Literature Review – Evaluation of Electrocoagulation as a wastewater treatment technology for meat processors

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Note that this report for Milestone 3 is the Milestone 1 report re-issued with additional information on operating costs for an existing full scale electrocoagulation treatment system as well as a 2018 quote on capital costs for a new electrocoagulation treatment system.

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1 EXECUTIVE SUMMARY

Electrocoagulation (EC) is a proven method for the treatment of red meat processing wastewater with numerous examples of its use around the world. It is capable of high wastewater contaminant removal efficiencies with very little sludge production. It is compact, quick and simple to operate. However, it is not a common treatment method used by red meat processors in Australia.

This report is a review of publicly available literature on the use of EC technology and its capability for treating meat processing wastewater. It considers the contaminants typically found in red meat processing wastewater and describes the processes by which these are removed by commonly used methods compared with using electrocoagulation. It concludes that electrocoagulation is a possible alternative to the treatment methods traditionally used for red meat processors e.g. sedimentation, floatation and/or chemical coagulation followed by biological treatment such as anaerobic and aerobic ponds.

Lab and full-scale trials have shown it is capable of removing contaminants from meat processing wastewater including up to and greater than 90% for BOD/COD, oil and grease and phosphorus. It is also capable of removing organic nitrogen (up to 50%) but less effective in removing ammonium nitrogen (15%). The process is quick with residence times of minutes compared to days for commonly used treatment methods.

A number of Australian trials on treatment of meat processing wastewater by electrocoagulation have provided good results with wastewater quality meeting the majority of the local water authority trade waste discharge limits. However, the addition of salt to aid the EC process produces a salty wastewater stream, which exceeds the discharge limits. In this case, additional treatment is required to remove the salt (membrane filtration).

EC produces relatively less sludge when compared with chemical coagulation and it is non-toxic. Analysis of sludge produced during an Australian trial found that it met local biosolids and fertiliser guidelines for most components. However, again, it contained high salt as well as high iron levels, which may have an impact of the use of this sludge for land application. A solution may be to mix the sludge with other fertilising products before it is applied to the land to dilute the levels of these components.

There is some research on the cost effectiveness of operating electrocoagulaton for meat processors. However, much of this is lab or pilot scale and inconclusive when compared with the cost of chemical coagulation (CC). There is additional research on the cost effectiveness of electrocoagulation compared with chemical coagulation for other non-meat processing waste streams with results showing CC is consistently at least 2-3 times higher to operate with some studies exceeding 10 times higher. The cost of electrical energy, anodes, chemicals and sludge disposal are all very important factors contributing to operational costs of wastewater treatment, with EC having high energy and relatively low chemical and sludge disposal costs. The literature review has highlighted that existing research on economics of EC is limited to comparing it with CC when there is potential for EC to be an alternative to broader secondary treatment methods including floatation and treatment ponds.

This literature review demonstrates that electrocoagulation is a possible and proven alternative to traditionally used treatment methods for meat processing wastewater in Australia. However, further research is required on the actual operating costs of EC for meat processing wastewater and its comparison with traditional treatment methods.

2 INTRODUCTION

Increasingly stringent environmental regulation for wastewater discharge and a desire to reuse greater volumes of water due to water security issues drives interest in complementary technology options for the treatment of red meat processing wastewater. Ideally, for space constrained processors, these technologies need to be capable of high removal efficiencies whilst being compact in size, easy to operate and energy efficient (Nguyen, et al., 2017).

As Table 1 indicates Australia has some of most stringent wastewater limits for slaughterhouse wastewater discharge in the world.

Table 1: Comparison of standard limits for slaughterhouse wastewater discharge
(Bustillo-Lecompte & Mehrvar, 2017).

Parameter	World Bank Standard	EU Standards	US Standards	Canadian Standards	Australian Standards
BOD (mg/L)	30	25	16-26	5-30	5-20
COD (mg/L)	125	125	n/a	n/a	40
TSS (mg/L)	50	35-60	20-30	5-30	5-20
TN (mg/L)	10	10-15	4-8	1.25	10-20

Water costs are also a consideration with Australian water authorities progressively passing on full cost recovery for water supply and treatment (Hamawand, et al., 2017). The cost of fresh water to Australian red meat processors in urban areas ranges from AUD$2.00 to $4.30 making treatment options that allow for water reuse attractive (The Ecoefficiency Group, 2017).

Primary physical treatment includes screening to remove the bulk of the coarse solids followed by some form of sedimentation, floatation and/or chemical coagulation to remove most of the fat and suspended solids. In many cases, the water is this then irrigated to pasture, however for those processors discharging to sewer or water bodies, further biological treatment processes are required to remove soluble solids and nutrients. In some cases, additional tertiary treatment may also be applied to remove pathogens by disinfection e.g. using chlorination and UV radiation. There are circumstances where biological treatment is not a favourable option. This is particularly so for small and medium processors who often have insufficient loads or volumes to warrant the use of large treatment ponds. Cost constraints, and a lack of space are also contributing factors.

This literature review examines the capability of EC to treat meat wastewater within an Australian context and compares the costs, benefits and challenges compared with traditional treatment technologies.

3 CHARACTERISTICS OF RED MEAT WASTEWATER

Red meat processors produce large volumes of wastewater ranging between about 5 and 10 kL/t HSCW (The Ecoefficiency Group, 2017). It can be dark in colour and offensive in odour and typically includes (Nwabanne & Obi, 2017) (Johns Enironmental and The Ecoefficiency Group, 2017):

- **Organics** - blood, soft tissue, urine and faeces
- **Nitrogen and phosphorus** – resulting from blood, urine and faeces. The disposal route for the wastewater will determine the level of treatment required to remove these nutrients. For example, if irrigating pasture or using wetlands as treatment it may be necessary to only partially remove the nutrients; while complete removal is typically required for discharge to water bodies.
- **Salt** (typically NaCl) - salt enters wastewater streams via urine, some water supplies (e.g. bore water) and cleaning chemicals. The removal of salt is particularly important where

wastewater is irrigated as the concentration of salt can be detrimental to soils and nearby water bodies.

- **Micro-organisms** - the presence of pathogenic (disease forming) and non-pathogenic microorganisms from animal manure and paunch
- **Chemicals -** chemicals such as surfactants and chlorine from cleaning and disinfection agents which impact on the pH of wastewater.

Wastewater contaminants are measured as follows:

- **Biological Oxygen Demand (BOD)** which is an estimate of the oxygen consuming requirements of decomposing organic matter.
- **Chemical Oxygen Demand (COD)** which is an estimate of oxygen consuming requirements of total organic and inorganic matter.
- **Total Suspended Solids (TSS)** which can transport other pollutants such as pathogens, nutrients and metals. These are larger than 2 microns.
- **Total Dissolved Solids (TDS)** including dissolved organics, inorganic salts and cleaning chemicals. These are smaller than 2 microns.
- **Oil and grease** that may be solid and emulsified
- **Nitrogen** measured as Total Kjeldahl Nitrogen (TKN) which is the sum of organic nitrogen (bound to organic substances), nitrogen found in ammonia (NH_3-N) and also ammonium (NH_4-N).
- **Phosphorus** – in the form of total phosphorus or phosphate
- **Pathogens** – faecal coliforms

Typical wastewater quality from a meat processing plant is shown in Table 2.

Table 2: Typical wastewater from a meat processing plant
(GHD Pty Ltd, 2015)

Parameter	General Value	Range
BOD (mg/L)	2,500	450 – 5,000
COD (mg/L)	5,000	1,300 – 13,000
TSS (mg/L)	4,000	500 – 8,000
Total Oil / Grease(mg/L)	1,250	100 – 2,500
TKN (mg/L)	250	100 – 600
Total Phosphorus (mg/L)	60	10 – 100
pH	7.3	6.0 – 9.0

4 COMPARISON OF WASTEWATER TREATMENT USING TRADITIONAL AND EC METHODS

Wastewater from red meat processing plants contains contaminants that need to be removed to varying degrees depending on the receiving environment, environmentally regulated discharge limits or the end use. Poor treatment and discharge can lead to the depletion of dissolved oxygen in water bodies, odour, sludge build-up, floating scum and the transmission of pathogens (Nwabanne & Obi, 2017). Treated wastewater is often irrigated however it may also be released to sewer or water bodies or reused on site.

This section reviews how contaminants are traditionally removed from meat processing wastewater streams and describes the process of how EC (as a single unit or when combined with other technologies) is also capable of removing these contaminants.

4.1 Removal of coarse materials

4.1.1 Traditional removal of coarse solids

Australian meat processing plants typically use screening and sedimentation as preliminary treatments to remove coarse solids and debris.

4.1.1.1 Screening

Screens are widely utilized by meat processors as they are inexpensive, require minimal maintenance and are not complicated to operate. They remove coarse solids and debris by interception. Technologies include screens over drains, catch basins, inclined static screens, rotary drum screens, vibrating screens and screw screen compactors. Screens are susceptible to binding with excessive grease, oils, blood coagulation and hair.

Screening removal efficiencies:

BOD - 5-20%
TSS - 5-30%
(Hamawand, et al., 2017).

4.1.1.2 Settling

Some processors allow solids to settle prior to treatment by reducing the flow rate in tanks. Sedimentation requires time and may cause odour issues. Collected solids also need to be intermittently disposed.

Settling effectiveness depends on the size of the suspended solids and can be as low as 10% but as high as 90% for the coarse particles (Bazrafshan, et al., 2012).

4.1.2 EC removal of coarse solids

A screening or settling process is an important step prior to any type of coagulation (chemical or electrocoagulation). Bazrafshan et al. undertook laboratory trials on slaughterhouse wastewater from a processing plant combining chemical coagulation and electrocoagulation. The study found that preliminary settling time was an important operational parameter for effective treatment (removal efficiencies were 14% BOD_5, 29% COD, 64% TSS and 33% TKN) (Bazrafshan, et al., 2012).

4.2 Removal of organics

4.2.1 Traditional removal of organics

Primary treatment aims to remove BOD, fine suspended solids and oils and grease using sedimentation, floatation and chemical coagulation. These treatment options typically produce large volumes of sludge. They are effective in removing SS, O&G and P through chemical precipitation. They are only partially effective in removing BOD, and N removal only includes what is captured in suspended protein (Warnecke, et al., 2008).

4.2.1.1 Sedimentation and floatation

In **primary clarifiers and save-alls** suspended solids sink to the bottom of a tank and are mechanically scraped out while fats and scum float to the top where they are skimmed off. **Dissolved Aeration Floatation (DAF**) units use injected air bubbles to help capture fat, grease and small particles that form

Save-alls

BOD/COD 20-25%
SS - 50-60%
O&G - 50-80%
(GHD Pty Limited , 2003)

a floating scum which is removed by scraping. Such systems can tolerate shock loads but produce greasy and oily sludges that may require dewatering.

DAFs

BOD/COD 30-40 %
SS - 50-65%
O&G - 60-80%
(GHD Pty Limited , 2003)

4.2.1.2 Centrifugal force

In hydrocyclones, less dense oil and grease phases exit at the top of the unit while heavier water flows from the bottom. These can be effective for non-rendering streams (Johns Enironmental and The Ecoefficiency Group, 2017).

Hydrocyclones

BOD/COD 10-30%
SS - 15-60%
O&G - 40-90%
(GHD Pty Limited , 2003)

4.2.1.3 Chemical coagulation and flocculation

Chemical coagulation and flocculation is commonly used by the meat processing industry to remove colloids and nutrients. Fine organic and inorganic colloidal particles in wastewater are suspended because they are firstly small and they have a very large surface area to mass ratio. This means the impact of gravitational forces is minimal and sedimentation is very slow (Ghernaout, et al., 2011). Secondly, like water molecules, colloids are held in the wastewater by electrical charges. Their outer layer is negatively charged so the particles repel each other and thus remain in a stable state in suspension. Stable colloids are difficult to remove from wastewater unless they are aggregated sufficiently to drop out of suspension. Chemical coagulation and flocculation reduce the net surface charge of the particles to a point where they attract each other and van der Waals forces can hold them together and allow aggregation.

Chemical coagulation (PACl)

COD - 75%
TP - 99.9%
TN - 88.8%
(Aguilar, et al., 2002).

Chemically dosed DAFs

BOD/COD 30-90%
SS - 50-90%
O&G - 60-80%
(GHD Pty Limited , 2003)

Chemical primary treatments used by meat processors include **chemically dosed DAFs and coagulation-flocculation units**. Coagulants with positively charged ions are used to destabilize colloidal particles so they form flocs. This is generally undertaken by dosing with metal based salts such as aluminium sulphate (alum) and iron coagulant such as ferric chloride and ferric sulphate. Flocculants using organic or inorganic polymers are then utilized to create even larger flocs.

Chemical treatment can be difficult as reactions are susceptible to changes in wastewater composition, pH, temperature, levels of mixing and so forth. Importantly, coagulation can also add to the wastewater's total dissolved solids content and chemicals can affect the efficiency of downstream biological treatments due to their toxicity (Hamawand, et al., 2017).

Following coagulation, secondary treatments remove dissolved and colloidal compounds, and this is typically done using biological treatment processes, explained in the following section. They are very effective in removing BOD and TDS but are a generator of SS. They can remove some P through cell biomass and some N if designed to do so (See 4.3 – Nutrient Removal). O&G hinders biological processes and so it is important that there is effective primary treatment.

Table 3: Removal efficiencies using different coagulants
(Hamawand, et al., 2017)

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			

4.2.1.4 Irrigation

Primary treatment may be sufficient for meat processors irrigating to pasture where the partial removal of nutrients is all that is required (Warnecke, et al., 2008).

