examples for the successful application of physical–biological combinations in meat processing wastewater treatment such as activated sludge-reverse osmosis (AS-RO) [59] which resulted in a very high removal of BOD, COD and nutrients (>99%); aerobic sequencing batch reactors-anaerobic filter (SBR-AF) [60] that also resulted in high COD removal (95%); and ultrasound-anaerobic digestion [61] that achieved high contaminants disintegration and a consequent increase in methane production.

Coupling physical treatments with the addition of chemicals for treating meat processing wastewater is effective for suspended solids, oil and grease, turbidity and inorganic contaminates. The classic example for this combination is coagulation/flocculation. There are many studies that investigated the use of coagulation/flocculation for treating meat processing wastewater as detailed earlier in Section 3.2.1. There are other physical–chemical combinations that have been applied for treating wastewater such the combination of ozone and activated carbon adsorption [62].

Chemicals addition, incorporated to biological treatment, is a successful treatment combination for inactivating unwanted microbes, removing nutrients and destructing refractory toxic organic materials. Different studies have jointly used various techniques for treating wastewater that fall within the definition of this combination category such as moving bed biofilm reactor with ozone [63] and SBR with Fenton reaction [64].

The most complicated combined system is physical–chemical–biological and it is normally implemented when the wastewater contains a wide range of contaminants with various degrees of structural complication. The most common example for this combination is the use of aerobic or anaerobic digestion with ultraviolet (UV) and H_2O_2 [65–67]. Another example for this combination is the use of vertical flow constructed wetland with trickling filter and ferric chloride (for dephosphatation) [68].

3.5. Energy-Generating Treatment Systems

The general perception around meat processing wastewater treatment is an energy intensive process; however, the positive side of this process is that it can be harnessed for generating energy. Several systems have been developed for converting wastewater into energy sources or using wastewater characteristics for driving treatments of other water types. Li et al. [69] proposed integrating reverse electrodialysis (RED) to reverse osmosis (RO) system to harvest energy, facilitate salty water treatment and recover water from brine solution. The system proposed by Li et al. [69] can generate energy through the transferring ions from concentrated solution (RO concentrate) to less concentrated solution (biologically treated secondary effluent). If the system is used with RO feed water, it can also be used to reduce the salinity of the feed resulting in less pressure requirements for forcing the feed through RO membrane. If it is used with RO concentrate, it can dilute the concentrate making it more feasible for recycle and water recovery.

Microbial fuel cells (MFC) is another way of converting the organic materials in wastewater in to energy. In MFC, the electrical power is produced due to microbial oxidation of organic and inorganic constituents of wastewater [70]. The MFC concept is not new; however, there are various configurations of MFC that have recently been tested by different researchers. Kong et al. [70] investigated the use of anaerobic fluidized bed microbial fuel cell (AFBMFC) for treating wastewater and generating electrical power. They found that using graphite granules as supporting granules electrode and effective transporter for biofilm was more effective than active carbon granules (power density of 530 mW/m^2 vs. 410 mW/m^2). Another study conducted by Liu et al. [71] suggested combining MFC with SBR for simultaneous energy generation and wastewater treatment. They have achieved a maximum power generated from MFC of 3.34 W/m^3 and current density of 14 A/m^3 in one typical cycle of filling, reaction, settling and decanting. MFC design has also been modified by integrating the emerging forward osmosis technology into it (OsMFC; osmotic microbial fuel cell) for desalinating seawater, treating wastewater and generating electrical power [72]. Two possible configurations for OsMFC system are: (a) OsMFC and RO where the bioelectricity is generated in OsMFC and diluted draw solution (the concentrate) is feed to RO so the treatment can be performed at less pressure requirements; and (b) OsMFC and microbial desalination cell (MDC) where the bioelectricity is generated in both OsMFC and MDC (more power generated than the first configuration) and again the saline solution gets diluted. Not all of the aforementioned ideas where tested with meat processing wastewater which is believed to have more energy generating constituents (high organic and microbial loads). Hence, these innovative concepts of recovering energy from wastewater should be driven from laboratory investigations to industrial applications especially for meat processing wastewater.

