


Treatment of poultry slaughterhouse wastewater using electrocoagulation: a review

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ABSTRACT

Poultry slaughterhouses are generally large consumers of fresh water, which is exhausted as wastewater characterized by a high concentration of biological oxygen demand (BOD), chemical oxygen demand COD, and fats, oil, and grease (FOG). Cost-effective methods are required for the treatment of poultry slaughterhouse wastewater, with the aim of attaining a high quality effluent that can be reused in industrial processes to promote sustainability. As compared to conventional treatment methods, electrocoagulation is an efficient and low-cost system. Electrocoagulation is environmentally friendly, treating wastewater without the need of chemicals, thus limiting secondary pollution. The metal anodes initiate electrochemical reactions for coagulation and flocculation. Its distinct advantages include compact installation and simple operation. This paper offers a comprehensive review of recent literature that has been dedicated to utilizing electrocoagulation for poultry slaughterhouse wastewater treatment. This paper also examines aspects such as theory, potential applications, current applications, as well as economical assessment of the technique.

Key words: efficiency, electrocoagulation, operating parameters, poultry slaughterhouse wastewater

HIGHLIGHTS

- Electrocoagulation combined with other processes achieves a high-quality effluent.
- Innovative technologies have not been thoroughly explored for electrocoagulation process in poultry slaughterhouse wastewater treatment.
- Recommendations have been offered for promising research areas in electrocoagulation.

INTRODUCTION

Poultry meat is a popular food item in most countries. It is a relatively affordable and nutritious protein source. Due to its popularity, the poultry meat sector continues to grow and industrialize in many parts of the world (Mottet & Tempio 2017). In South Africa, the poultry meat sector has also advanced alongside the global trends as it is regarded as the largest commercial poultry meat producer in Africa (Nkukwana 2018). This activity is associated with high economic gains but, similar to any other food-processing activities, poultry processing is water-intensive, consuming about 26.5 litres per bird (Avula *et al.* 2009; Paulista *et al.* 2018; Williams *et al.* 2019). The potable water is required for various operations (stunning and slaughtering; de-feathering; evisceration; trimming and carcass washing; de-boning; chilling; cleaning and waste disposal) as shown in Figure 1 (Bustillo-Lecompte & Mehrvar 2017; Njoya 2017). An equally large amount of this used water is generated as wastewater laden with nutrients, fats, oil and greases (FOG), faeces, carcass debris, blood, feathers, pathogens and traces of heavy metals (Paulista *et al.* 2018; Terán Hilares *et al.* 2021).

While poultry processing plants generate meat supply and useful by-products, the discharge of raw and improperly treated poultry slaughterhouse wastewater (PSW) can have serious environmental implications as well as increase health hazard risks to animals and human beings (Njoya *et al.* 2019). PSW entering ground and surface water lead to oxygen depletion which destroys aquatic life, while nitrogen and phosphorus may prompt

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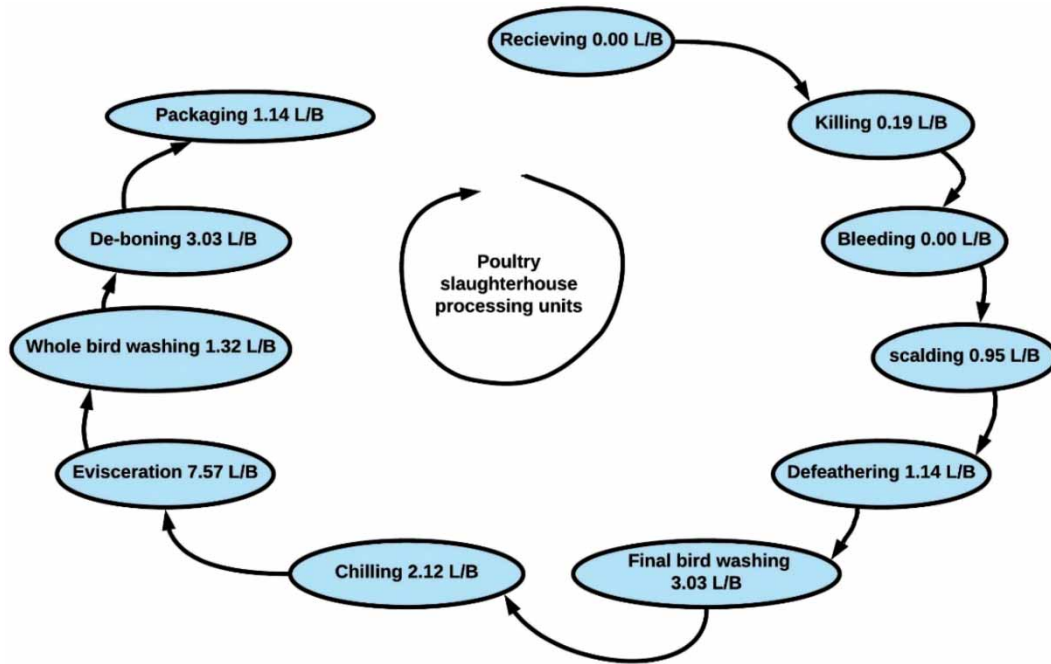


Figure 1 | Water consumption in poultry slaughterhouses, quantified in litres per bird (L/B), adapted from Njoya (2017).

eutrophication, and also turn water sources into bacteria-laden public health hazards (Yaakob *et al.* 2018; Njoya *et al.* 2019). Furthermore, due to the recent droughts and their expected recurrence in the future, water and wastewater management at poultry processing plants is a critical factor that can contribute to mitigating adverse effects by reducing potable water usage and also promote water reuse (Basitere *et al.* 2020).

PSW is generally treated by a variety of biological, chemical and physical processes. Most of these methods are only responsible for treating PSW adequate for discharge to the environment without recycling (Fatima *et al.* 2021). Land application is one of the treatment methods after preliminary treatment for PSW involving biodegradable materials. However, this process depends on climate change and may contaminate soil and groundwater (Bustillo-Lecompte & Mehrvar 2015). Anaerobic or aerobic treatment methods are cost-effective and capable of operating under natural conditions; however, the presence of FOG may greatly inhibit the activity of the microbes (Njoya 2017). Chemical coagulation is very effective in removing fine particles and reducing the time required to settle out suspended solids; however, it requires frequent use of chemical reagents and thus generates secondary pollutants (Moussa *et al.* 2017). Membrane systems are highly effective and steady with high strength wastewater, but require periodic maintenance and high capital investment (Crini & Lichtfouse 2019; Shahedi *et al.* 2020). Table 1 shows the benefits and drawbacks of different treatment technologies for PSW treatment.

Electrocoagulation (EC) has recently been used as an efficient alternative to the available PSW treatment methods (Kobyia *et al.* 2006b). It is an advanced technology that combines the advantages of conventional coagulation, flotation, oxidation and adsorption processes in one stage (An *et al.* 2017; Emerick *et al.* 2020; Tegladza *et al.* 2021). Organic pollutants of poultry processing effluents are degraded via redox reactions using a 'clean reagent' (Ensano *et al.* 2019). EC is also an environmentally benign process, contaminant removal is done with no addition of supplementary chemicals, hence low volumes of sludge and less harmful materials are generated. Lack of additional chemicals also eliminates the detrimental effects of reagents and chemicals usually used in conventional treatment processes (Ensano *et al.* 2019; Emerick *et al.* 2020). It is also characterized by virtue of various benefits including amenability to automation, cost effectiveness, and short treatment time compared to conventional treatment methods (Peralta-Hernández *et al.* 2014; Yildirim *et al.* 2019). However, EC has some major setbacks such as electrode passivation, regular sacrificial anode replacement, and also its application may be limited in countries with higher costs of electricity (Vasudevan 2012; Mousazadeh *et al.* 2021). High electricity costs can be minimized by using renewable energy sources, which allow the use of sustainable technology (Al-Qodah *et al.* 2020).

