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Electrocoagulation treatment of dairy processing and slaughterhouse wastewaters

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Abstract

The dairy processing and slaughterhouse industries consume large volumes of water and their waste effluents often contain high levels of chemical oxygen demand (COD), biochemical/biological oxygen demand (BOD) and fertilising nutrients. Therefore, water treatment is necessary to reduce the levels of these contaminants prior to discharge or reuse of the water. In this short review paper we provide a brief overview of electrocoagulation (EC) technology and summarise the current literature relating to the use of EC treatment to clean dairy processing and slaughterhouse wastewaters.

Keywords: electrocoagulation; agriculture; wastewater; dairy; meat;

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Nomenclature

(aq)	aqueous
(g)	gas
(l)	liquid
(s)	solid
AISI	American Iron and Steel Institute
Al	aluminium
BOD	biochemical/biological oxygen demand
C	coulombs
COD	chemical oxygen demand
EC	electrocoagulation
F	Faraday's constant
Fe	iron
Hard	water hardness
I	current
M	molar mass
N	nitrogen
NTU	nephelometric turbidity unit
O&G	oil and grease
P	phosphorus
PACl	poly-aluminium chloride
PSW	poultry slaughterhouse waste
t	process time
TDS	total dissolved solids
TN	total nitrogen
TOC	total organic carbon
TP	total phosphorus
Trb	turbidity
TS	total solids
TSS	total suspended solids
US	United States of America
UVA	ultraviolet A
w	ion dosage from anode
z	valency

1. Introduction

Dairy processing and slaughterhouse industries require large volumes of water for their operations and therefore generate a considerable amount of waste effluents. The amount of wastewater effluent from dairy food production is around 2.5 times the volume of food product created [1]. Moreover, it has been estimated that the meat industry accounts for approximately a third of the total freshwater consumed by the global agricultural sector [2]. Meat and dairy production are both industries which continue to grow rapidly in response to world population growth, increasing affluence and higher consumer demand [3].

Ideally, wastewaters from dairy processing and slaughterhouses should be cleaned on site to avoid contamination of the local environment and enable recirculation of water back into plant operations. Dairy and meat processing effluents often contain high levels of organic materials and fertiliser nutrients. Therefore, they present a high risk to waterways and soil and can lead to environmental damage if they are not treated appropriately before being discharged [4, 5]. For example, discharge of COD into rivers can cause eutrophication and lead to rapid depletion of dissolved

oxygen, which subsequently results in loss of aquatic life [4]. Disposal of untreated wastewater on land can cause surface water-logging as well as biological and heavy metal contamination of ground water [6]. Furthermore, Shete and Shinkar [7] described how dairy effluents, in particular, will rapidly decompose in tropical regions and release foul odours that can attract flies and mosquitos which carry malaria and other dangerous diseases. Substantial variations in the quantity and quality of dairy effluents provide a technical challenge for treatment solutions prior to discharge. Such variations can be seasonal due to higher processing in the summer months, while significant hourly changes can occur due to cleaning regimes or a switch to the type of dairy product made [1].

Slaughterhouse wastewater presents a biological risk to humans and other animals due to the presence of pathogens, pharmaceuticals and toxic chemicals which are used for plant cleaning [2]. This harmful potential means that the disposal of slaughterhouse and dairy waste is often subject to local legislations which have been put in place to protect public health [2, 4]. For example, COD in slaughterhouse wastewater often requires 95% reduction, with similar levels of treatment being required for both N and P, before final discharge into the environment [2].

Currently, the UK dairy processing and slaughterhouse industries both use technologies such as chemical dosing, reverse osmosis, anaerobic digestion, dissolved air floatation and membrane bioreactors to treat their wastewaters [1, 8, 9]. In recent years, a number of studies have investigated the potential of incorporating the process of EC alongside or instead of the more conventional treatment technologies for dealing with these waste effluents. This short review paper aims to give a brief overview of EC and the potential for the technology in dairy processing and slaughterhouse industries.

