OPTIMISATION OF ELECTROCOAGULATION PROCESS IN THE TREATMENT OF POULTRY SLAUGHTERHOUSE WASTEWATER

by

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DECLARATION

I, Philadelphia Vutivi Ngobeni, declare that the contents of this thesis represent my unaided work and that the thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

Philadelphia Vutivi Ngobeni 30 November 2021

Signed **Date**

ABSTRACT

Due to rapid urbanisation and industrial growth, the production and discharge of raw and poorly treated poultry slaughterhouse wastewater increase yearly. This has serious environmental and health consequences because it disrupts ecosystems' normal operations. As a result, the development of efficient and long-lasting wastewater treatment methods is becoming increasingly important. When compared to traditional processes, electrocoagulation is one of the more promising approaches because it is efficient and simple, has short treatment times, and produces little sludge. The biological approach employs the synergistic application of biological pre-treatment using low-cost hydrolytic enzymes, is an efficient, cost-effective, sustainable, and environmentally friendly technology for treating high strength lipid-rich wastewater. The primary goal of this research was to look into the feasibility of biological pre-treatment using hydrolytic enzymes in combination with the electrocoagulation technique to reduce pollutants in poultry slaughterhouse wastewater.

The feasibility of the electrocoagulation technique in removing chemical oxygen demand (COD) and fats, oils and grease (FOG) was studied using iron electrodes. A screening design of the experiment (DoE) was used to identify the most important factors influencing the electrocoagulation removal process. These variables were identified as current density, pH, reaction time, and Ecoflush™ (with or without). The central composite design (CCD) with forty runs was used in the present study. The biological treatment resulted in 85-99% FOG reduction and 20-50% COD reduction, odourless effluent, indicating that PSW was biodegradable. The EC process produced a high-quality clarified effluent without solids in suspension with 92.4% COD reduction and 99% FOG reduction after 60 minutes of reaction. The best conditions were obtained by using a pH of 3.05, a current density of 66.9 A/m^2, 74-minutes of treatment time and without Ecoflush™. The combination of both processes did not perform as expected when compared to the separate processes. Despite the low removal percentages of some pollutants, the present study proved the ability of the biological treatment with novel Ecoflush™ for treating lipid-rich wastewater such as PSW largely for the removal of FOG. This proves the capability of its use as a pre-treatment for other conventional methods such as anaerobic digestion.

This study also showed that EC is a promising treatment method for PSW effluent. Even though the nitrogen removal was insufficient compared to conventional wastewater treatment technologies, there are several benefits of EC treatment, including short retention time, small footprint, no mixing, and elimination of coagulants addition. These characteristics enable EC technology to be used alone or in conjunction with other technologies for a wide variety of wastewater treatment applications. The treatment cost was also viable.

DEDICATION

This thesis is dedicated to my dearly loved children, Nompilo, Okuhle, and Langa

Thank you for understanding when I was not fully present for you during this study. I hope that the sacrifices you have endured to enable me to pursue this dream will be repaid to you in the future with many possibilities of happiness and prosperity.

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RESEARCH OUTPUT

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Manuscript 1

Title: Treatment of poultry slaughterhouse wastewater using electrocoagulation: a review

Journal: *Water Practice and Technology* **(**https://doi.org/10.2166/wpt.2021.108)

Authors: **Ngobeni, P.V.**, Basitere, M. and Thole, A.

Ngobeni, P.V - Conceptualisation, Experimental design, Data collection, Data analysis, Drafting and Editing of manuscript

Basitere, M. and Thole, A – Conceptualisation, Experimental design, Manuscript editing

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Authors: **Ngobeni, P.V.**, Basitere, M. and Thole, A.

Ngobeni, P.V - Conceptualisation, Experimental design, Data collection, Data analysis, Drafting and Editing of manuscript

Basitere, M. and Thole, A – Conceptualisation, Experimental design, Manuscript editing

PREFACE

The structure of this thesis is provided in Figure vi.1.

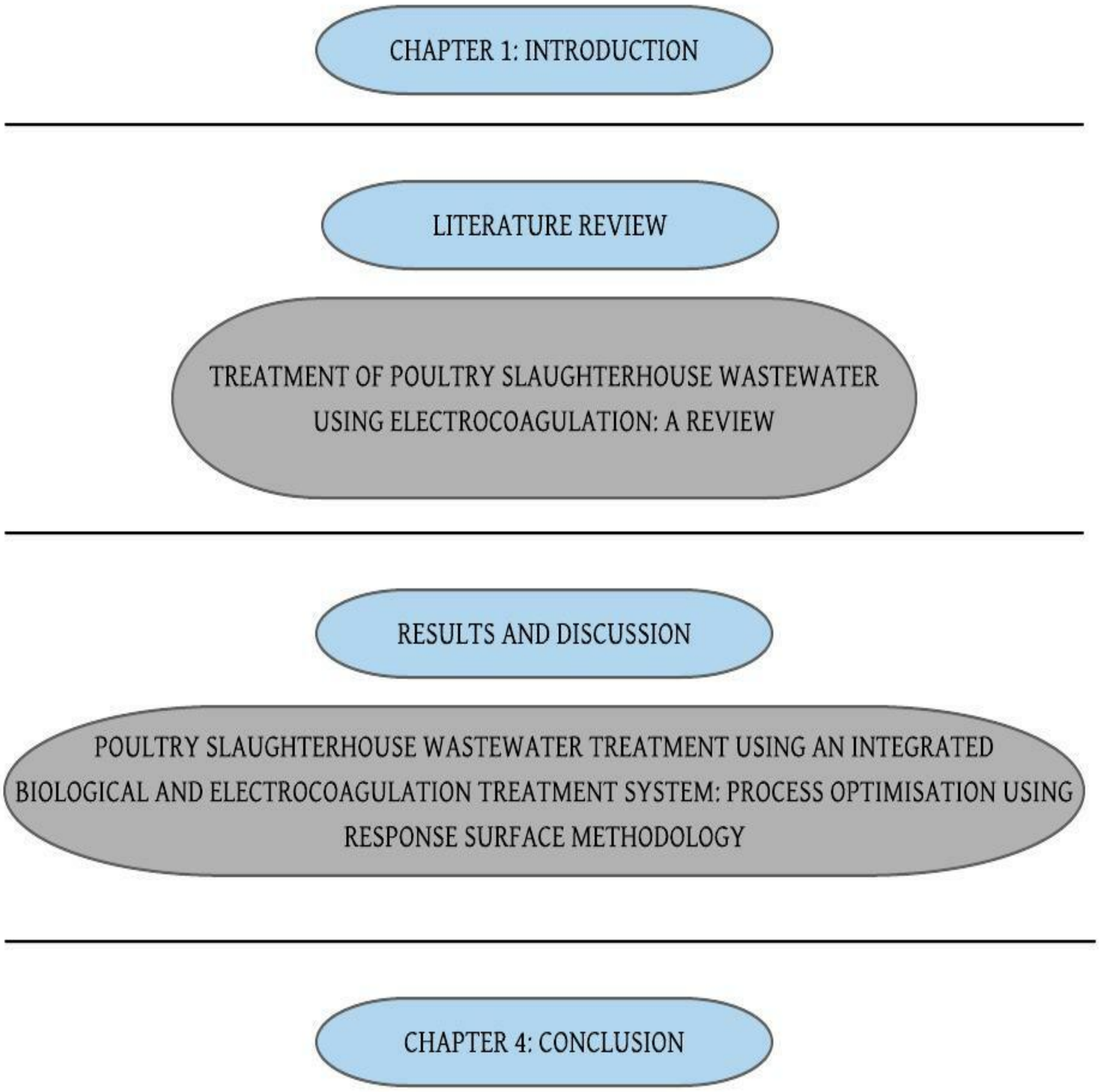

Figure vi.1: The thesis road map

LAYOUT OF THESIS

This thesis consists of the following 4 chapters:

- **Chapter 1** provides a background to the research problem, motivates this study, elaborates on the hypotheses of its outcome, gives the aims and objectives of this study, provides its relevance, and delineates its scope.
- **Chapter 2** provides a brief overview of the current global and national water situation, the water usage of poultry processing plants, PSW characterisation, and the legislation governing the discharge of PSW. This section also explains why electrocoagulation treatment is the most suitable treatment option for this type of wastewater and the need for biological pre-treatment. Therefore, the operational conditions, challenges, and advantages of this treatment option are listed.
- **Chapter 3** describes the materials, equipment, and methods used to set up and operate the biological pre-treatment and electrocoagulation systems used in this study. It specifies the operating conditions of each treatment system and the sampling, analytical and statistical methods and equipment used to analyse the experimental data. This chapter also presents the results relating to the performance of the individual treatment systems and the overall designed PSW treatment system and includes a detailed discussion thereof.
- **Chapter 4** provides the overall conclusion of this study with recommendations for further research.

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LIST OF ABBREVIATIONS

Abbreviation	Definition
BOD_5	Biochemical oxygen demand
CoCT	City of Cape Town
COD	Chemical oxygen demand
EC	Electrocoagulation
FOG	Fats, oil, and grease
pH	Potential of hydrogen
PSW	Poultry slaughterhouse wastewater
RT	Retention time
SA	South Africa
TDS	Total dissolved solids
TOC	Total organic carbon
TSS	Total suspended solids
VFAs	Volatile fatty acids
VSS	Volatile suspended solids
UF	Ultrafiltration
WWTP	Wastewater treatment plant

CHEMICAL FORMULAE

Element/Compound	Description
Al^{3+}	Aluminium cation
Fe^{3+}	Ferric ion
H_2	Hydrogen
H_2O	Water
H_2S	Hydrogen sulphide
NH_3	Ammonia
NH_4^+	Ammonium
NO_3^-	Nitrate
PO_4^{3-}	Phosphate
SO_3^{2-}	Sulphite
SO_4^{2-}	Sulphate

GLOSSARY

Term	Explanation
Aerobic	Conditions where biochemical reactions are dependent on oxygen which acts as the electron donor.
Biodegradable matter	Organic matter can be decomposed into basic molecules through biological processes carried out by a wide range of microorganisms.
Characteristics	General physical, biochemical and biological classes of wastewater elements.
Consortium	Grouping of various microorganisms for a common interest.
Nutrient	Essential element required for the growth of plants and animals is often found in nitrogen and phosphorus in wastewater.

CHAPTER 1

INTRODUCTION

Chapter 1: INTRODUCTION

1.1 Background of the research problem

Global meat production has risen dramatically in recent years, with a continual doubling growth forecast until 2050 (Mottet and Tempio, 2017). In South Africa (SA), the poultry industry is the largest and fastest-growing sector in agriculture, accounting for more than 16% of the country's gross domestic product. It has grown from a collection of backyard operations to a complex and highly interconnected enterprise with rising chicken output over the past 100 years (Adetunji, 2017). Around 76% of the birds are utilised for meat production in the South African poultry business, while 24% is for egg production (The South African Poultry Association Industry Profile, 2015). Poultry products account for more than half of all animal protein consumed in South Africa each year.

The production of poultry products demands large quantities of water for cleaning, rinsing, and disinfecting carcasses and poultry products, as well as sanitizing and disinfecting facilities and equipment to maintain the high standards of quality and hygiene required for the production of poultry products (Bustillo-Lecompte and Mehrvar, 2015). In a typical South African poultry processing plant, the average water footprint of chicken is 15-20 litres of water used each bird processed (CSIR, 2010). The poultry sector has significant environmental implications related to water consumption, resulting in the generation of more high-strength wastewater (Hamawand et al., 2017). The wastewater produced is considerably more polluted than domestic sewage wastewater (Njoya, 2017).

High concentrations of biodegradable organic matter, primarily lipids and proteins, are found in poultry slaughterhouse wastewater (PSW) (Valladão et al., 2007). Furthermore, PSW contains significant amounts of phosphorus, nitrogen, organic carbon, heavy metals, nutrients, detergents, and disinfectants (Bustillo-Lecompte and Mehrvar, 2015).