Table 1 | Main advantages and disadvantages of several poultry slaughterhouse wastewater treatment technologies

Treatment technology	Advantages	Disadvantages	References
Biological treatment	Good removal efficiency can be attained in the system, even at high loading rates and low temperature	Necessary to create an optimally favourable environment	Crini & Lichtfouse (2019), Fard <i>et al.</i> (2019), Rajab <i>et al.</i> (2017)
	The construction and process operation of these reactors are simple	The process start-up takes a long time due to low progress rate of microbes to be active	
Chemical precipitation	Removes ionic substances	Chemical consumption (lime, alum or aluminium sulphate, ferric chloride, polyaluminum chloride and sodium aluminate, and calcium hydroxide)	Terán Hilaes <i>et al.</i> (2021), Prazeres <i>et al.</i> (2019)
	Significant reduction in the chemical oxygen demand and suspended particles	High sludge production, special handling, and further treatment	
Membranes	High effluent quality High volumetric load possible	High operating cost Membrane fouling	Sardari <i>et al.</i> (2018), Fatima <i>et al.</i> (2021), Goswami & Pugazhenthii (2020), Malmali <i>et al.</i> (2018)
Ultrasound	Can degrade toxic organic compounds into small molecules	Regular ultrasound probe replacement	Abdelhay <i>et al.</i> (2020), Emerick <i>et al.</i> (2020), João <i>et al.</i> (2020)
	High efficiency for microorganism inactivation.	Difficult to scale-up	
Advanced oxidation process	Rapid reaction rates Can treat nearly all organic materials	Removal of residual peroxide Complex chemistry tailored to specific pollutants	Davarnejad & Nasiri (2017), Abdelhay <i>et al.</i> (2017)
Electrocoagulation	No addition of chemicals	Regular sacrificial anode replacement	Meiramkulova <i>et al.</i> (2020a), Zarei <i>et al.</i> (2018), Akarsu <i>et al.</i> (2021)
	Able to remove the smallest colloidal particles as the fine charged particles are more easily attracted to the electric field	Formation of deposits of an impermeable film on the surface of the electrodes during electrolysis	
	Low sludge production	High electricity costs	

The objective of this study was to critically review the EC system as a method of treatment for PSW. The treatment background, potentials, emerging challenges, and an update on current research developments are summarized. The techno-economic analysis was analysed to get a clear view for future industrial application for PSW treatment. To conclude, the perspectives for future research and recommendations of EC treatment were discussed including a proposed study for an effective treatment of PSW.

Theoretical background of electrocoagulation technology

EC technology is a treatment process that treats wastewater by applying electric current as the main power source (Zaied *et al.* 2020). Generally, the power supply used in EC is either alternating current (AC) or direct current (DC) (Meiramkulova *et al.* 2020b). From literature, the majority of the studies used the latter as their main power supply (Abdul-Baqi & Thamir 2015; Aljaberi 2018; Nasrullah *et al.* 2019). Several experiments have been carried out proving that EC is the most suitable method to treat wastewater. These wastewaters consist of dyes (Naje *et al.* 2015; Ya *et al.* 2019); bilge water (Asselin *et al.* 2008a); arsenic (Aswathy *et al.* 2016; Thakur & Mondal 2017; Gilhotra *et al.* 2018; Bian *et al.* 2019); tannery (Deghles & Kurt 2016; Thirugnanasambandham & Sivakumar 2016; Jallouli *et al.* 2020; Villalobos-Lara *et al.* 2021); phenol (Vasudevan 2012); oil (Tir & Moulai-Mostefa 2008; Merma *et al.* 2020); heavy metals (Al-Shannag *et al.* 2015; Al-Qodah & Al-Shannag 2017); humic substances (Ulu *et al.* 2014; Hasani *et al.* 2019), and pharmaceuticals (Dindaş *et al.* 2020). EC is also employed for the treatment of agri-food industry wastewater similar to poultry slaughterhouse effluents containing organic matter. These wastewaters could be classified as distillery (Aziz *et al.* 2016); winery (Kirzhner

et al. 2008); brewery (Tejedor-Sanz *et al.* 2017; Papadopoulos *et al.* 2020); baker's yeast (Gengec *et al.* 2012; Al-Shannag *et al.* 2014); molasses (Tsiptsias *et al.* 2015); potato (Koby *et al.* 2006a); dairy (Varank & Sabuncu 2015; Akansha *et al.* 2020); restaurant (Adegoke & Abayomi 2020); and cheese whey (Tirado *et al.* 2018).

In essence, EC is an electrochemical based process in which oxidation and reduction reactions occurs. In its simplest form, it consists of an anode and cathode, commonly aluminium or iron, which are connected to a power source. The electrodes are both submerged in the aqueous solution being treated (Mahtab *et al.* 2009; Shahedi *et al.* 2020). Once current flows, the 'sacrificial' anode, either aluminium or iron, undergoes oxidation to produce metal ions, which act as coagulant agents in the aqueous solution *in situ* (Chaturvedi 2013; Barrera-Díaz *et al.* 2018). Electrolytic gases (H_2 and O_2) are simultaneously generated from the cathode to bring about electroflotation by adhering to agglomerates and carrying them to the water surface (Jame 2012; Chaturvedi 2013). The coagulant species are able to destabilize the suspended organic matter, contaminants, and the colloidal particles present in wastewater and consequently reduce their concentration (Gheraout *et al.* 2019). It is schematically shown in Figure 2. Destabilization is achieved mainly by means of four distinct mechanisms (Vepsäläinen & Sillanpää 2020):

1. Compression of electrical double layer. Increase of counter ion concentration in the bulk solution.
2. Adsorption. Charge neutralization of negatively charged colloids by cationic hydrolysis products.
3. Inter-particle bridging. Polymer chain is absorbed into multiple particles, molecular weight increases.
4. Precipitation. Impurities are trapped and removed in the amorphous hydroxide precipitate produced.

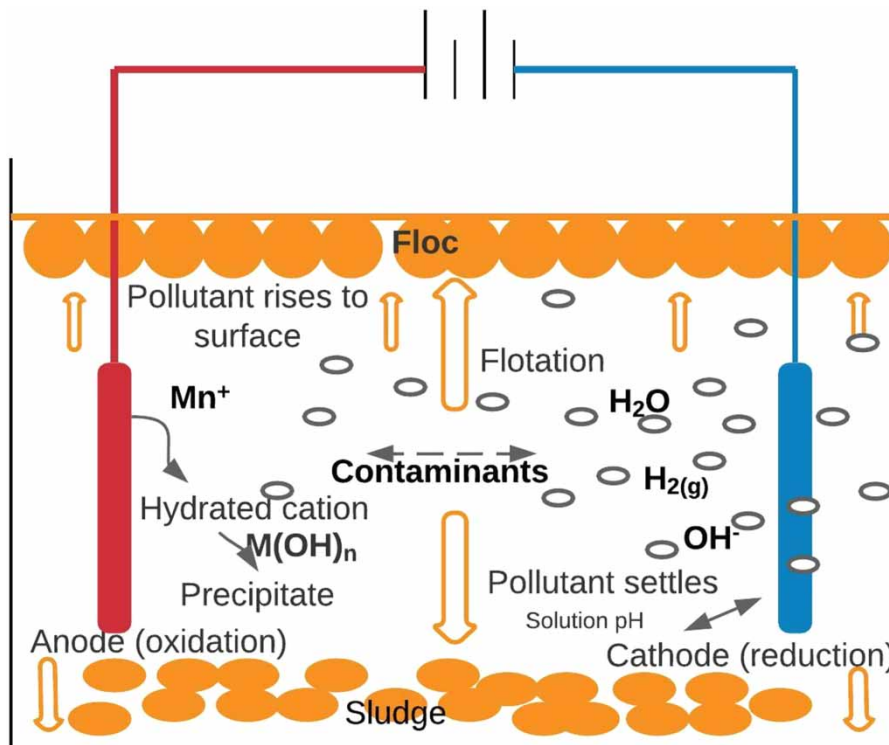


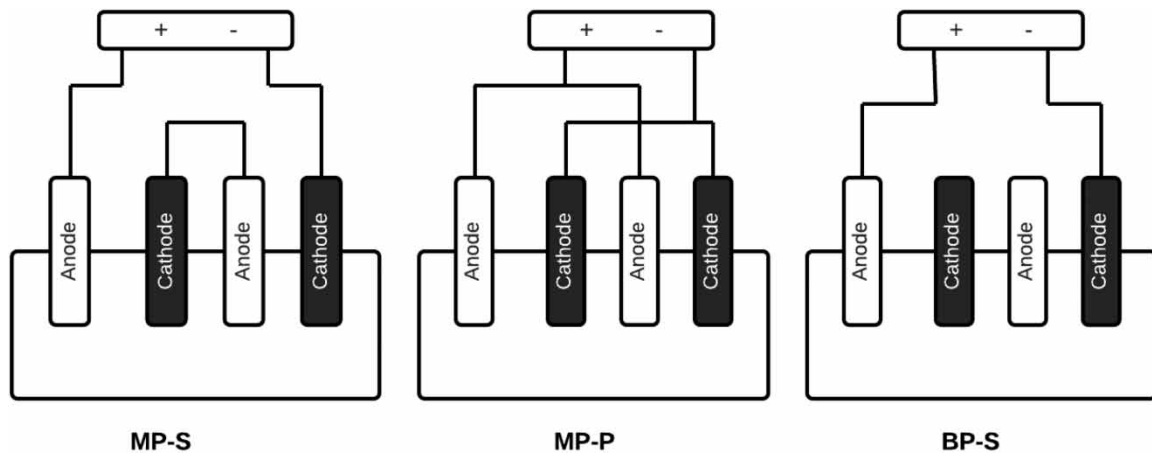
Figure 2 | Interactions occurring within the electrocoagulation reactor, adapted from Chaturvedi (2013).