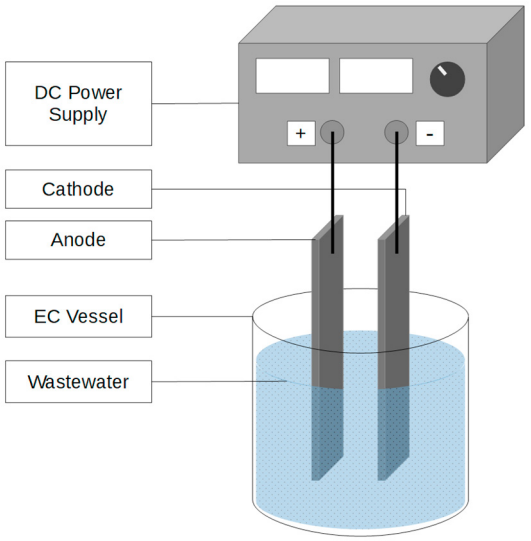

Fig. 1. An electrocoagulation (EC) cell in its most basic batch form.

2. General overview of electrocoagulation technology

Typically, EC equipment consists of DC-powered cathode and anode electrodes, which are partially submerged into a tank that contains a contaminated solution (Fig. 1). These electrodes can vary in shape, size and number, but rectangular-shaped plates are often used [10]. The most common metals used to manufacture EC electrodes are Al and Fe because they are cost effective, widely available and non-hazardous [4, 10]. The EC system can be operated in batch or continuous modes by either treating a fixed volume of waste effluent per process cycle or treatment of a continuous flow of the waste stream, respectively.

Electrolysis is used in EC to cause the dissolution of the metal (sacrificial) anode into the wastewater. The flux of metal ions from the sacrificial anode act as a coagulating agent for binding contaminants. Once in solution, Al^{3+} and Fe^{2+} ions will react with OH^- groups to form hydroxides, which bind contaminants either by complexation or electrostatic attraction [11]. Often, the dispersion of the coagulant is aided by a short burst of fast mechanical stirring.

After the contaminants have been bound together, the resultant increase in their particle size enables the use of low-cost filtration or sedimentation technology to remove coagulated solids, which enables the subsequent recovery of clean water. In addition to dissolution of metal ions, H_2 gas is produced at the cathode and the presence of Cl^- ions in a waste stream can result in gaseous Cl_2 bubbles being formed at the anode [10]. Release of gas bubbles in the EC cell assists with the treatment process by providing buoyancy to some coagulated contaminants, which causes them to float to the surface, from where they may be skimmed off [12].

The key chemical reactions which occur at the anode and cathode when using Al and Fe electrodes are represented by the following equations [10]:

At the anode:

$$Al_{(s)} \rightarrow Al^{3+}_{(aq)} + 3e^-$$

$$Fe_{(s)} \rightarrow Fe^{2+}_{(aq)} + 2e^-$$

$$2Cl^-_{(aq)} \rightarrow Cl_{2\,(g)} + 2e^-$$

At the cathode:

$$2H_2O_{(l)} + 2e^- \rightarrow H_{2(g)} + 2OH^-_{(aq)}$$

The release of metal ions from the anode (w) (or ion dosage) can be quantified theoretically by using Faraday's law:

$$w = \frac{I\,t\,M}{z\,F}$$

Where I is the current (A), t is the process time (s), M is the molar mass of the electrode metal (g/mol), z is the valency of the anode metal and F is Faraday's constant (96,485 C/mol). However, as outlined by Kuokkanen *et al.,* [13] the theoretical amount of anode dissolution is often exceeded during EC operation due to pitting corrosion.

In addition to processing time, the applied current and choice of electrode material, the overall efficiency of the EC process is also dependent on parameters of the waste influent such as the conductivity and pH [9]. Greater conductivity in the wastewater stream lowers ohmic resistance of the electrolysis circuit. This reduction in electrical resistance lowers the voltage that is necessary to treat a required load, which subsequently lowers the electrical consumption of the process [9].

The dominant species of Al and Fe ions formed is determined by the pH of the waste stream [14]. When using Al electrodes an excess of Al^{3+} cations are formed in a pH below ~4, $Al(OH)_3$ is mainly active between pH 4-12 and aluminate anions (e.g. AlO_4^{5-}) are dominant when the pH exceeds ~12. The valency of dissolved Fe can be controlled by pH and used to predict the formation of $Fe(OH)_2$ or $Fe(OH)_3$ coagulants in the solution. The Fe^{2+} ions are highly soluble and therefore an alkaline pH is beneficial for their oxidation into trivalent cations which are optimal for Fe coagulation of contaminants [10, 15]. Table 1 provides a summary of the advantages and disadvantages of using EC technology.