1.2 Statement of the research problem

The effluent from poultry slaughterhouse wastewater contains high concentrations of organic matter such as chemical oxygen demand (COD) and biological oxygen demand (BOD_5); suspended solids and colloidal matter, such as total suspended solids (TSS) and fats, oils, and grease (FOG); and nutrients such as nitrogen and phosphorous. Due to the predominance of the pollutants, the wastewater does not meet the industrial discharge standard regulations. For this reason, the poultry slaughterhouse wastewater cannot be disposed of into the environment without prior treatment as it can pollute natural water sources and harm aquatic life. The management of environmental pollution and the treatment of wastewater is of great concern. There is a need to design affordable and sustainable poultry slaughterhouse wastewater technologies suitable to treat industrial effluents, optimising environmental, health, and socio-economic benefits. Slaughterhouses are therefore required to implement strategies on how efficiently water can be used in the industry while complying with the municipal discharge standards.

1.3 Hypothesis

It is hypothesised that biological pre-treatment followed by an electrocoagulation system can effectively reduce pollutants from poultry slaughterhouses to meet industrial wastewater discharge standards.

1.4 Research aims and objectives

This study aimed to evaluate the feasibility of treating PSW to a water quality standard compliant with the wastewater and industrial effluent discharge standards and safe for re-use purposes, using a biological pre-treatment followed by an electrocoagulation system.

The specific objectives were to:

- To characterise the poultry slaughterhouse wastewater, assessing the physicochemical and microbial properties of the wastewater,
- To identify the conditions in which the microorganisms in the eco-flush perform best (whether anaerobic or aerobic or facultative microorganisms),
- To assess the effectiveness of biological pre-treatment coupled with electrocoagulation process on the removal of COD, FOG, TSS, ammonia, and orthophosphates,
- Determine the performance of the overall PSW treatment system for the removal of organic matter, suspended solids, and nutrients from the PSW,
- To evaluate the response of PSW to the various treatment stages.

1.5 Research questions

1. What are the characteristics of the poultry slaughterhouse wastewater?
2. How effective is a pre-treatment stage in removing FOGs and reducing COD in the PSW?
3. How effective is the Pre-treatment coupled with the electrocoagulation process in treating PSW compared to the electrocoagulation stage?
4. What are the process adjustments on the electrocoagulation technique that can be done to

efficiently produce treated wastewater that meets the industrial wastewater discharge standards; can it be reused as process water?

1.6 Significance of the research

The laboratory-scale PSW treatment system used in this study successfully treated medium-strength PSW under various operating conditions. Using biological pre-treatment and/or electrocoagulation systems for PSW treatment proved practical, cost-effective, and eco-friendly. There was no requirement to add chemicals into the system, simple equipment requirement, and produced no secondary waste. This study gave information on the effectiveness and efficiency of the combined biological and electrocoagulation processes in removing organic matter, suspended particles, and nutrients from PSW. As water is at risk of being overused around the globe, this study may help poultry processing plants by reducing the amount of wastewater released and potable water consumed, lowering discharge costs and fines, and enhancing the efficiency of their processes through energy savings.

1.7 Delineation of the Study

This study does not cover the post-treatment of PSW and the biochemical interactions of the microbial agents involved in the aerobic process.

1.8 Summary

Poultry slaughterhouse wastewater is an environmental hazard that requires improved management and treatment to limit its impact on the environment and the health of those exposed to it. This project sought to address these issues by investigating using biological pre-treatment in combination with an electrocoagulation treatment system. It was also necessary to characterize the wastewater to be treated, identify the challenges of related treatment processes, and address them to carry out beneficial treatment operations.

CHAPTER 2

TREATMENT OF POULTRY SLAUGHTERHOUSE WASTEWATER USING ELECTROCOAGULATION: A REVIEW

Chapter published as

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2 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 grows and industrialises in many parts of the world (Mottet and Tempio, 2017). In South Africa, the poultry meat sector has also advanced alongside the global trends as it is regarded as the most significant commercial poultry meat producer in Africa (Nkukwana, 2018). This activity is associated with high economic gains, but similar to any other food-processing activity, 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 2-1 (Bustillo-Lecompte et al., 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).

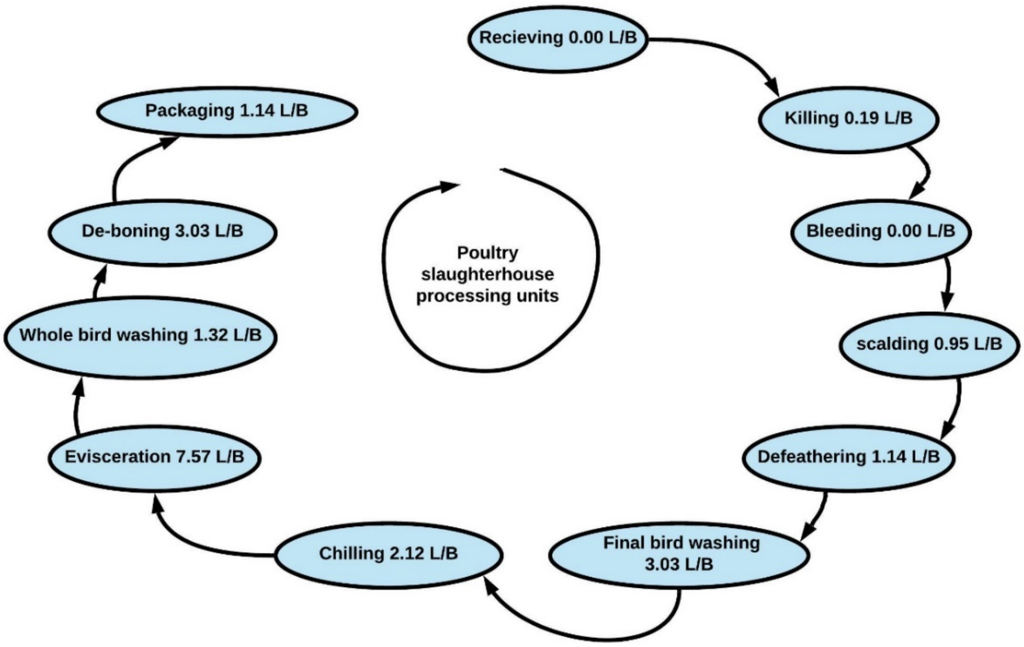

Figure 2-1: Water consumption in poultry slaughterhouses, quantified in litres per bird (L/B), adapted from (Njoya, 2017).

While poultry processing plants generate meat supply and valuable by-products, the discharge of raw and improperly treated poultry slaughterhouse wastewater (PSW) can have serious environmental implications and increase health hazard risks to animals and human beings (Njoya et al., 2019). PSW entering the ground and surface water lead to oxygen depletion, which destroys aquatic life. At the same time, nitrogen and phosphorus may prompt eutrophication and 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 mitigate adverse effects by reducing potable water usage and promoting water re-use (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 and Mehrvar, 2015). Anaerobic or aerobic treatment methods are cost-effective and capable of operating under natural conditions. However, the presence of FOG may significantly inhibit the activity of the microbes (Njoya, 2017). Chemical coagulation effectively removes fine particles and reduces 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 and 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 (Kobya 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 supplementary chemicals; hence low volumes of sludge and less harmful materials are generated. The lack of additional chemicals 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 characterised by 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 significant 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 minimised by using renewable energy sources, which allow the use of sustainable technology (Al-Qodah et al., 2020).

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 summarised. The techno-economic analysis was analysed to get a clear view of future industrial applications for PSW treatment. To conclude, the perspectives for future research and recommendations of EC treatment were discussed, including a proposed study for the effective treatment of PSW.

Table 2-1: Main advantages and disadvantages of several poultry slaughterhouse wastewater treatment technologies.

Treatment technology	Advantages	Disadvantages	Reference
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 and Lichtfouse, 2019, Fard et al., 2019, Rajab et al., 2017)
	The construction and process operation of these reactors are simple	The process start-up takes a long time due to the 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 Hilares et al., 2021, Prazeres et al., 2019)
	Significant reduction in the chemical oxygen demand and suspended particles	High sludge production, special handling, and further treatment	
Membranes	High effluent quality	High operating cost	(Sardari et al., 2018, Fatima et al., 2021, Goswami and Pugazhenthi, 2020, Malmali et al., 2018)
	High volumetric load possible	Membrane fouling	
Ultrasound	Can degrade toxic organic compounds into small molecules	Regular ultrasound probe replacement	(Abdelhay et al., 2020, Emerick et al., 2020, João et al., 2020)
	High efficiency for microorganism inactivation.	Difficult to scale-up	
Advanced oxidation process	Rapid reaction rates	Removal of residual peroxide	(Davarnejad and Nasiri, 2017, Abdelhay et al., 2017)
	Can treat nearly all organic materials	Complex chemistry tailored to specific pollutants	
Electrocoagulation	No addition of chemicals	Regular sacrificial anode replacement	(Meiramkulova et al., 2020a, Zarei et al., 2018b, Akarsu et al., 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	

2.1 The theoretical background of electrocoagulation technology

EC technology is a treatment process that treats wastewater by applying electric current as of the primary 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 the literature, most of the studies used the latter as their primary power supply (Abdul-Baqi and 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 and Mondal, 2017, Gilhotra et al., 2018, Bian et al., 2019); tannery (Deghles et al., 2016, Thirugnanasambandham et al., 2016, Jallouli et al., 2020, Villalobos-Lara et al., 2021); phenol (Vasudevan, 2012); oil (Tir and Moulai-Mostefa, 2008, Merma et al., 2020); heavy metals (Al-Shannag et al., 2015, Al-Qodah and 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 a 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 (Tsioptsias et al., 2015); potato (Kobya et al., 2006a); dairy (Varank et al., 2015, Akansha et al., 2020); restaurant (Adegoke et al., 2020); and cheese whey (Tirado et al., 2018).

In essence, EC is an electrochemical based process in which oxidation and reduction reactions occurs. Its simplest form 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 (Chaturvedi, 2013, Jame, 2012). The coagulant species can destabilise the suspended organic matter, contaminants, and the colloidal particles present in wastewater and consequently reduce their concentration (Ghernaout et al., 2019). It is schematically shown in Figure 2-2. Destabilisation is achieved mainly employing four distinct mechanisms (Vepsäläinen and Sillanpää, 2020):

(i) Compression of the electrical double layer. Increase of counter ion concentration in the bulk solution.

(ii) Adsorption. Charge neutralisation of negatively charged colloids by cationic hydrolysis products.

(iii) Inter particle bridging. The polymer chain is absorbed into multiple particles, molecular weight increases.

(iv) Precipitation. Impurities are trapped and removed in the amorphous hydroxide precipitate produced.

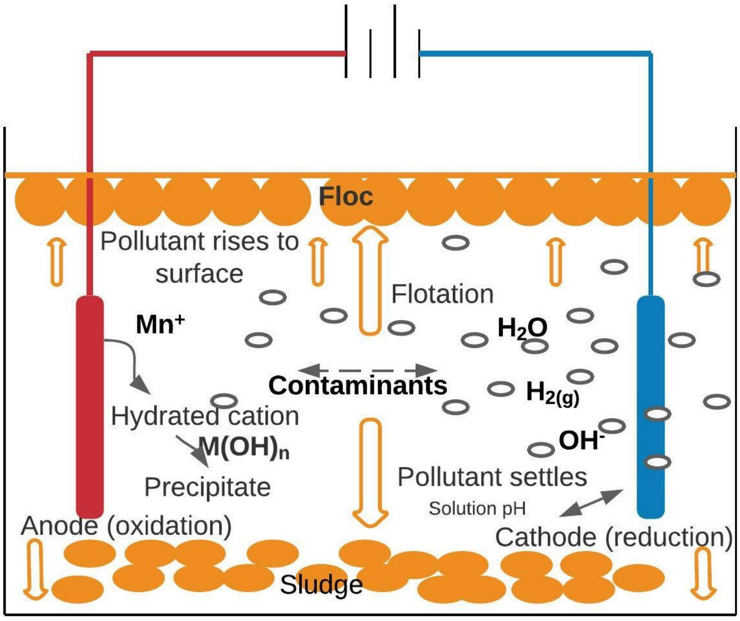

Figure 2-2: Interactions occurring within the electrocoagulation reactor adapted from (Chaturvedi, 2013)

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 (Potrich et al., 2020, Shahedi et al., 2020, Al-Qodah et al., 2017, Bolisetty et al., 2019). Iron may be oxidised into divalent Fe(II), and trivalent Fe(III) forms by atmospheric oxygen or anode oxidation during the coagulation. In contrast, aluminium oxidises only in trivalent form Al(III). Further, Fe(II) can oxidise to Fe(III) under appropriate oxidation-reduction potential and pH conditions (Doggaz et al., 2018, Vepsäläinen and 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 2-2: 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 influences the contaminant removal efficiency and the energy consumption cost (Zaied et al., 2020). The most distinctive electrodes connection is classified into monopolar-serial (MP-S), monopolar-parallel (MP-P), and bipolar series (BP-S) (Moussa et al., 2017, Ozyonar, 2016). These electrode configurations are shown in Figure 2-3. In MP-S connection, individual couple anode-cathode is linked internally where they are not linked with the outer electrodes, whereas in MP-P connection, a particular sacrificial anode is linked with another 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).

