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Optimization of electroflotation for cattle slaughterhouse wastewater treatment: Effects of current density and quantity of electrodes

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ABSTRACT

The elevated demand for meat results in a corresponding increase in the intensity of slaughtering practices. The volume of wastewater generated increases with the number of animals slaughtered in the abattoir. This study aimed to evaluate the effectiveness of the electroflotation method in reducing pollutant parameters in liquid waste from slaughterhouses. This research employed a batch system and Graphite and aluminum electrodes. Electrical voltage variations are 5 V (T1), 10 V (T2), and 15 V (T3), while the number of plates is three pairs (V1), four pairs (V2), and five pairs (V3). The characteristics of abattoir wastewater consist of a chemical oxygen demand (COD) of 2,360 mg/L, a biochemical oxygen demand (BOD) of 1,487 mg/L, total suspended solids (TSS) of 280 mg/L, fat and oil content of 1,251 mg/L and ammonia concentration of 67,057 mg/L. The optimal pollutant reduction efficacy is achieved with a voltage fluctuation of 15 V and five pairs of electrode plates (10 plates). The reduction efficiencies are as follows: COD at 94.2%, BOD at 96.6%, TSS at 97.02%, ammonia at 84.82%, and oil and fat at 91.77%. An augmentation in electric power and the quantity of plates is associated with reduced COD, BOD, TSS, oil and fat concentrations, and ammonia levels. This indicates an enhanced level of elimination efficiency. The greater the O_2 and H_2 gas production, the more bubbles are generated. This suggests that electroflotation is more effective in diminishing pollutants in wastewater from the livestock abattoir.

Keywords: cattle slaughterhouse wastewater, electroflotation, electrolysis, gas generation, graphite.

INTRODUCTION

The burgeoning global population has increased demand for various food products, including beef consumption (Bustillo-Lecompte & Mehrvar, 2015a). According to the 2020 OECD study, the average meat consumption in Indonesia was 1.8 kg per capita in 2017 (OECD, 2020). This meat consumption trend has led to a substantial rise in beef slaughter, totaling 2.5 billion cattle annually during the Islamic festival of Idul Adha (Sutarno & Setyawan, 2015). Cattle slaughterhouses play a crucial role in the meat production sector and are essential sources of wastewater generation (El Abdouni et al., 2021). These facilities exhibit substantial water consumption rates, ranging from 2.5 to 40 cubic meters per metric ton of meat processed during butchering and intermittent cleaning of remaining residues (International Finance Corporation's Guidance Notes, 2012). However, water use ranges from 0.4 to 3.1 m³ per animal slaughtered. This is, of course, influenced by operational processes and the species of animals, which cause variability in effluent composition.

Wastewater from cattle slaughterhouses has a significant organic load, blood, fat, infectious agents from blood and feces, and numerous other substances. The elevated flow and variability of wastewater lead to significant concentrations of biological oxygen demand (BOD), chemical oxygen demand (COD), and nutrients (phosphorus and nitrogen), adversely affecting aquatic ecosystems and human health (Al-Mutairi et al., 2004; Bustillo-Lecompte & Mehrvar, 2015; Liew et al., 2020; Olaniran et al., 2019). Consequently, wastewater treatment is vital to protect water sources before releasing wastewater into water systems.

Slaughterhouse wastewater treatment often employs chemical, biological, and integrated physical-chemical methods. Integrated physical-chemical treatments can effectively diminish pollutants in abattoir effluent, but they need substantial chemical usage and generate significant sludge (Al-Mutairi et al., 2004; Bustillo-Lecompte & Mehrvar, 2015). Furthermore, the use of biological processes, such as anaerobic, aerobic, and combination anaerobic-aerobic methods, provides drawbacks due to the necessity for extensive land area, elevated operational expenses, bacterial vulnerability to chemicals, and prolonged processing durations. (Mickova, 2015a, 2015b; Muddemann et al., 2019). Aerobic processing requires substantial energy due to the extensive use of aerators, whereas anaerobic processing generates substantial amounts of sludge solids and leads to the accumulation of suspended solids (Show & Lee, 2017). Consequently, proficient and efficient management is essential for treating abattoir effluent.