Table 1. The positives and negatives of using electrocoagulation to treat waste streams

Positives	Negatives
Low energy requirement	Regular replacement of anodes and cathodes
Small equipment footprint	Requires a source of electricity
Suitable for decentralised/rural operation	Fouling or passivation of electrode plates can cause process inefficiency
No requirement for hazardous chemicals	
Low risk of secondary contamination	
Low capital cost	
Low operating expense	
Reduction in sludge volume	
Can remove a variety of contaminants	

3. Electrocoagulation applications in the livestock food processing sector

3.1. The dairy industry

In recent years, a number of studies have investigated the potential of incorporating EC into onsite treatment of dairy wastes [6, 9, 16, 17] (Table 2). These studies have demonstrated that EC can remove turbidity, P, N and COD from dairy wastewater. Şengil and özacar [9] used bipolar steel EC electrodes in batch modes to treat a mixture of effluents from a dairy factory. The researchers showed that COD removal efficiency increased from 88 to 98% when the initial concentration of COD was increased from 1,550 to 19,800 mg/L. Tchamango *et al.,* [18] experimented with synthetic dairy wastes created from the dilution of semi-skimmed milk powder and lactose. Their experiments where made using an Al anode, a current of 43 A/m^2 and a treatment time of 30 minutes; they achieved 81 and 89% removal of N and P, respectively. Notably, the (61%) reduction of COD by EC in this study was much lower than that achieved by Şengil and özacar [9] and this can be attributed to the superiority of steel for removing contaminants such as lactose. The investigators went on to compare the efficiency between EC and conventional chemical dosing using aluminium sulphate. The molar concentration of Al required for treatment was consistent but the mass of the chemical required was 10 times greater [18].

Ghahremani *et al.,* [17] compared the use of Al, Fe and stainless steel anodes to treat raw samples of mixed wastewaters from a dairy factory. Their best EC performance was achieved using Fe which reduced COD in the effluent from 1,605 to 285 mg/L (a reduction of 82%). Lopes Geraldino *et al.,* [16] used Fe anodes in batch mode to complete a detailed study in which pH, treatment time and current were varied. Surface response methodology indicated that the most successful removal of COD could be achieved when the pH was increased from 3.3 to 4.5 by the addition of $Ca(OH)_2$ prior to using a current density of ~36 A/m^2 for 60 minutes. These conditions removed over 90% of turbidity and COD while raising the pH of the treated effluent to 7.5. Lopes Geraldino *et al.,* [16] went on to estimate that $1.04 (US) was the operating cost for treating each m^3 of dairy wastewater used in their case study.

Qasim and Mane [6] investigated a range of EC parameters to treat milk and ice cream production wastewaters. In their study, they successfully reduced the COD, turbidity and hardness of the wastewater effluents. The investigators demonstrated that when using Al electrodes for 60 minutes COD, turbidity and hardness could be reduced in dairy wastewater by 39, 51 and 41%, respectively. While using the same EC reactor conditions 49% of COD, 82% of turbidity and 30% of hardness were removed from ice cream waste (Table 2). Bassala *et al.,* [19] tested a novel EC reactor design (which consisted of an array of Al electrodes) to treat synthetic dairy wastewater and reported that 98% of P and 80% of COD could be removed for a treatment cost of $0.026 (US) m^{-3}.