4. Industrial Practice and Examples

The temperature of the wastewater from Australian red meat processing industry is what makes anaerobic digestion process a suitable option. At many Australian abattoirs, the high organic loading rate (OLR) and high content of fat are responsible of crust problem and low efficiency of the main treatment unit (anaerobic pond). 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. Increasing the number of physical treatment processes may significantly reduce the wastewater temperature. This may negatively impact the biological treatment process; for this reason, chemical treatment may be suitable option to reduce physical treatment steps.

Table 12. List of many abattoirs in Australia and their usage of chemicals [73] (data collected by the author).

Abattoir	Cleaning Chemicals	WWT 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	n/a	No treatment, just evaporation pond
E	yes	n/a	No treatment, just evaporation pond
F	yes	n/a	No treatment, just evaporation pond
G	yes	n/a	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 sulphate 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 acid 98% 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 sulphate and anionic polymer	Shaker screening, balance tank, chemical DAF, equalizer tank, DAF aeration and then to sewage

Table 12 lists several Australian abattoirs, and brief descriptions of the chemicals in use and the wastewater treatment plants. Many of these abattoirs do not treat their wastewater. In many cases, the wastewater is treated by evaporation in evaporation ponds. There are some other abattoirs that use physical treatment only. Only a small portion of these abattoirs is using chemicals and only one abattoir is recycling 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 are using the last product (treated wastewater) for irrigation of crops for cattle consumption inside the facility. The information in Table 12 has been collected by visiting and carrying out phone conferences with these abattoirs.

5. Wastewater Treatment and Energy

Due to the interdependency in production process (waste water-energy nexus); i.e., wastewater treatment needs energy and energy generation could be increased by increasing amount of wastewater, an efficient technology and management is crucial for shifting cost components of the operation to a profit. Energy use efficiency is related to reduction of GHG emissions for curbing global climate change and therefore, a simultaneous reduction of energy consumption and increase in energy harvesting from wastewater is a crucial element for sustainability [74], it saves money and reduces environmental impacts by improving energy and water efficiency.

The energy usage associated with red meat wastewater is typically linked with aeration and sludge management as a result of treatment. Anaerobic digestion of sludge is a key process for harvesting energy from wastewater [75,76]. Wastewater treatment plants (WWTPs) can achieve energy self-sufficiency by anaerobic digestion of sludge which generates biogas [77] and later converted into electricity [78]. Anaerobic processes appear to be economically more attractive than aerobic processes [77]. However, it should be noted that this technology might be effective and economic, but is positively associated and sensitive to hydraulic retention time and plant area as well as energy and amount of sludge [79].

Some case studies demonstrated that covered anaerobic lagoons generate energy and produce minimal sludge; for example, the Sheboygan Regional wastewater treatment plant in USA produces biogas by an anaerobic digestion process; converts the biogas into heat and 2300 MW of electricity, with no carbon emissions from its electricity input because of the energy harvesting processes; and is nearly 100% self-sufficient. The digested biosolids are then dried and can be land applied as fertilizer [80,81]. The Steinhof WWTP (61,643 m^3/d) could also provide a good example of the state of wastewater treatment in Germany [81]. Steinhof WWTP has an average electricity intensity of 0.373–0.413 kg CO_2-e/m^3, and it can offset 0.558–0.618 kg CO_2-e/m^3 (150%) via the Combined-Heat-Power (CHP) plant, which means all of the carbon can be neutralized and the plan can produce more electricity than it requires [81]. The Strass WWTP in Austria can produce an energy surplus of 8% [82].

An Australian study [83] showed that many WWTPs in Australia do not perform as well as their German and US counterparts in terms of energy efficiency and there is room for improvement in terms of energy efficiency [83]. An Australian study [84] reveals an innovative high-rate sequencing batch reactor (SBR) based wastewater treatment process with short sludge retention time (SRT) and hydraulic retention time (HRT) is characterised with increased methane production with no excess energy demand and substantial carbon removal.