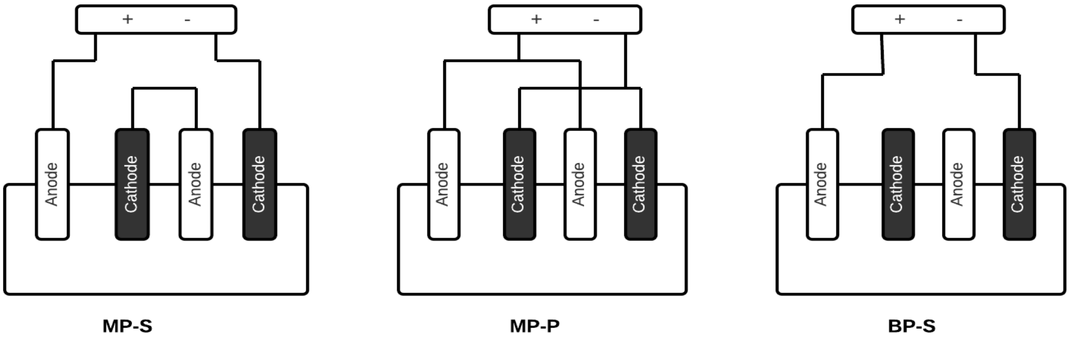

Figure 2-3: Different configurations of electrodes adapted from (Moussa et al., 2017)

Various studies in the literature have investigated the effect of electrode orientation on the EC process. It has been found that the orientation variation of the electrodes has different impacts on the EC process depending on the targeted pollutant (Zaied et al., 2020). A vast majority of researchers have used the 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, such as removing 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 anode at the bottom and horizontal electrode orientation with anode at the top, as shown in Figure 2-4. 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 higher operating costs than the MP-P and BP arrangement.

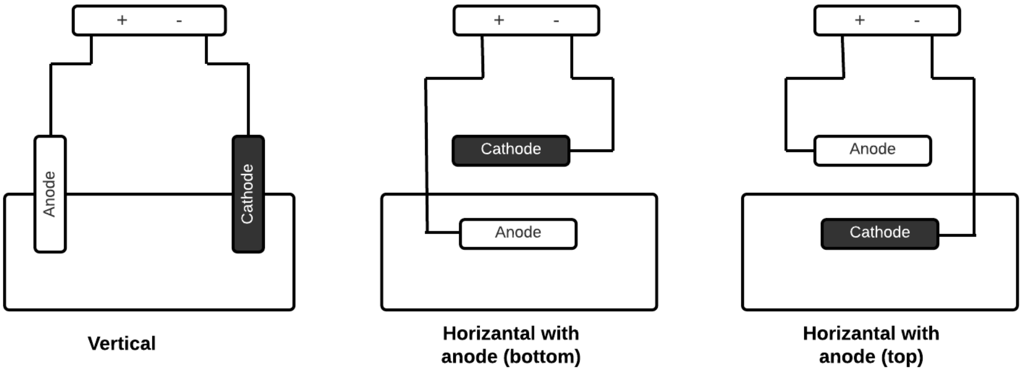

Figure 2-4: Different modes of electrode orientation adapted from (Nasrullah et al., 2018).

2.2 Electrocoagulation reactor design and operation

Although EC has been used for many years to treat water and wastewater successfully, the available literature does not give a systematic approach to EC reactors' design and operation (Holt et al., 2005). Reactor design is an essential factor for the chemical interaction and treatment process of EC. The reactor design affects operational parameters such as bubble path, flotation effectiveness, floc formation, fluid flow regime, and mixing or settling characteristics (Sahu et al., 2014, Kobya et al., 2020). Therefore, it is 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 2-5. The EC reactor can be operated in batch as well as continuous mode, and these configurations are the first distinction between the alternative designs of the reactor (Rodrigues et al., 2020, Carmona-Carmona et al., 2020, Sahu et al., 2014). From the classification of the electrocoagulation system, it is clear that the majority of applications fall into the latter category.

Continuous systems continuously feed 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). On the other hand, batch reactor applications are flow-less 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 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).

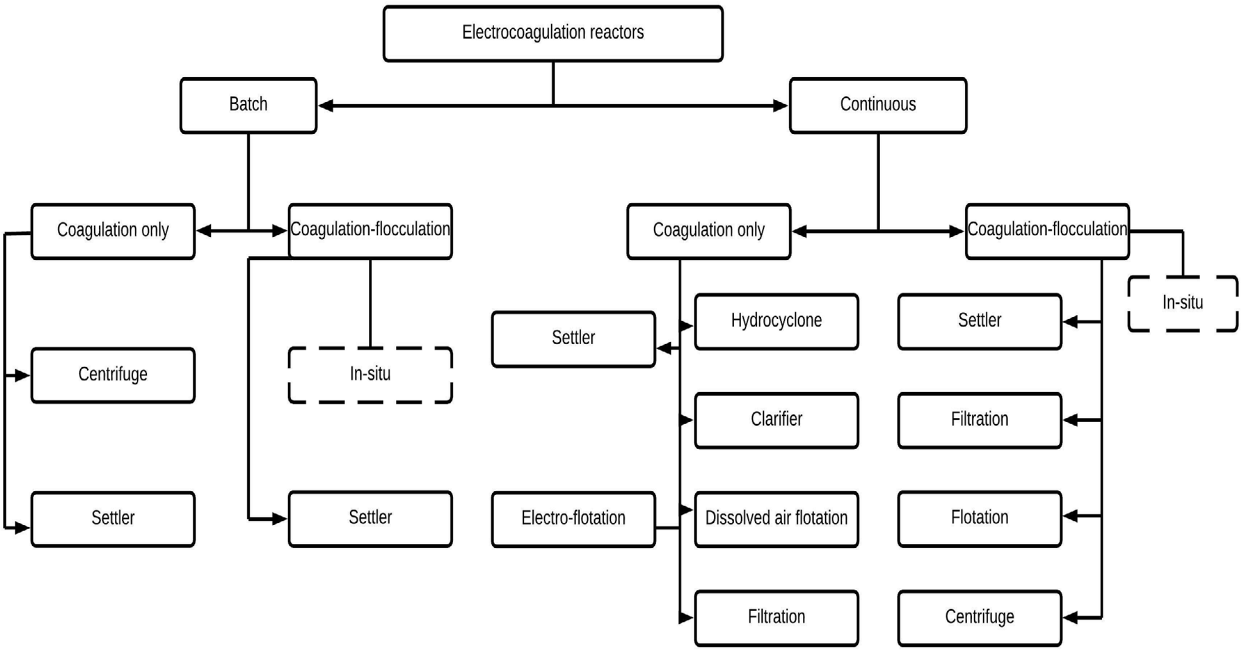

Figure 2-5: Classification of electrocoagulation systems adapted from (Holt et al., 2005)

2.3 Poultry slaughterhouse wastewater characteristics

The composition of wastewater generated from poultry processing plants is complex and highly-strength wastewater (Basitere, 2017, Terán Hilares et al., 2021). The primary pollutant in PSW is organic matter which mainly originates from poultry blood (Bazrafshan et al., 2012). The detergents and disinfectants used for sanitisation and cleaning add to the complexity, representing about 18-20% of the total wastewater generated (Bustillo-Lecompte et al., 2017, Terán Hilares 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 (Aziz et al., 2019, Yaakob et al., 2018, Akarsu et al., 2021). The variability of the diverse composition of PSW characteristics can be seen in Table 3.

Many countries have implemented various approaches 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 (Aziz et al., 2019, Bustillo-Lecompte et al., 2017, 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, 1998b). Pollution prevention also contributes to protecting water resources, where a person responsible for polluting a water resource is responsible for covering the costs of remediating the pollution (Harpe and Ramsden, 2000).

Table 2-3: Poultry slaughterhouse effluent characteristics reported in the literature.

Parameters	**Units**	**Debik and Coskun, 2009**	**Yordanov, 2010**	**Rajakumar et al., 2011**	**Rajab et al., 2017**	**Basitere et al., 2019**
Chemical Oxygen Demand (COD)	mg/L	2360,49	3610-4188	-	2711 ± 487	5126 ± 2534
Total Chemical Oxygen demand (TCOD)	mg/L	-	-	3000-4800	-	-
Biochemical Oxygen Demand (BOD5)	mg/L	-	1900-2200	750-1890	930 ± 96	2477 ± 1347
Soluble Chemical Oxygen Demand (SCOD)	mg/L	590,3	-	1030-3000	-	-
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 (CaCO3)	mg/L	185,25	-	600-1340	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	1594,66	-	-	-	-
Total Suspended Solids (TSS)	mg/L	-	2280-2446	-	835 ± 162	1654 ± 1695
Total Dissolved Solids (TDS)	mg/L	515	-	-	917 ± 135	1138 ± 294
Total Volatile Solids (TVS)	mg/L	1386	-	-	-	-
Ammonium (AM)	mg/L	-	-	-	85 ± 32	216 ± 56
Ph	–	6,17	-	7-7,6	6,8 ± 0,2	6,13–7,24
Turbidity	NTU	-	-	-	>1000	719 ± 201
Electrical conductivity	mS/cm	-	-	-	0,8 ± 0,109	1,6 ± 0,414
Salinity	mg/L	-	-	-	-	916 ± 179

– Not reported

2.4 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, FOG, TSS, TN, TP, and pathogens. COD is an important measurement of the number of organic pollutants in wastewater; a high concentration of COD suggests a large amount of oxidisable soluble and particulate organic matter in the wastewater. Similarly, BOD indicates the amount 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 suitable for treating PSW with 99% phosphorous 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 various 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 gut 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% 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; this indicates that EC is a robust treatment process for organic matter, nutrients and pathogens, which are difficult to be effectively removed 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

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Table 2-4: 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	(Kobya et al., 2006b)
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	(Bayar et al., 2011)
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	(Eryuruk et al., 2018)
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	(Tezcan Ün et al., 2009)
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	(Asselin et al., 2008a)
Electrolysis time (10-90 minutes)		Through 60 or 90 min	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	(Godini et al., 2012)
Current density	Fe-Fe	0,014 A/cm^2	94.5% 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	(Bayar et al., 2014)
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	(Combatt et al., 2017)
Electrolysis time (40 minutes)				
Initial pH (4)		7,5		
Initial pH(6.4)	Al-Gr (graphite)		76-85% COD	(Paulista et al., 2018)
Current density (3-15 mA/cm^2)		3 A/cm^2	93-99% colour	
Electrolysis time (3-75min)			95-99% TSS	

– No data

2.5 Electrocoagulation process parameters

Several operational parameters as shown in Figure 2-6, have an impact on the performance of the EC process for the removal of PSW contaminants. These parameters are discussed in the section below.