> **Nitrogen removal through irrigation and the passage of wastewater through the soil**
> Organic N - 60-65%
> Total N 65-85%
> (Boeriu, et al., 2013).

4.2.1.5 Biological

Anaerobic lagoons are a well-established treatment option that degrade organic compounds using anaerobic bacteria in the absence of oxygen. Such systems have low sludge production and minimal energy requirements. They are relatively inexpensive, require minimal maintenance and offer the potential to collect biogas. They do however have higher space requirements, higher residence times of 20 to 40 days (MLA and AMPC, 2010), can release odours and are subject to upsets with a slow recovery rate. Anaerobic treatment systems are more effective if fats and suspended solids are removed by pre-treatment and also often require additional treatment stages to remove remaining nutrients and pathogens. They are either covered by a self-forming scum that helps to maintain anaerobic conditions or a synthetic floating cover.

> **Anaerobic Lagoons**
> COD 60-97%
> TSS – 60-90%
> O&G – 70-90%
> (Pagan, et al., 2002)

Aerated ponds degrade organic compounds using aerobic bacteria in the presence of oxygen. They are often employed after anaerobic treatment. Biological breakdown is faster as oxygen/air is added. They produce less odour and have a greater ability to adjust to changes in temperature and load. They do however require high levels of energy consumption to operate aerators and produce high levels of sludge.

> **Aerated ponds**
> BOD/COD 50-80%
> Nitrogen 0-10%
> (Pagan, et al., 2002)

Facultative ponds also degrade organic compounds using aerobic bacteria however they rely on the oxygen being transferred by algae or wind. They are cheaper to operate than aerated ponds however they cannot handle high strength wastewater and generate high levels of sludge.

> **Facultative ponds**
> BOD/COD 60-90%
> N 10-20%
> (Pagan, et al., 2002)

Activated sludge systems recycle sludge to maintain high bacterial levels in what is effectively an intensified aerobic pond. They are capable of high removal efficiencies but are expensive to build and operate, and vulnerable to upset (Warnecke, et al., 2008). See Section 4.3 on nutrient removal.

> **Activated sludge**
> BOD/COD – 85-97%
> SS – 95-98%
> N – 0-50%
> (Pagan, et al., 2002)

Trickle filters are made up of a vessel containing inert media which support microbiological growth that degrade organics.

> **Trickle filter with clarification**
> BOD - 80 – 90 % (low rate filters)
> BOD - 65 – 85 % (high rate)
> (GHD Pty Ltd, 2015)

Reed beds comprise of gravel/sand basins that are planted with wetland plants/reeds. The main transformation processes are ammonification, nitrification and denitrification where organic nitrogen is converted to nitrogen gas (N_2). Phosphorus typically enters wetlands and reedbeds attached to suspended particles or in a dissolved form (PO_4). The particles settle and dissolved phosphorus accumulates quickly in sediments by sorption and precipitation. The soils however can only hold limited amount of phosphorus and new soils need to be introduced (Kostel, date unknown).

Constructed horizontal and vertical subsurface wetlands use adsorption, biodegradation, filtration, photooxidation and sedimentation. They offer the advantage of low energy consumption and sludge production. There have been limited studies on the application of constructed wetlands to treat meat processing wastewater. Gutierrez-Sarabia et al. demonstrated that when following a high rate anaerobic pond, a subsurface-flow wetland in Mexico could achieve high efficiencies for small abattoirs (65L/day) (Gutiérrez-Sarabia, et al., 2004). Rivera used a two-stage horizontal subsurface wetland system to treat abattoir wastewater also in Mexico with mean removal efficiencies for 87.4% COD, 89% SS and 73.6% organic N of 89%. Both studies found poor removal rates for inorganic nitrogen (Rivera, et al., 1997). This technology may only be suitable for very small operators with no space constraints. Rivera suggesting a trench length of 960 – 1125 m would be required to treat 30kL a day (Rivera, et al., 1997).

Wetland after anaerobic pond
BOD_5 - 91%
(30% by the wetland)
COD - 89%
TSS - 85%
Organic N - 80%.
(Gutiérrez-Sarabia, et al., 2004).

Membrane processes including microfiltration, ultrafiltration, nanofiltration (NF), and reverse osmosis. A recent laboratory study by Jensen et al. for two Australian abattoirs suggests that using high rate anaerobic digestion with a membrane biomass retention system (AnMBR) could achieve efficiencies of 95% COD removal. Nutrient capture is also possible with 78–90% of nitrogen and 74% of phosphorus in the wastewater released to the treated permeate as ammonia and phosphate. The results were consistent with AnMBRs treating municipal and industrial wastewaters and showed membrane fouling was not a substantial barrier to the application of AnMBRs to slaughterhouse wastes. High-strength wastewater can however cause membrane fouling issues that restrict the permeation rate (Zhou, et al., 2015). The study found an inability to manage fouling at very high solids concentrations (>20 g/L) (Jensen, et al., 2015). The costs associated with membranes currently limits widespread application (Dvořák, et al., 2016).

AnMBR
COD - 95%
N - 78–90%
P - 74%
(Jensen, et al., 2015)

4.2.2 EC removal of organics

Following primary treatment, wastewater is pumped to a balance tank and dosed with brine before entering the EC unit. The unit consists of electrolytic cells, each with a pair of corrosive metal sheets (an anode electrode and a cathode electrode). The electrodes, often made of aluminium or iron, can be organized in different arrangements, spacing and lengths with varying effects on removal efficiencies. The anodes continuously produce ions and thus eventually need to be replaced and are often called the sacrificial anode.

The plates are connected externally to a power source and immersed in the wastewater. The power source supplies the electron current that drives chemical reactions at the electrodes. The voltage needed for reactions to occur is called the potential. EC units also include a resistance box to regulate the current density (mA/m^2) and a multimeter to read the current values (Ampere).

The electrical DC current causes a number of reactions which promote dissolution, coagulation, floatation and flocculation. Figure 1 outlines the electrocoagulation process. The difference between chemical coagulation and electrocoagulation is the source of coagulant. In electrocoagulation, the source of the coagulant is the cations produced by degradation of the anode metal and the activation energy applied which promotes the formation of oxides (Hamawand, et al., 2017).The steps of the process are detailed below.

1. Dissolution

   - The anode oxidises (gives away electrons) to produce positively charged ions (cations). Over time the anode will completely dissolve (sacrificial anode) and will need to be replaced.
   - EC thus introduces metal coagulant ions in situ unlike chemical coagulation where they are added through external dosing. The current density affects the amount of metal ions released from the electrode.
   - Simultaneously with the anodic reaction is reduction of water at the cathode into hydrogen oxide ions and hydrogen gas.

At the anode:
Metal → Metal+ + $electron^{e-}$
e.g. $Al = Al^{3+} + 3^{e-}$
$Fe \leftrightarrow Fe^{3+} + 3^{e-}$

At the cathode:
$2H_2O + 2^{e-} \leftrightarrow H_2 (gas) + 2OH^-$

2. Coagulation

Charge neutralisation

- The aim of this step is to destabilise the colloidal suspension by reducing the energy barrier and thus allowing particles to aggregate. The cations are adsorbed onto the surface of the colloids causing the thickness of their electrical double layer to compress and become neutralized (destabilized).
- It is the thickness of this layer that effects the colloid's ability to repulse other particles.
- Different metals have different destabilization abilities which is why the type of electrodes used is important (See Section 7.7 on Electrode Type).

Hydroxide precipitation

- The metal cations M^+ and OH^- ions generated at the electrode behave in a similar way with the aluminium or iron of the chemical coagulants. The metallic cations generated from the anode hydrolyse to form hydroxide compounds.
- Sweep flocs are created (large aggregates of $Al(OH)_3$ or $Fe(OH)_3$ that are positively charged. The negatively charged colloidal particles are electrostatically attached to the *sweep* flocs in the neutral pH water (Ghernaout & Ghernaout, 2012). In other cases, the hydrolysed metal species are adsorbed on the colloid or emulsified oils and grease surface where they create bridges between the particles (Bazrafshan, et al., 2012).

In the solution:
$M(OH)_3 \leftrightarrow M^{3+} + 3OH^-$
$Fe3+ + 3OH- \leftrightarrow Fe(OH)_3$
$Al^{3+} + 3OH^- \rightarrow Al(OH)_3$

3. Floatation

- The hydrogen gas bubbles carry the colloidal particles to the top of the tank.

4. Flocculation tank

- After the treated wastewater leaves the EC chamber, the destabilised colloids are allowed to flocculate. Flocculation is the physical process that brings particles together once they have been destabilized by the coagulation. In some cases polymers are added.

5. Desludging and dewatering

- The sludge and effluent then enter a clarifier where sludge is siphoned off the top for dewatering while the clean effluent flows out of the bottom ready for discharge or reuse. The sludge is then de-watered using devices such as filter presses and settling ponds.

Ozyonar & Karagozoglu found that using EC to treat slaughterhouse wastewater reduced COD by 78.3% (Al electrodes) and 76.7% (Fe electrodes) and oil and grease levels by 94.7% (Al) and 95.9% (Fe) (Ozyonar & Karagozoglu, 2014). When compared with chemical coagulation (CC) treatment Ozyonar & Karagozoglufound EC achieved significantly higher removal rates, particular for COD (CC removal rates between 27.6% and 36.4%).

Studies over the last decade suggest EC is capable of removing around 80% of COD using Al electrodes and around 70% using Fe electrodes. EC removal for oils and greases was typically over 90% due to floatation, the reduction of electrostatic repulsion between the air bubble and oil droplets and an increase of oil droplet hydrophobicity (Cerqueira, et al., 2014).

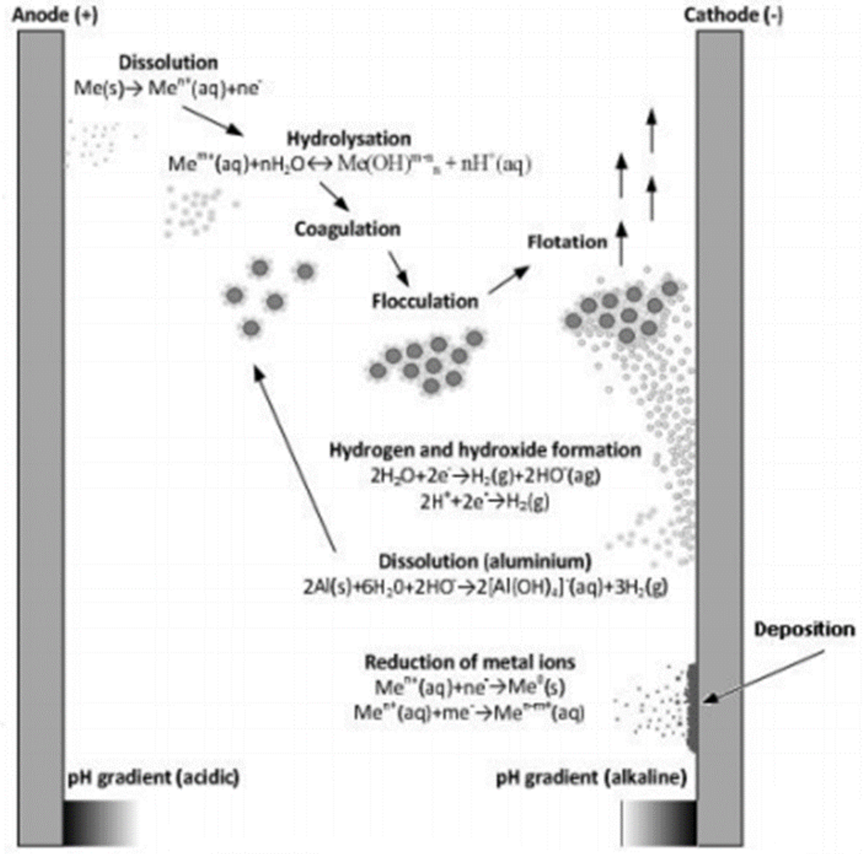

Figure 1: The electrocoagulation process (Eyvaz, et al., 2014)

Similar removal efficiencies were found by Asselin et al. with an 82% reduction in COD using EC to treat poultry slaughterhouse wastewater and a 99% reduction of oil and grease (Asselin, et al., 2008). Orssatto et al. also achieved 81% reduction in COD when treating pig slaughterhouse and packing plant wastewater in Brazil (Orssatto, et al., 2017). Tezcan et al. conducted lab tests using EC to treat cattle slaughterhouse wastewater and achieved 81.7% removal rates for COD using Al electrodes and 70.2% for Fe electrodes.

High levels of organic removal were achieved in a pilot study at an Australian red meat pressing plant with results of 80- 90% removal of COD, 90-95% TSS and 90-95% O&G for the treatment of diluted rendering stickwater (Tetreault, 2003).

Bande found the presence of NaCl reduced the size of hydrogen gas bubbles so they rose slowly to the surface with greater opportunities for collision with oil drops (Bande, et al., 2007).

A trial conducted by MLA in Australia on a red meat processor (cattle) investigated the feasibility of EC and achieved significant contaminant reductions (BOD 97%, COD 90%, TSS 99%, FOG 98%). There were also significant reductions in phosphorus, discussed further in the section on nutrient removal (Inovin Pty Ltd and Anor, 2018).

Table 4 is a summary of results of various studies on removal efficiency of EC.

Table 4: Removal of organics from meat processing wastewater using EC.