A conventional municipal WWTP commonly consists of primary, secondary, and advanced treatment stages. Compared with other stages, the wastewater collection and primary treatment stage in WWTPs are less energy intensive, influenced by design and operation including transportation distance. The energy intensity of raw wastewater collection and pumping during primary treatment is in the range of 0.02–0.1 kWh/m^3 in Canada, 0.045–0.14 kWh/m^3 in Hungary, 0.04–0.19 kWh/m^3 in New Zealand, and 0.1–0.37 kWh/m^3 in Australia [85]. The energy consumption of secondary wastewater treatment stages depends on technology choice: the average energy input of conventional activated sludge (CAS) treatment systems is 0.46 in Australia, 0.269 in China, 0.33–0.60 in USA, and

0.30–1.89 kWh/m^3 in Japan [86]. Kenway et al. [87] forecast energy use for wastewater treatment and pumping in Australia for 2030 and discussed in the following Table 13.

Table 13. Forecasting energy use in 2030 [87].

Purpose	Lower Energy Intensity	Upper Energy Intensity	Energy Intensity Used for Projections
-	GJ/ML	GJ/ML	GJ/ML
Water Treatment and Pumping	-	-	-
Conventional water treatment plant	0.36	1.8	1.08
Conventional water pumping	0.25	6.26	1.96
Reverse osmosis on treated wastewater for reuse	3.6	5.4	4.5
Reverse osmosis on sea water	12.6	14.4	13.5
Pumping energy for reuse	3.6	7.2	5.4
Pumping energy for desalination	3.6	7.2	5.4
Waste water Treatment and Pumping	-	-	-
Primary wastewater treatment plant	0.5	1.0	0.8
Secondary wastewater treatment plant	1.0	2.0	1.65
Tertiary wastewater treatment plant	2.0	5.0	3.25
Conventional wastewater pumping	0.25	1.55	0.74

Given the fact that energy projections are very sensitive to the technologies used, future energy use to 2030 assumed that existing sources yielded water at similar energy requirements to those measured for 2006–2007. Upper and lower estimates for energy intensities for technologies such as desalination and wastewater reuse are provided. Compare to the CAS system, oxidation ditch (OD) treatment systems have higher energy demands of 0.5–1.0 in Australia, 0.302 in China, or 0.43–2.07 kWh/m^3 in Japan because of longer hydraulic retention time (HRT) and higher energy consumption for higher specific-oxygen demand [84,88,89].

Recently microbial fuel cells (MFCs) have attracted attention as a novel technology for converting the chemical energy in organic compounds into electricity and biohydrogen [90], it is possible to produces energy and treats the wastewater simultaneously using MFC device. However, one of the big obstacles of commercialization of MFC is high capital cost [91] and the proper membrane has not been found yet [92]. Therefore, MFC still needs significant advances before it becomes competitive with other technologies such as anaerobic biological conversion [93].

Table 14 shows energy consumption by different units is a small-scale WWTP. The total energy consumption is found to be about 1.03 kWh/m^3 of wastewater treatment [94]. However, this may be significantly less than the figures for large-scale WWTP, it may be suitable for wastewater treatment at a typical abattoir. Figure 3 show the flow process diagram of the WWTP that presented in Singh et al. [94] which included units such as chemical treatment, settling tanks, and disinfection. These are the main units required for a wastewater treatment with chemical coagulants. Based on this information and water consumption of 3500 m^3/day (260 days/year), energy consumption from a small WWTP installed at a meat facility can be around 937,300 kWh per year which cost around $468,650 per year (average cost of electricity in Queensland/Australia is $0.5/kWh). The water from this WWTP can be recycled to the facility and used to reduce the use of the supplied fresh water. This is a reasonable expenditure considering the average cost of fresh water supplied to abattoirs in Australia is around $0.75/m^3.

Table 14. Energy consumption from a small wastewater treatment plant WWTP [94].

Unit	Electrical Energy (kWh/m^3)	Manual Energy (kWh/m^3)	Chemical Energy (kWh/m^3)	Total Energy (kWh/m^3)
Sump	0.2	0.003	-	0.203
Primary settling tank (PST)	0.09	0.019	0.096	0.205
Dosing Tank	0.04	0.046	-	0.086
Rotatory biological contractor (RBC)	0.09	0.002	-	0.092
Secondary settling tank (SST)	0.17	0.008	-	0.178
Disinfection tank	0.03	0.006	-	0.036
Sand filter	-	0.01	-	0.01
Carbon filter	-	0.01	-	0.01
Treated water tank	0.18	-	0.003	0.183
Sludge storage tank	-	0.027	-	0.027
Total	0.8	0.131	0.099	1.03