Aluminium and iron are the widely used electrodes in literature for various wastewater treatments in the EC process because of their increased ion production potentials, availability, low price, and non-toxicity (Al-Qodah & Al-Shannag 2017; Bolisetty *et al.* 2019; Potrich *et al.* 2020; Shahedi *et al.* 2020). Iron may be oxidized into divalent Fe(II), and trivalent Fe(III) forms by atmospheric oxygen or anode oxidation during the coagulation, whereas aluminium oxidizes only in trivalent form Al(III). Further, Fe(II) can oxidize to Fe(III) under appropriate oxidation-reduction potential and pH conditions (Doggaz *et al.* 2018; Vepsäläinen & Sillanpää 2020). The oxidation and reduction reactions in the EC process take place at both electrodes, as shown in Table 2. The presence of oxygen and neutral pH are necessary to achieve a suitable rate of reaction (Chaturvedi 2013; Naje *et al.* 2017).

Table 2 | Chemical reactions at the anode and cathode

Iron electrode	Aluminium electrode
Anodic reactions	Anodic reactions
$Fe \rightarrow Fe^{2+} + 2e^{-}$	$Al \rightarrow Al^{3+} + 3e^{-}$
Cathodic reactions	Cathodic reactions
$2H_2O + 2e^{-} \rightarrow H_2 + 2OH^{-}$	$3H_2O + 3e^{-} \rightarrow \frac{3}{2}H_2 + 3OH^{-}$
Overall	Overall
$Fe + 2H_2O \rightarrow Fe(OH)_2 + H_2$	$Al^{3+} + 3H_2O \rightarrow Al(OH)_3 + 3H^{+}$

Electrode arrangement has an influence on the contaminant removal efficiency as well as the energy consumption cost (Zaied *et al.* 2020). The most distinctive electrode connections are classified into monopolar-serial (MP-S), monopolar-parallel (MP-P), and bipolar series (BP-S) (Ozyonar 2016; Moussa *et al.* 2017). These electrode configurations are shown in Figure 3. In the MP-S connection, the individual couple anode-cathode is linked internally where it is not linked with the outer electrodes, whereas in MP-P connection, particular sacrificial anode is linked with other anode directly; similar arrangements for cathodes also exist. In the BP-S connection, a particular electrode present changed polarity at particular electrode edges which are subjected to the electrode charge (Moussa *et al.* 2017). The bipolar electrodes assembly is in serial connection at all times (Zaied *et al.* 2020).

**Figure 3** | Different configurations of electrodes, adapted from Moussa *et al.* (2017).

Various studies in literature have investigated the effect of electrode orientation on the EC process and it has been found that the orientation variation of the electrodes have different impacts on the EC process depending on the targeted pollutant (Zaied *et al.* 2020). A vast majority of researchers have used vertical orientation of electrodes in EC treatment such as PSW (Meiramkulova *et al.* 2019), organics removal from bilge water (Aswathy *et al.* 2016), and nitrate removal from water solution (Al-Marri *et al.* 2020). Some researchers have also conducted comparative assessments between horizontal and vertical electrode orientation; for example, for removal of chromium (Kamar *et al.* 2018), and oil separation from wastewater (Fadali *et al.* 2016). Recently, Nasrullah *et al.* (2018) investigated various types of electrode design to treat palm oil mill effluent using high current intensity application in the EC process. The different designs were vertical electrode orientation, horizontal electrode orientation with the anode at the bottom and horizontal electrode orientation with the anode at the top, as shown in Figure 4. The highest removal efficiency was achieved by selecting vertical orientation, MP-S arrangement obtaining 74% COD, 70% BOD and 66% SS. Although the MP-S arrangement had a higher removal efficiency, an economic assessment showed that it had higher operating costs than the MP-P and BP arrangement.

Electrocoagulation reactor design and operation

Although EC has been used for a considerable number of years to successfully treat water and wastewater, the available literature does not give a systematic approach in the design and operation of EC reactors (Holt *et al.* 2005). Reactor design is an essential factor for the chemical interaction and treatment process of EC. Operational

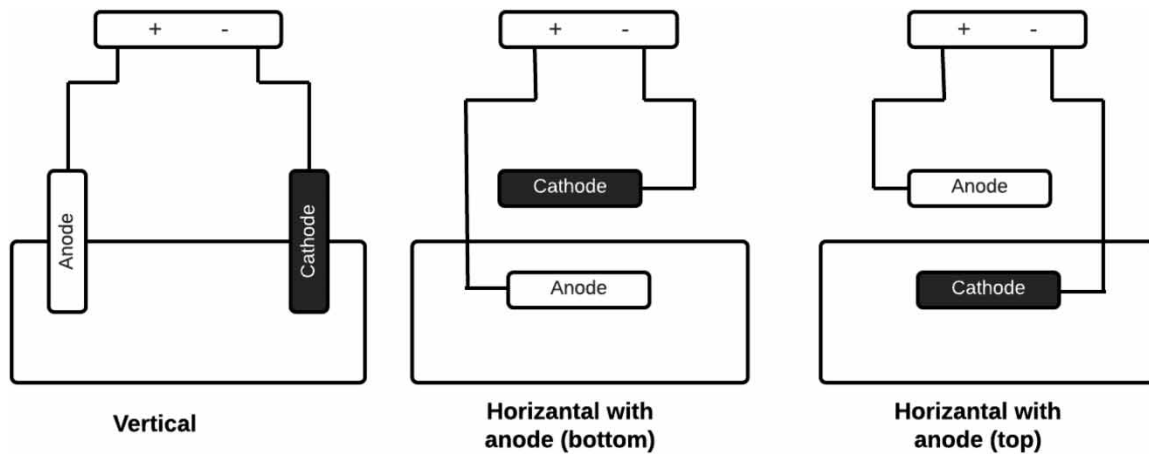


Figure 4 | Different modes of electrode orientation, adapted from Nasrullah *et al.* (2018).

parameters such as bubble path, flotation effectiveness, floc formation, fluid flow regime, and mixing or settling characteristics are affected by the reactor design (Sahu *et al.* 2014; Kobyas *et al.* 2020). It is therefore difficult to compare the performance of the reactors (Moussa *et al.* 2017). From the available literature, the EC reactor designs may be classified as shown in Figure 5. The EC reactor can be operated in batch as well as continuous mode, these configurations are the first distinction between the alternative designs of the reactor (Sahu *et al.* 2014; Carmona-Carmona *et al.* 2020; Rodrigues *et al.* 2020). From the classification of the electrocoagulation system, it is clear that the majority of applications fall into the latter category.

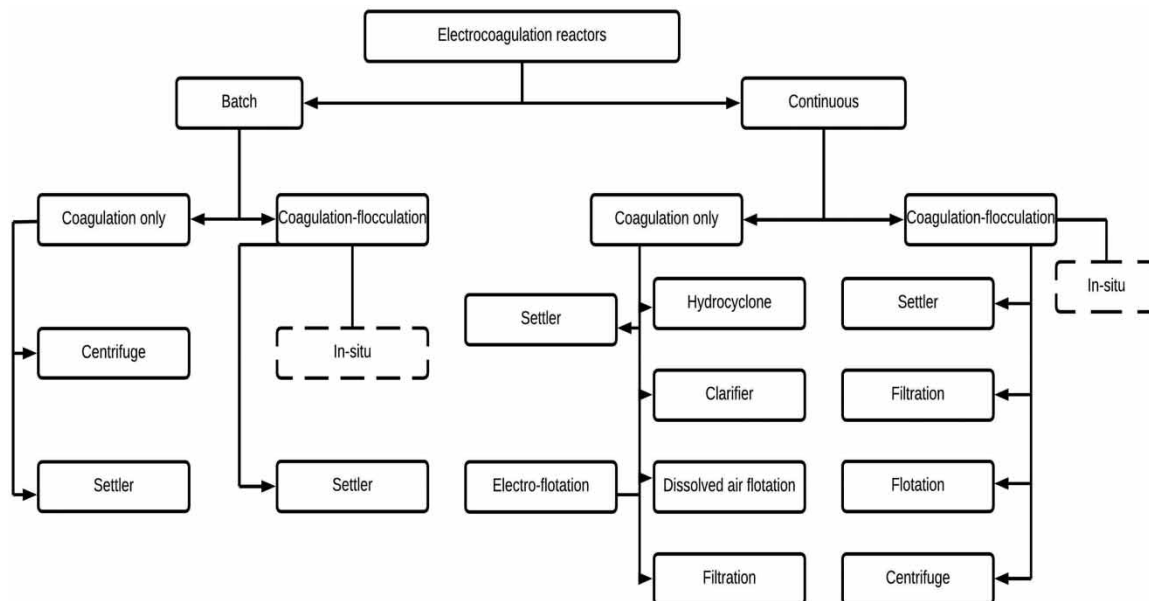


Figure 5 | Classification of electrocoagulation systems, adapted from Holt *et al.* (2005).