	COD	BOD	TSS	Turbidity	O&G	Details
WW - slaughterhouse, Turkey (Ozyonar & Karagozoglu, 2014)						Batch Reactor
% reduction using EC for Al	78.3			90.2	94.7	Al electrodes pH 4, 100 A/m^2, 20 min
% reduction using EC for Fe	76.7			92.8	95.9%	Fe electrodes pH 6, 100 A/m^2, 20 min
% reductions using CC only	36.4			93.6	89.8	$Al_2(SO_4)_3.18H_2O$ pH 7, 200 mg, Al^{3+}/L
	27.6			88.6	85.9	$FeSO_4.7H_2O$ pH 7,200 mg Fe^{3+}/L
	37.4			89.9	75.6	$FeCl_3.6H_2O$ pH 7, 100 mg, Fe^{3+}/L
EC treating poultry slaughterhouse WW in Quebec, Canada (Asselin, et al., 2008)						
	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	Mild steel (Fe), bipolar arrangement, 60 min but COD removed in first 20min, pH 6.15-9.13, 0.3A current applied
Initial WW	1270±30 (soluble) 334634±30 (soluble) (Total)	2939±210	977±83	156082± 880	853±119	
Treated Wastewater	634±56 (soluble) 605±56 (Total)	420±20	102±37	152± 45	13±4	
% reduction using EC	50± 4% (Soluble) 82± 2% (total)	86 ± 2	90±4	89 ± 4	99 ± 1%	
WW - pig slaughterhouse and packing plant, 5200 m3/day Paraná State, Brazil (Orssatto, et al., 2017)						
Before treatment	4730 (mg of O_2/L)					Al electrodes batch reactor, pH 6.46, conductivity 3.91 mS cm^{-1}, 20 min, 30 V
% reduction using EC	81.10%					
WW - cattle slaughterhouse Eskisehir, Turkey (Tezcan Ün, et al., 2009)						
% reduction using EC	81. 7 (Al) 70.2 (Fe)					Al & Fe electrodes, achieved within 1 h, 25 mA cm^{-2}
% reduction with addition of Na_2SO	86.4% (Al)					
EC treating WW from municipal slaughterhouse in Meknes City, Morocco (Khennoussi, et al., 2013) Paper in Spanish so limited details available						
Before Treatment	2240 (mg of O_2/L)				900 & 1100	Fe & Al electrodes, 12 V, 25 min
% reduction using EC	92.6%				62.5%	

	COD	BOD	TSS	Turbidity	O&G	Details
WW – Red meat processor, Australia (Tetreault, 2003)						
% reduction using EC	85-90%		90-95%		90-95%	1:1 diluted stickwater, 27 – 30°C, 4.5 kL/hr, 200 A, 50 V (DC)
EC treating meat processing WW, Australia (Inovin Pty Ltd and Anor, 2018)						
Before treatment	8365 mg/L	5324 mg/L	3910 mg/L		1715 mg/L	Fe electrodes Lab scale trial 6-9 V, 30-70 A 120 l/hr
After treatment	835 mg/L	117 mg/L	6 mg/L		<5 mg/L	
% reduction using EC	90%	97%	99%		99%	

4.3 Removal of nutrients

Released wastewater containing nitrogen and phosphorus in excess of discharge limits can contribute to eutrophication processes and algal blooms that can pose a threat to water resources, aquatic ecosystems and human health. Discharge regulations vary widely throughout Australia but are becoming increasingly stringent. While the use of treated wastewater for irrigation as a source of nitrogen, phosphorous and carbon can increase plant production and reduce fertilizer inputs consideration must be given to the impact of the accumulation of phosphorous and nutrients and dissolved salts on groundwater contamination, soil salinity and through excess runoff (Matheyarasu, 2015). Typical nutrient discharge limits are shown in Table 5.

Table 5: Typical nutrient discharge limits

(Johns Enironmental and The Ecoefficiency Group, 2017).

Receiving environment	Nitrogen	Phosphorus
Sewer	NH_3 ≤ 50 mg/L TN ≤ 100 mg/L	TP ≤ 10-20 mg/L
River discharge	NH_3 ≤ 1 mg/L TN ≤ 50 – 100 mg/L (site specific) Also typical load based limits	TP ≤ 1 – 40 mg/L (very site specific)
Land irrigation (soil & crop specific)	TH: 250 – 500 kg/ha/yr load based limits	TP: 30 – 40 kg/ha/yr load based limits

4.3.1 Traditional removal of Phosphorous

There are several technologies traditionally used in the removal of phosphorous from meat wastewater streams. Table 6 outlines removal efficiencies achieved by the following technologies.

DAFs

- Some phosphorous removal is achieved during primary treatment (DAF process), however this is largely as a byproduct of the treatment process rather than specifically targeting phosphorus (Johns Enironmental and The Ecoefficiency Group, 2017).

Chemically precipitated in activated sludge basins

- Phosphorous can also be chemically precipitated in activated sludge basins. This may require some supplementary alkalinity dosing using lime, MHL etc. to maintain pH.

Biological removal in activated sludge plants

- Activated sludge plants recycle sludge to maintain high bacterial levels in what is effectively an intensified aerobic pond. In activated sludge plants phosphorus can be removed by certain phosphorus accumulating bacteria (Bio-P removal). This involves an initial anaerobic/reactor phase with very high levels of readily biodegradable carbon and low nitrate and oxygen levels allowed by an aerobic phase/reactor where phosphorus is taken up by bacteria at a high rate. The sludge containing the phosphate is dewatered and can be reused for composting and land rehabilitation. Bio—P removal however is not often used due to problems associated with the cost of achieving high biodegradable carbon levels and maintaining low nitrate levels in the anaerobic phase.

Crystallisation

- Crystallisation is an emerging technology that involves the recovery of phosphorus and nitrogen through precipitation of compounds such as struvite ($MgNH_4PO_4.6H_2O$). The process involves magnesium dosing and is fast (1-2 hours) compared to biological removal and cost efficient ($1 per kg P covered verses $11/kg P for iron or alum dosing) (Jensen, et al., 2013). The complete removal of phosphorous would only result in around 10% of nitrogen removal from the wastewater and thus this technology cannot work in isolation (Jensen, et al., 2013).

Table 6: Technologies for phosphorus removal and typical removal rates
(Johns Enironmental and The Ecoefficiency Group, 2017)

Technology	Typical P removal (mg/L)
Dosed DAF	< 5- 10
Chemical precipitation in activated sludge basins	< 5- 10
Biological removal in activated sludge plants (Bio-P)	< 1 – 2
Crystallisation (Struvite)	> 10

4.3.2 EC removal of phosphorous

Electrocoagulation is also capable of removing phosphorous. The main mechanism of the EC process for phosphorus removal is the generation of metal and hydroxyl ions to form coagulant species that can absorb and/or precipitate contaminants which can then be separated. The reaction works mainly with soluble phosphorus (Nguyen, et al., 2016) (Figure 2).

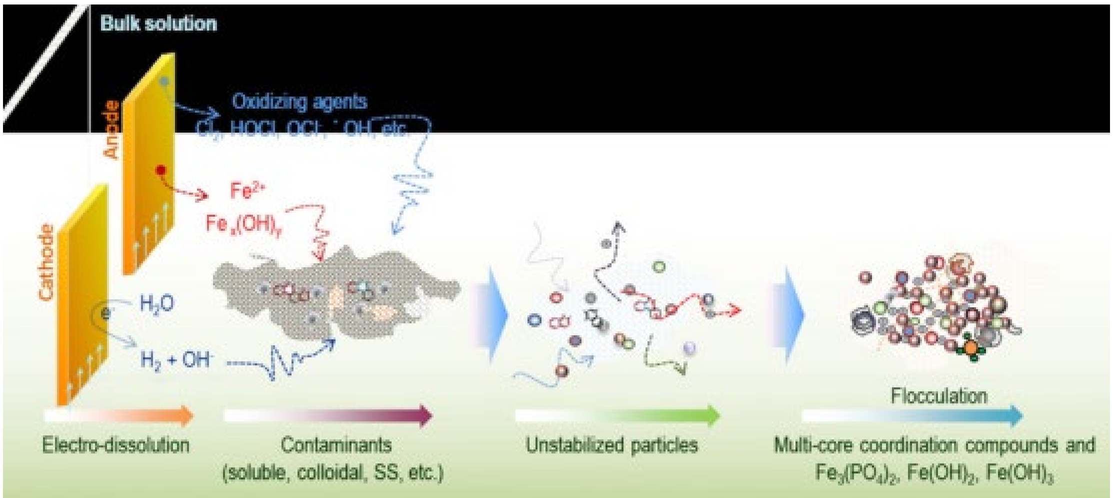

Figure 2: Phosphorus removal by EC (Nguyen, et al., 2016).

A recent Australian study by MLA sought to determine if electrocoagulation/electro-advanced oxidation (EC/EAO) technology was a viable option for removal of Total Phosphate (TP) from abattoir effluent. The process averaged 99% phosphorous removal. Khennoussi et al. also achieved high removal rates of orthophosphate (95.4%) when treating municipal slaughterhouse wastewater (Khennoussi, et al., 2013).

Table 7: Removal efficiency for P rates using EC.

	Phosphate	Details
WW from red meat abattoir, Australia (Inovin Pty Ltd and Anor, 2018)		
	Total P (mg/L)	Electrocoagulation/Electro-Advanced Oxidation Reactor (Water Miner) Fe electrodes Addition of NaCl Range of effluents and parameters – average taken for results presented in report. Additional nutrient removal: Magnesium 39%. Potassium 9%
Before Treatment	71	
Reduction using EC	1.3	
Reduction using EAO	0.6	
% reduction using EC and EAO	99%	
WW – Red meat processor, Australia (Tetreault, 2003)		
% reduction using EC	TP 70-90%	1:1 diluted stickwater, 27 – 30° C, 4.5 kL/hr, 200 A, 50 V (DC)
WW from municipal slaughterhouse Meknes, Morocco (Khennoussi, et al., 2013)		
Before Treatment	35	Fe & Al electrodes Addition of NaCl 12 V Contact time of 25 min
% reduction using EC	95.4	

4.3.3 Traditional removal of nitrogen

Nitrogen in red meat abattoir wastewater is mostly present as organic (from dissolved organics) or in lesser amounts (16-40%) ammonium nitrogen (from urine and rendering) (Johns, et al., 1995).

TKN is the estimate of the sum of the organic nitrogen and the ammonia nitrogen. Under anaerobic and aerobic conditions mineralization of the biodegradable fraction of organic nitrogen occurs. Ammonia nitrogen in meat processing wastewater is generally the product of this mineralization (US EPA, 2004). Very little is in oxidized forms of nitrogen such as nitrate and nitrite due to the lack of oxygen in the wastewater stream (US EPA, 2004).

There can be some reduction in nitrogen levels during primary and secondary treatment due to the separation of particulate matter due to settling or cell synthesis. However, this is often not sufficient for discharge quality (US EPA, 2004). Biological and physicochemical unit processes can be added to the treatment train to remove nitrogen.

Advanced removal of nitrogen from wastewaters is generally undertaken biologically and is a two-step process. Firstly, nitrification resulting in the oxidation of ammonia to nitrite, followed by the oxidation of nitrite to nitrate. Secondly, denitrification where the nitrite and nitrate are reduced producing nitrogen gas (end product) plus small amounts of nitrous oxide and nitric oxide.

Nitrification and denitrification are performed in different parts of the same reactor (Biological Nutrient Reactors e.g. Biolac) or occur in the same reactor space, but at different times in the cycle (Sequencing Batch Reactors).

See Table 8 for technologies that can be employed by meat processors to remove N and typical removal rates.

Table 8: N removal in meat processing
(Johns Enironmental and The Ecoefficiency Group, 2017)

Technology	Mode	Typical N removal
Aerated ponds	Continuous	Approx. 65%
Dosed DAF	Continuous	Approx. 50%
Biological Nutrient Reactors	Continuous	Greater than 80%
Sequencing Batch Reactors	Intermittent	Greater than 80%

4.3.4 EC removal of Nitrogen

Nitrogen found within meat processing wastewater is generally in the form of organic nitrogen or inorganic ammonia nitrogen. Electrocoagulation will remove some organic nitrogen however, it is not very effective in removing ammonia nitrogen (Aoudj, et al., 2017). This is supported by the results of an Australian trial where a 48% reduction in organic nitrogen was achieved and only a 15% reduction in ammonia nitrogen (Inovin Pty Ltd and Anor, 2018). An earlier MLA pilot study found removal rates of 50-60% for TKN was possible when EC was used to treat stickwater (Tetreault, 2003). This is comparable with removal rates with dosed DAF and aerated ponds (Table 8). High removal rates for TKN were obtained by Bazrafshan et al. by treating red meat processing water firstly with chemical coagulation and then electrocoagulation. See Table 10.

Aoudj et al. found that ammonia has only a weak affinity towards the electrogenerated coagulants. However, they found that ammonia reduction increased as the pH and temperature of the EC water increased causing ammonia stripping due to the Joule effect.

$NH_4^+ + OH^- \rightarrow NH_3 + H_2O$

Aoudj et al. found the secondary step of electrocoagulation resulted in a reduction of ammonia ascribed to indirect oxidation caused by chloride ions. Hypochlorous acid or hypochlorite ions oxidise ammonia into gaseous nitrogen or nitrate (Aoudj, et al., 2017).