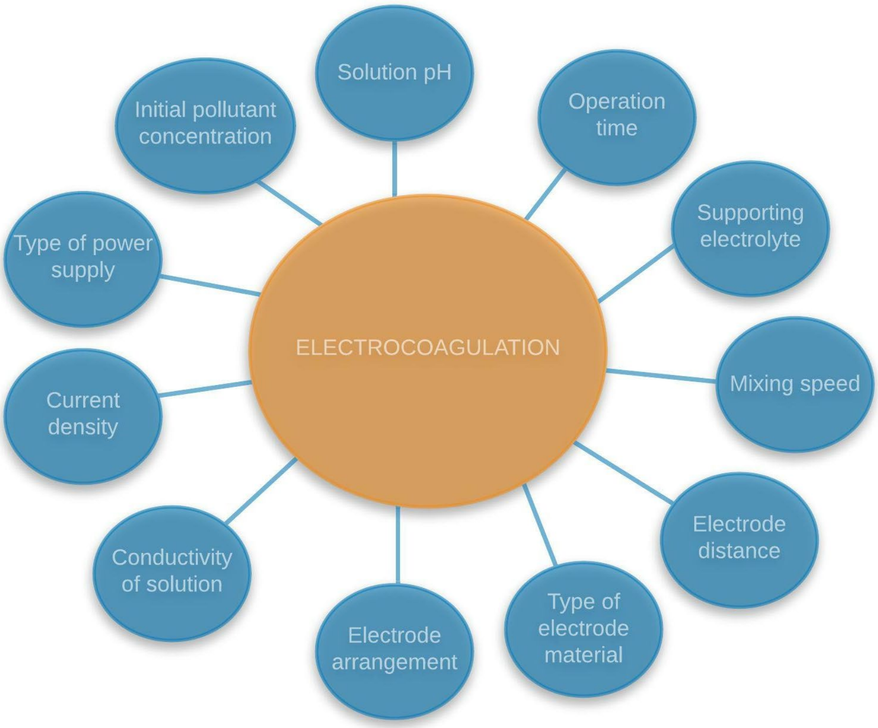

Figure 2-6: Operating parameters influencing the electrocoagulation process performance.

2.5.1 Initial pH

pH is described as an influencer for the contaminants distribution and coagulants produced in the EC process (Zaied et al., 2020). According to Mousa et al. (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 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 aluminium electrode and 60% COD using the iron electrode. However, when reduced to pH 2, COD removal efficiencies increased to 93% using aluminium and 85% (Fe) using the 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 and 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 $Al(OH)_3$ is formed which can 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 2-7, 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 $Al(OH)_4$ and $Fe(OH)_4$ ions form, which are a 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).

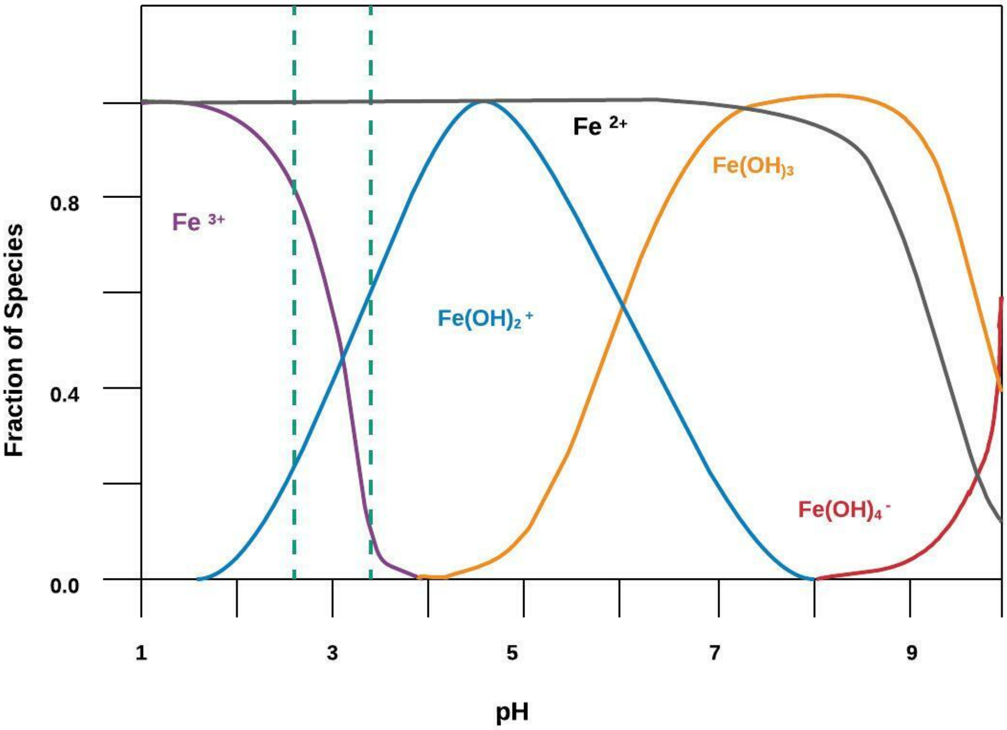

Figure 2-7: Iron species in an aqueous solution as a function of pH, adapted from (Bokare and Choi, 2009)

2.5.2 Electrolysis time

Electrolysis time is an important parameter that affects the treatment efficiency of the EC process. It may increase or decrease with the current density or pH of the sample (Naje et al., 2017). In a study done by Asselin et al. (2008a), 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 appears to range between 20-30 minutes (Bayar et al., 2011, Thirugnanasambandham et al., 2014, Kobya et al., 2006b, Yetilmezsoy et al., 2009).

2.5.3 Conductivity and supporting electrolyte

Conductivity adjustment is generally undertaken with the addition of a supporting electrolyte such as sodium chloride (NaCl) or sodium sulphate (Na_2SO_4) (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 Na_2SO_4 caused an increase in COD removal efficiency, and energy consumption was considerably reduced with increasing conductivity in the treatment of cattle slaughterhouse using EC. Similarly, Eryuruk et al. (2018) used Na_2SO_4 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 Na_2SO_4. The addition of electrolytes such as NaCl 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

2.5.4 Mixing speed

Generally, the stirring speed is kept constant for most EC studies of PSW treatment, typically within 100–300 rpm (Bayar et al., 2014, Kobya et al., 2006b, 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 $Al(OH)_3$ 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 optimise stirring speed as it influences removal efficiency and floc properties.

2.5.5 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 passed 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 and 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 the destabilisation of contaminant molecules. On the other hand, a study of the influence of current density and pH on the treatment of slaughterhouse wastewater employing 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/m^2. 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 (the current drawn is directly proportional to voltage input). Therefore, optimum current density supply in the EC process is very important.

2.5.6 Type of power supply

Generally, the EC process uses a direct current (DC) power supply which may lead to the formation an impermeable of oxide film on the cathode, which causes the passivation of anode bringing about an increase of the electrolytic cell resistance and decreasing the ionic transfer this increases energy consumption (Moussa et al., 2017). Sacrificial anodes can be replaced periodically, however, the replacement of electrodes increase 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 and Sivakumar, 2009). Yang et al. (2015) highlighted that passivation could be prevented by the addition of a sufficient amount of chloride ions 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.

2.5.7 Electrode configuration

The electrode arrangement is also an important factor for treatment efficiency. Depending on the geometry of the reactor, electrodes can be organised 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 mild steel BP-S connection had better performance than MP connection due to the higher surface area for sufficient anodic oxidation in the treatment of PSW. On the contrary, the monopolar configuration was reported to be better in the treatment of oily wastewater (Asselin et al., 2008b).

2.5.8 Material of electrode

The performance and treatment efficiency of an EC process depends 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, i.e., aluminium, iron, steel, copper, zinc, graphite, and many others (Zarei et al., 2018a, Islam, 2019, Budiyono and Seno, 2010, Meiramkulova et al., 2020b, Asselin et al., 2008a). 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 ball of 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 were 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 the weak settleability of Fe^{2+} ions. Fe^{2+} is the common ion produced on site of electrolysis of iron electrodes. It has high solubility at acidic or neutral pH and could be oxidised readily into Fe^3+ by dissolved oxygen in the water and are hard to settle (Emamjomeh and 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).

2.5.9 Electrode distance

The electrode spacing is a controlling parameter that affects the reactor's size and 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 mobility of the ions present, and this effect can also be reduced by the agitation of the bulk solution (Nasrullah et al., 2012). The inter-electrode 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 by low-energy consumption. An increase in inter-electrode spacing, increases cell voltage, causing an increase in 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.

2.6 Hybrid electrocoagulation processes

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

2.6.1 Electrocoagulation with chemical coagulation

Chemical coagulation is a process that includes the addition of inorganic coagulants or polymers in wastewater to destabilise 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 hybrid electrocoagulation with iron and aluminium electrodes, Na_2SO_4 and a pH of 7.8.

The optimum parameters included a 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 and 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 was 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.

2.6.2 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 an extremely high oxidising ability and decompose organic compounds in a shorter time (Pawar et al., 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 and Gandhimathi, 2012, Xu et al., 2020). At a pH below 3, the electro-Fenton process becomes less effective (Nidheesh and 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. H_2O_2 which decreased COD significantly by 95.48%.

2.6.3 Electrocoagulation followed by a membrane treatment system

Pre-treatment is required to increase the efficiency and life expectancy of the membrane by minimising fouling, scaling (Fatima et al., 2021). It also changes the properties of the wastewater making membrane separation more efficient (Obotey Ezugbe and 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 removing 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.

2.6.4 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/cm^2 post-treatment with EC, confirming the success of the combination of the treatment processes. Microorganisms such as *Bacilli subtills*, *Pseudomonas aeruginosa*, and *Proteus vulgaris* were used to prove that electrochemical degradation and biological oxidation could reduce 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 re-used. 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. The 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 the 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, purifying the wastewater as required to discharge into the environment and re-use 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 2-8 to treat PSW, articulating the different stages of the treatment in sequential order: Enzymatic pre-treatment → Screening → Electrocoagulation → Membrane filtration → Ultraviolet → Holding tank. Due to a 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 re-used in the poultry industry. This prevents the usage of methods such as chlorination from disinfecting the water, which can lead to hazardous by-products (Bustillo-Lecompte and Mehrvar, 2015). The clean water is then stored in a holding tank.

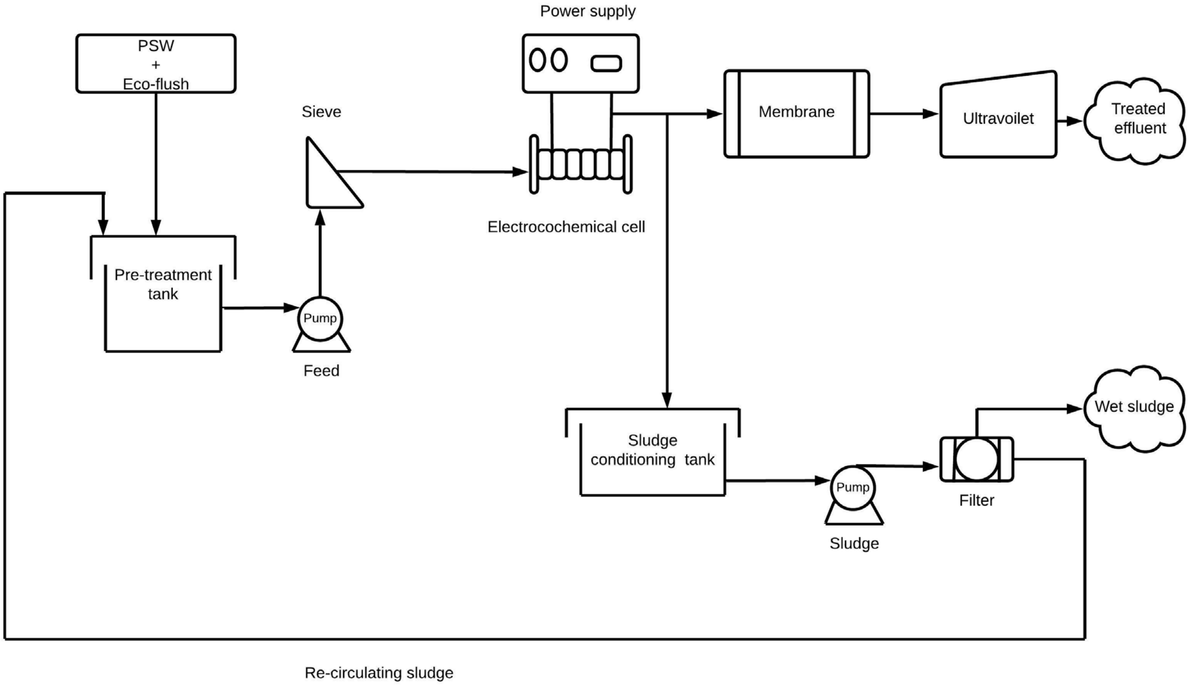

Figure 2-8: Proposed integrated system to treat poultry slaughterhouse wastewater

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 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 re-using PSW to ease the burden on fresh water resources. Due to low footprint requirement, environmental sustainability, and great potential of operation without 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.