Other investigators have studied the incorporation of advanced oxidation processes into EC treatment of dairy wastewater [4, 12, 20]. Torres-Sánchez *et al.*, [12] looked at the potential for combining Fenton's reaction, ozone treatment and EC to process the waste created by an ice cream factory. Fenton's reaction can be applied during EC by the addition of H_2O_2 to the process when using Fe anodes. The reaction between hydroxyl radicals (from H_2O_2) and Fe^{2+} increases the oxidation state of Fe to Fe^{3+}. The application of ozone to EC can also contribute to oxidation in the wastewater either directly or by the further addition of hydroxyl radicals. Torres-Sánchez *et al.*, [12] used electrodes

with a periodic interchange of circuit polarity. The addition of H_2O_2 at a ratio of 5:1 (H_2O_2:Fe^{2+}) in combination with an ozone stream of 250 mg/h was able to enhance COD removal to 70% compared to the 37.3% achieved by the EC-only control. In a recent study, Tirado *et al.*, [4] tested a range of anode materials for EC of dairy waste and applied a photoelectro-Fenton reaction by using a UVA lamp. This process combination was able to remove approximately 50% of total organic carbon from cheese whey wastewater. The authors identified the energy consumption of the UVA to be economically unfavourable and suggested the use of direct sunlight as a potential alternative [4].

3.2. The slaughterhouse industry

A number of studies have demonstrated the potential of EC for treating slaughterhouse wastes [5, 8, 11, 21–24] (Table 2). Research in this area has included variation of pH [5], current density [21], treatment time [24] and the influence of dilution [11].

Bazrafshan *et al.*, [8] used a combined chemical and EC process to treat effluent collected from a cattle slaughterhouse. Firstly, chemical coagulation with PACl was used before collecting the supernatant and carrying out further treatment utilising bipolar batch EC with Al electrodes. The study showed that after using a PACl dosage of 100 mg/L and then applying 40 V for 1 hour of EC the COD and BOD levels were reduced to levels below the requirements for discharge in Iran. The authors noted that the energy consumption of the EC stage was 90 kWh/m^3. Bazrafshan *et al.*, [8] highlighted a common challenge of treating slaughterhouse waste which is the difficulty associated with removing the high quantities of fat, oil and grease that they contain.

Ahmadian *et al.*, [24] varied the total number of Fe electrodes, the current density applied (5-25 A/m^2) and used various treatment times (10-50 min) to treat slaughterhouse waste in batch mode. Increasing all of the parameters led to a higher average removal efficiency for BOD, COD, suspended solids and N. In their study, Ahmadian *et al.*, [24] demonstrated that the rate of removal of these attributes over time correlated well with a first order kinetics model.

Other studies using EC have focused on treatment of wastewater from PSW [5, 11, 21, 23]. Thirugnanasambandham *et al.,* [11] treated PSW with a COD strength of 5,500 mg/L. The investigators completed a range of lab tests and analysed their findings by using a response surface experimental design. Their resultant model predicted that the optimum EC operational conditions for treatment of PSW were to use an initial pH of 6, 30% pre-dilution of the influent with water, electrolyte dose of 1,075 mg/L and a current density of 14 mA/cm^2. This process was able to achieve over 90% removal of COD while consuming an electrical load of 3.48 kWh/L. Kobya *et al.*, [23] used both Al and Fe electrodes to treat their source of PSW and showed that COD removal efficiency decreased inversely in relation to the initial pH of the waste. Even though the initial COD (26,000-29,000 mg/L) in the EC work completed by Kobya *et al.*, [23] was much higher than that tested by Thirugnanasambandham et *al.,* [11], the authors still managed to accomplish 93 and 85% removal (in 25 mins) when applying a current density of 150 A/m^2 to Al and Fe electrodes, respectively. Bayar *et al.*, [5] also investigated the use of Al EC to process PSW. Bayar *et al.*, [5] reported that the highest removal efficiencies were obtained when using an initial pH of 3. The authors demonstrated that it is important to optimise stirring during flocculation. When the stirring speed was low (100 rpm) coagulation was limited by collisions and attachments between flocs. Conversely, when using high-speed stirring (>150 rpm) flocs disintegrated due to turbulence [5]. Asselin *et al.*, [21] reported that Al and Fe electrodes had similar effectiveness for treating the PSW used in their study, both achieving close to 80% COD removal. Their economic assessment concluded that the EC cost of treating 1 m^3 of PSW amounted to $0.71 (US).