$3HOCl + 2NH_4^+ \rightarrow N_2 + 3H_2O + 5H^+ + 3Cl^-$

$3ClO^- + 2NH_4^+ \rightarrow N_2 + 3H_2O + 2H^+ + 3Cl^-$

$5HOCl + NH_4^+ \rightarrow NO_3^- + H_2O + 6H^+ + 4Cl^-$

$4ClO^- + HN_4^+ \rightarrow NO_3^- + H_2O + 2H^+ + 4Cl^-$

Water soluble nitrate (NO_3^-) and nitrite ions (NO_2^-) can be can be reduced to nitrogen gas, ammonia and hydroxylamine (NH_2OH). Often salt (sodium bicarbonate $NaHCO_3$) is required to maintain pH levels as the electrolyte gradually becomes alkaline. Chloride-salt can be added to reduce the amount of ammonia and nitrite produced. In this process the chlorine is oxidized at the anode and reacts with water to form hypochlorous acid (HOCl) which in turn reacts with nitrite and ammonia to produce nitrate and nitrogen (Mook, et al., 2012). The process is outlined in Table 9.

Table 9: General mechanisms involved in the electrochemical reduction of nitrate (Mook, et al., 2012)

Process	Reaction steps
Cathodic water electrolysis	$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$
Anodic water electrolysis	$4OH^- \rightarrow O_2 + 2H_2O + 4e^-$
Reactions of nitrate ion and water molecules	$NO_3^- + H_2O + 2e^- \rightarrow NO_2^- + 2OH^-$ $NO_3^- + 3H_2O + 5e^- \rightarrow ½\, N_2 + 6OH^-$ $NO_3^- + 6H_2O + 8e^- \rightarrow NH_3 + 9OH^-$
Reaction of nitrite ion and water molecules	$NO_2^- + 2H_2O + 3e^- \rightarrow ½\, N_2 + 4OH^-$ $NO_2^- + 5H_2O + 6e^- \rightarrow NH_3 + 7OH^-$ $NO_2^- + 4H_2O + 4e^- \rightarrow NH_2OH + 5OH^-$
Reduction of nitrate (especially sodium nitrate) to produce ammonia	$NO_3^- + 2H_2O \rightarrow NH_3 + 2O_2 + OH^-$
Sodium bicarbonate added to maintain pH of electrolyte	$NaNO_3 + NaHCO_3 + H_2O \rightarrow NH_3 + 2O_2 + Na_2CO_3$
Chlorine formed in anodic electrolysis	$2Cl^- \rightarrow Cl_2 + 2e^-$
Reaction of chlorine and water molecules	$Cl_2 + H_2O \rightarrow HOCl + H^+ + Cl^- +$
Reaction of nitrite and hypochlorite ions	$NO_2^- + HOCl \rightarrow NO_3^- + Cl^- + H_2O$
Reaction of ammonium and hypochlorite	$2NH_4^+ + 3HOCl \rightarrow N_2 + 5H^+ + 3Cl^- + 3H_2O$

Table 10: Removal efficiency for Nitrogen using EC

	Nitrogen	Ammonia	Details
WW from red meat abattoir, Australia (Inovin Pty Ltd and Anor, 2018)			
	Total N (mg/L)	(mg/L)	Electrocoagulation/Electro-Advanced Oxidation Reactor Fe electrodes Addition of NaCl Range of effluents and parameters – average taken for results presented in report.
Before Treatment	450	245	
Reduction using EC	260	228	
Reduction using EC and AO	234	206	
% reduction using EC and AO	48	15	
WW – Red meat processor, Australia (Tetreault, 2003)			
% reduction using EC	TKN 50-60%		1:1 diluted stickwater 27 – 30° C, 4.5 kL/hr, 200 A, 50 V (DC)
WW Zahedan City Iran, 250 cows/day, 60 m3/day (Bazrafshan, et al., 2012)			
EC combined with CC	TKN (mg/L)		Lab trials 40V Poly aluminium chloride (100 mg/L) Bipolar batch reactor Al electrodes connected in parallel
• Influent after screening	137 ± 12		
• After 24h sedimentation	92 ± 12		
• After CC	116		
After EC	7		

4.4 Removal of pathogens

Pathogens are found in meat processing wastewaters due to the presence of faecal material.

4.4.1 Traditional removal of pathogens

Maturation ponds are suitable for disinfection to reduce pathogenic microorganisms and reduce BOD to low levels. They allow sunlight and oxygen penetration and encourage algal growth.

In some cases, tertiary treatment is employed to remove pathogens e.g. disinfection by chlorination and UV radiation.

4.4.2 EC removal of pathogens

Electrochemical disinfection during electrocoagulation occurs due to combining three effects (Ndjomgoue-Yossa, et al., 2015):

1. A direct effect of the electric field on bacteria cells which affects the permeability of the cell membrane.
2. The effect of any electrolytes added to increase conductivity such as NaCl that produce oxidants such as ClO^-, ClO_2. These participate in the oxidation of organic compounds and also disinfect the wastewater by diffusing through the cell walls of microbes to produce a dysfunction in the internal enzyme groups which inactivates the cells (Ndjomgoue-Yossa, et al., 2015) (Nguyen, et al., 2017).
3. Charge neutralisation on microorganisms by cations and metallic hydroxides which act by sweep flocculation or enmeshment and adsorption.

Khennoussi et al. found electrocoagulation-floatation enabled a reduction of up to 5 logarithmic units of coliforms and 100% elimination of bacteria. The treatment also reduced the red wastewater colour by 90% (Table 11). Drougi showed reduction in *E.coli* of 2-4 log units and HAFA (heterotrophic aerobic and facultative anaerobic bacteria) of 1–3 log units.

Table 11: Coliform removal from slaughterhouse wastewater by electrocoagulation
(Khennoussi, et al., 2013)

	Faecal coliforms (UFC/ mL)	Details
WW from municipal slaughterhouse (Khennoussi, et al., 2013)		
Before Treatment	$67x10^3$	Fe & Al electrodes Addition of NaCl 12 V Contact time of 25 min
Reduction using EC	Decrease of three logarithmic units	

Modern EC plants incorporate disinfection processes, for example, the inclusion of an electro advanced oxidation zone where hydrogen peroxide (H_2O_2) and hydroxyl radicals and a trace amount of chlorine is generated for disinfection (Inovin Pty Ltd and Anor, 2018).

4.5 Summary of treatment process efficiency

As discussed in previous sections, electrocoagulation is a proven effective technology for the removal of meat processing wastewater contaminants. A summary of removal efficiencies compared with traditional treatment methods is shown in Table 12.

Table 12: Summary of treatment process efficiencies and comparison to Electrocoagulation

	BOD/COD	TSS	O&G	N	P	References
Electrocoagulation	80% COD (Al electrodes) 70% -90% COD (Fe electrodes)		90%	50-60%	Up to 99%	Refer to Sections 4.1 - 4.4
Screening and settling	5-20% BOD	5-30%				(Hamawand, et al., 2017) (Pagan, et al., 2002)
Save-alls	20-25%	50-60%	50-80%			(GHD Pty Limited , 2003)

	BOD/COD	TSS	O&G	N	P	References
DAFS	30-40%	50-65%	60-80%		<5-10	(GHD Pty Limited , 2003) (Johns Enironmental and The Ecoefficiency Group, 2017) (Hamawand, et al., 2017)
Hydroclones	10-30%	15-60%	40-90%			(GHD Pty Limited , 2003)
Chemical coagulation (PACl)	75% COD			88.8%	99.9%	(Aguilar, et al., 2002)
Chemically dosed DAFs	30-90%	50-90%	60-80%		Approx 50%	(GHD Pty Limited , 2003) (Johns Enironmental and The Ecoefficiency Group, 2017)
Anaerobic Lagoons	60-97% COD	60-90%	70-90%			(Pagan, et al., 2002)
Aerated ponds	50-80%			0-10%	Approx 65%	(Pagan, et al., 2002) (Johns Enironmental and The Ecoefficiency Group, 2017)
Activated sludge	85-97%	95-98%		0-50%	<5-10 (chemical) <1-2 (biological)	(Pagan, et al., 2002) (Johns Enironmental and The Ecoefficiency Group, 2017)
Trickle filter with clarification	80-90% low rate 65-85% high rate					(GHD Pty Ltd, 2015)
Wetland following anaerobic pond	90% BOD/COD (30% by wetland)	85%		80% organic N		(Gutiérrez-Sarabia, et al., 2004)
Biological nutrient reactors					> 80%	(Johns Enironmental and The Ecoefficiency Group, 2017)
Sequencing batch reactors					> 80%	(Johns Enironmental and The Ecoefficiency Group, 2017)
Crystallisation (struvite)					>10	(Johns Enironmental and The Ecoefficiency Group, 2017)
Irrigation and passage through soils				Organic N 60-65% TKN – 60-85%		(Boeriu, et al., 2013)

5 SLUDGE GENERATION AND QUALITY

The quantity and quality of sludge generated has a large impact on the cost benefits of a treatment technology. High sludge volumes can have a significant cost impact especially with the rising dewatering, transport and landfill costs. Similarly, the quality and contamination levels within the sludge will have an impact on disposal options. Good quality sludge can often be disposed of as compost or for landspreading which can generally be more cost effective than landfill. However, if there are high levels of contaminants it may not be accepted as compostable waste.

Electrocoagulation produces much less sludge volume than chemical coagulation and the sludge formed is more stable and non-toxic. One full scale application of EC reported a 90% reduction in sludge compared with CC (Moussa, et al., 2016).

Australian EC supplier, Inovin, is currently (2018) undertaking a pilot trial using EC to treat meat processing wastewater. Initial results of an analysis of the sludge produced indicate that the sludge quality was well within the New South Wales Biosolids and Fertiliser guidelines for most elements and is a suitable fertiliser. However, it showed elevated TDS levels (8,800 compared with the guidelines of < 2,000 mg/L) and elevated chloride levels (33,800 compared with <8,000 mg/kg). These are as a result of salt addition to aid the EC process (See Section 7.2 on conductivity) indicating that the sludge would likely need to be blended with other fertilisers to achieve lower levels more amenable to land application.

Iron levels (Fe) were also extremely high in the sludge at 110,000 and 279,000 mg/kg compared with guideline figures for land application of greater than 4,000 mg/L. These initial results seem excessive and need to be confirmed. An MLA pilot study on electrocoagulation of stickwater reported Fe and Al levels in sludge of 30 g/kg and 2.4 g/kg (Tetreault, 2003). While iron is essential for plant growth, excess levels of iron in soil can cause iron toxicity in plants which inhibit them from taking up other trace elements (Suresh, 2005). The World Bank indicates healthy soil iron levels of 29-50 ppm (mg/kg) for most crops (Cantisano, n.d.).

6 HYBRID ELECTROCOAGULATION

6.1 Electrocoagulation with chemical coagulation

Hybrid processes have been applied to increase removal efficiencies. Bazrafshan et al. undertook laboratory trials to determine if the combination of chemical coagulation (addition of Poly Aluminum Chloride (PACl) -100mg/L) followed by electrocoagulation was capable of meeting discharge to sewer with limits (Bazrafshan, et al., 2012). The study found chemical coagulation (1,725 mg/L COD remaining) alone was not able to meet discharge standards but when combined with electrocoagulation limits were met (13 mg/L COD remaining). Ozyonar and Karagozoglu (Ozyonar & Karagozoglu, 2014) also found removal rates for COD and O&G with just chemical coagulation were considerably lower than for EC (Ozyonar & Karagozoglu, 2014). Tezcan et al. also combined EC with chemical coagulation by adding PACl. COD removal increased to 81.1% when 100mg/L of PACl was added and to 94.4% when 750 mg/L of PACl added. Addition of 500mg/L PACl was required to meet Turkey's discharge limits (Tezcan Ün, et al., 2009).

6.2 Electrocoagulation with the Fenton process

Tezcan et al. also investigated conducting EC concurrently with the Fenton process and found 81.1% COD removal could be achieved by adding 9% H_2O_2. In the Fenton process, $FeSO_4$ and H_2O_2 (Fenton's reagent), at low pH, results in Fe^{2+} catalytic decomposition of H_2O_2. This produces hydroxyl radicals that have extremely high oxidizing ability and decompose organic compounds in a shorter time. Texcan et al. concluded hybrid processes were superior to EC alone for the removal of both COD and turbidity from cattle-slaughterhouse wastewater (Tezcan Ün, et al., 2009).

The Fenton process was also incorporated in an EC plant in an Australian trial. Disinfection takes place in an electro advanced oxidation zone through generation of hydroxyl radicals (Inovin Pty Ltd and Anor, 2018) reducing pathogen levels.

Table 13: Removal of organics from meat processing wastewater using hybrid EC

	COD	BOD	TSS	Turbidity	Details
WW Zahedan City Iran, 250 cows/day, 60 m^3/day (Bazrafshan, et al., 2012)					
EC combined with CC	mg/L	mg/L	mg/L		Lab trials 40V PACl (100mg/L) Bipolar batch reactor Al electrodes connected in parallel
• Influent after screening	5817 ± 473	2543 ± 362	3247 ± 845		
• After 24hr sedimentation	4159 ± 281	2204 ± 177	1174702 ± 84		
• After CC	1725	1217			
• After EC	13	10			
WW from cattle slaughterhouse Eskisehir, Turkey (Tezcan Ün, et al., 2009)					
% reduction using EC & CC	81.1				Addition of PACl 100g./L
	84.0				300g/L
	92.1				500g/L
	94.4				750g/L
% reduction using EC & Fenton process	73.8	91			Addition of H_2O_2 3%
	78.7	91			6%
	81.1	91			9%
WW from red meat processor, Australia (Inovin Pty Ltd and Anor, 2018)					
% reduction using EC & Electro-Advanced Oxidation	90	97	99	98	Average results for treatment of 4 streams – CAL effluent and influent, red and green streams

7 EC PROCESS PARAMETERS AND OPERATIONAL CHALLENGES

The performance of the EC process depends on many operational parameters (Figure 3).

Figure 3: The many operating parameters influencing the EC process performance (Eyvaz, et al., 2014).