2.7 Interaction of process parameters and optimisation using computational techniques

Optimisation 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 optimise processes. The objective for RSM is to evaluate the relative significance of several affecting factors and complex interactions during many variable optimisation 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 utilisation, 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/cm^2), and electrolyte dose (500-1250 mg/l) in a batch EC process for PSW; experimental data was optimised using the Box-Behnken design (BBD) and the interaction effects between these parameters were statistically significant on COD removal efficiency. Davarnejad and Nasiri (2017), treated PSW using the electro-Fenton technique. Electrolysis time, pH, H_2O_2/Fe^{2+} molar ratio, current density, and volume ratio of H_2O_2/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 maximise efficiency. The interaction facilitated 92.37% COD and 88.06% colour removal at optimum conditions.

2.8 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, the 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 based on \$/kg COD removed, which was 0.015 and 0.027 for iron and aluminium electrodes, respectively. In a study by Asselin et al. (2008), 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, significantly less than the total energy consumption reported for the 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 et al. (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 over 10 times higher. As the studies were not undertaken on poultry processing effluents, it is difficult to directly compare.

2.9 Future perspective and recommendation

- From the above discussion on economic analysis, it is clear that there is limited research and data on the economic feasibility of a full-scale EC system 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 and its comparison with conventional treatment methods.
- Electrode passivation is one of the disadvantages of the EC process that leads to a reduction in the removal efficiency. Although passivation can be rectified by electrodes regular cleaning, the addition of chloride ions, or applying alternative currents (Vasudevan, 2012), more studies should investigate electrode passivation to find methods to reduce/reverse the adverse effects. There is no generic solution to the electrode passivation problem.
- Aluminium and iron electrodes are amongst the most popular used electrodes. In literature, aluminium electrodes showed higher pollutant removal than iron (Kobya 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 their effect on the treatment efficiency of EC.

- Another major challenge is high electricity consumption which directly affects the operating costs. EC processes use electricity produced from non-conventional energy sources. However, Zaleschi et al. (2012) recently 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 to 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).
- 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 aid in reducing electrical energy consumption.

2.10 Summary

EC has a good potential for the treatment of PSW. It has gained interest due to its low sludge generation, ease of control, robustness, possibility to utilise renewable energy resources as a source of electrical power. It 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 operations 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 a more effective reactor design.

CHAPTER 3

POULTRY SLAUGHTERHOUSE WASTEWATER TREATMENT USING AN INTEGRATED BIOLOGICAL AND ELECTROCOAGULATION TREATMENT SYSTEM: PROCESS OPTIMISATION USING RESPONSE SURFACE METHODOLOGY

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3 Introduction

The poultry industry holds a prominent position among livestock-based trades due to its enormous potential to drive rapid economic growth (Bustillo-Lecompte & Mehrvar, 2015). Although this industry has notable achievements in socio-economic development, the volume of effluent generated is also very high (Bayar et al., 2011). Given global and local challenges such as water scarcity, pollution of surface water, the spread of water-borne diseases, and levies imposed by municipal councils on industries for the discharge of untreated wastewater, it is critical for industries to select and implement enhanced wastewater treatment strategies aimed at reducing the concentration of contaminants (Rajab et al., 2017). Alternative wastewater treatment strategies, such as electrooxidation, electroflotation and electrocoagulation, have been investigated in the last decade (Yasir et al., 2020). The latter has grown in popularity.

Electrocoagulation (EC) is an electrochemical process that presents an excellent alternative for poultry slaughterhouse wastewater (PSW) treatment; it can handle fluctuations in pollutant quality and quantity and can remove persistent pollutants from wastewater (Niazmand et al., 2020; Nidheesh et al., 2021). The main advantages of the EC process are (i) rapid breakdown of organic compounds, (ii) no addition of supplementary, (iii) environmental compatibility, (iv) high efficiency in pollutant degradation, and (v) cost-effectiveness. EC is based on passing electric current to degrade organic contaminants via redox reactions (Ozturk & Yilmaz, 2019). Through oxidation (equation 3-1), the anode generates metal cations, hydroxyl ions (OH^-), and dihydrogen (H_2) by water reduction at the cathode (equation 3-2). In (equations (3-3) -(3-5)), OH^- reacts with metal cations in the reaction medium to form metal hydroxides. The latter plays a significant role in pollutant removal in the EC process by (i) adsorption, (ii) coagulation, and (iii) flotation. The electrodes can be arranged in a monopolar or bipolar mode. The most common materials are aluminium and iron in plate forms (Ngobeni et al., 2021). The following are simplified reactions occurring at the electrodes (iron electrodes) (Eryuruk et al., 2018):

Oxidation: $Fe \rightarrow Fe^{2+} + 2e^{-}$ Equation 3-1

Reduction: $2H_2O + 2e^{-} \rightarrow H_2 + 2OH^{-}$ Equation 3-2

Reaction medium: $O_2 + Fe^{2+} + 2H_2O \rightarrow 4Fe^{3+} + 4OH^{-}$ Equation 3-3

$Fe^{2+} + 2OH^{-} \rightarrow Fe(OH)_2$ Equation 3-4

$Fe^{3+} + 3OH^{-} \rightarrow Fe(OH)_3$ Equation 3-5

The efficient treatment of lipid-rich wastewater, such as PSW, poses considerable technical and economic barriers due to its susceptibility to lipids that account for more than 67% of the wastewater's particulate COD (Damasceno et al., 2012). Operational challenges such as electrode passivation, which occurs when an impermeable film deposits on the surface of electrodes, reduce current and, as a result, the intensity of the redox process efficiency are one of the major problems for EC (Kobya et al., 2006). The contents in the lipids may be challenging to degrade using EC, as the fats, oil, and grease (FOG) may coat the electrode, thus creating a barrier for electrical conduction (Bazrafshan et al., 2012). Furthermore, this wastewater contains significant phosphorus, nitrogen, organic carbon, heavy metals, nutrients, detergents, and disinfectants attributed to residual blood, excreta, fat, feather, and stomach (Bustillo-Lecompte & Mehrvar, 2015). EC is also ineffective at eliminating ammonia nitrogen.

In this context, biological systems under aerobic conditions using EcoFlush^{TM} can achieve high organic matter and nutrient removal efficiencies. This technology has already showcased its efficacy in remediating PSW (Meyo et al., 2021; Dyosile et al., 2021). The study by Meyo et al. (2021) evaluated the performance of an expanded granular sludge bed reactor (EGSB) coupled with a membrane bioreactor (MBR) system using a novel microbial consortium (Ecoflush^{TM}) to treat PSW. The removal efficiency of 50% TSS, 70% COD and 82% FOG were observed. Similarly, Dyosile et al. (2021) assessed the use of a multistage system to treat PSW. The enzymatic pre-treatment (Ecoflush^{TM}) achieved removal efficiencies of 56% COD, 38% TSS, and 80% FOG. Therefore, it is hypothesized that EC combined with a biological system under aerobic conditions using EcoFlush^{TM} can be an effective method for a highly efficient operation to achieve a satisfactory quality of the final product, especially for this type of wastewater that contains various contaminants.

Therefore, the purpose of this study was to investigate the significance of a biological treatment under aerobic conditions combined with electrocoagulation to treat wastewater generated from the poultry industry. The work involved characterisation of the wastewater, assessment of biodegradation under aerobic pre-treatment conditions using Ecoflush^{TM}, and optimization of electrocoagulation on COD and FOG reduction under various operating parameters, including initial pH, current density and reaction time. To date, no research has been conducted on the removal efficiencies of the aerobic/electrocoagulation process using RSM in PSW. Furthermore, electrocoagulation systems are still being improved as a long-term sustainable technology.

3.1 Materials and methods

3.1.1 Poultry Slaughterhouse Wastewater Source

The poultry slaughterhouse wastewater (PSW) used in this study was collected from a poultry slaughterhouse located in the Western Cape, South Africa (SA). The facility slaughters 20 000 chickens per day, producing approximately 450 m^3 of PSW daily. The wastewater emerging from various operations such as stunning and slaughtering, de-feathering, evisceration, trimming, carcass washing, de-boning, chilling, packaging, cleaning of facilities and equipment was filtered using a 10 – 30 mm mechanical screen to remove suspended solids before further treatment. The PSW samples used in this study were obtained by grab sampling with plastic scoops from an equalisation tank, collected in separate polypropylene airtight storage containers, and kept at 4 °C in a refrigerator in the laboratory before use. Aliquots were then sampled for PSW characterisation.

3.1.2 Characterisation of Poultry Slaughterhouse Wastewater

The PSW samples were characterised for chemical oxygen demand (COD), fats, oils and grease (FOG), suspended solids (SS), ammonia nitrogen (NH_3-N), phosphates (PO_4^{3-}), heterotrophic plate count, total coliform, and *Escherichia coli* (E-coli), which were analysed at Bemlab (Somerset West, SA) using standard methods by Environmental Protection Agency (EPA) for water and wastewater analyses shown in Table. Physicochemical parameters such as pH, salinity, conductivity, and total dissolved solids (TDS) were measured using a multi-parameter instrument (SensoDirect 150, USA), and turbidity was determined using a turbidimeter (HI-93414-02, HANNA, USA).

Table 3-1: Methods used for characterizing poultry slaughterhouse wastewater

Parameters	Method
COD	EPA method 3289
FOG	EPA method 10056
SS	EPA method 4993
NH_3-N	EPA method 4511
PO_4^{3-}P	EPA method 4511
Heterotrophic Plate Count	EPA method 1454
Total coliforms	EPA method 6386
E Coli	EPA method 6386

3.1.3 Experimental setup and procedure

The experimental set-up used in this study is as shown in **Figure 3-1**.

3.1.3.1 Biological pre-treatment process

The biological pre-treatment of PSW was carried out in a 25 L polypropylene container at ambient temperature (24 ^{0}C). A volume of 100 ml Eco-flush™ (Mavu Biotechnologies Pty Ltd., SA) was added to 20 L of raw PSW. The mixture was aerated for 24 h using a Resun Ac 9906 six-outlet air pump (Hydroponic, SA) to sparge air into the pre-treatment tank using silicone tubes connected to two diffusers that provided sufficient micro-bubble formation into the system. The micro-bubble formation ensured a steady, adequate supply of dissolved air for optimal aerobic bacteria proliferation. The aerated mixture settled for a further 24 h. This allowed sufficient time for the Eco-Flush™ to digest the FOG and protein found in the PSW. Skimming was carried out to remove the FOG. In the process of scrapping, some solids trapped in the FOG were removed. After settling, the mixture was strained using two sieves with apertures of 1.18 mm and 53 μm, respectively. The strained product was recycled into a 25 L holding tank. This product was fed into the electrocoagulation (EC) reactor as the raw feed. The operating conditions used in this study were reported in a previous study by Bingo et al. (2021), who optimised the system while treating PSW from the same site.

3.1.4 Electrocoagulation experiments

Electrocoagulation treatment was carried out in a plexiglass batch reactor having a dimension of 0.15 m x 0.10 m x 0.12 m with a working volume of 2 L. Iron was used as anode and cathode in a monopolar configuration with a total effective surface area of 807 cm^2. The electrodes were connected to a direct current digital power supply (PS 8000 T, EA Elektro-Automatik, Germany), characterised by the ranges 0 – 20 A for current and 0 – 16 V for voltage. The electrodes were fully submerged into PSW in the reactor and operated at a steady room temperature of 25 ± 0.5 °C during all experiments. The EC unit was constantly agitated at a rotational speed of 300 rpm by a magnetic stirrer (MS-H-Pro Plus, DLAB Instruments Ltd., China). Optimisation of three numeric factors: initial pH (3–10), current density (13–72 A/m^2), reaction time (6–74 min), and one categorical factor: Eco-flush™ (with or without) were studied on the maximisation of two response variables: %COD reduction and %FOG reduction, using response surface methodology (RSM) based on a full factorial central composite design (CCD) with three levels for each factor (Table 3). The experimental design matrix was generated using Design-Expert® Software Version 12 (Stat-Ease, Inc., Minneapolis, USA).