Electroflotation is an alternative technology that has demonstrated efficacy in treating several types of wastewater, ranging from those containing heavy metals to organic effluents from agricultural and industrial sources (Adjeroud et al., 2018; Mansour et al., 2007; Mohtashami & Shang, 2019; Paulista et al., 2018). This technique possesses several advantages, including cost-effectiveness, flexibility, environmental sustainability, and energy efficiency (Adjeroud et al., 2018; Mansour et al., 2007). Numerous contaminants have been demonstrated to be eliminated, including algae, oil and grease, surfactants, minerals, and some latex particles. (Alam & Shang, 2017; Baierle et al., 2015; Bande et al., 2008; Bassala et al., 2017; Bayramoglu et al., 2004; Belkacem et al., 2008; Chen et al., 2000; Eryuruk et al., 2018; Mirshafiee et al., 2018; Orssatto et al., 2017). However, limited studies have been conducted on actual cattle slaughterhouse effluent utilizing the electroflotation method, focussing on varying plate quantities and current densities.

Electroflotation is a technique for separating and purifying water by generating hydrogen and oxygen gases at the cathode and anode during oxidation and reduction reactions. The technique can separate components of ions and suspended solid particles, resulting in a viable alternative for wastewater treatment (Alam & Shang, 2017). Electroflotation, an electrochemical variant of flotation, typically exhibits superior separation efficiency compared to traditional dissolved air flotation, owing to the generation of smaller and more numerous hydrogen and oxygen bubbles through electrolysis (Burns et al., 1997; Gu & Chiang, 1999; Il'in & Sedashova, 1999; Kyzas & Matis, 2016). The generated bubbles will adhere to the suspended particles, forming flocs that decrease overall density, resulting in their ascent to the surface and flotation. The fundamental principle of EF is to facilitate the removal of aggregated particles by harnessing the buoyancy imparted by gas bubbles (Burns et al., 1997; Gu & Chiang, 1999; Il'in & Sedashova, 1999; Kyzas & Matis, 2016). Its effectiveness in treating diverse wastewater, including oily effluents, mining discharges, groundwater, food processing waste, industrial sewage, and metal-laden waters, has been well-established (Comninellis & Chen, 2010). Comparisons of wastewater treatment results using the electroflotation method show significant similarities, indicating that electroflotation is a potential alternative for managing wastewater from cattle slaughterhouses.

This study investigates the influence of varying electrical voltage and the quantity of aluminum-graphite electrode pairs on contaminant removal efficiency in slaughterhouse wastewater through electroflotation. Additionally, the study aims to analyze the molar amount of hydrogen and oxygen gases produced and their gas-generating rates for contaminant reduction within the wastewater through electroflotation.

MATERIALS AND METHODS

Source of cattle slaughterhouse wastewater

Cattle slaughterhouse wastewater (CSW) was taken from the Tamangapa Slaughterhouse in Makassar City, Indonesia. Generated as a by-product of meat production and facility cleaning, the CSW contained a substantial load of blood, proteins, and lipids. Notably, the slaughterhouse needed wastewater treatment infrastructure, discharging untreated effluent, including solid waste, directly into the municipal sewer system. Before electrocoagulation (EC) treatment, the collected wastewater underwent a manual screening process to remove macroscopic contaminants such as hair, skin, and particles exceeding 1 mm. Wastewater sampling adhered to the Standards National Indonesia SNI 6989.59:2008. A total of 1.5 L of CSW was collected from the Tamangapa Slaughterhouse for each experimental run. This study employed a batch-mode electroflotation reactor with a working volume of 800 mL. The cattle slaughterhouse wastewater samples were diluted at a 1:1 (equal to a two-fold dilution). The dilution was necessary to overcome the high electrical resistance associated with high wastewater concentrations, which can hinder electrolysis.

Consequently, the resulting current and voltage tend to be lower. Additionally, dilution was performed to facilitate the research process. The physicochemical characteristics of the raw CSW are presented in Table 1.