Continuous systems have a continuous feed of wastewater and operate under (pseudo) steady-state conditions, with a constant pollutant concentration and effluent flowrate. Continuous systems are better suited for industrial processes such as water treatment plants that require high production rates (Holt *et al.* 2005; Naje *et al.* 2017). Batch reactor applications on the other hand are flowless processes that operate with a fixed wastewater volume per treatment cycle (Al-Shannag *et al.* 2014). The use of batch reactors is to study the effect of operating parameters (Naje *et al.* 2017). The disadvantage is that the conditions within the reactor change with time, as the coagulant is produced in the reactor with the anode dissolution (Mollah *et al.* 2004). Batch reactors are used

at the laboratory scale and in scientific research. According to Mousazadeh *et al.* (2021), most of the EC treatments are based on systems in batch mode, and only in recent years are researchers turning their attention to continuous systems. The continuous system has become more economical than the batch and more adequate in the production system (Naje *et al.* 2017).

Poultry slaughterhouse wastewater characteristics

The composition of wastewater generated from poultry processing plants is complex and considered as high strength wastewater (Basitere 2017; Terán Hilaes *et al.* 2021). The main pollutant in PSW is organic matter, which mostly originates from poultry blood (Bazrafshan *et al.* 2012). The detergents and disinfectants used for sanitization and cleaning purposes add to the complexity, representing about 18–20% of the total wastewater generated (Bustillo-Lecompte & Mehrvar 2017; Terán Hilaes *et al.* 2021). The composition generally depends on various factors such as the size of the slaughterhouse, the type of bird slaughtered, the processing loads and the method of operation used (Yaakob *et al.* 2018; Aziz *et al.* 2019; Akarsu *et al.* 2021). The variability of the diverse composition of PSW characteristics can be seen in Table 3.

Table 3 | Poultry slaughterhouse effluent characteristics reported in literature

Parameters	Units	Debik & Coskun (2009)	Yordanov (2010)	Rajakumar <i>et al.</i> (2011)	Rajab <i>et al.</i> (2017)	Basitere <i>et al.</i> (2019)
Chemical Oxygen Demand (COD)	mg/L	2,360,49	3,610–4,188	–	2,711 ± 487	5,126 ± 2,534
Total Chemical Oxygen demand (TCOD)	mg/L	–	–	3,000–4,800	–	–
Biochemical Oxygen Demand (BOD5)	mg/L	–	1,900–2,200	750–1,890	930 ± 96	2,477 ± 1,347
Soluble Chemical Oxygen Demand (SCOD)	mg/L	590,3	–	1,030–3,000	–	–
Fat, oil and grease (FOG)	mg/L	535,33	289–389	–	281 ± 63	715 ± 506
Volatile Fatty Acids (VFA)	mg/L	–	–	250–540	–	375 ± 213
Total alkalinity (CaCO ₃)	mg/L	185,25	–	600–1,340	160 ± 21	499 ± 158
Total Nitrogen (TN)	mg/L	–	–	–	153 ± 32	–
Nitrate	mg/L	–	–	–	–	3,33 ± 4,45
Phosphate	mg/L	–	–	–	51 ± 2	38 ± 6
Total Solids (TS)	mg/L	1,594,66	–	–	–	–
Total Suspended Solids (TSS)	mg/L	–	2,280–2,446	–	835 ± 162	1,654 ± 1,695
Total Dissolved Solids (TDS)	mg/L	515	–	–	917 ± 135	1,138 ± 294
Total Volatile Solids (TVS)	mg/L	1,386	–	–	–	–
Ammonium (AM)	mg/L	–	–	–	85 ± 32	216 ± 56
pH	–	6,17	–	7–7,6	6,8 ± 0,2	6,13–7,24
Turbidity	NTU	–	–	–	>1,000	719 ± 201
Electrical conductivity	mS/cm	–	–	–	0,8 ± 0,109	1,6 ± 0,414
Salinity	mg/L	–	–	–	–	916 ± 179

– Not reported.

Various approaches have been implemented by many countries to properly manage industrial effluent discharges ranging from pollution prevention, end of pipe treatment methods and legislative control based on effluent standards (Ntuli 2012). The latter has been largely used by municipalities and other administrative bodies as a pollution control tool (Bustillo-Lecompte & Mehrvar 2017; Aziz *et al.* 2019; Basitere *et al.* 2019). In South Africa, the national standards and tariffs for water services are provided by local municipalities as per the rules set out by the Water Services Act (Republic of South Africa, 1998). Pollution prevention also contributes to protecting water resources, where a person responsible for polluting a water resource is responsible to cover the costs of remediating the pollution (Harpe & Ramsden 2000).

Electrocoagulation process for poultry slaughterhouse wastewater contaminants removal

In the last two decades, the EC process has been applied to remove pollutants from PSW wastewater. According to Meiramkulova *et al.* (2020b), the parameters commonly used to describe PSW are COD, BOD, and FOG, TSS, TN, TP, and pathogens. COD is an important measurement of the amount of organic pollutants in wastewater; a high concentration of COD suggests a large amount of oxidizable soluble and particulate organic matter in the wastewater. Similarly, BOD indicates the amount of dissolved oxygen (DO) consumed by biological organisms and a high BOD level also signifies large quantities of organic matter in wastewater (Fatima *et al.* 2021). In Table 4, a summary of published results of PSW treatment using the EC process is shown. It is clear from Table 4 that the EC process has been successfully used to remove the most abundant organic matter found in PSW. The removal efficiency in these studies is relatively high; it can be noted that EC has multiple contaminant removal capabilities with COD above 80% and FOG above 90% of the mentioned studies. EC is capable of removing phosphorus, Combatt *et al.* (2017) found the EC process to be suitable for the treatment of PSW with 99% phosphorus removal. EC is also capable of removing organic nitrogen, Potrich *et al.* (2020) examined the performance of EC for nutrient removal in slaughterhouse wastewater. Removal efficiencies of up to 97% BOD, 93% COD, 84% TN, and 81% TSS were achieved. PSW is also contaminated with a variety of pathogenic microorganisms such as faecal coliforms and *Escherichia coli*, *Salmonella* and *Shigella* bacteria, parasite eggs, amoebic cysts and *Streptococcus* bacteria, which mainly originate from faeces and cleaning of guts and pose a threat to human beings and the environment. In a study conducted by Meiramkulova *et al.* (2020b), EC was found to be efficient in microbial inactivation with approximately 63.95–99.83% of microbes removed by the EC unit. In these results, the PSW is completely purified and the residual traces of hydroxides (aluminium/iron) in the treated water are within the standard discharge limits. The sludge produced is also non-toxic, which indicates that EC is a powerful treatment process for organic matter, nutrients and pathogens that are difficult to effectively remove by conventional methods. Table 4 also shows that Al–Al, Fe–Fe, or Al–Fe are the most used pairs of electrodes. This could be attributed to the fact that both Fe and Al are affordable, non-toxic, and excellent electricity conducting materials. In addition, the previous studies were conducted in an acidic medium.

Electrocoagulation process parameters

Several operational parameters as shown in Figure 6, which have an impact on the performance of the EC process for the removal of PSW contaminants. These parameters are discussed in the section below.

Initial pH

pH is described as an influencer for the contaminant distribution and coagulants produced in the EC process (Zaied *et al.* 2020). According to Mousa & Hadi (2016), the initial pH affects the conductivity of the wastewater and electrode dissolution. The pH of the wastewater changes during the operating process and this change depends on the type of electrode material and on initial pH (Aziz *et al.* 2016). Generally, PSW has a neutral pH of values between (4.9 and 8.1) with a mean pH of 6.9. Due to this, pH adjustment is generally not required in PSW treatment (Hamawand *et al.* 2017). In a study by Kobya *et al.* (2006b) EC was used to treat PSW, an initial pH of 6.7 yielded a removal efficiency of 70% COD using an aluminium electrode and 60% COD using an iron electrode. However, when reduced to pH 2, COD removal efficiencies increased to 93% using aluminium and 85% (Fe) using an iron electrode. In the EC treatment of wastewater, aluminium and iron cations with an oxidation number of (+3) are used (Doggaz *et al.* 2018; Vepsäläinen & Sillanpää 2020). Aluminium electrodes operate best in acidic and neutral pH. This is because between pH values of 4 and 9.5 the major ion species $\text{Al}(\text{OH})_3$ is formed, which is able to effectively trap colloids and contaminants as it precipitates. Iron electrodes operate best in acidic, neutral and slightly alkaline pH (Sahu *et al.* 2014). As shown in Figure 7, iron electrodes produce mostly Fe^{2+} around pH 8 but will start to generate Fe^{3+} species as the pH lowers. The lower the pH level, the more soluble the iron will be (Sahu *et al.* 2014). In highly alkaline wastewater, the least removal efficiency occurs when $\text{Al}(\text{OH})_4$ and $\text{Fe}(\text{OH})_4$ ions form, which are poor coagulants (Sahu *et al.* 2014). Due to the generation of hydrogen and hydroxide ions at the cathodes, the pH of the wastewater treated using EC may also increase slightly (Naje *et al.* 2017).