7.1 Initial and final pH

EC is able to produce flocs over a wider range of pH values and more rapidly than chemical coagulation (Harif, et al., 2012). At low pH values, EC can also diminish the need for pH adjustment (Harif, et al., 2012).

Red meat processing wastewater typically has a pH value between 4.9 and 8.1 with a mean of 6.9 (Hamawand, et al., 2017). The initial pH of the solution (called this because the pH changes in the process) is an important operating parameter as it affects the conductivity of the wastewater and electrode dissolution (Moussa, et al., 2016).

Aluminium and iron cations with an oxidation number of +3 are used almost exclusively in the coagulation and flocculation of wastewater (Huitle, et al., 2018). Aluminium electrodes operate in acidic and neutral pH (Sahu, et al., 2014). This is because between pH values of 4 and 9.5 the major ion species generated is $Al(OH)_3$ which is able to effectively trap colloids and pollutants as it precipitates. The least removal efficiency occurs in highly alkaline wastewater when $Al(OH)_4$ forms which is a poor coagulant. Iron electrodes operate in acidic, neutral and slightly alkaline pH (Sahu, et al., 2014). Iron electrodes will produce mostly Fe^{2+} around pH 8 but will start to generate Fe^{3+} species as the pH lowers (Nwabanne & Obi, 2017). Lowest removal efficiency occurs in highly alkaline wastewater when $Fe(OH)_4$ is formed which is a poor coagulant (Sahu, et al., 2014).

As meat processing wastewater is typicaly pH neutral, pH adjustment is generally not required. Kobya found however that when EC was used to treat poultry-house wastewater with an initial wastewater pH of 6.7 the removal efficiency of COD was 70% (Al) and 60% (Fe). When reduced to pH 2, removal efficiencies increased to 93% (Al) and 85% (Fe).

The pH of the wastewater treated using EC may increase slightly due to generation of hydrogen and hydroxide ions at the cathodes (Nwabanne & Obi, 2017) (Budiyono & Johari, 2010). Tezcan et al. found the pH of cattle wastewater following EC treatment increased from 7.8 to 8.76 (Al electrode) and to 9.05 (Fe electrode) which was still within discharge limits (Tezcan Ün, et al., 2009). The Australian MLA trial which included iron electrodes showed a slight increase in pH from 6.8 to 7.4 (Inovin Pty Ltd and Anor, 2018).

7.2 Conductivity

Conductivity influences the ability of the wastewater to facilitate the passage of current. For the EC process to work, ions must travel through the wastewater. High conductivity reduces the electrical resistance of the wastewater, decreases cell voltage and reduces energy consumption. Conductivity adjustment is typically undertaken with the addition of an electrolyte such as sodium chloride (NaCl) (Sahu, et al., 2014) or sodium sulphate(Na_2SO_4) (Tezcan Ün, et al., 2009). As water is a polar solvent, NaCl will break down into Na^+ and Cl^- ions. When voltage is applied across electrodes the positively charged ions (Na^+) move to the negative electrode and negatively charged ions (Cl^-) move to the positive electrode and increase the current.

Both Tezcan et al. and Eryuruik et al. treated cattle-slaughterhouse wastewater with EC (iron rod electrodes) with supporting electrolyte concentrations Na_2SO_4 (Tezcan Ün, et al., 2009) (Eryuruk, et al., 2011). Both found the use of electrolytes decreased electrical energy consumptions and COD. Tezcan et al. found electrical energy consumption and voltage decreased from 547 $kWhm^{-3}$ to 158 $kWhm^{-3}$ with increasing Na_2SO_4 concentrations up 0.1M (Tezcan Ün, et al., 2009). At the same time, it was found increasing Na_2SO_4 increased COD removal (Figure 4). Eryuruk et al. found removal efficiency of 66.0% could be increased to 72.0% at current density of $40mA/cm^2$ and 0.1M Na_2SO_4 using iron rods (Eryuruk, et al., 2011).

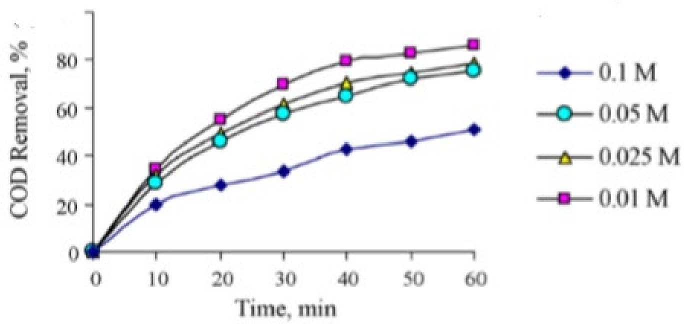

Figure 4: Effect of salt concentrations on COD removal (Al electrodes, pH 7.8, $20mAm^{-3}$)
(Tezcan Ün, et al., 2009)

COD removal while high for 0.01 M concentrations, fell from 86.4% to 50.5% at concentrations of 1M due to excess SO_4^{2-} interacting with OH^- ions and possibly inhibiting corrosion of the Al electrode (Tezcan Ün, et al., 2009).

Nguyen et al. found when treating municipal water that phosphorous removal rates could be increased by increasing NaCl concentrations while also shortening electrolysis time and reducing specific electricity consumption (Nguyen, et al., 2016). Nguyen et al. also notes that equally important is that the EC generates chlorine reactions at the anode that create Cl_2, HOCl, OCl^-, OH^- and H_2O_2 which contribute to wastewater disinfection and help to oxidize organic compounds (Nguyen, et al., 2016) (Nguyen, et al., 2017)

A disadvantage of the addition of electrolytes such as NaCl is the tendency to produce salty effluents. This is an issue for meat processors depending on the wastewater receiving environment. Wastewater with high salt levels is not suitable for irrigation purposes and may not meet environmental license requirements (Inovin Pty Ltd and Anor, 2018). Additional treatment to remove salt would be required.

7.3 Current density

Current density is the amount of electric current per cross-sectional area of electrodes (measured as mA/m^2). It is an important parameter as it can be directly managed by the wastewater operator and controls the reaction rate. Faraday's Law shows the direct relationship between current density and the amount metallic electrodes that will dissolve (i.e. the number of metal ions produced). Note, experimental data has shown ion concentrations are actually higher in reality than would be predicted by the Faraday's law due to a phenomenon that has been called superfaradiac efficiency. (Picard, et al., 2000).

Faraday law

No. moles of metal dissolved
= current (A) X electrolysis time (t)
Faraday Constant X charge of the cation (z)

Bubble size is affected by the size of the current as well as the pH. Bubbles are typically around 20-70 µm (Huitle, et al., 2018). The greater the current the larger the bubble. Smaller bubbles favour sedimentation while larger bubbles favour floatation as the primary way to remove the particles (Comninellis & Chen, 2009). The pH affects bubble size with the smallest hydrogen bubble forming when pH is neutral (Adhoum, et al., 2004).

7.4 Electrolysis time

It is possible to calculate the amount of metal that will be dissolved (amount of coagulant) using current and time. Thus, time is a critical parameter. However optimum electrolysis time remains a constant and contaminant removal efficiencies do not increase as electrolysis time increases. That is because once sufficient amounts of floc are produced for the removal of the contaminants, there is no requirement for additional flocs and the time required to produce them (Fayad, 2017).

Nwabanne et al. noted that when treating abattoir wastewater turbidity removal efficiency increased with an increase in electrolysis time, however it did not significantly increase after 20 mins (Nwabanne & Obi, 2017). Nwabanne et al. also found that longer reaction times lead to greater electricity consumption. An optimal removal efficiency of 65.65% for turbidity was obtained in 30 minutes and current density of 2.5 A. Asselin et al. also observed in the treatment of poultry wastewater that while the trial allowed 60 minutes for electrolysis, COD removal was greatest in first 20 minutes (Asselin, et al., 2008).

Research therefore indicates that optimal times for the EC process appears to fall between 20-30 minutes.

7.5 Floc development

During coagulation microflocs collide and bond to produce larger flocs. Harif et al. studied the formation of flocs in both electrocoagulation and chemical coagulation (Harif, et al., 2012). He found flocs were formed during electrocoagulation when the particles collided as they have negligible repulsive forces which enabled them to stick together but also cause them to form tenuous structures. For this reason, they were able to form flocs much faster than chemical coagulation. Harif et al. found in chemical coagulation there were still substantial repulsive force so they relied on many collision frequencies to form stable flocs. The process is slower and the flocs are more resistant to shear force.

Burrangong Meat Processors trialled a pilot scale electrocoagulation system capable of treating approximately 10 kL/h of cooled, diluted stickwater from the facility's Low Temperature Rendering Plant (COD of 120,000 mg/L; BOD_5 of 35,000 mg/L; TN of 3,000 mg/L; TP of 500 mg/L; and TSS of 23,000 mg/L) (Tetreault, 2003).

The initial focus of the trial was to establish the best type of equipment to permit separation of the EC sludge from the treated effluent for beneficial reuse. There were problems with floc development due to the location of equipment and excessive turbulence from pumping/mixing of the effluent which affected the floc and were not overcome.

The trials were successful for the undiluted stick water stream with 1:1 dilution with recycled treated effluent giving best results. Under these conditions a frothy stream was created that rapidly separated in the downstream saveall unit to give creamy coloured floating sludge. When not diluted, the wastewater needed to be treated first to remove free, unemulsified fat to prevent deposition on the electrodes. The trial demonstrated the importance of carefully managing floc development.

Table 14: Conservative estimate and probable "typical" pollutant removals for the electrocoagulation unit treating 50% diluted stickwater
(Tetreault, 2003)

% Removal	COD	TSS	TKN	TP	O&G
Conservative estimate	85	90	50	70	90
Under optimal conditions	90	95	65	90	95

7.6 Power supply

EC is typically operated using Direct Current (DC). The use of Alternating Current (AC) is showing promise with higher efficiency and energy reductions. However, it is yet to be examined in the treatment of meat processing wastewater.

DC while causing oxidation at the anode also causes an oxide layer to form on the cathode (passivation). The layer decreases the current flow between the two electrodes which reduces the efficiency of the system and increases power consumption and maintenance requirements to clean and replace the plates.

Zang et al. found using an alternating current prevented passivation on Al and Fe electrodes (Zang, et al., 2015). The electrodes must however be of the same material (Fayad, 2017). Eyvaz et al. produced an alternating current pulse (ACP) by an adjustable time-relay integrated with already existing DC power supply for EC applications. When ACP was applied to brewery wastewater, which like red meat processing water is high in organic matter, it enabled 20 % more COD removal for both Fe and Al electrodes in half the time (Eyvaz, 2016). Mollah et al. found using just AC power slowed down electrode consumption when compared with DC (Mollah, et al., 2001). Vasudevian et al. found using both AC and DC (removal of cadmium from water) achieved higher removal rates whilst also lowering energy consumption (Vasudevan, et al., 2001).

Zang et al. found the addition of chloride ions, supplied by NaCl, can help to break down the passive layer on electrodes (Zang, et al., 2015). The small size of the chloride ion penetrates the oxide film and forms acids. Its strong adsorption on metal lattices prevents repassivation.

Hydro mechanical cleaning and mechanical cleaning have also been used to reduce the impact of passivation (Holt, et al., 1999).

7.7 Electrode type

To achieve higher surface levels for treatment, mono- or bi-polar electrodes are set up in series or parallel connections (Figure 5) (Moussa, et al., 2016). Research shows different arrangements suit different removal efficiencies and treatment costs (Moussa, et al., 2016). Little research has been undertaken in this area for meat processing wastewater. Most available literature refers to 'bipolar' series where the outermost electrodes are directly connected to the external power sources while the inner electrodes are not.

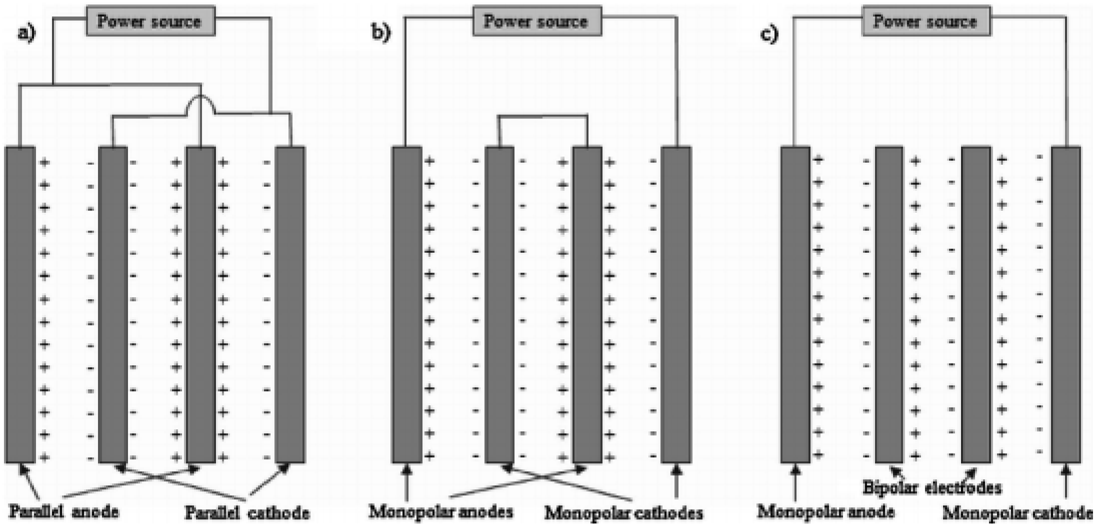

Figure 5: EC electrode connections: a. Monopolar-parallel (MP-P) b. Monopolar series (MP-S) and Bipolar series (BP-S)
(Moussa, et al., 2016)

Literature on the use of EC shows both Al and Fe electrodes are typically used to treat meat processing wastewater. Al and Fe electrodes produce cations with an oxidation number of +3, that are used in the coagulation and flocculation of wastewater (Huitle, et al., 2018). Iron produces cations with a lower charge and can thus be a slightly weaker coagulant at some pH levels compared with Al. However, it is cheaper so is sometimes a preferable option based on cost (Fayad, 2017) . Tetreault found the best results treating red meat processing water were achieved using a combination of Fe and Al electrodes. The Al electrodes were particularly beneficial for phosphorus removal and sludge appearance (Tetreault, 2003).