Experimental setup

This quantitative experimental study investigates the application of electroflotation as a novel method for treating slaughterhouse wastewater. The research focuses on the impact of operational parameters, precisely electrical voltage and electrode pair quantity, on contaminant removal efficiency within the wastewater. Furthermore, the study quantifies hydrogen and oxygen gas moles for pollutant elimination. The selection of these variables was informed by Shah (2019), which posit that current density (correlated with electrical voltage) and electrode type influence bubble formation. The study employed three, four, and five electrode pairs, while electrical voltage varied at 5, 10, and 15 V.

The dependent variable in this study is the efficacy of pollutant reduction in cattle slaughter wastewater. The criteria for assessing reduction efficiency include COD, BOD, total suspended solids (TSS), oil and grease, and ammonia (NH_3-N). These criteria pertain to the Indonesian Minister of Environment Regulation Number 2 of 2006 on effluent quality standards for abattoir operations. The independent variables are electric voltage and the quantity of aluminum-graphite electrode pairs.

Electroflotation design

The reactor design was meticulously planned to accommodate the experimental variations associated with the electroflotation method. The reactor employed is a simple cylindrical configuration with electrodes, consisting of a 1000 ml volume with a 70 mm diameter and a height of 95 mm, as illustrated in Figure 1. A batch reactor was employed in this experiment at a constant temperature of 20 °C for 15 minutes.

Table 1. Characteristics of cattle slaughterhouse wastewater

Parameter	Unit	Results	Dilution results	Quality standards*
pH	unit	6.18	7.08	6-9
COD	mg/L	2360	1150	200
BOD	mg/L	1487	993.3	100
TSS	mg/L	280	183.3	100
Oil and grease	mg/L	1251	875	15
Ammonia	mg/L	67.057	66.532	25

Note: *Indonesian Minister of Environment Regulation No. 5 of 2014 concerning CSWW Quality Standards.

Table 2. Experiment matrix

Number of electrode pairs (N)	Voltage (V)		
	T_1	T_2	T_3
V_1	V1T1	V1T2	V1T3
V_2	V2T1	V2T2	V2T3
V_3	V3T1	V3T2	V3T3

Note: V1 = three electrode pairs (6 pieces), V2 = four electrode pairs (8 pieces), V3 = five electrode pairs (10 pieces), T1 = electrical voltage of 5 V, T2 = Electrical voltage of 10 V, T3 = electrical voltage of 15 V.

This experiment employs graphite and aluminum electrodes selected for their conductivity and stability within an electrolytic environment. The electrode measures 100 mm in length, 50 mm in width, and 2 mm in thickness. The electrodes of graphite and aluminum are paired with each other. The apparatus consisted of two parallel electrodes linked externally to a direct current power source. The cathode electrode was composed of graphite, while the anode electrode was aluminum (Al). A gap of 2 cm was set between the electrodes. The output DC voltage and current ranged from 5–15 V and 1.56–14.60 A, respectively. The electrolysis time was consistently maintained at 15 minutes. An ammeter and voltmeter were used to monitor current intensity and voltage during electroflotation.

Measurement analysis

Influent and effluent samples were collected for comprehensive analysis. Standard methods measured BOD, COD, TSS, Oil and Grease, and Ammonia (Baird et al., 2017). Wastewater samples were subjected to triplicate testing to enhance data accuracy. Influent samples, representing the initial pollutant concentration, were obtained directly from the wastewater source. Effluent samples, reflecting the final pollutant concentration, were collected from the treatment system's outlet. The pollutant removal efficiency (%) after treatment was calculated using the following formula where C_0 and C_1 for the influent and effluent concentration:

$$\% \; Removal = \frac{c_0 - c_1}{c_0} \times 100 \; \% \qquad (1)$$

Electrochemical reactions and gas generating rate

In electroflotation, the oxygen and hydrogen bubbles are generated at an anode and a cathode, respectively, as below:

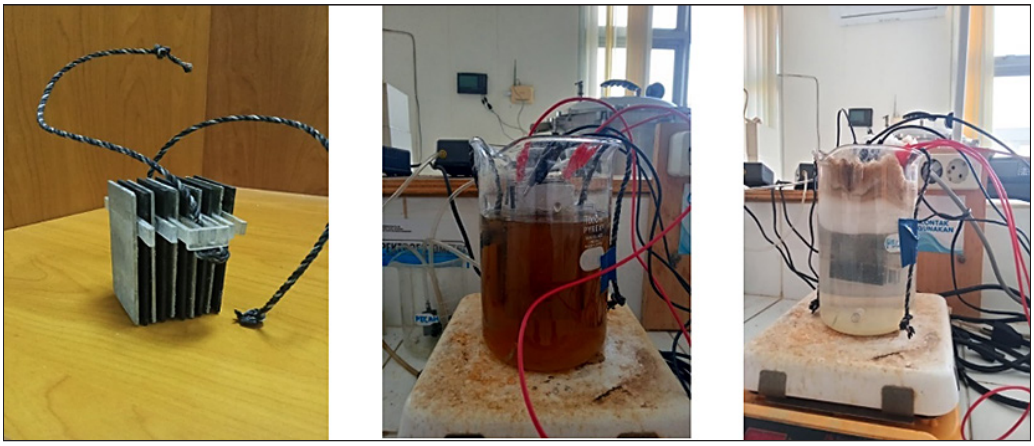


Figure 1. Reactor (a) electrode pairs, (b) reactor with influent, (c) reactor with effluent

Table 3. Electric current and current density from variations in electric voltage and number of electrodes

Variables	Electrical current (Ampere)	Current density (mA/cm^2)	Time (second)
V1T1	1.56	7.61	900
V1T2	4.63	22.58	
V1T3	7.20	33.90	
V2T1	3.00	10.98	
V2T2	7.60	27.83	
V2T3	10.25	37.54	
V3T1	4.25	20.73	
V3T2	9.50	46.43	
V3T3	14.60	71.22	

Note: Experimental results of 2024.

Chemical reaction in anode:

$$2H_2O_{(l)} = O_{2(g)} + 4H^+_{(aq)} + 4e^- \quad (2)$$

Chemical reaction in cathode:

$$2H^+_{(aq)} + 2e^- = H_{2(g)} \quad (3)$$

The total reaction is

$$2H_2O = 2H_2 + O_2 \quad (4)$$

Equation (11.3) demonstrates that the amount of hydrogen gas generated is twice that of oxygen gas. The gas-generating rate can be calculated according to Faraday's law (Comninellis & Chen, 2010).

$$Q_H = \frac{IV_0}{n_H F} \quad (5)$$

$$Q_O = \frac{IV_0}{n_O F} \quad (6)$$

where: Q_H is the rate of hydrogen (H_2) gas generation (L/s^{-1}) at the normal condition; Q_O is the rate of oxygen (O_2) gas generation (L/s^{-1}) at the expected condition, V_0 is the molar volume of gases under standard conditions (22,4 L/mol), F is the Faraday's constant (96,500 C mol of the electron), n_H is the electron transfers number of H_2 (2 mol electrons per mole H_2) and n_O is the electron transfers number of O_2 (4 mol electrons per mole O_2). The total gas generation rate can be determined by combining the individual rates of hydrogen and oxygen production using the equation below:

$$Q_g = Q_H + Q_0 = \frac{IV_0}{n_O F}(one\ \frac{1}{n_H} + \frac{1}{n_O}) = 1.74\ x\ 10^{-4}\,\mathrm{I} \quad (7)$$

where: Q_g is the total gas generation rate (L/s^{-1}) at standard conditions.

In determining the number of moles of H_2 and O_2 gas produced, the following equation is used:

$$Mole\ electron\ (Faraday) = \frac{I \times t}{F} \quad (8)$$

where: I is electrical current (A), t is retention time (minutes), and F is Faraday constant (96,500).

Statistical analysis

Multiple linear analysis was employed to examine the impact of electric voltage and the number of electrodes on the reduction efficiency of COD, BOD, TSS, oil and grease, and ammonia.