Table 2. A summary of literature related to electrocoagulation of dairy and slaughterhouse wastewaters

Effluent type [Ref]	Conductivity, pH of waste (μS/cm), ()	Electrode material (anode/ cathode)	Pre-EC treatment Post-EC treatment	Optimum current density, pH, treatment time (A/m^2), (), (min)	Initial contamination (mg/L)	Optimum removal efficiency (%)	Optimum energy use (kWh/m^3)
Dairy Wastewater [17]	1810-2200 7.4-7.7	Al/Al Fe/Fe[a] SS/SS	n.d. Filtration	30 (V) 7.4-7.7 120	COD 1350-1605	COD 82	n.d.
Dairy Wastewater [25]	n.d. 10.2 ± 0.010	Al/Al[b] Fe/Fe	n.d. n.d.	5 (V) 5.0 60	COD 4682.7 ± 16.8 Trb 1126 ± 0.5 (NTU)	COD 97.0-97.4 Trb 99.1-99.6	n.d.
Dairy Wastewater [16]	1066 ± 62.43 3.30 ± 0.11	Fe/Fe	n.d. n.d.	~36[c] 4.5 60	COD 11817 ± 1.228 Trb 1347 ± 194 (NTU)	COD 96.36 Trb 99.98	4.5
Dairy Wastewater [6]	1082.2 ± 8.5 7.10 ± 0.12	Al/Al	n.d. n.d.	n.d. 7.10 ± 0.12 60	COD 8960 ± 16.4 Hard 130 ± 2.3 TDS 543.4 ± 5.2 Trb 49.5 ± 1.4 (NTU)	COD 39 Hard 41 TDS 46 Trb 51	n.d
Dairy Wastewater [9]	1200 6.0-7.5	Fe/Fe	pH, conductivity adjustment Filtration (11μm)	6 7 1	COD 18300 O&G 4570	COD 98 O&G 99	0.054[c]
Dairy Wastewater [20]	710-945 6.5-7	Al[d] Fe	n.d. n.d	150 6.5-7 20	COD 1200-1900	COD 70	~6[e]
Dairy Wastewater [20]	710-945 6.5-7	Al[d] Fe	n.d. Electro-Fenton	150 6.5-7 20	COD 1200-1900	COD 79.2	~6[e]
Cheese Whey Wastewater [4]	15500 5.64	Al Fe SS[f]	n.d. Filtration (0.45μm)	300 5.64 60	TOC 29563 TSS 5880 Trb 6978 (NTU)	TOC 22-27 TSS 65 Trb 50	21.9[c]
Ice Cream Wastewater [6]	794.4 ± 9.1 6.25 ± 0.15	Al/Al	n.d. n.d.	n.d. 6.25 60	COD 11900 ± 21.3 Hard 412 ± 4.6 TDS 399.4 ± 6.7 Trb 31.1 ± 1.8 (NTU)	COD 49 Hard 30 TDS 95 Trb 82	n.d.
Ice Cream Wastewater [12]	3670 4.4	Al/Fe	Settling Fenton/Ozone	50 4.4 120	COD 5902	COD 70	4
Synthetic Dairy Wastewater [19]	11640 2-10	Al/Al	n.d. n.d.	0.65 6 20	COD 780 TP 28.6 TSS 198 Trb 440 (NTU)	COD 80 TP 98 TSS 100 Trb 100	0.163
Synthetic Dairy Wastewater [26]	220 6.3-6.8	Fe/Fe	n.d. n.d.	270 7.0 50	COD 3900 TN 113.18 TS 3090 Trb 1744 (NTU)	COD 70 TN 92.75 TS 48.2 Trb 99.8	7.53[c]
Synthetic Dairy Wastewater [18]	600-1600 6.88-7.05	Al/Al	n.d. Filtration	43 7 30	COD n.d. TN n.d. TP n.d. Trp n.d.	COD 61 TN 81 TP 89 Trp 100	n.d.
Cattle Slaughterhouse Wastewater [8]	9140 ± 1512 7.31 ± 0.12	Al/Al	2 mm screening + 24 hr settling + PACl (100mg/L) coagulation + pH adjustment n.d.	40 (V) 7.31 ± 0.12 60	BOD_5 2543 ± 362 COD 5817 ± 473 TSS 3247 ± 845 TN 137 ± 12	BOD >99 COD >99 TSS 97 TN 94	90
Poultry Slaughterhouse Wastewater [21]	473 ± 14 6.15–6.46	Al/Al Fe/Fe[a]	Screen filter (2 mm) Polymer (LPM 9511 10 mg/L)	3.9[c] 6.1-6.5 60	BOD 2930 ± 210 COD 3340 ± 180 O&G 853 ± 119 TS 2380 ± 380 TSS 1560 ± 880 Trb 977 ± 83 (NTU)	BOD 86 ± 2 COD 82 ± 2 O&G 99 ± 1 TS 64 ± 6 TSS 89 ± 4 Trb 90 ± 4	4.19 ± 0.12