The initial pH of PSW was adjusted to the required value using 0.1M hydrochloric acid (HCl) and sodium hydroxide (NaOH). Before each experimental run, electrodes were mechanically polished with abrasive paper and thoroughly rinsed with deionised water to remove any solid residue on the surface. Any stubborn impurities remaining on the surface were removed by dipping the electrodes for 5 min in 0.1 HCl. At the end of each experimental run, the treated effluent was allowed to settle for 30 min. A sample of the supernatant was sampled and characterised for COD and FOG to ascertain the process efficiency. All the experiments were run as per the design matrix.

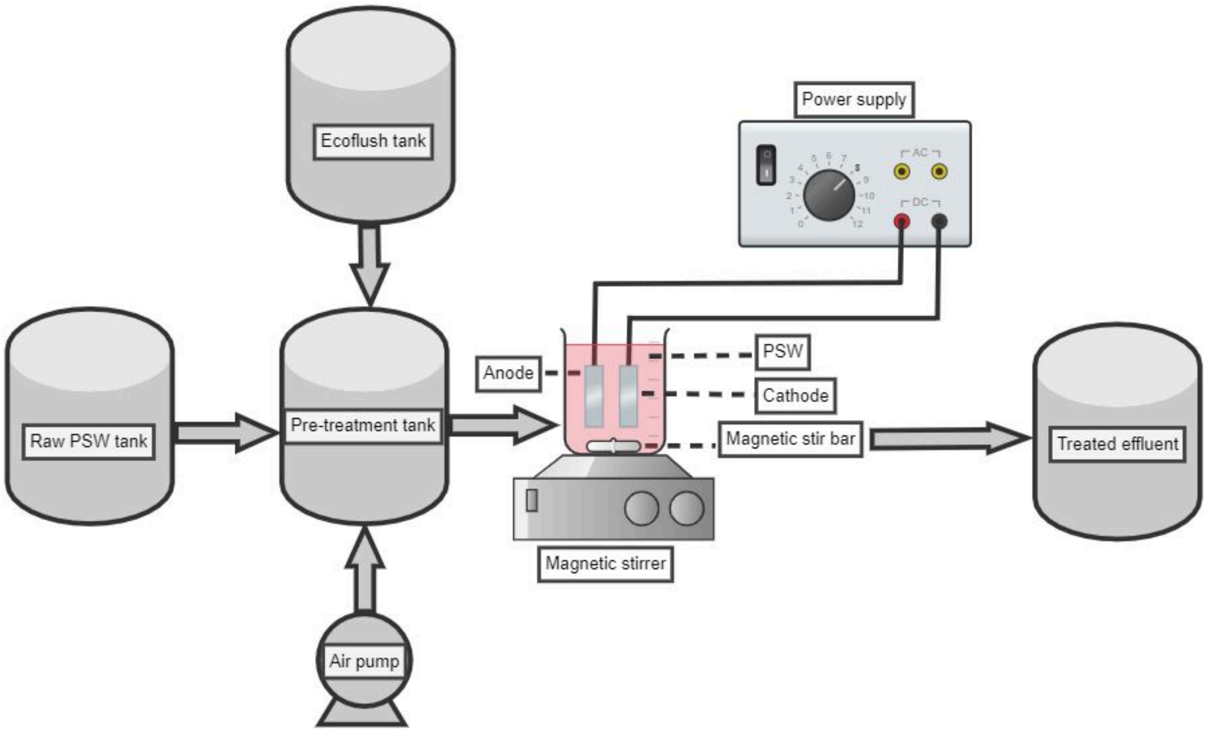


Figure 3-1*:* Schematic diagram of an integrated biological pre-treatment and electrocoagulation process used in this study

3.2 Modelling and statistical analysis

Design-Expert® Software allowed the fitting of quadratic empirical models (Eqs. 3-7 – 3-10) onto the experimental data using multiple regression analysis. The software performed multiple regression analysis, including ANOVA at 95% confidence interval (CI), to evaluate the interactions between process variables and the responses. The relationship between the responses and four independent variables were evaluated by developing the second-order polynomial mathematical models (Eq. 3-6). The fitted models only included significant terms ($p>0.05$) except when maintenance of the hierarchal structure was required. Optimisation analysis was performed to find combinations of process variables that would maximize %COD and %FOG reduction using the proposed best-fitting model equations.

$$Y = \beta_o + \sum_{j=1}^{k} \beta_j X_j + \sum_{j=1}^{k} \beta_{jj} X_j^2 + \sum_i \sum_{<j=2}^{k} \beta_{ij} X_i X_j + e_i \qquad \textbf{Equation 3-6}$$

Where Y is the response; β_o is the model intercept coefficient; β_j, β_{jj} and β_{ij} are the interaction coefficients of linear, quadratic, and second-order terms, respectively; X_iX_j are independent variables

(i and j range from 1 to k); k is the number of independent parameters (k=4 in this study); e_i is the error.

3.3 Economic analysis of electrocoagulation

The poultry processing industry must achieve excellent performance in PSW management while remaining cost-competitive. Economic feasibility studies are required to determine the viability of scaling up new technologies from pilot to full-scale deployment (Wang et al., 2020). Cost-effective analysis for the EC process in PSW treatment considers operation and maintenance, electrode depreciation, and sludge handling costs. However, environmental benefits are undervalued as they are not taken into account in conventional economic feasibility studies (Hernández-sancho et al., 2009).

The valuation of these benefits is required to justify an appropriate investment policy, and the contributions available in the literature are limited. Hernández-sancho et al., (2009) proposed a method for estimating shadow prices for pollutants removed during a treatment process. The value represented the environmental benefit (cost avoided) of not discharging pollution. This is a ground-breaking approach to calculating the economic value of wastewater treatment. When the benefits were weighed against the internal costs of the treatment process, they provided a valuable indicator of the viability of PSW treatment.

3.3.1 Determination of electrical energy consumption

The electrical energy consumption of the present EC treatment process was calculated using the following equation (Ferniza-garcía et al., 2017):

$$\mathrm{E} = \frac{\mathrm{VIt}}{\mathrm{V_s}}$$ **Equation 3-11**

where E is the electrical energy ($\mathrm{kW\ h/m^3}$), V is the cell voltage in volt (V), I is the current in ampere (A), Vs is the volume of PSW (m^3), and t is the time of electrocoagulation process (h).

3.3.2 Determination of chemical cost

$$\mathrm{C_{chemical}}\left(\frac{g}{m^3}\right) = \frac{\mathrm{Ch}}{\mathrm{Vs}}$$ **Equation 3-12**

where Ch is the quantity of chemical used (g) and Vs is the volume of PSW (m^3).

3.3.3 Determination of electrode material cost

$$\mathrm{C_{electrode}} = \frac{ItM}{zFV} x10^3$$ **Equation 3-13**

where V is the volume (L) of cold meat wastewater, F is the Faraday constant (96,485 C/mol), Z is the Al balance (+3), M is the atomic weight for Fe (55.85 g/mol), t is the time (s) for electrolysis and I is functional current (Amperes).

3.3.4 Determination of operating cost

The operating cost of the present EC treatment process was calculated using the following equation (Thirugnanasambandham et al., 2015):

$$\text{Operating cost}\left(\frac{\text{USD}}{\text{m}^3}\right) = \text{aC}_{\text{energy}} + \text{bC}_{\text{electrode}} + \text{cC}_{\text{chemical}} \qquad \textbf{Equation 3-14}$$

where $\text{aC}_{\text{energy}}$ is the electricity price of $(0.13\ \text{USD/kW h})$ obtained from South African government energy sector, $\text{bC}_{\text{electrode}}$ is the electrode material price 1.23 USD/kg Fe, obtained from the global metal market and $\text{cC}_{\text{chemical}}$ is the cost of chemicals which can be added (in this present study, sodium hydroxide and hydrochloric acid with a price of 0,4 and 0,55 USD/kg respectively).

3.4 Results and discussion

3.4.1 Characteristics of poultry slaughterhouse wastewater

Comprehensive PSW analysis results (**Table 3-2**) were compared to those reported by previous studies (Zarei et al., 2018; Ozturk & Yilmaz, 2019). Interestingly, wastewater from the same type of slaughterhouse industry exhibited a wide variation in the characteristics. This substantial variation indicates that the characteristics of PSW are site-specific and largely depend on local conditions as a result of different operational requirements and techniques (Del Pozo et al., 2003). The PSW effluent had high electrical conductivity, which is essential for the optimum performance of EC. It eliminates the need to add a supporting electrolyte required to facilitate current passage during treatment, thereby reducing electrical energy consumption and operating costs (Eryuruk et al., 2011). The maximum concentrations of TSS (8319 mg/L) were eight times higher than the stipulated limit value for discharge into the municipal sewer (City of Cape Town, 2014). Compared with the effluents discharge standards (City of Cape Town, 2014), PSW presented pH at acidic region (6.19-7.24) and was the only parameter that did not exceed the limit.

As expected, the COD and FOG concentrations were very high, which may be related to the nutrition and size of the birds slaughtered at the time of sampling (Njoya et al., 2019). There was a high ammonia nitrogen content, and PSW is expected to contain high concentrations of nitrogen in the protein from the blood (Del Pozo et al., 2003). The PSW also had a foul odour that of "rotten eggs," which may be due to the presence of compounds in the digestive tracts of animals, such as proteins, fats, and carbohydrates which undergo microbial decomposition under aerobic conditions and release of sulphides (Wiyarno & Widyastuti, 2015). The primary odour source in PSW is hydrogen sulphide gas, volatile organic sulphur compounds such as volatile fatty acids, nitrogenous compounds, and organic particulate material. The high concentrations of organic matter in the form of FOG present a challenge associated with the treatment of PSW (Basitere et al., 2019). Hence, a pre-treatment unit may be required (Meyo et al., 2021; Dyosile et al., 2021).

Table 3-2 : Characteristics of poultry slaughterhouse wastewater

		Permissive levels[a]	(Zarei et al., 2018)	Ozturk & Yilmaz, (2019)	Raw PSW	Pre-treatment
Parameters	Units	Range	Average	Range	Range	Range
pH	–	12	7.95	7.03 – 8.23	6.19 – 7.24	5.48 – 6.75
Electrical conductivity	mS/cm	500	49.87	1.36 – 3.04	0.95 – 2.47	2.97 – 3.45
TDS	Ppm	4000	–	–	634 – 1701	953 – 1620
Salinity	Ppm	–	–	–	489 – 1395	961 – 1328
Turbidity	NTU	–	–	–	316 – >1000	278 – 887
COD	mg/L	5000	3810	3968 – 5239	3750 – 14681	798 – 6490
SS	mg/L	1000	46.45	475 – 1800	405 – 8319	106 – 247
FOG	mg/L	400	–	50 – 407	280 – 1668	<1.0 – 183
NH_4^-N	mg/L	–	–	20 – 38	53 – 312	92 – 219
PO_4^{-3}	mg/L	25	–	72.25 – 190.48	30.8 – 56	134 – 178
Heterotrophic Plate Count	cfu/mL	–	–	–	>3000	–
Total coliforms	cfu/100 mL	–	110000	–	>2000	–
E coli	cfu/100 mL	–	–	–	>2000	–

[a] Maximum limit of permitted discharges of wastewater and industrial effluent (City of Cape Town, 2014)

– Not indicated

3.5 Evaluation of the biological pre-treatment performance

During the biological pre-treatment, 85% to 99% FOG reduction was achieved. Hydrocarbon chains in the FOG and other organic matter were weakened by hydrolytic enzymes present in the Ecoflush™ (Meyo et al., 2021). One of the most significant aspects was the low readily biodegradable COD (20% to 50%), which was even lower than previously reported in the literature. The post-biological effluent exhibited lower turbidity and odour, but a higher electrical conductivity was observed due to increased NH_4^+ and most likely NO_3^- concentrations. The hydrolysis of proteins produces amino acids and ammonia while the bubbling of air in the Eco-flush™ reactor promoted the oxidation of hydrogen sulfide, resulting in odour reduction. Similarly, Del Pozo & Diez, (2005) found that the organic matter removal efficiency was very high (93%), while the nitrogen removal efficiency was initially low (29%) but later increased (up to 82%) as the aerated volume was increased. It is conceivable that the raw PSW may have contained some aerobic bacteria that was present in the balancing tank at the time of sampling. These were then stimulated during the aeration of the Eco-flush™ reactor. Kibangou et al., (2021) observed the presence of bacteria and methanogenic archaea in raw tannery wastewater sampled from a balancing tank. Nonetheless, a good combination of anaerobic, anoxic, and aerobic processes is required for the biological removal of nutrients (N and P) (Del Pozo & Diez, 2005).