RESULTS AND DISCUSSIONS

The influence of voltages and the quantity of electrode pairs on the efficiency of removal

The electrical voltage and the number of electrode pairs significantly affect the efficiency of electroflotation in treating cattle abattoir wastewater. The electrical voltage triggers electrochemical reactions, a core principle in the electroflotation process. Moreover, the quantity of electrodes (anode and cathode plates) affects the stability of these reactions and the volume of gas bubbles produced. The combined effect of these variables on the effectiveness of cattle slaughterhouse wastewater treatment is demonstrated in the following analysis. The removal efficiency of all parameters under varying electrical voltage and plate pair configurations are depicted in Figure 2 and Figure 3. The impact of electrical voltage and the number of electrodes on the removal efficiency of chemical oxygen demand, biological oxygen demand, total suspended solid, oil and grease, and ammonia will be assessed based on a multivariate linear regression using IBM SPSS Statistics 22.

Analysis parameter of chemical oxygen demands

Figure 2a depicts variations in electrical voltage, and the number of electrodes employed significantly influences COD values. The initial COD concentration of the slaughterhouse wastewater was measured at 440 mg/L, and a reduction to 137 mg/L was observed. Regarding the reduction in COD parameter achieved through the electroflotation method, Arslan-Alaton et al. (2008) propose that organic matter is degraded via an indirect oxidation process facilitated by strong oxidants such as chloride ions within the water, as illustrated in Equations 9 and 10. Moreover, this study reveals a chloride ion concentration of 1084.41 mg/L (Cl^-) in the wastewater.

$$2Cl^- \rightarrow Cl_2 + 2e (9)$$

$$Cl_2 + H_2O \rightarrow HOCl + H^+ + Cl^- \quad (10)$$

Floc formation arises from the inherent characteristics of floc formers during the flotation process, leading to robust fractionation or adsorption of surfactants on the surface, which creates a monolayer (Gamage et al., 2012; Liew et al., 2020). Consequently, the dissolved substances intended for removal transition from the gas phase to liquid, resulting in foam. Thus,