Table 2. (continued) A summary of literature related to electrocoagulation of dairy and slaughterhouse wastewaters

Effluent type [Ref]	Conductivity, pH of waste (μS/cm), ()	Electrode material (anode/ cathode)	Pre-EC treatment Post-EC treatment	Optimum current density, pH, treatment time (A/m^2), (), (min)	Initial contamination (mg/L)	Optimum removal efficiency (%)	Optimum energy use (kWh/m^3)
Poultry Slaughterhouse Wastewater [5]	2858 6.73	Al/Al	pH adjustment n.d.	10 3 30	COD 2171 Trb 176.6 (NTU)	COD 85 Trb 98	~3[e]
Poultry Slaughterhouse Wastewater [22]	1430 7.05	Al/Al[a] Fe/Fe	Screen filter, pH adjustment n.d.	30 4.0 40	COD 3899	COD 86	n.d.
Poultry Slaughterhouse Wastewater [23]	1990 6.7 n.d.	Al/Al Fe/Fe	Screen filter n.d.	150 2-3 25	COD 26000-29000 O&G 1500-1800	COD 93 (Al) 85 (Fe) O&G 94 (Al) 99 (Fe)	0.5-1 (Al) ≥0.3. (Fe)
Poultry Slaughterhouse Wastewater [11]	n.d. n.d.	Fe/Fe	pH adjustment + 30% (dilution) n.d.	140 6 15	COD 5500	COD 95	3480
Slaughterhouse Wastewater [24]	n.d. 7.1 ± 0.3	Fe/Fe	1 mm sieve Filtration (0.45μm)	25 7.1 ± 0.3 50	BOD_5 2060 ± 429 COD 2770 ± 537 TN 101 ± 26 TSS 3130 ± 541	BOD_5 97 COD 93 TN 84 TSS 81	n.d.

[a]Electrode(s) which provided optimal results. [b]Al and Fe electrodes provided comparable performance. [c]Value calculated from available parameters. [d]Al and Fe electrodes were both utilised with a pole changer. [e]Approximated from figure in cited article. [f]Al, Fe, and Stainless steel all tested as cathodes and anodes. Stainless steel (AISI 304) cathode + Fe anode provided optimal results. COD: Chemical oxygen demand; BOD: Biochemical/Biological oxygen demand; Trb: Turbidity (Nephelometric turbidity unit); O&G: Oil and grease; TN: Total nitrogen; TOC: Total organic carbon; TP: Total phosphorus; TS: Total solids; TSS: Total suspended solids; TDS: Total dissolved solids; Hard: Water hardness.

4. Future work and conclusions

Table 2 highlights the range in EC power consumption (kWh/m^3) required by various investigators to process meat and dairy wastes. Only a limited number of studies cited in this report have included a cost analysis. The construction of detailed life cycle analyses are crucial to quantify the capex, opex and environmental impact before widespread adoption of EC technology in the slaughterhouse meat and dairy processing industries can occur.

The literature reviewed here demonstrates that EC has good potential for use in treatment of dairy processing and slaughterhouse meat industry wastewater effluents. Typically, investigators have been able to remove over 75% of COD from both dairy and meat waste effluents when using Al and Fe electrodes in batch for less than 1 hour.

The application of EC technology for treatment of dairy and meat effluents remains in its infancy and information about larger-scale operation of EC for the treatment of these waste effluents is still lacking. Therefore, more pilot-scale studies would be beneficial for supporting the transition of the technology from laboratory to industrial scale. Furthermore, the vast majority of studies have applied batch EC methodologies but there may be cost benefits associated with implementing continuous EC treatment. Further work should include more comprehensive integration of EC with technologies such as membrane separation, reverse osmosis, ozonation and anaerobic digestion.

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