There is very little literature on the preferred shape of electrodes however while more complex geometrical shapes are sometimes proposed (such as balls or punched plates to increased surface area) simple planar electrodes are typically used for ease of maintenance (Fayad, 2017).

8 APPLICATION OF ELECTROCOAGULATION TECHNOLOGY TO TREAT WASTEWATER IN OTHER INDUSTRIES

Electrocoagulation is not a new technology with Dietrich first patenting the concept in 1906. In recent decades it has been used by a wide variety of industries. Table 15 is a summary of a review of literature undertaken by Moussa et al. showing removal efficiency rates achieved in the food, paper, refinery, tannery and textile industries using electrocoagulation.

Table 15: Contaminant removal efficiency of EC by industry application
(Moussa, et al., 2016)

Contaminant Removed	Food Industry	Paper Industry	Tannery and Textile Industry	Refinery Waters
COD	50-98.84%	41-98%	42-82%	57-97%
BOD	52-98%	50-92%	35%	
Colour	52-100%	84-100%	84.-100%	
Oil / Grease	99%		96%	95%
TSS	89-98%		65->80%	
TDS			42%	
Turbidity	56-99%	92-97%	96%	
TN	75-93%			
TP	99.7%			
FC	100%			
Total Coliform	93%			
Bacterial Indicators	99.9%			
Phenols		97-08%		97-100%
Cresols				100%
Sulfate				93%
Sulfide		96.7-90%		58->90%
Arsenic		88-91.5%		
Lignin		31-88%		
Chromium		46-98%		
Zinc			80%	
Ammonia			43.1%	
Dye Red 81			>98%	
Dispersive Dye			49-63%	
Reactive Dye			81-100%	

9 ECONOMIC ANALYSIS OF ELECTROCOAGULATION

9.1 Operational costs of EC

Operational costs of EC include cost of electricity consumption, electrode replacement, cost of any additional chemical use or additives, sludge dewatering and disposal and also labour and maintenance. The latter costs are rarely taken into consideration in literature ((Fayad, 2017) and this is also the experience in this literature review. Ozyonar & Karagozoglu outlines a number of formulae that can be used to calculate the costs involved in operating EC units (Ozyonar & Karagozoglu, 2014):

Consumption of electrical energy:

$$Ce = \frac{U \times i \times t}{V},$$

where:

Ce	energy consumption (Wh/m^3)
U	electric potential difference applied in the system (V)
i	electrical current applied (A)
t	application time (h)
V	volume of effluent treated (m^3)

Consumption of electrodes:

$$M_{cel} = \frac{i \times t \times M}{(F \times n) V},$$

where:

M_{cel}	mass of electrodes consumed per volume(kg/m^3)
i	electrical current applied (A)
t	application time (s)
M	molar mass of the predominant element of the electrode (26.98 g mol^{-1})
F	Faraday constant (96,485.3329 s A mol^{-1})
n	number of electrons involved in the anode oxidation reaction
V	volume of effluent treated (m^3).

Costs of operation:

$$Co = \alpha Ce + \beta M_{cel} + La + DC,$$

where:

Co	cost of operation ($/m^3)
α	cost of electrical energy ($/kWh)
Ce	energy consumption (kWh/m^3)
β	mass cost of aluminum ($/kg)
M_{cel}	mass consumed (kg/m^3)
La	Cost of labour ($/m^3)
DC	Cost of sludge disposal ($/m^3)

Based on these formulae and operating conditions of 25 min retention time and an electrical current of 1.08A, Ozyonar & Karagozoglucalculated the following costs for treatment of wastewater from a pig slaughterhouse and packing plant in a batch reactor:

- Electricity consumption - 14.2 kWh/m^3;
- Aluminium consumption - 0.189 kg/m^3 ($AU2.14 AUD per kg of Al); and
- Total operating cost - $AU5.96 /m^3 (using $AU0.28 /kWh, $AU1.56 for disposal costs for the residual sludge, including transportation and charges for waste disposal. Based on $US1 = $AU1.39) (Ozyonar & Karagozoglu, 2014).

Asselin et al. calculated EC operational costs for slaughterhouse wastewater treatment to be $AU0.99/m^3 (Asselin, et al., 2008). However, electricity consumption was only 4.19 kWh/m^3 (electric current only 0.3 A) and energy costs were lower at $AU0.08 /kWh. Electrode consumption was $0.40/m^3 Fe, polymer consumption $AU0.07 /m^3 and sludge disposal $AU0.17 /m^3. (Based on $US1 = $AU1.39).

Drogui et al. reported an operational cost of $AU1.66 /m^3 using Fe electrode(0.68 $/m^3 for energy, $0.20 /m^3 for disposal and $0.78 /m^3 for electrodes) and $AU2.76 /m^3 using Al electrode, ($0.73 /m^3 for energy, $0.27 /m^3 for disposal and $1.76 /m^3 for electrodes) with 6.1-6.4 V and current density 5 A/m^2 (Drogui, et al., 2008). High values for EC are closely rated to high electricity costs. Tones successfully used a photovoltaic module to operate the EC for dye removal to reduce costs (Tones, 2015).

An MLA pilot study for treatment of stickwater used 1.54 kWh/m^3 for processing of 6.5kL/hr (200 A @ 50 V) cost of electrode consumption at 0.03-0.05 $/kL for a mix of Fe & Al electrodes (Tetreault, 2003).

An Australian commercial EC supplier (sales brochure information) suggests power consumption of 1.5 kWh/m^3 with additional pumping power requirement of 0.6 kWh/m^3 and electrode and polymer costs of $0.38 /m^3 (Inovin, 2018).

A red meat processor in NSW, Australia treats 37 kL of meat processing wastewater each day over a 6 hour period. The following costs are in Australian dollars and are for a relatively old system (>10 years) which may be upgraded. The system includes two sets of Fe electrocoagulation plates which are operated together and draw 3.6 kW of power each with total electricity consumption of 43.2 kWh/day. There is additional electricity use for pumps, stirrers and a filter cake press (v belt) of 7.25 kW over 6 hours or 43.4 kWh/day. Total electricity consumption for the system is 86.6 kWh over 6 hours @ 30 c/kWh. This equates to $6,495 in electricity costs (5 days per week and 50 weeks per year) and is 2.34 kWh/kL wastewater treated. The system includes 29 Fe electrode plates per unit at a total cost of $606 per unit. The two units are changed every three weeks costing the processor $1332 every three weeks (this includes $60 labour cost per changeover). There are additional chemical costs of $390 per month for a 25 kg bag of polymer for the filter press. The system produces 300-600 kg of sludge per day which is mixed with paunch material and has a zero disposal cost. Additional labour costs are $120 per day (4 hours) to manage the treatment system (Coe, 2018)

The above-mentioned results are summarised in Table 16. There are wide variations in the operating cost data found in the research with most data coming from lab or pilot scale trials. This aspect is discussed further in the following section (9.2). The data is also not directly comparable due to incomplete data sets (e.g. sludge disposal cost not always included) and variation in electrode and electricity costs and consumption. As seen, electricity consumption ranges between 1.54 to 14.2 kWh/m^3 which transfers to a large variation in energy costs. The data provided by (Coe, 2018) is for an existing full-scale system which is currently in operation.

Table 16: Reported operating costs for electrocoagulation of meat processing waste ($AUD)

Description	Total operating cost $/m³	Electricity use $/m³	Electricity cost $/kWh	Electrode Use $/m³	Polymer use $/m³	Sludge disposal $/m³	Details	Reference
Pig slaughter house waste	$5.96 based on $US1: $AU1.39	3.9 (14.2 kWh/m³)	0.28	0.40 0.189kg/m³ & $2.14 /kg Al	-	1.56	1.08 A. Pilot scale batch reactor	(Ozyonar & Karagozoglu, 2014)
Poultry slaughter house	$1.67-$2.76 based on $CAN1: $AU1.07	0.68-0.73 10.6 – 11.4 kWh/m³	0.064	0.78-1.76 $244/ tonne (Fe), $1707/ tonne (Al)	-	0.20-0.27 $64.2/ tonne	Lab scale trials 6.1-6.4 V 5 A/m²	(Drogui, et al., 2008)
Slaughter house waste	$0.99	0.33 (4.2 kWh/m³)	0.08	$0.40 Fe	0.07	0.17	Lab scale 0.3 A, 30 V	(Asselin, et al., 2008)
Rendering stickwater from meat processing	$0.27 (electricity + electrode)	0.22 (1.54 kWh/m³)	0.14 assumed	0.03-0.05 Fe & Al mix			Pilot scale 200 A, 50 V. 6.5 kL/hr	(Tetreault, 2003)
Commercial brochure – industrial strength wastewater	$0.67 (electricity + electrode)	0.29 (2.1 kWh/m³)	0.14 assumed	0.38 Fe plates and polymers				(Inovin, 2018)
NSW Red Meat Processor	$3.63 (electricity, electrode, polymer)	0.702 (2.34 kWh/m³)	0.3	2.4	0.53 (V belt press)	zero	Full scale in operation	(Coe, 2018)

9.2 Comparison with traditional chemical coagulation

When EC costs are compared against other technologies it is generally only compared against CC. Hamawand et al. has undertaken an extensive review of chemical treatment in the Australian meat processing industry and concluded that the energy requirements associated with chemical coagulation is insignificant when compared with other physical or biological units (Hamawand, et al., 2017). Hamawand has calculated that for a small meat processing chemical coagulation and disinfection plant (see Figure 6 below) total energy would be in the order of 1.03kWh/m³. This figure is significantly less than energy consumption for EC reported by Asselin (lab scale, 4.19 kWh/m³) and Ozyonar & Karagozoglu (pilot scale batch reactor 14.17 kWh/m³).

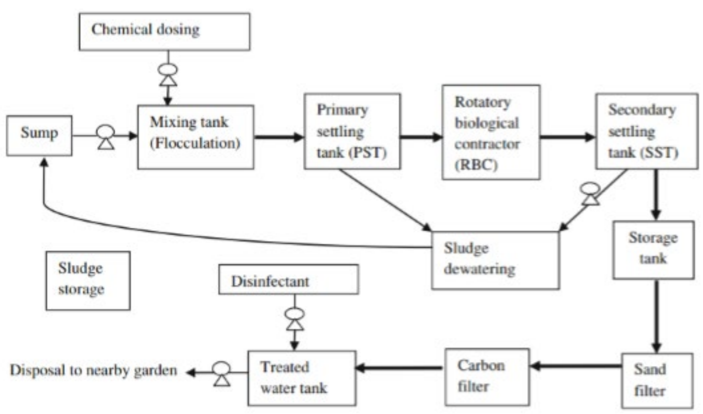

Figure 6: Flow diagram of a small chemical treatment plant
(Hamawand, et al., 2017)

Hamawand also details chemical consumption costs (Table 17) which are also considerably lower than Al electrode consumption of around $AU0.40/m^3 reported by Asselin and Ozyonar.

Table 17: Chemical consumption costs for chemical coagulation of slaughterhouse wastewater

Chemical	Chemical consumption kg/m^3 wastewater	Cost $AU/m^3 wastewater treated*	COD removal
Alum	0.75	$0.15	65%
Ferric sulphate	0.75	$0.26	65%
Ferric sulphate and anionic polymer	0.37	$0.47	46-89%
Ferric chloride and chitosan	0.16	$0.22	53%

*Based on $US1 = $AU1.39. (Hamawand, et al., 2017)

In an attempt to compare total operating costs of electrocoagulation and chemical coagulation, Table 18 summarises costs for meat processing waste found in literature. While it appears that CC is more cost effective than EC, the information is inconclusive as there are wide variations and missing data sets (e.g. sludge disposal costs) and some costs calculated from lab or pilot scale trials[1] with estimations of expected operating costs. EC produces less water bound sludge than CC (Hamawand, et al., 2017) with Moussa et al. reporting a 90% reduction in sludge for one full scale application of EC compared with CC (Moussa, et al., 2016). Therefore, sludge disposal costs can have a large impact on CC operating costs compared with EC.

Moussa et al. reported on economic costs of full-scale electrocoagulation versus full-scale chemical coagulation for non-meat processing systems treating identical flowrates and quality of respective wastewater streams with findings indicating that CC cost at least 2-3 times as much or even 35 times as much as EC to operate (Moussa, et al., 2016). However, as these trials were not undertaken on meat processing wastewater, is difficult to directly compare this to the meat industry. The findings of these studies are listed below:

- Textile wastewater –electrocoagulation cost of $0.25 /m^3 and chemical coagulation cost of the same wastewater at 3.2 times higher (Bayramoglu et al. (2007) cited by Mousa et al).
- Cadmium from wastewater – 100% removal using EC at a cost of $US0.06 which included cost of electrodes (aluminium), electrical energy and chemical addition (pH adjustment). An equivalent CC system was $US2.10 (Khaled et al. (2007) cited by Moussa et al).
- Metallurgical wastewater – for the same flowrate (110 m^3/yr), total treatment cost of $US739 /yr for EC and $US1,351 /yr for CC (Rodriguez et al. (2007) cited by Moussa et al).
- Tannery wastewater – 1.7 $/m^3 for EC and 3.5 $/m^3 for conventional method (Espinoza-Quiñones et al. (2009) cited by Moussa et al.).
- Treatment of various hazardous waste liquid streams - a commercial waste water treatment facility replaced traditional chemical precipitation with EC and reduced chemical costs from $100,000 per month to $10,000 without compensating treated water quality. Sludge generation also reduced by 90%.