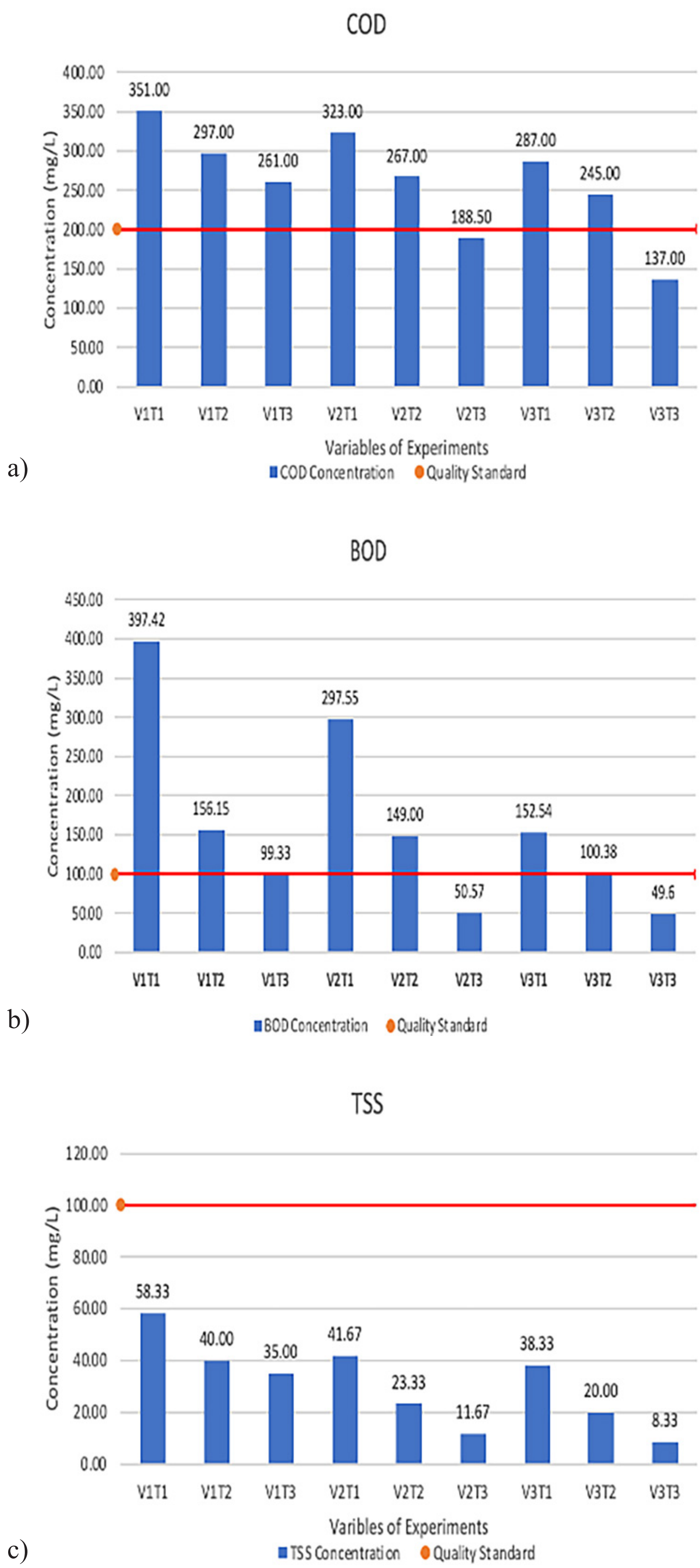
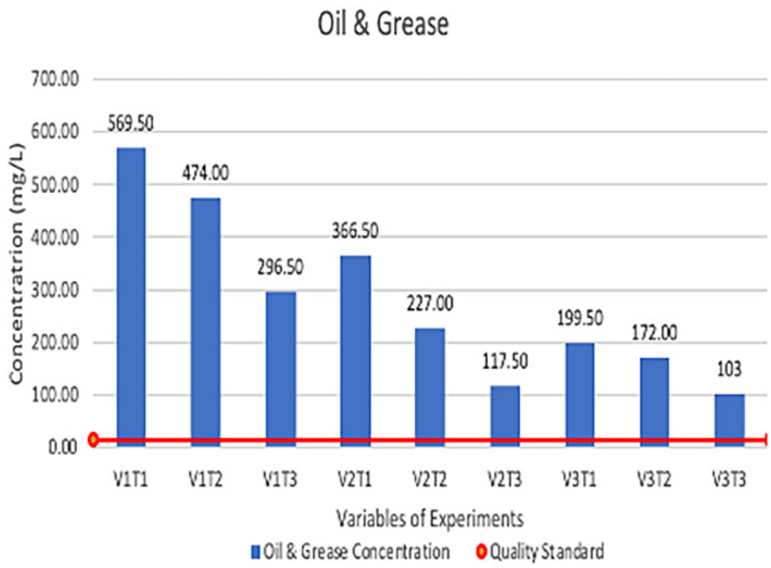
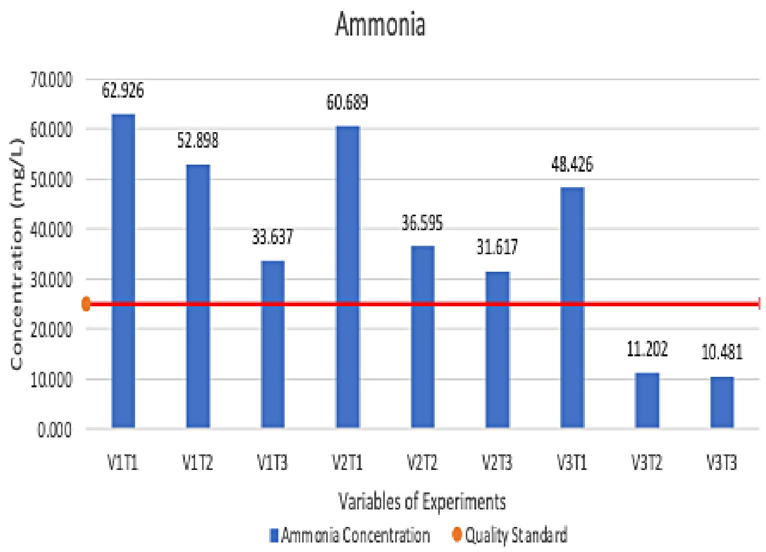