Electrolysis time

Electrolysis time is an important parameter that affects the treatment efficiency of the EC process. It may increase or decrease with current density or pH of the sample (Naje *et al.* 2017). In a study done by Asselin *et al.* (2008a),

Table 4 | A summary of evaluated factors and efficiency using electrocoagulation process for poultry slaughterhouse wastewater treatment

Evaluated factors and conditions	Electrode/connection type	Optimum	Efficiency (%)	References
Initial pH 6,7	Al-Al	2	93% COD, 90% FOG	<i>Kobyra et al. (2006b)</i>
Current density (25–200 A/m ²)	Fe-Fe	150 A/m ²	85% COD, 98% FOG	
Electrolysis time (2,5–40 minutes)	Monopolar	25 minutes		
Initial pH (3–7)	Al-Al	3	85% COD	<i>Bayar et al. (2011)</i>
Current density (0,5–2 mA/cm ²)	Monopolar	1.0 mA/cm ²		
Electrolysis time (5–60 minutes)		30 minutes		
Stirring speed (100–250 rpm)		150 rpm		
Initial pH (3–9)	Fe-Fe	3	95.5% COD	<i>Eryuruk et al. (2018)</i>
Current density (30–50 mA/cm ²)	Monopolar	50 mA/cm ²		
Electrolysis time (15–90 minutes)				
Supporting electrolyte (0.05–0.1 mg/l)				
Initial pH (7,8)	Al-Al		94.4% COD	<i>Tezcan Ün et al. (2009)</i>
Current density (10–25 mA/cm ²)	Fe-Fe		81.1% COD	
Electrolysis time (60 minutes)	Monopolar			
Supporting electrolyte (0.05–0.1 mg/l)		0.05 mg/l		
Stirring speed (100 rpm)				
Initial pH (6.11–6.50)	Mild steel or Al	Mild steel	82% COD	<i>Asselin et al. (2008a)</i>
Electrolysis time (10–90 minutes)		Through 60 or 90 minutes	99% FOG	
Current intensities (1.0–3.0 A)	Monopolar			
Current intensities (0.3–1.5 A)	Bipolar	Bipolar		
Initial pH (6.5)	Al-Al		95.6% COD, 92.5% FOG	<i>Godini et al. (2012)</i>
Current density	Fe-Fe	0.014 A/cm ²	94.46% COD, 95.3% FOG	
Electrolysis time (2.5–40 minutes)	Monopolar	25 minutes		
Stirring speed (300 rpm)				
Initial pH (2–8)	Al-Al	3	85% COD	<i>Bayar et al. (2014)</i>
Current density (1 mA/cm ²)	Monopolar	1 mA/cm ²		
Electrolysis time		20 minutes		
Current density (30 A/cm ²)	Al-Al		86% COD	<i>Combatt et al. (2017)</i>
Electrolysis time (40 minutes)				
Initial pH (4)		7.5		
Initial pH (6.4)	Al-Gr (graphite)		76–85% COD	<i>Paulista et al. (2018)</i>
Current density (3–15 mA/cm ²)		3 A/cm ²	93–99% colour	
Electrolysis time (3–75 min)			95–99% TSS	

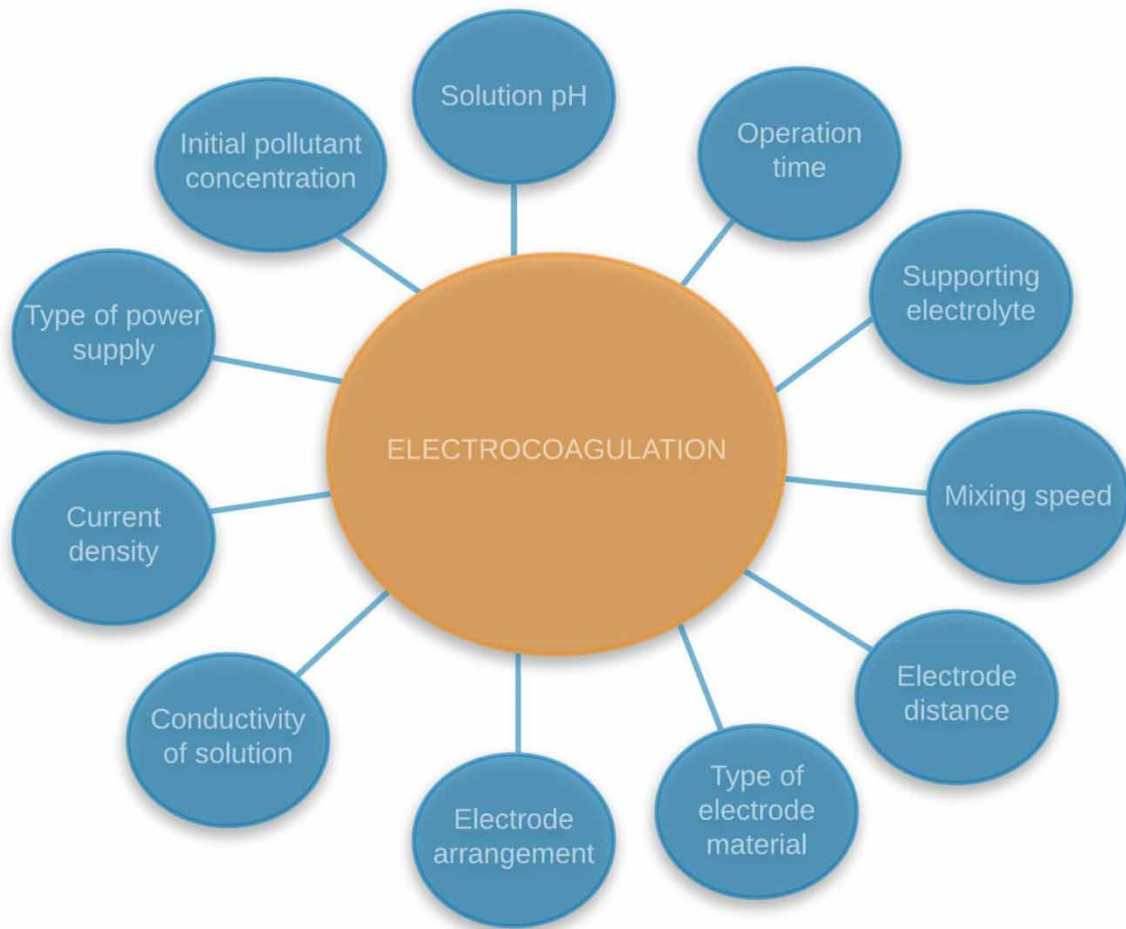


Figure 6 | Operating parameters influencing the electrocoagulation process performance.

the COD removal rate increased rapidly in the first 20 minutes, which was due to the increase of the coagulant; the COD gradually slowed down with the extension of the electrolysis time while the trial allowed 60 minutes for electrolysis in the treatment of PSW. Similarly, Bayar *et al.* (2011) reported that the highest COD removal efficiency of 85% was achieved in 20 minutes. Literature shows that longer reaction times lead to greater electricity consumption, and it also indicates that optimal electrolysis times for the EC process appear to range between 20–30 minutes (Kobyta *et al.* 2006b; Yetilmezsoy *et al.* 2009; Bayar *et al.* 2011; Thirugnanasambandham *et al.* 2014).

Conductivity and supporting electrolyte

Conductivity adjustment is generally undertaken with the addition of a supporting electrolyte such as sodium chloride (NaCl) or sodium sulphate (Na₂SO₄) (Tezcan Ün *et al.* 2009). Water is a polar solvent, thus ionic compounds, such as NaCl, dissolve and dissociate to form Na⁺ and Cl⁻ ions, which are electrolytes (Graça *et al.* 2019). When voltage is applied across the electrodes, the positively charged ions (Na⁺) move to the negative electrode and the negatively charged ions (Cl⁻) move to the positive electrode and increase the current. High conductivity reduces the electrical resistance of the wastewater, decreases cell voltage and reduces energy consumption (Ghernaout *et al.* 2019). In a study by Tezcan Ün *et al.* (2009), higher concentrations of Na₂SO₄ caused an increase in COD removal efficiency, and energy consumption was considerably reduced with increasing conductivity in the treatment of cattle slaughterhouse wastewater using EC. Similarly, Eryuruk *et al.* (2018) used Na₂SO₄ as a supporting electrolyte; however, no positive effect on COD removal efficiency was observed and also the energy consumption was not affected significantly. The low removal rate was attributed to the increase of the passivation layer caused by the addition of the Na₂SO₄. Addition of electrolytes such as NaCl