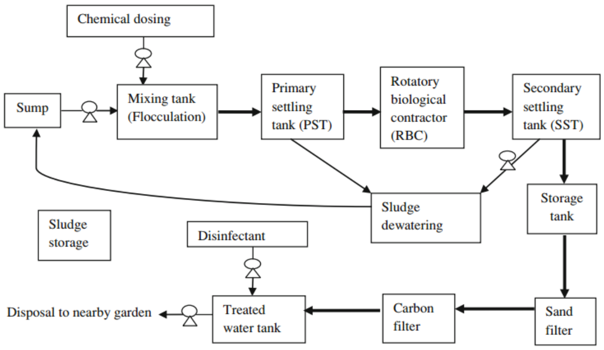


Figure 3. Process flow diagram of a small WWTP [94].

6. Innovative Coagulants

In recent years, there has been considerable interest in the development of natural coagulants, see Table 15. 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 [5]. These coagulants have not been tested for treating abattoir wastewater in Australia.

Table 15. 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		

In a study by Chuentongaram [95], 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 [95].

Morales et al. [96] 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 dose achieve up to 78% of turbidity reduction. In A study by Lagasi et al. [97], *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 218.4 NTU to 42 NTU (reduction 80.8%) was observed when de-oiled *Moringa* was used. The ordinary *Moringa* reduced turbidity from 218.4 NTU to 68 NTU (reduction 68.9%).

It is obvious from the above that these natural coagulants such as chitosan and *Moringa oleifera* extracts are good alternatives for the chemical coagulants.

Another natural coagulant is tannin, which is a naturally sourced compound that is environmentally safe. Khwaja and Vasconcellos [98] reported a method for recovering tallow from meat processing wastewater. 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 3.2 L/s Entrapped Air Flotation (EAF) unit. The results are shown in Table 16, the reduction in each of BOD_5, TSS and FOG are around 73% and greater.

Table 16. Field trial results for tannin-based coagulant tested on beef wastewater [98].

Parameters	Influent (mg/L)	Reduction (%)
BOD_5	3425	73
TSS	1230	76
FOG	1090	74
TKN	220	45
TP	64	27

7. 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. In addition, 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. 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, 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 (separated by gravity) can achieve around 90% removal for the coarse particles.

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.

In case of abattoir B (Table 12), Table 17 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. In addition, the weight of sludge produced in case of this combination is around 123t. Compared to alum, which is around 546 t, the sludge produced by this combination is less by 77%.

Table 17. 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)	Consumed t/Year	Cost (AUD/Year)	Sludge (t/Year *)
Ferric chloride	160	0.16	250	0.04	116	29,120	116
Chitosan	10	0.01	1500	0.015	7.3	10,920	7.3
Total	-	-	-	0.055	123.3	40,040	123.3

* Based on the amount of coagulants only.

Figure 4, scenario I, chemical DAF is recommended to eliminate problems associated with crust formation at the biological treatment stage. After biological treatment, the wastewater will be refined 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% . 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 control 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/m^3·day (low rate anaerobic digesters such as ponds).

Figure 4, scenario II, chemical treatment can be installed at a last stage of the treatment system. 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. The biological process can be removed from the treatment system.

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. 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 activities and biological hazards. When chemicals 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, and biodegradable chemicals are highly recommended.

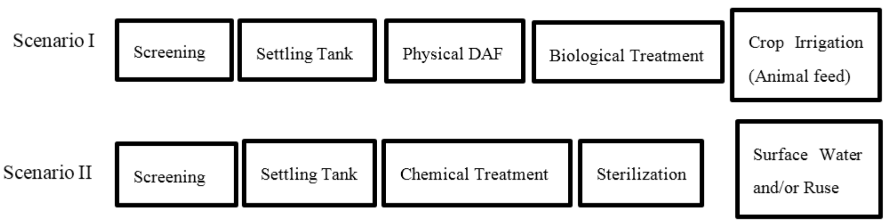


Figure 4. Scenarios for wastewater treatment from slaughterhouses.