[1] Lab scale – bench scale with low flow rates of several litres/min. Pilot scale – site based with flowrates of several kL/hr.

Table 18: Reported costs for coagulation of meat processing wastewater

Cost $/m³ wastewater	Inputs/inclusion in cost	Details	Reference
Chemical coagulation			
0.15 – 0.47	0.16-0.75 kg/m³ Chemical cost	Slaughterhouse waste. Alum and Ferric compounds. Chemical consumption only. Excludes sludge disposal costs	(Hamawand, et al., 2017) Refer Table 17 of this report.
0.14	1.03 kWh/m³ Electrical energy	Calculated for small meat processing chemical coagulation and disinfection plant	(Hamawand, et al., 2017)
Electrocoagulation			
5.96	Electricity, electrode use & sludge disposal	Calculated (estimated) cost for pig slaughterhouse waste 0.28 c/kWh. Refer Table 16	(Ozyonar & Karagozoglu, 2014)
2.9	Electricity use, electrode & sludge disposal	Full scale. Poultry slaughterhouse waste. 0.064 $/kWh. Refer Table 16	(Drogui, et al., 2008)
0.99	Electricity use, electrode & sludge disposal	Lab scale. 0.08 $/kWh. Slaughterhouse waste. Refer Table 16	(Asselin, et al., 2008)
0.27	Electricity & electrode use	Pilot scale, 200 A, 50 V. 6.5 kL/hr	(Tetreault, 2003)
0.67 (electricity – 0.29 & electrode cost – 0.38)	1.5 kWh/m³	Red meat slaughterhouse waste Commercial brochure assumes 14 c/kWh	(Inovin Pty Ltd and Anor, 2018)
$3.93 (electricity – 0.702, electrode – 2.4 & polymer – 0.53	Electricity use (2.34 kWh/m³), electrode use, polymer use (v belt press) and zero sludge disposal	Fully operational existing plant treating 37 kL/day over 6 hours, 5 days/week. 0.3$/kWh	(Coe, 2018)

There are numerous research papers with information on the economic cost of EC. Where costs are compared with other technologies they are generally only compared with CC. Some papers attempt to compare electricity consumption, electrode decay and sludge disposal costs of EC against chemical coagulant costs and electricity use (pumps, stirrers). In addition, many of the costs cited are for lab or pilot scale EC systems or have been calculated from first principles and scaled up and there is wide variation in results (Table 16 and Table 18). There were a number of full-scale comparisons of EC with CC and in each of these, chemical coagulation costs were minimum of 2-3 times higher with one study 10 times higher and another as much as 35 times higher (Moussa, et al., 2016). It should be noted that these comparisons were not for meat processing, which is somewhat limiting of their value for the meat industry. Further research into the costs of EC for treating meat processing wastewater as well as comparison against a fuller range of treatment technologies that provide the same contaminant removal results would be beneficial.

9.3 Capital Costs

As an indication of capital costs, an Australia supplier has quoted prices in the order of $US 550,000 for a 100 kL/day system through to about $US 1 million for 1 ML/day (Inovin, 2018). The unit has an electrocoagulation zone followed by a disinfection zone using Fenton's process (Section 6.2). The costs exclude sludge dewatering, site commissioning and freight.

The same supplier has provided costing for a treatment system. Further details can be found in the Milestone 2 report for this project. The estimated cost of the proposed treatment system is $AUD703,725. The cost includes the design and supply of a 130 m^3/day effluent treatment system with a primary electrocoagulation reactor and secondary electro-advanced oxidation reactor. The quote includes sludge dewatering equipment, an activated glass filtration system and a nano filtration system to reduce salt levels in the wastewater. The system is designed to comply and/or exceed Hunter Water, NSW, Australia Trade Waste Discharge Limits. Installation is not included in the budget estimate (Powell, 2018).

10 SUMMARY OF EC AS MEAT PROCESSING WASTEWATER TREATMENT METHOD

A summary of the advantages and disadvantages of EC are provided below, many of them acknowledged by (Murat, et al., 2014) and (Moussa, et al., 2016):

Advantages

- **EC has multiple contaminant removal capabilities** – studies over the last decade suggest EC is capable of removing around 70-80% of COD (Cerqueira, et al., 2014) and 90% for oil and grease. A recent Australian commercial lab-scale trial indicated at least 90% removal of BOD/COD, 98% of oil and grease and 99% of total suspended solids (Inovin Pty Ltd and Anor, 2018).
- **EC is capable of removing phosphorus** – several studies have reported removal of total phosphorus by up to 99% (Inovin Pty Ltd and Anor, 2018) (Khennoussi, et al., 2013).
- **EC is capable of removing organic nitrogen** – studies have reported removal of up to 50% of organic nitrogen. It is less effective in removing ammonium nitrogen with studies indicating in the order of 15% removal (Inovin Pty Ltd and Anor, 2018) (Bazrafshan, et al., 2012) (Tetreault, 2003).
- **EC is capable of removing pathogens** – Khennoussi et al. found electrocoagulation-floatation enabled a reduction of up to 5 logarithmic units of coliforms and 100% elimination of bacteria. Drougi showed reduction in *E.coli* of 2-4 log units and HAFA (heterotrophic aerobic and facultative anaerobic bacteria) of 1–3 log units.
- There is **less water bound sludge** produced than conventional chemical coagulation (Hamawand, et al., 2017). Moussa et al. reported a 90% reduction in sludge for one full scale application of EC compared with CC (Moussa, et al., 2016).
- **Sludge produced is non-toxic**. Analysis of sludge produced during a lab scale trial indicated that it met local authority guidelines for fertiliser and biosolids, however had elevated salt levels (See Section 5). One study indicated excessively high iron levels, however it is unclear if the results were accurate. This is an important parameter to investigate further.
- **EC requires no or minimal additional chemical** additives compared with chemical coagulation. However, salt addition in some cases is an issue (see below).
- **Treated effluent is clear, colourless and odourless**. Khennoussi et al. reported a 90% reduction in red colouring.
- It is **easy to operate and complete automation is possible**.

- Short residence times are required with studies indicating 30 minutes to one hour of treatment compared to several days for biological treatment (ponds).
- It can be **designed for any size with minimal footprint**. The footprint of an EC plant is significantly lower than traditional treatment with biological treatment ponds (less than 25% of the space (Inovin, 2018) making it suitable for space constrained sites.
- **Operates on a low current** with potential to **use renewable power** sources (Tones, 2015).

Disadvantages

- **Sacrificial anodes** (typically Fe or Al based) need to be replaced regularly
- **Cathode passivation** can reduce the effectiveness of EC units
- The process **requires minimum conductivity** which is addressed through **salt addition**. This produces a salty effluent stream that affects reuse options and be in excess of environmental license requirements depending on the receiving environment (Inovin Pty Ltd and Anor, 2018). Additional treatment may be required (membranes) to remove salt.
- **Operating costs can be high if electricity is expensive**, however there is potential to incorporate solar PV (Tones, 2015).

There is limited publicly available research and data on the costs of full-scale electrocoagulation systems for treating meat processing waste compared with other treatment technologies. A number of lab and pilot scale studies vary significantly and are inconclusive in making comparisons (Section 9.2). (Moussa, et al., 2016) cites five studies comparing EC and CC for the treatment of various full-scale industrial waste streams and in each of these, chemical coagulation was at least 2-3 times higher with one study as much as 35 times higher (See Section 9.2).

11 CONCLUSION

Electrocoagulation is a proven wastewater treatment technology with numerous examples of its use around the world for the treatment of industrial strength wastewater. Lab and full-scale trials have shown it is capable of removing contaminants from meat processing wastewater including up to and greater than 90% for BOD/COD, oil and grease and phosphorus. It is capable of removing organic nitrogen (up to 50%) but less effective in removing ammonium nitrogen (15%).

Two recent lab scale trials of meat processing wastewater have provided good results with wastewater quality meeting the majority of local water authority discharge limits. However, the addition of salt to aid the EC process produces a salty wastewater stream, which exceeds discharge limits. In this case, additional treatment is required to remove the salt via membrane filtration adding to the capital and operating costs of the system.

One lab scale trial analysed the quality of sludge produced from EC and found that it met local biosolids and fertiliser guidelines for all components. However, again, it contained high salt levels, which has an impact of the use of this sludge for land application. A solution would be to mix the sludge with other fertilising products before it is applied to the land to dilute salt levels. The question of Fe and Al concentrations in sludge and suitability for direct land application is inconclusive and requires further investigation. Potentially high concentrations can be managed through blending with other materials.

There is some research on the cost effectiveness of operating electrocoagulaton for meat processors, however, much of this is lab or pilot scale and inconclusive when compared with the cost of chemical coagulation. However, there is additional research on cost effectiveness of full-scale electrocoagulation compared with chemical coagulation for other non-meat processing waste streams with results that CC is consistently at least 2-3 times higher to operate with some studies in excess of 10 times higher. Electricity pricing is a very important factor and has a high impact on operational costs as does cost of electrode replacement and sludge disposal.

Electrocoagulation is a possible alternative to the treatment methods traditionally used for red meat processors i.e. chemical coagulation followed by biological treatment (anaerobic and aerobic ponds). It is a quicker process and has a relatively small footprint and produces significantly less sludge. A disadvantage is that, unlike anaerobic treatment, there is no generation of biogas, which is a potential energy source. Further research is required on the actual full-scale operating costs of EC for meat processing wastewater and its comparison with traditional (biological) treatment methods.

12 BIBLIOGRAPHY

Adhoum, N., Monser, L., Bellakhal, N. & Belgaied, J., 2004. Treatment of electroplating wastewater containing Cu2 +, Zn2 + and Cr(VI) by electrocoagulation.. *Journal of Hazardous Materials,* Volume 112, p. 207–213.

Aguilar, M. et al., 2002. Nutrient removal and sludge production in the coagulation–flocculation process. *Water Research,* 36(11), pp. 2910-2919.

Ahmadian, M. et al., 2012. Kinetic study of slaughterhouse wastewater treatment by electrocoagulation using Fe electrodes. *Water Science and Technology,* 66(4), pp. 754-760.

Al-Shaikhli, S., 2013. *Optimisation of Coagulation/Flocculation Process Using Natural Coagulants in Raw Water Treatment,* s.l.: The University of Southern Queensland, Toowoomba, Australia.

Aoudj, S., Khelifa, A. & Drouiche, N., 2017. Removal of fluoride, SDS, ammonia and turbidity from semiconductor wastewater by combined electrocoagulationeelectroflotation. *Chemosphere,* Issue 180, pp. 379-387.

Asselin, M., Drogui, P., Benmoussa, H. & Blais, J., 2008. Effectiveness of electrocoagulation process in removing organic compounds from slaughterhouse wastewater using monopolar and bipolar electrolytic cells. *Chemosphere,* Volume 72, pp. 1727-1733.

Bande, R., Prasad, B., Mishra, I. & Wasewar, K., 2007. Oil field effluent water treatment for safe disposal by electroflotation. *Chemical Engineering,* Volume 137, p. 503–509.

Barrera-Díaz, C., Bilyeu, B., Roa-Morales, G. & Balderas-Hernández, P., 2008. A comparison of iron and aluminium electrodes in hydrogen peroxide-assisted electrocoagulation of organic pollutants. *Environmental Engineering Science,* 25(4), pp. 529-537.

Barrera-Diaz, C. et al., 2006. Electrochemical treatment applied to food processing industrial wastewater. *Industrial and Engineering Chemistry Research,* 45(1), pp. 34-38.

Bayar, S., Yıldız, Y., Yılmaz, A. & Irdemez, S., 2011. (2011) The effect of stirring speed and current density on removal efficiency of poultry slaughterhouse wastewater by electrocoagulation method.. *Desalination,* Volume 280, pp. 103-107..

Bayar, S., Yildiz, Y., Yilmaz, A. & Koparal, A., 2014. The effect of initial pH on treatment of poultry slaughterhouse wastewater by electrocoagulation method.. *Desalination Water Treatment,* Volume 52, pp. 3047-3053..

Bazrafshan, E. et al., 2012. Slaughterhouse Wastewater Treatment by Combined Chemical Coagulation and Electrocoagulation Process. *PLoS ONE,* 7(6), p. e40108.

Boeriu, L., Cirstolovean, L., Fratu, M. & Nastac, C., 2013. The Tertiary Treatment Stage Of Wastewater. *Bulletin of the Transilvania University of Braşov,* 6(55), pp. 207- 212.

Budiyono, W. & Johari, S., 2010. Study on treatment of Slaughterhouse wastewater by Electro-coagulation technique. *International Journal of Science and Engineering,* Volume 1, pp. 25-28.

Bustillo-Lecompte, C. & Mehrvar, M., 2017. Chapter 8: Slaughterhouse Wastewater: Treatment, Management and Resource Recovery. In: *Physico-Chemical Wastewater Treatment and Resource Recovery.* s.l.:Z. IntechOpen.

Butler, B., 2018. *Struvite or Traditional Chemical Phosphorus Precipitation – What Option Rocks?.* s.l.:AMPC.