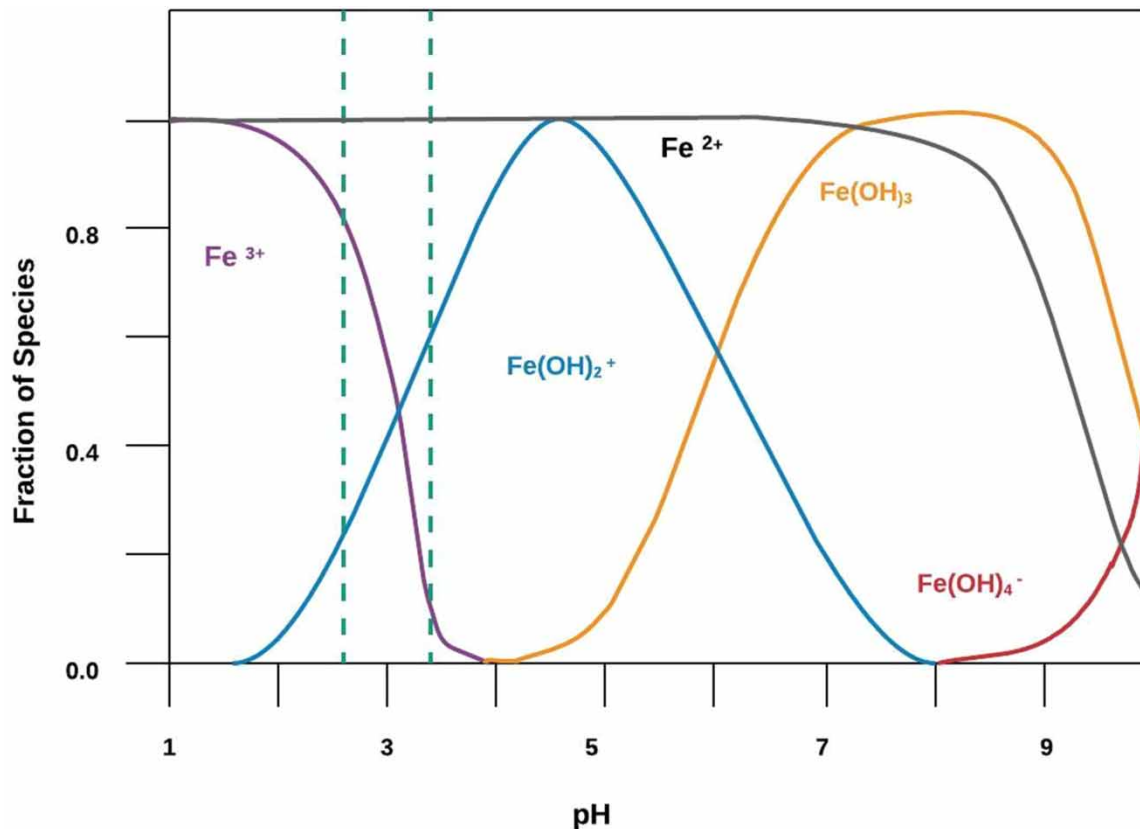


Figure 7 | Iron species in an aqueous solution as a function of pH, adapted from Bokare & Choi (2009).

and Na_2SO_4 at high concentrations is a disadvantage as highly saline wastewater can be the result and may not meet environmental discharge requirements and therefore need additional treatment.

Mixing speed

Generally, the stirring speed is kept constant for most EC studies of PSW treatment, typically within 100–300 rpm (Koby *et al.* 2006b; Bayar *et al.* 2014; Thirugnanasambandham *et al.* 2014). The effect of stirring speed on COD removal from PSW was investigated by Bayar *et al.* (2011). When the stirring speed was low at 100 rpm, coagulation was limited by collisions and attachments between flocs. It was noted that when mixing speed was increased from 100–150 rpm, it enhanced the movement of ions and $\text{Al}(\text{OH})_3$ flocs were attached, which was favourable for precipitation, thus increasing the overall COD removal efficiency. However, when high-speed stirring was increased beyond the optimum range (150–250 rpm), flocs disintegrated in the reactor and formed small flocs that are hard to remove from water, leading to a decrease in COD removal efficiency. It was found that it is important to optimize stirring speed as it influences removal efficiency and floc properties.

Current density

Current density is the only operational parameter that can be controlled directly, as the electrode spacing is fixed, the current is continuously supplied influencing the dominant pollutant separation mode. (Naje *et al.* 2017). Current density directly determines both coagulant dosage and bubble generation rates, and strongly influences both solution mixing and mass transfer at the electrodes. The amount of metal dissolved or deposited is dependent on the quantity of electricity that passes through the electrolytic solution (Sahu *et al.* 2014). The optimal current density invariably involves a trade-off between operational costs and efficient use of solution pH, temperature, and flow rate (Shahedi *et al.* 2020). At high current densities, the extent of anodic dissolution increases, and in turn, the amount of hydroxo-cationic complexes increases too, which results in an increase in the removal of the colour and COD (Vepsäläinen & Sillanpää 2020). In a study by Bayar *et al.* (2011), an increase of current density from 0.5–2.0 mA/cm^2 also increased removal efficiencies. A current density of 1.0 mA/cm^2 provided 85% of COD and

98% turbidity removal efficiency. This is due to the high amount of ions produced on the electrodes promoting destabilization of contaminant molecules. On the other hand, a study of the influence of current density and pH on the treatment of slaughterhouse wastewater by means of EC with aluminium electrodes was investigated (Bayar *et al.* 2014). High removal efficiencies at low pH and current density values were obtained. Kobya *et al.* (2006b) reported a COD removal efficiency of 92% aluminium and 85% iron, with FOG removal efficiency of 94% aluminium and 99% iron with current densities above 150A/m². The highest allowable current density may not be the most efficient mode of running the reactor. Despite the higher removal efficiencies, high current densities are not beneficial from an economic perspective as increasing the electrical power reduces the lifespan of the electrodes (current drawn is directly proportional to voltage input). Therefore, optimum current density supply in the EC process is very important.

Type of power supply

Generally, the EC process uses direct current (DC) power supply, which may lead to the formation of an impermeable oxide film on the cathode, which causes the passivation of the anode, bringing about an increase of the electrolytic cell resistance and decrease the ionic transfer; this increases energy consumption (Moussa *et al.* 2017). Sacrificial anodes can be replaced periodically; however, the replacement of electrodes increases the running costs of the system (Tetreault 2003). Hydro-mechanical cleaning and mechanical cleaning have also been used to reduce the impact of passivation (Emamjomeh & Sivakumar 2009). Yang *et al.* (2015) highlighted that passivation could be prevented by the addition of a sufficient amount of chloride ions, which can help to break down the passive layer on electrodes. The small size of the chloride ion penetrates the oxide film and forms acids. Its strong adsorption on metal lattices prevents re-passivation. Yang *et al.* (2015) also found that using an alternating current prevented passivation on Al and Fe electrodes. The use of alternating current (AC) is showing promising results, with higher efficiency and energy reductions. Mollah *et al.* (2001), found using AC power slowed down electrode consumption when compared with DC. It is yet to be further examined in the treatment of poultry processing wastewater.

Electrode configuration

Electrode arrangement is also an important factor for the treatment efficiency. Depending on the geometry of the reactor, electrodes can be organized in different arrangements, spacing and length for optimised maximum removal efficiencies (Naje *et al.* 2017). Demirci *et al.* (2015) investigated the effect of different electrode connections (MP-P, MP-S, BP-P) on the colour and turbidity removal and total treatment cost of EC of textile wastewater treatment. The results proved that the removal efficiencies for all three connections were similar. Asselin *et al.* (2008a) found that the mild steel BP-S connection had better performance than the MP connection due to the higher surface area for sufficient anodic oxidation in the treatment of PSW. On the contrary, monopolar configuration was reported to be better in the treatment of oily wastewater (Asselin *et al.* 2008b).

Material of electrode

The performance and treatment efficiency of an EC process depend on the choice of electrode material, which depends on the cost-effectiveness, and availability of the electrode material (Sahu *et al.* 2014). Various electrode materials have been used in the EC process, such as aluminium, iron, steel, copper, zinc, graphite, and many others (Asselin *et al.* 2008a; Budiyo & Seno 2010; Zarei *et al.* 2018; Islam 2019; Meiramkulova *et al.* 2020b). Among them, aluminium or iron electrodes have been reported to be very successful for wastewater treatment; iron is preferred, because it is relatively cheaper than aluminium (Zaied *et al.* 2020). Recently, a novel steel wool was used in a study by Nasrullah *et al.* (2018) to treat palm oil mill effluent and it was effective by removing pollutants fast and was also found to be cost-effective. The application of steel wool was found to be the highest compared to iron and aluminium in which it was able to remove 74% COD, 70% BOD and 66% SS. In a study by Kobya *et al.* (2006b), the removal percentage of COD by applying aluminium electrodes was 93%, which was more than that of iron electrodes, which was 85%. However, regarding FOG, the removal efficiency of iron electrodes (98%) was more than that of aluminium electrodes (90%). Similarly, Godini *et al.* (2012), Yetilmezsoy *et al.* (2009) also found the aluminium electrode to be slightly more effective for COD (95.6%) removal and the iron electrode to be slightly more effective for FOG (95.3%) removal. The weak performance of iron electrodes on COD removal in comparison with aluminium electrodes is because of weak settleability of the Fe²⁺ ion. Fe²⁺ is the common ion produced on site of electrolysis of iron electrodes. It has high solubility at acidic or neutral

pH and could be oxidized readily into Fe^{3+} by dissolved oxygen in water and are hard to settle (Emamjomeh & Sivakumar 2009). Despite aluminium electrodes showing a higher COD removal efficiency in many studies in comparison with Fe electrodes, Al produces a significant amount of sludge (Bayramoglu *et al.* 2006).