Although the biological treatment was able to provide high organic removal efficiencies in terms of FOG, a subsequent treatment process, such as EC treatment, is a viable option for handling a wide variety of other inorganic pollutants that could improve the final PSW quality characteristics. The slaughterhouse, as previously stated, produces high-strength wastewater with high COD which requires extended aeration when treated aerobically. Direct application of an aerobic treatment unit is associated with high costs of aeration and sludge disposal, necessitating an anaerobic pre-treatment stage (Rajab et al., 2017). For this reason, anaerobic pre-treatment is an efficient and cost-effective solution for this kind of wastewater as it significantly reduces sludge volume and beneficially produces biogas (Del Pozo et al., 2003).

Table 3-3: Experimental design matrix showing variables and their respective outcomes

	Factor				Response	
Run	A:pH	B:Current density(A/m^2)	C:Reaction time(mins)	D:Ecoflush	COD reduction(%)	FOG reduction(%)
1	9	60	60	With	16.1	99.7
2	5	60	20	With	12.1	99.3
3	5	25	60	Without	76.7	99.9
4	7	43	40	Without	65.9	99.9
5	5	60	60	With	20	99.5
6	9	25	20	With	29	95.9
7	7	43	40	Without	62.4	99.9
8	5	60	60	Without	85.7	99.9
9	7	72	40	With	20.8	99.7
10	7	43	40	With	23	99.7
11	10	43	40	Without	63.7	98.6
12	5	25	20	Without	69.9	99.5
13	7	43	40	With	25.4	99.8
14	7	43	40	Without	64	99.9
15	7	43	40	With	20.3	99.9
16	7	13	40	With	22.5	93.7
17	9	60	20	With	29.1	99.9
18	7	43	6	Without	56.8	99.7
19	7	72	40	Without	70.4	99.9
20	7	43	40	Without	66.1	99.9
21	7	43	74	With	23	99.9
22	9	60	60	Without	68.8	99.9
23	7	43	40	With	22.7	99.5
24	9	60	20	Without	61.3	99.8
25	5	25	60	With	11.3	99.9
26	9	25	60	Without	62.7	99
27	7	13	40	Without	63.2	99.3
28	9	25	60	With	54.2	95.9
29	7	43	40	With	13	99.5
30	7	43	40	Without	65.9	99.9
31	10	43	40	With	31	98.3
32	7	43	40	Without	65.6	99.9
33	5	60	20	Without	80.3	99.9
34	7	43	6	With	13.5	98.1
35	7	43	74	Without	75.6	99.9
36	3	43	40	With	4.7	99.9
37	7	43	40	With	9.1	99.9
38	5	25	20	With	2	99.8
39	9	25	20	Without	63.7	99.1
40	3	43	40	Without	66.7	99.9

3.6 Mono and synergistic effect of operational factors on process efficiency

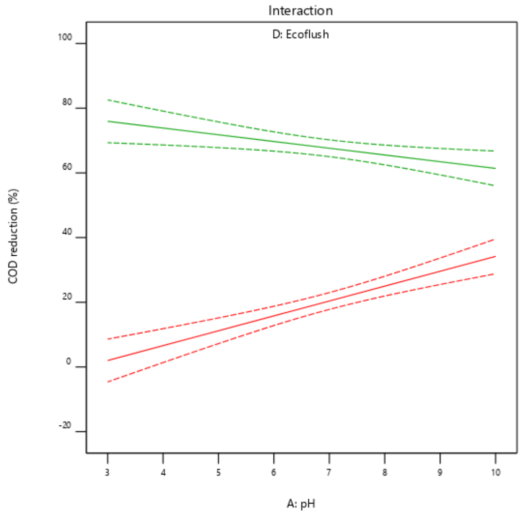
The results from this study indicated the significant impact ($p<0.05$) of pH, retention time, and the interaction of pH and current density on both COD and FOG reduction (**Table 3-5**). However, Ecoflush was not significant ($p>0.05$) on the removal of FOG due to the high efficiency (96–100%) of EC in removing FOG and hence its addition did not positively impact FOG removal. The integrated system achieved 93–100% FOG removal. Work by Meyo et al., (2021), Dlamini et al., (2021), and Dyosile et al., (2021) reported high 89–100% FOG while treating PSW using Ecoflush. Although FOG is known to negatively impact the efficiency of EC due to their adherence on the surface of electrodes causing their insulation, their impact was not observed in this study. This may have been due to the operating current density range used in this study.

A better COD reduction was obtained when the EC unit worked at lower pH, higher current density and retention time (RT). It is known that the amount of current density determines the coagulant dosage and size of the bubble production, and hence affects the growth of flocs (Nwabanne & Obi, 2017). However, current density had an insignificant ($p>0.05$) impact on the integrated system for COD reduction and on the EC unit for FOG reduction. It had a significant ($p<0.05$) impact on the integrated system during FOG removal. Lower FOG removal efficiencies (93%) were observed at opposite extremes of the interaction between pH and current density due to the impact of these factors on Ecoflush and EC, respectively. The high %COD and %FOG reduction in acidic medium agrees with the findings of Bayar et al., (2011) and Eryuruk et al., (2018).

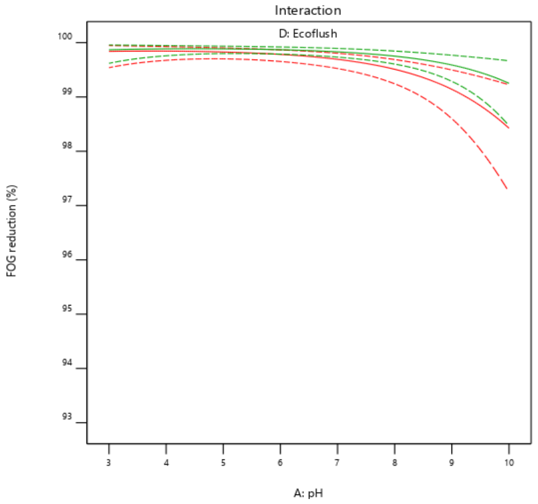
The treatment process achieved up to 99% FOG reduction without Ecoflush™ while operating at initial pH between 2 and 8. This indicates that iron electrodes used in the present study operate best in acidic, neutral, and slightly alkaline pH, producing mostly Fe^{2+} around pH 8 but generating Fe^{3+} species as the pH lowers (Sahu et al., 2014). This was in agreement with a study by Godini et al., (2012). Operating pH influences the growth rates of microorganisms as well as the bioavailability of compounds that may stimulate or inhibit microorganisms. The majority of aerobic bacteria and even distribution of unionised and ionised pollutants such as H_2S and NH_3 is at neutral pH (Adetunji, 2017). After EC treatment, pH changes in the effluent were observed. This is attributed to hydrogen evolution and the generation of OH^- ions at the cathodes (Nwabanne & Obi, 2017). In the present study, the initial pH (6.19-7.24) of raw PSW was ideal for both treatment systems and this eliminates the need for pH adjustment.

As expected, process efficiency linearly improved with an increase in RT. This is because, with an addition in the electrolysis time, more ions will be dissolved in the wastewater, leading to an increase in flocs formation. It should be noted that the higher the reaction time, the more power is consumed (Ngobeni et al., 2021). However, the increases became insignificant above 20 mins retention time. The interactions of RT with other factors on the process efficiency was insignificant ($p>0.05$) except with

Ecoflush for FOG removal. The literature indicates that the optimal reaction time for oily wastewater treatment ranges between 20-30 minutes (Thirugnanasambandham et al., 2015; Bayar et al., 2011).



A



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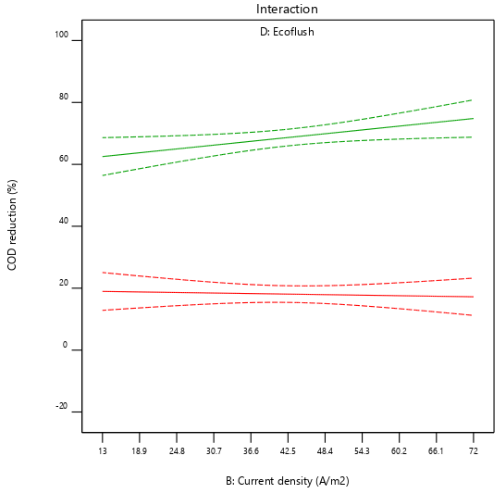

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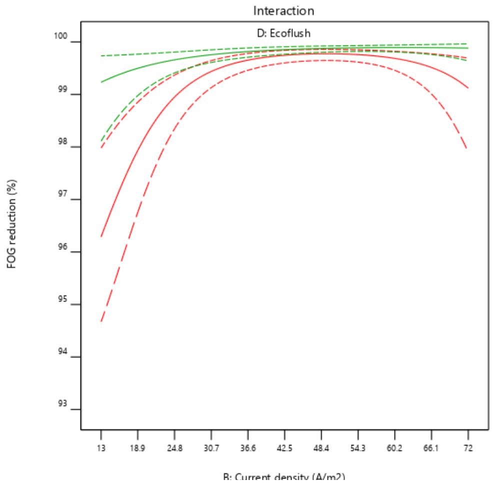

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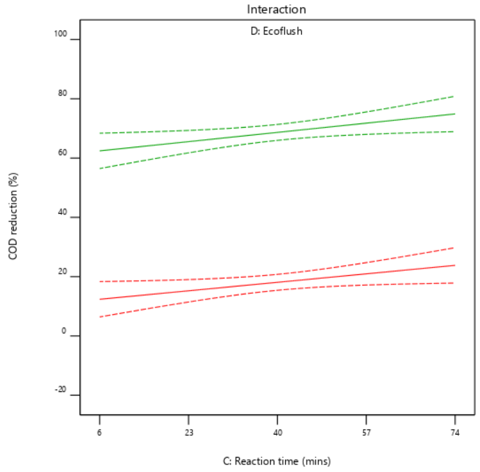

E

Figure 3-2: Interaction of numeric operating factors with (red) and without (green) Ecoflush™ and their impact on COD and FOG reduction: A– pH on COD reduction, B– pH on FOG reduction, C– current density on COD reduction, D– current density on FOG reduction, and E– reaction time on COD reduction

3.7 Process optimisation and analysis of variance

The fractional design space (FDS=0.99) and the signal: noise ratios were sufficiently greater than the recommended 0.8, while the adequate precision for all the empirical models were desirable>4 (Stat-Ease, Inc., Minneapolis, USA). The correlation coefficients (R^2) and adj. R^2 values which corrected the R^2 values in terms of sample size and several model terms indicated that only 4.2 and 3.6% for COD, 14 and 24% for FOG could not be explained by the models, respectively.

The ANOVA results indicated that all models were significant (F test, $p<0.05$), and there were minimal chances that this may have occurred due to noise (Table 4). The general quadratic polynomial equations did fit the %COD and %FOG reduction data very well (Lack of fit: F test, $p\leq0.05$)]. Therefore, Eq. 3-7 – Eq. 3-10 were used to navigate the design space and to optimise the cumulative %COD and %FOG reduction as plotted in **Figure 3-3**. Based on the interest to maximise COD and FOG reduction, the theoretical optimum operating conditions at a desirability 1, were determined as pH=3.1, current density=66.9 A/m^2, retention time=74 mins and without Ecoflush™. These optimum conditions were expected to achieve a reduction efficiency of 100% for both COD and FOG.