8. Economical Analysis

The type of the coagulant is responsible for the size of the sludge produced and, consequently, the cost of the treatment operation rises. In general, the amount and the characteristics of the sludge produced during the coagulation/flocculation process depend on the type and dosage of the coagulant used and the operating conditions. A study by Amuda and Alada [28] 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 [28]. Aguilar et al. [29] showed that the use of coagulant aids reduction in the volume of the produced sludge up to 41.6%. The volume of produced sludge dropped from 410 mg/L to 190 mg/L when anionic polymer was used with alum.

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). In addition, 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.

To summarize the findings of this section, Table 18 presents most of the coagulants that have potential to be used in treating wastewater from the red meat processing industry. It is obvious that ferric chloride in combination with chitosan has the lowest cost per meter cubic treated (see Figure 5). 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 sulphate and anionic polymer. Although the removal efficiency of this combination is slightly lower than alum (see Figure 6), these chemicals have a positive impact on the biological process.

Table 18. Coagulants that have potential to be used in treating wastewater from the red meat processing industry.

Chemicals	Dose kg/m^3	Cost AUD/m^3	Sludge, kg/m^3	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 sulphate	0.75	0.19	0.75	65	Positive impact on the AD
Ferric sulphate + Anionic polymer (AP)	0.375 0.012	0.34 * 0.069 *	0.375 0.012	46–87	Polymer has toxic impact on AD, low sludge volume
Ferric chloride + Chitosan	0.16 0.01	0.04 0.015	0.16 0.01	53.7	Positive impact on the AD, low sludge volume

* based on 1 AUD = 1 USD.

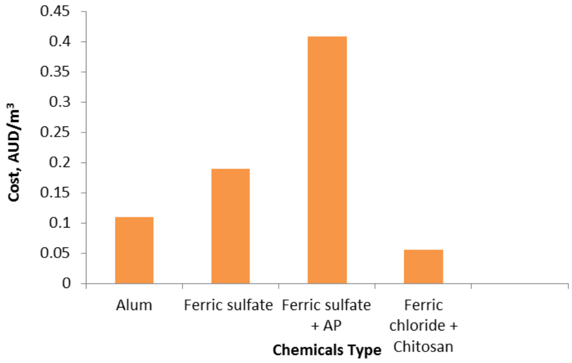


Figure 5. Chemical coagulant prices on the international market.

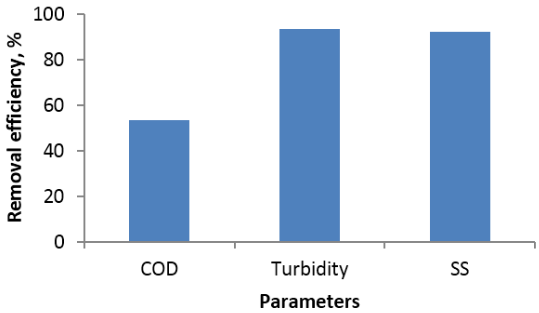


Figure 6. Removal efficiency of the combination of ferric chloride and chitosan.

9. Conclusions

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 controlled 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% and 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.

To conclude, chemical treatment is essential for reuse and/or recycles the treated wastewater in the facility. Wastewater treatment chemicals 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 can reduce the amount of chemicals required and the sludge produced and, consequently, reduce energy consumption. The annual operation cost related to energy of a small WWTP using chemical coagulants is around $500,000.

Acknowledgments: This article is part of a report published and funded by Australian Meat Processor Corporation (AMPC). The report was published on May 2015 on the AMPC website. AMPC has accepted for the authors to re-publish in international journal to enhance public access to the information. The original information in the report has been revised to address energy related to wastewater treatment.

Author Contributions: Ihsan Hamawand wrote the original report (literature review) for AMPC and extracted this article from the report. Ihsan Hamawand, Anas Ghadouni and Jochen Bundschuh, added new sections related to energy, revised the article, addressed the reviewers & the editor comments and edited the English language. Sara Hamawand, Raed A.Al-Jebori, Sayan Chakrabarty and Talal Yusaf contributed in adding to and revising some of the existent sections to address energy subject in wastewater treatment, also helped with reviewing and revising the language and the technical information in the article.

Conflicts of Interest: The authors declare no conflict of interest.

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