Electrode distance

The electrode spacing is a controlling parameter that affects the size of the reactor and the energy consumption and can significantly impact the overall cost of the treatment (Bayramoglu *et al.* 2006). The space between the electrodes also affects the reactions in the electrolysis reactor (Bayramoglu *et al.* 2006). During electrolysis, the solution close to the cathode becomes more concentrated because of the different mobilities of the ions present, and this effect can also be reduced by agitation of the bulk solution (Nasrullah *et al.* 2012). The interelectrode gap gets partially filled with gases during electrolysis, which increases its electrical resistance. Narrower gaps enhance mass transfer characteristics and decrease ohmic loss. A narrow spacing of less than 10 mm is accompanied with low-energy consumption. An increase in interelectrode spacing increases cell voltage, causing an increase in the power consumption (Bayramoglu *et al.* 2006). Bayar *et al.* (2011), Thirugnanasambandham *et al.* (2014), Kobya *et al.* (2006b), Asselin *et al.* (2008a) reported constant spacing between the electrodes of 5 mm, 15 mm, 11 mm, and 1.5 cm, respectively, in the treatment of PSW.

Hybrid electrocoagulation processes

Electrochemical processes are increasingly gaining ground as an alternative to conventional treatment and as a complementary treatment (pre-treatment or post-treatment). In recent years, there has been a growing interest in merging two or more treatment methods (such as coagulation-flocculation, aerobic/anaerobic and membranes) with EC to increase the overall efficiency and to attain the desired treated effluent compared to either of the technologies as a stand-alone process.

Electrocoagulation with chemical coagulation

Chemical coagulation is a process that includes the addition of inorganic coagulants or polymers in wastewater to destabilize pollutants. Aluminium sulphate (alum), ferrous sulphate, ferric chloride, and polyaluminium chloride (PACl) are the most common types of coagulants in the chemical market used for wastewater treatment due to their effectiveness, high coagulant efficiency and availability (Hamawand *et al.* 2017). Tezcan Ün *et al.* (2009) investigated a hybrid electrocoagulation with iron and aluminium electrodes, Na_2SO_4 and a pH of 7.8. The optimum parameters included PACl, coagulation with 0.75 g/L PACl concentration and the treatment process was capable of removing 94.4% COD. Bazrafshan *et al.* (2012) achieved 99% COD removal with 100 mg/L PACl to treat slaughterhouse wastewater. The efficiency of the process increased with increasing dosages of PACl. Both studies by Tezcan Ün *et al.* (2009) and Bazrafshan *et al.* (2012) found chemical coagulation as a stand-alone process did not meet discharge standards but when combined with EC the limits were met. In a study by Ozyonar & Karagozoglu (2014), the treatment performance of EC and chemical coagulation were compared on slaughterhouse wastewater. The removal efficiencies were obtained at 78.3%, 94.7%, and 90.2% for aluminium electrodes, and 76.7%, 92.8%, and 95.9% for the iron electrode for COD, FOG, and turbidity respectively. For chemical coagulation, the use of coagulants were compared. The removal efficiencies were 36.4% COD, 93.6% FOG, and 89.8% turbidity for aluminium sulphate; 27.6% COD, 88.6% FOG, and 85.9% turbidity for ferric chloride; 37.4% COD, 89.9% FOG, and 75.6% turbidity for ferric sulphate. From the results obtained, EC was more effective than chemical coagulation.

Electrocoagulation with the Fenton process

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 (Pawar & Gawande 2015). pH plays an important role in the electro-Fenton process. In literature, an optimum pH of 3 has been reported for most studies (Nidheesh & Gandhimathi 2012; Xu *et al.* 2020). At a pH below 3, the electro-Fenton process becomes less effective (Nidheesh & Gandhimathi 2012; Xu *et al.* 2020). Tezcan Ün *et al.* (2009) investigated conducting EC concurrently with the Fenton process and found 81.1% COD removal could be achieved by adding 9% H_2O_2 . The authors concluded that hybrid processes were superior to EC as a stand-alone method for the removal of both COD and turbidity from cattle-slaughterhouse wastewater. Eryuruk *et al.* (2018) also studied the removal of organic matter from PSW using

a combined electro-Fenton process. The optimal dose was 0.2 mg/l. H₂O₂ which decreased COD significantly by 95.48%.

Electrocoagulation followed by membrane treatment system

Pre-treatment is required to increase the efficiency and life expectancy of the membrane by minimizing fouling, scaling (Fatima *et al.* 2021). It also changes the properties of the wastewater, making membrane separation more efficient (Obotey Ezugbe & Rathilal 2020). In a study by Sardari *et al.* (2018), EC was followed by ultrafiltration for treating PSW and 5 minutes of electrolysis time reduced fouling on the ultrafiltration membrane significantly. Meiramkulova *et al.* (2020a) investigated the performance of an integrated membrane process with EC pre-treatment on PSW. The findings showed that the EC pre-treatment unit was highly effective for the removal of parameters such as turbidity, colour, TSS, COD, and BOD by 71–85%. In addition, the EC pre-treatment resulted in a low rate of cake formation on the membrane.

Electrocoagulation with biological treatment

Biological treatment methods exploit bacteria, algae, fungi, and yeasts for the degradation of organic matter in industrial effluents. Yetilmezsoy *et al.* (2009) studied the performance of a batch-EC system on anaerobically pre-treated poultry manure wastewater. High removal efficiencies of 90% COD and 92% residual colour efficiency with electrolysis time of 20 minutes, pH of 5, and current density of 15 mA/cm² post-treatment with EC, confirmed the success of the combination of the treatment processes. Microorganisms such as *Bacilli subtilis*, *Pseudomonas aeruginosa*, and *Proteus vulgaris* were used to prove that the combination of electrochemical degradation and biological oxidation was capable of reducing COD from the organic industrial wastes (Basha *et al.* 2009). Following the experiments, COD reduced from 48,000 mg/L to 17,000 mg/L by 80% and it was concluded that the water could be reused. Recently, Meyo *et al.* (2021) used a novel microbial consortium (Ecoflush) to treat PSW for an expanded granular sludge bed reactor (EGSB) coupled with a membrane bioreactor (MBR) system. Removal efficiency of 50% TSS, 70% COD and 82% FOG were observed. The anaerobic digestion that followed after the enzymatic pre-treatment stage removed 90% TSS, >70% COD and >90% FOG. Further removal of 80% FOG and >95% for both COD and TSS were achieved using MBR. Similarly, Dyosile *et al.* (2021) assessed the use of a multistage system to treat PSW. The enzymatic pre-treatment achieved removal efficiencies of 56% COD, 38% TSS, and 80% FOG. The overall removal efficiency of the multistage system was 99% (COD, TSS, and FOG). The treated effluent met the effluent discharge standard.

From the results reported in literature, it can be concluded that a single process is not as effective as the combination of two or more techniques for PSW treatment. Integrated processes exhibit excellent performance by providing high efficiency for pollutant removal, purify the wastewater as required to discharge into the environment and reuse for industrial purposes. Each component within the integrated process tends to complement the drawbacks of the other, thereby enhancing the production of more quality treated effluent. With an increase in stringent discharge standards and insufficient freshwater resources, more hybrid EC processes need to be explored. A proposed integrated system is illustrated in Figure 8 to treat PSW, articulating the different stages of the treatment in a sequential order: Enzymatic pre-treatment → Screening → Electrocoagulation → Membrane filtration → Ultraviolet → Holding tank. Due to the high quantity of organic matter in PSW, the wastewater is aerobically pre-treated similar to the one reported by Dyosile *et al.* (2021), Meyo *et al.* (2021), to remove suspended solids and to bio-delipidate FOG to improve the effluent quality. The screens are to remove residual suspended solids from the pre-treatment to prevent clogging of downstream equipment. The pre-treated effluent is fed into an electrochemical cell to further remove organic pollutants. The electrochemical cell is not very effective in removing ammonia nitrogen and residual iron/aluminium hydroxide from the effluent. For this reason, the treated effluent from the electrochemical cell is submitted to the membrane filtration for further nutrient and residual metal hydroxide removal to achieve high quality effluent, and then the ultraviolet will aid as a post treatment to inactivate microorganisms without the need of any chemicals, to obtain clean water which can be reused in the poultry industry. This prevents the usage of methods such as chlorination to disinfect the water which can possibly lead to hazardous by-products (Bustillo-Lecompte & Mehrvar 2015). The clean water is then stored in a holding tank.