For COD reduction with Ecoflush™:

$$\mathbf{Y_1 = -76.94884 + 10.07236A + 1.37447B + \ 0.770394C0.128781AB - 0.014168BC}$$

Equation 3-7

For COD reduction without Ecoflush™:

$$\mathbf{Y_2 = 34.92281 + 3.39263A + 0.939701B + 0.070888C - \ 0.128781AB + 0.002644BC}$$

Equation 3-8

For FOG reduction with Ecoflush™:

$$\mathbf{Y_3 = 6.38443 - 1.16837A + 0.028399B + 0.017488C + 0.039282AB - 0.067013A^2 - 0.002884B^2}$$

Equation 3-9

For FOG reduction without Ecoflush™:

$$\boldsymbol{Y_4} \mathbf{= 1.53005 + 0.249074A + 0.055609B + 0.017488C \ + \ 0.008364AB - 0.067013A^2 - 0.000893B^2}$$

Equation 3-10

Table 3-4:. Summary of the statistical results of the fitted models

Parameter	COD model	FOG model
R^2	0.9640	0.8396
Adjusted R^2	0.9517	0.7767
Predicted R^2	0.9109	0.6088
Adequate precision	27.9845	15.5485
Mean	43.95	3.06
SD	5.68	0.7333
%CV	12.93	23.96
PRESS	2320.41	36.72

CV=coefficient of variation PRESS=predicted residual error sum of squares

Table 3-5: Analysis of variance for chemical oxygen demand and fats, oils and grease reduction

COD				**FOG**			
Source	**Mean Square**	**F-value**	**p-value**	**Source**	**Mean Square**	**F-value**	**p-value**
Model	2511.91	77.77	< 0.0001	Model	7.17	13.33	< 0.0001
A-pH	180.58	5.59	0.0250	A-pH	11.16	20.75	< 0.0001
B-Current density	60.71	1.88	0.1809	B-Current density	9.99	18.59	0.0002
C-Reaction time	340.44	10.54	0.0029	C-Reaction time	3.37	6.27	0.0184
D-Ecoflush	23874.69	739.13	< 0.0001	D-Ecoflush	1.93	3.58	0.0688
AB	325.17	10.07	0.0036	AB	11.13	20.70	< 0.0001
AD	1270.52	39.33	< 0.0001	AD	0.3043	0.5660	0.4581
BC	65.10	2.02	0.1664	BD	0.0379	0.0706	0.7924
BD	118.44	3.67	0.0654	A^2	2.51	4.66	0.0395
CD	0.6212	0.0192	0.8907	B^2	9.78	18.18	0.0002
BCD	138.55	4.29	0.0474	ABD	4.69	8.72	0.0063
Residual	32.30			B^2D	2.75	5.11	0.0318

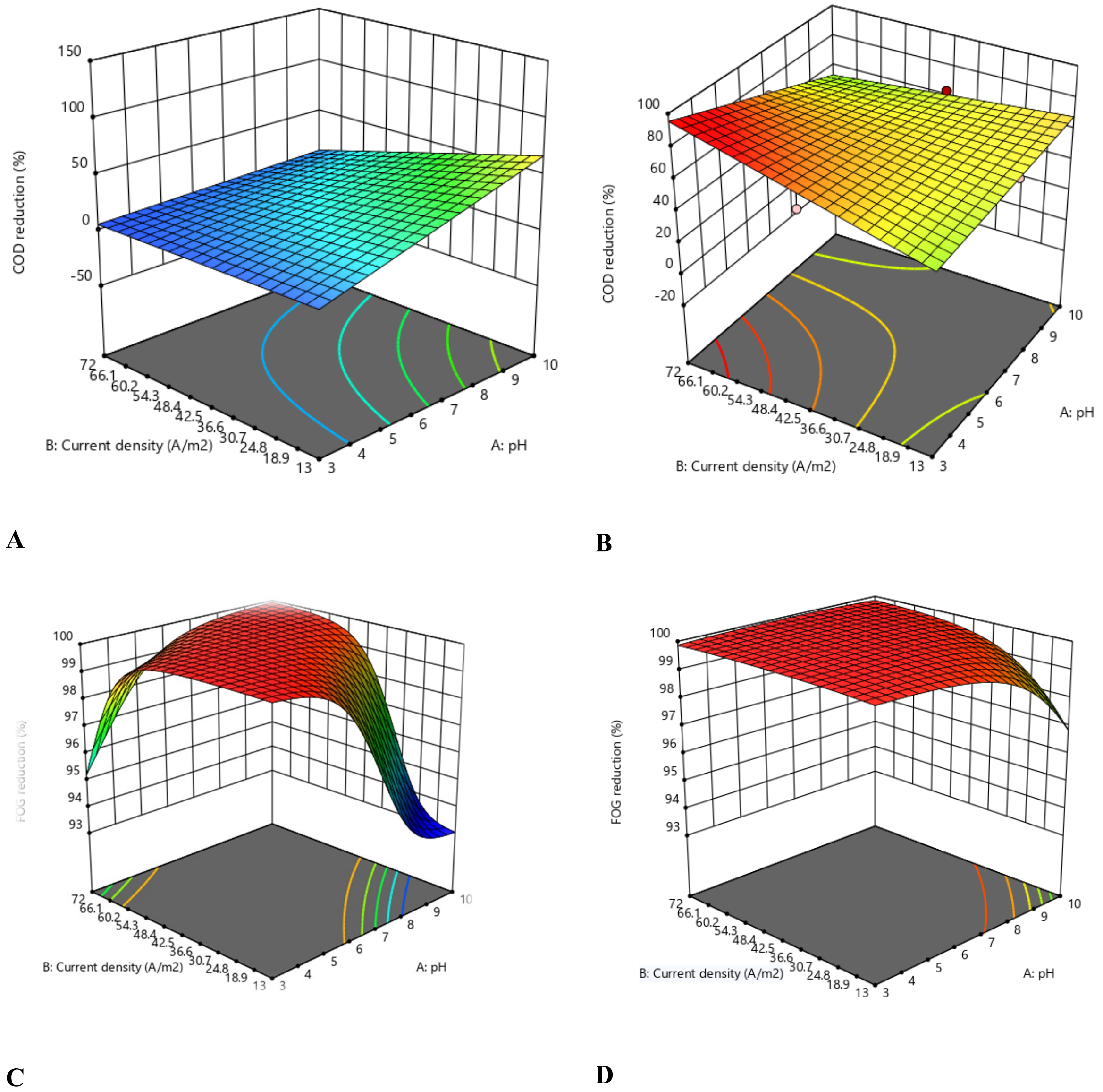

Figure 3-3: Effect of operating parameters on process efficiency: A – current density and pH on COD reduction (with Ecoflush™), B– current density and pH on COD reduction (without Ecoflush™), C –current density and pH on FOG reduction (with Ecoflush™); D – current density and pH on FOG reduction (without Ecoflush™).

3.8 Validation of process optimum conditions

Additional experiments were conducted to validate the theoretical optimal conditions (pH=3.05, current density=66.9 A/m^2, reaction time= 74 minutes and without Ecoflush™). According to the repeat experiments, 92.37% COD removal and 99.85% FOG reduction were achieved (**Table 3-7**). The actual experimental removal efficiency and the model prediction data were in very close agreement with less than 8.0% and 0.04% error for COD and FOG, respectively. This confirms the models' accuracy in predicting reduction efficiencies. These results are in agreement with Godini et al. (2012) and Kobya et al. (2005) who achieved 90.4% and 85% COD reduction while using EC, respectively. The treated effluent also met the stipulated discharge standards as shown in **Table 3-6**.

Table 3-6: Comparison of the treated effluent with City of Cape Town's discharge standards

		Permissive levels [a]	Treated effluent
Parameter	Units	Range	Range
pH	–	12	3.43
Electrical conductivity	mS/cm	500	4.97
TDS	ppm	4000	2.5 x 10^6
Salinity	ppm	–	2.67 x 10^6
Turbidity	NTU	–	1.78
COD	mg/L	5000	1770
SS	mg/L	1000	234
FOG	mg/L	400	2.5
NH_4^-N	mg/L	–	120
PO_4^{-3}	mg/L	25	9.4
Heterotrophic Plate Count	cfu/mL	–	1
Total coliforms	cfu/100 mL	–	Not detected
E coli	cfu/100 mL	–	Not detected

[a] Maximum limit of permitted discharges of wastewater and industrial effluent (City of Cape Town, 2014)

– Not indicated

Table 3-7*: Validation of the theoretical optimum*

Response	Predicted value (%)	Actual value (%)	Error (%)
COD reduction	100	92.37	7.63
FOG reduction	99.89	99.85	0.04

COD: chemical oxygen demand FOG: fats, oils and grease

3.9 Calculation of operational costs

It should be noted that the best removal efficiencies were obtained with a high current density of 66.9 A/m2, implying that the system will require more electricity and may increase its overall energy consumption. As a result, it is critical to compute the operational cost for each set of parameters to assess the price feasibility of the proposed computational methods. These calculations were carried out in the manner described in Section 3.3. These findings imply that computational techniques such as RSM are capable of determining the best parameters to maximize COD and FOG removal while minimizing operation costs. They can also be very useful in performing more precise and, in some cases, less expensive laboratory experiments.

3.10 Summary

This research allowed for the optimization of biological and electrocoagulation processes using response surface methodology, as well as the treatment of PSW under optimal conditions. The biological treatment resulted in 85-99% FOG reduction and 20-50% COD reduction, odourless effluent, indicating that PSW was biodegradable. The combination of both processes did not perform as expected when compared to the separate processes. Despite the low removal percentages of some pollutants, the present study proved the ability of the biological treatment with novel Ecoflush™ for treating lipid-rich wastewater such as PSW largely for the removal of FOG. This proves the capability of its use as a pre-treatment for other conventional methods such as anaerobic digestion. The best conditions were obtained by using a pH of 3.05, a current density of 66.9 A/m^2, 74-minutes treatment time and without Ecoflush™). 9 kWh/m^3 of electricity was used. The EC process produced a high-quality clarified effluent without solids in suspension with 92.4% COD reduction and 99% FOG reduction after 60 minutes of reaction.

This study also showed that EC is a promising treatment method for PSW effluent. Even though the nitrogen removal was insufficient compared to conventional wastewater treatment technologies, there are several benefits of EC treatment, including short retention time, small footprint, no mixing, and elimination of coagulants addition. These characteristics enable EC technology to be used alone or in conjunction with other technologies for a wide variety of wastewater treatment applications. The treatment cost was also viable. As a result of this research, electrocoagulation is demonstrated to be an effective method for treating PSW. In addition, RSM is extremely useful for EC modelling and optimization. As a result of the findings, RSM can be used to treat PSW on both a pre-industrial and industrial scale.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS AND RECOMMENDATIONS

This study provided an insight into the global water crisis induced by the lack of proper water and wastewater management systems in poultry slaughterhouses that contribute to the growing global water scarcity. As a result, alternative treatments for PSW were proposed and described. Subsequently, the focus was on biological treatment using hydrolytic enzymes (Ecoflush™) to reduce pollutants in poultry processing wastewaters under aerobic conditions. EC process was also thoroughly described and investigated by varying different operating parameters to treat PSW. Furthermore, the optimisation of the performance of EC with Ecoflush™ and without Ecoflush™ was approached using Design-Expert®. Although there was an enhanced reduction of organic load (FOG) from PSW when using Ecoflush™ as proposed in this work, the comparison of the performances suggested that EC alone without Ecoflush™ pretreatment presents the best alternative.

The findings and the conclusions of this work provide the basis for future research in several areas:

- Future research must concentrate on gaining a better understanding of the behaviour of pollutants present in PSW, as well as the mechanisms of their degradation through the use of hydrolytic enzymes.
- A study of the parameters influencing the electrocoagulation performance of the iron electrode would be beneficial, as this electrode material demonstrated excellent removal efficiencies. Parameters such as temperature and type of supporting electrolyte should be evaluated in addition to those presented in this study.
- A comprehensive design of experiments should be used to optimise the electrocoagulation process in terms of removal efficiency and energy consumption.
- Further work may consider post-treatment processes after the EC process for the removal of NO_3^-, NH_4^+, and PO_4^{3-} such as membrane or UV/ozone processes.

CHAPTER 5

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REFERENCES

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