Caňizares, P. et al., 2009. The pH as a key parameter in the choice between coagulation and electrocoagulation for the treatment of wastewaters. *Journal of Hazardous Materials,* Volume 163, pp. 158-164.

Cantisano, A., n.d.. *Know your soil: A handbook for organic growers and gardeners in temperature and sub-tropical regions.* [Online] Available at: siteresources.worldbank.org/INTARD/927371-1112696905204/20434336/knowyoursoil.pdf
[Accessed 16 9 2018].

Cerqueira, A., Souza, P. & Marques, M., 2014. Effects of direct and alternating current on the treatment of oily water in an electroflocculation process. *Brazilian Journal of Chemical Engineering,* 31(3), pp. 693 - 701.

Chan, Y., Chong, M., Law, C. & Hassell, D., 2009. A review on anaerobic-aerobic treatment of industrial and municipal wastewater.. *Chemical Enegineering,* Volume 155, p. 1e2.

Chen, G., 2004. Electrochemical technologies in wastewater treatment. *Separation and purification technology,* 38(1), pp. 11-41.

Coe, R., 2018. *Personal communication, Operations Manager, Alexander Downes Meats, Kurri Kurri, NSW.* s.l.:s.n.

Comninellis, C. & Chen, G., 2009. *Electrochemistry for the Environment.* New York: Springer.

Dillon, P., n.d. *Meat Update - Water reuse in the meat industry—Opportunities and issues.* s.l.:s.n.

Drogui, P., Asselin, M., Brar, S. & Benmouusa, H., 2008. Electrochemicalremoval of pollutants from agro-industry wastewaters. *Separation and Purification Technology,* 61(3), p. 301–310.

Dvořák, L., Gómez, M., Dolina, J. & Černín, A., 2016. Anaerobic membrane bioreactors—a mini review with emphasis on industrial wastewater treatment:applications, limitations and perspectives, Desalination and Water Treatment. *Desalination and Water Treatmen,* 57(41), pp. 19062-19076.

Emamjomeh, M. & Sivakumar, M., 2009. ., (a), Review of pollutants removed by electrocoagulation and electrocoagulation/flotation processes. *Journal of Environmental Management,* Volume 90, p. 1663–1679.

Eryuruk, K., Tezcan, U. & Bakir Ogutveren, U., 2011. *Treatment of Cattle-Slaughterhouse Wastewater Using Tubular Electrocoagulator.* Singapore, IPCBEE.

Eyvaz, M., 2016. Treatment of Brewery Wastewater with Electrocoagulation: Improving the Process Performance by Using Alternating Pulse Current. *International Journal fo Electrcochemical Science,* Volume 11, p. 4988 – 5008.

Eyvaz, M., Gürbulak, E. & Kara, S., 2014. Preventing of Cathode Passivation/Deposition in Electrochemical Treatment Methods – A Case Study on Winery Wastewater with Electrocoagulation. In: *Modern Electrochemical Methods in Nano, Surface and Corrosion Science.* s.l.:Intech.

Fayad, N., 2017. *The application of electrocoagulation process for wastewater treatment and for the separation and purification of biological media,* s.l.: Chemical and Process Engineering, Université Clermont Auvergne.

Fredheim, L., 2018. *Oil and Grease Value Assessment Tool.* s.l.:AMPC.

Gaurina-Medjimurec, N., 2015. *Handbook of Research on Advancements in Environmental Engineering.* US: Engineering Science Reference.

GHD Pty Limited , 2003. *Assessment of hydrocyclones for fat removal from meat processing wastewater streams,* s.l.: MLA.

GHD Pty Ltd, 2015. *Trickling Filter Technology for Treating Abattoir Wastewater,* s.l.: AMPC.

Ghernaout, D. & Ghernaout, B., 2012. Sweep flocculation as a second form of charge neutralisation—a review. *Desalination and Water Treatment,* 44(1-3), pp. 15-28.

Ghernaout, D., Naceur, M. & Ghernaout, B., 2011. A review of electrocoagulation as a promising coagulation process for improved organic and inorganic matters removal by electrophoresis and electroflotation. . 28,. *Desalination water Treatment,* 28(1-3), pp. 287-320.

Gutiérrez-Sarabia, A. et al., 2004. Slaughterhouse wastewater treatment in a full-scale system with constructed wetlands.. *Water Environment Research,* 76(4), p. 334–343.

Hamawand, I. et al., 2017. A Critical Review on Processes and Energy Profile of the Australian Meat Processing Industry. *Energies,* 10(731).

Harif, T., Khai, M. & Adin, A., 2012. Electroaguation verses chemical coagulation: Coagulation/flocuation mechanisms and resulting floc characteristics. *Water Research,* Volume 46, pp. 3177-3188.

Holt, P., Barton, G. & Mitchell, C., 1999. *Electrocoagulation as a wastewater treatment.* Castlemaine, Victoria, s.n.

Huitle, C., Rodrigo, M. & Scialdone, O., 2018. *Electrochemical Water and Wastewater Treatment.* s.l.:Elsevier Science & Technology.

Inovin Pty Ltd and Anor, 2018. *P.PIP.0567 - Evaluation of an Electro-Coagulation/Electro-Advanced Oxidation Technology for removing Total Phosphate from Abattoir Effluent,* s.l.: MLA.

Inovin, 2018. *Inovin Water Miner - Electrocoagulation Technology Brief - Commercial Brochure,* www.inovin.com.au: Inovin.

Jensen, P., Huelsen, T., Batstone, D. & Keller, J., 2013. *Review and evaluation of the application of anaerobic ammonium removal technology for wastewater treatment,* s.l.: MLA & AMPC.

Jensen, P. et al., 2015. Anaerobic membrane bioreactors enable high rate treatment of slaughterhouse wastewater. *Biochemical Engineering Journal,* Volume 97, pp. 132-141.

Johns Enironmental and The Ecoefficiency Group, 2017. *Wastewater Management in the Australian red meat processing industry,* s.l.: AMPC.

Johns, M., Harrison, M., Hutchinson, P. & Beswick, P., 1995. Sources of nutrients in wastewater from integrated cattle slaughterhouses. *Water Science and Technology,* 32(12), pp. 53-58.

Kabdasli, I., Arslan-Alaton, I., Olmerz-Hanci, T. & Tunay, O., 2012. Electrocoagulation applications for industrial wastewaters: a critical review. *Environmental Technoogy Review,* 1(1), pp. 2-45.

Khennoussi, A., Chaouch, M. & Chahlaoui, A., 2013. Treatment of the effluent from a red meat slaughterhouse by electrocoagulation flotation with iron electrodes. *Revue des Sciences de l'Eau,* 26(2), pp. 135-150.

Koparal, A. & Öğütveren, U., 2002. Removal of nitrate from water by electroreduction and electrocoagulation. *Journal of Hazardous Materials,* 89(1), pp. 83-94.

Kostel, J., date unknown. *How do wetlands remove nutrients.* [Online] Available at: http://www.wetlands-initiative.org/nutrient-removal/ [Accessed 12th Sept 2018].

Kumar, M. et al., 2009. Treatment of bio-digester effluent by electrocoagulation using iron electrodes. *Journal of Hazardous Materials,* 165(1), pp. 345-352.

L, G. & Büyükgüngör, H., 2011. Treatment of slaughterhouse plant wastewater by using a membrane bioreactor. *Water Science and Technology,* 64(1), p. 214–219.

Matheyarasu, R., 2015. *Nutrient management in abattoir wastewater irrigated soils.* s.l.:University of South Australia.

Mechelhoff, M., 2008. *Aluminium electochemistry in electrochemical reactors,* s.l.: Imperial College London.

Mittal, G., 2006. Treatment of wastewater from abattoirs before land application—A review. *Bioresource Technology ,* Volume 97, p. 1119–1135.

MLA and AMPC, 2010. *Meat Technology Update.* s.l.:s.n.

MLA, 2003. *Assessment of hydrocyclones for fat removal from meat processing wastewater,* s.l.: s.n.

Mollah, E., Schennach, R., Parga, J. & Cocke, D., 2001. Electrocoagulation (EC) — science and applications. *Journal of Hazardous Materials,* 84(1), pp. 29-41.

Mook, W. et al., 2012. Removal of total ammonia nitrogen (TAN), nitrate and total organic carbon (TOC) from aquaculture wastewater using electrochemical technology: A review. *Desalination,* Volume 285, pp. 1-13.

Moussa, D., El-Naas, M., Nasser, M. & Al-Marri, M., 2016. A comprehensive review of electrocoagulation for water treatment: Potentials and challenges. *Journal of Environmental Management,* pp. 1-18.

Murat, E., Gurbulak, E., Kara, S. & Yuksel, E., 2014. Preventing of cathodpassivation/deposition in electrochemical treatment methods - A case study on winery wastewater with elecrocoagulation. In: *Modern Electrochemical Methods in Nano, Surface and Corrosion Science.* s.l.:Intech.

Ndjomgoue-Yossa, A., Nanseu-Njiki, C., Kengne, I. & Ngameni, E., 2015. Effect of electrode material and supporting electrolyte on the treatment of water containing Escherichia coli by electrocoagulatio. *nternational Journal of Environmental Science and Technology,* Volume 12, p. 2103–2110.

Nguyen, D. et al., 2016. Can electrocoagulation process be an appropriate technology for phosphorus removal from municipal wastewater?. *Science of the Total Environment,* Volume 563-564, p. 549–556.

Nguyen, D. et al., 2017. Influences of operational parameters on phosphorus removal in batch and continuous electrocoagulation process performance. *Environmental Science and Pollution Research,* 24(32), pp. 25441-25451.

Nwabanne, J. & Obi, C., 2017. Abattoir Wastewater Treatment by Electrocoagulation Using Iron Electrodes. *Der Chemica Sinica,* 8(2), pp. 254-260.

Nwabanne, J. & Obi, C., 2017. Abattoir Wastewater Treatment by Electrocoagulation Using Iron Electrodes. *Der Chemica Sinica,* 8(2), pp. 254-260.

Orssatto, F. et al., 2017. Optimization of the pretreatment of wastewater from a slaughterhouse and packing plant through electrocoagulation in a batch reactor. *Environmental Technology,* 38(19), pp. 2465-2475.

Ozyonar, F. & Karagozoglu, B., 2014. Investigation of technical and economic analysis of electrocoagulation process for the treatment of great and small cattle slaughterhouse wastewater. *Desalination and Water Treatment,* 52(1-3), pp. 74-87.

Pagan, R., Renouf, M. & Prasad, P., 2002. *Ecoefficiency Manual for Meat Processing,* s.l.: Meat and Livestock Australia.

Picard, T., Cathalifaud-Feuillade, G., Mazet, M. & Vandensteendam, C., 2000. Cathodic dissolution in the electrocoagulation process using aluminium electrodes.. *Journal of Environmental Monitoring,* 2(1), pp. 77-80.

Powell, B., 2018. *Evaluation of Electrocoagulation/Electro-Advanced Oxidation Technology for treating meat processing wastewater,* s.l.: AMPC Milestone 2 Report Project No. 2018_1140.

Rivera, F. et al., 1997. The application of the root zone method for the treatment and reuse of high-strength abattoir waste in Mexico. *Water Science and Technolog,* 35(5), pp. 271-278.

Sahu, O., Mazumdar, B. & Chaudhari, P., 2014. Treatment of wastewater by electrocoagulation: a review. *Environmental Science and Pollution Research,* Volume 21, p. 2397–2413.

Suresh, S., 2005. Characteristics of soils prone to iron toxicity and management - A review. *Agricultural Review,* 26(1), pp. 50-58.

Tetreault, A., 2003. *PRENV.011 - Electrocoagulation Process for Wastewater Treatment ,* s.l.: MLA and EC Pacific Pty Ltd.

Tezcan Ün, Ü., Koparal, A. & Bakir Öğütveren, Ü., 2009. Hybrid processes for the treatment of cattle-slaughterhouse wastewater using aluminum and iron electrodes. *Journal of Hazardous Materials,* 164(2), pp. 580-586.

The Ecoefficiency Group, 2017. *Water Recycling in the Australian Meat Processing Industry – a review. The Ecoefficiency Group. Prasad, P. Price, N. Gaffel, J. Johns, M.,* s.l.: AMPC, Project 2016-1034.

Tones, A., 2015. *Estudo da aplicação da técnica de eletrofloculação na remoção da cor em misturas de corantes têxteis,* s.l.: s.n.

US EPA, 2004. *Technical Development Document for the Final Effluent Limitations Guidelines and Standards for the Meat and Poultry Products Point Source Category (40 CFR 432),* s.l.: s.n.

Vasudevan, S., Lakshmi, J. & Sozhan, G., 2001. Effects of alternating and direct current in electrocoagulation process on the removal of cadmium from water. *Journal of Hazardous Materials,* 192(1), pp. 26-34.

Warnecke, M., Farrugia, T. & Ferguson, C., 2008. *Review of abattoir water usage reduction, recycling and reuse,* s.l.: AMPC & MLA.

Wong, H., Shang, C., Cheung, Y. & Chen, G., 2002. *Chloride assisted electrochemical chemical disinfection..* Taiwan, s.n.

Zang, Z. et al., 2015. The behaviour of dissolution/passivation and the transformation of passice films during electrocoagulation: influences of initial pH, Cr(IV) concentratios and alternative pulse current. *Electrochimica Acta,* Volume 153, pp. 149-153.

Zhou, J., Wandera, D. & Husson, S., 2015. Mechanisms and control of fouling during ultrafiltration of high strength wastewater without pretreatment.. *Journal of Membrane Science,* Volume 488, p. 103–110.