Meiramkulova *et al.* (2020c) investigated the performance of an integrated poultry slaughterhouse wastewater treatment plant for a recyclable high-quality effluent. The recyclable effluent was achieved using an integration of electrochemical methods, membrane filtration, and ultraviolet (UV) disinfection. The authors found that EC

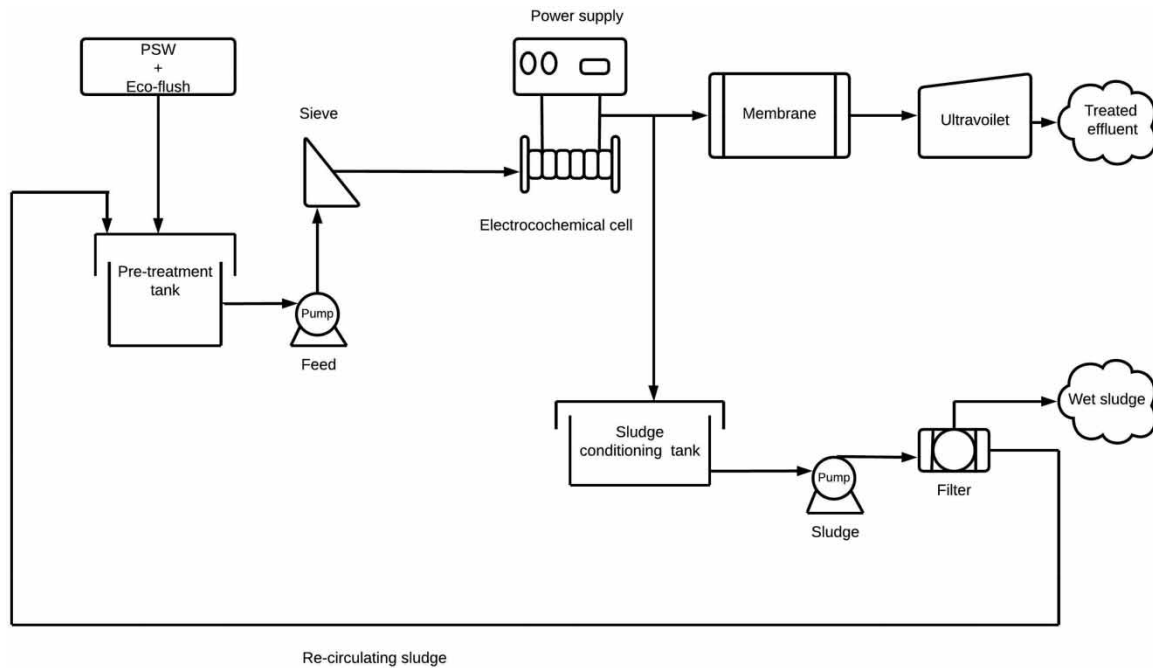


Figure 8 | Proposed integrated system to treat PSW.

played an important role as pre-treatment units before the membrane filtration to reduce fouling; while the membrane filtration unit removed the majority of the suspended and dissolved solids including microorganisms. The ultraviolet disinfection unit eliminated the remaining microorganisms as part of quality enhancement.

The proposed system is intended for recycling and reusing PSW to ease the burden on fresh water resources. Due to low footprint requirement, environmental sustainability and great potential of operation without the need for extensive control, this research undeniably stands out to be the future of PSW treatment. This study can provide a base for other future research in this area.

Interaction of process parameters and optimization using computational techniques

Optimization of process variables during wastewater treatment can be achieved by using computational techniques. Thirugnanasambandham *et al.* (2014) explained. Response surface methodology (RSM) as a collection of mathematical and statistical procedures whose purpose is to develop, refine, and optimize processes. The objective for RSM to evaluate the relative significance of several affecting factors and complex interactions during many variable optimization processes, and it is also used for multiple regression and correlation analyses. RSM makes treatment process modelling simple and efficient in terms of time and resource utilization, as it reduces the number of experimental runs required to generate sufficient information for a statistically acceptable result. Thirugnanasambandham *et al.* (2014), used RSM to evaluate the interactive effects of initial pH (4–9), solution dilution (10–30%), current density (10–20 mA/cm²), and electrolyte dose (500–1,250 mg/l) in a batch EC process for PSW; experimental data was optimized using the Box-Behnken design (BBD) and the interaction effects between these parameters were statistically significant on COD removal efficiency. Davarnejad & Nasiri (2017) treated PSW using the electro-Fenton technique. Electrolysis time, pH, H₂O₂/Fe²⁺ molar ratio, current density, and volume ratio of H₂O₂/PSW were chosen as independent variables that affect the EF reaction; COD and colour removal were the dependent variables. A five-factor with a three-level BBD in conjunction with RSM was applied to maximize efficiency. The interaction facilitated 92.37% COD and 88.06% colour removal at optimum conditions.

Economic analysis

Achieving excellent performance with EC technologies in PSW treatment and making it cost-competitive with conventional methods is critical for the poultry processing industry. In some studies, economic feasibility of the EC process was investigated, with special emphasis being placed on total energy consumption and operating costs (i.e. costs of electrode materials, electricity, electrode replacement, chemicals used for pH and electric conductivity

adjustment). Bayramoglu *et al.* (2006), studied the economic assessment of EC for the treatment of PSW. Iron electrodes were preferable as the total operating cost was between 0.3 and 0.4 $\$/m^3$, which was nearly half that of aluminium electrodes. The total operating cost was also calculated on the basis of $\$/kg$ COD removed, which was 0.015 and 0.027 for iron and aluminium electrodes, respectively. In a study by Asselin *et al.* (2008a), EC operated under the optimal conditions involved a total cost of 0.71 $\$/m^3$ of treated PSW effluent. The total cost included energy consumption at a current of 0.3A (4.19 $kW h/m^3$), electricity energy cost (0.25 $\$/m^3$), electrode consumptions (0.29 $\$/m^3$) iron, polymer cost (0.05 $\$/m^3$) and metallic sludge disposal (0.12 $\$/m^3$). EC is generally compared against chemical coagulation. In a study by Hamawand *et al.* (2017), the authors calculated the energy requirement cost for using chemical coagulation for a meat processing plant. The total energy consumption for chemical coagulation was 1.03 $kW h/m^3$, which was significantly less than the total energy consumption reported for EC process by Asselin *et al.* (2008a). However, the information was inconclusive as there was missing data such as sludge disposal costs and the estimation of the operating costs may vary significantly as some costs were calculated from a lab or pilot scale. Additionally, Mousa & Hadi (2016) studied the cost-effectiveness of a full scale EC compared with chemical coagulation for industrial processing effluent. Chemical coagulation was consistently 2–3 times higher to operate than EC, with some studies in excess of 10 times higher. As the studies were not undertaken on poultry processing effluents, it is difficult to make a direct comparison.

Future perspective and recommendation

1. From the above discussion on economic analysis, it is clear that there is limited research and data on the economic feasibility of full-scale EC systems as a treatment method for PSW. For this reason, further research into the full-scale operational costs of EC for treating poultry processing effluents would be beneficial, as well as its comparison with conventional treatment methods.
2. Electrode passivation is one of the disadvantages of the EC process that leads to the reduction in the removal efficiency. Although passivation can be rectified by regular cleaning of electrodes, addition of chloride ions or by applying alternative currents (Vasudevan 2012), more studies should investigate electrode passivation to find methods to reduce/reverse the adverse effects as there is no generic solution to the electrode passivation problem.
3. Aluminium and iron electrodes are amongst the most popular electrodes used. In literature, aluminium electrodes showed higher pollutant removal than iron (Kobyas *et al.* 2006b; Godini *et al.* 2012). However, aluminium is more expensive than iron and produces a significant amount of sludge (Hamawand *et al.* 2017). More studies need to investigate different electrode materials and the effect they may have on the treatment efficiency of EC.
4. Another major challenge is high electricity consumption, which directly affects the operating costs. EC processes use electricity produced from non-conventional energy sources. However, recently Zaleschi *et al.* (2012) used solar power to do a comparative study of EC and chemical coagulation processes applied for wastewater treatment. Solar-powered EC was found to be a sustainable process for wastewater treatment that can be applied for small communities in remote locations. The use of solar energy reduces the operation cost. For this reason, energy sources such as solar power, hydroelectric power, geothermal energy and other renewable energy sources should be considered as they are more sustainable than fossil fuels (Banos *et al.* 2011; Al-Hamamre *et al.* 2017).
5. The EC technology also faces strong competition from the existing well-established wastewater treatment technologies such as aerobic/anaerobic, coagulation-flocculation and membrane technologies. Therefore, the integration of the EC technology with the existing technologies would improve its chances of success and would also aid in the reduction of electrical energy consumption.

CONCLUSION

EC has a good potential for the treatment of PSW. It has gained interest due to its low sludge generation, ease of control, robustness, the possibility to utilize renewable energy resources as a source of electrical power, and offers rapid remediation of high strength wastewaters. From the review, it is evident that EC has the flexibility to be used with other treatment methods in an integrated system, which has shown improved and promising results. The use of combined treatment methods could give rise to a new area of research and investigation, and it can also reduce

the consumption of electrical energy. The application of the technology remains in its infancy, and information about larger-scale operation is still lacking. The majority of EC studies were performed using small-scale batch reactors, whereas most industrial applications require reactors operating in a continuous mode. Therefore, more comprehensive pilot-scale studies would be beneficial for supporting the transition of the technology from the laboratory to the industrial scale, to evaluate the performance of EC units operating in continuous flow mode with more effective reactor design.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 29 June 2021; accepted in revised form 25 October 2021. Available online 16 November 2021