Figure 2. Effluent concentration of COD (a), BOD (b), TSS (c), oil and grease (d), and ammonia (e).



d)



e)

Figure 2. Effluent concentration of COD (a), BOD (b), TSS (c), oil and grease (d), and ammonia (e).

dissolved organic substances are segregated through adsorption rather than buoyancy. An increase in bubble formation at the cathode, resulting from the ineffectiveness of aluminum ions, enhances flotation capacity (Nguyen et al. 2020). Under optimal electrical voltage conditions, increased bubble production from the anode signifies elevated oxygen gas generation, thereby improving COD efficiency. Additionally, electroflotation (EF) and electrocoagulation (EC) constitute an electrochemical technique for the remediation of contaminated water, effectively addressing soluble or colloidal pollutants, including wastewater with heavy metals, emulsions, and suspensions, as well as potable water for the removal of lead or fluoride (Belkacem et al., 2008)

Figure 3 indicates that the elimination efficiency of the COD parameter escalates with an increase in electric voltage. Conversely, COD elimination also transpires with an increase in the variety of plate numbers. The maximum COD elimination effectiveness achieved was 94.2% in the V3T3 variant. The minimum was seen in the V1T1 variant at 85.1%. The rising electric current leads to the formation of an oxidizer as a by-product of electroflotation, resulting in the oxidation and decomposition of several organic and inorganic substances. Flocculants that aggregate organic and inorganic substances are generated as a natural response from electroflotation and will be elevated by H_2 and O_2 gas bubbles. During the electroflotation process in wastewater treatment, pollutants ascend to the surface by adhering to

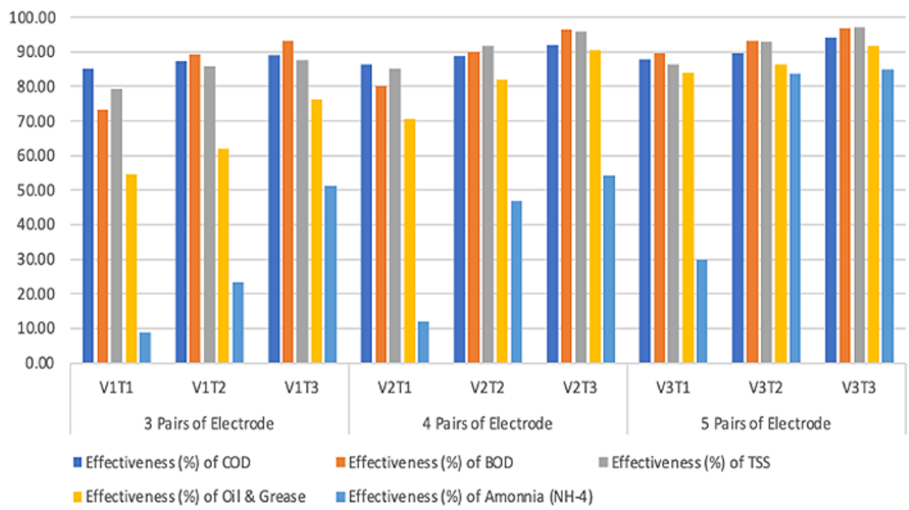


Figure 3. Efficiency removal on all parameters

the hydrogen and oxygen bubbles generated (Martínez-Huitle & Panizza, 2018). Furthermore, the reactions involving chloride ions present in wastewater could yield chlorine gas, hypochlorous acid, and hypochlorite compounds, which are potent oxidizing agents that oxidize organic pollutants, resulting in the formation of CO_2, H_2O, and inorganic acids (Arslan-Alaton et al., 2008).

As summarized in Table 4, the simultaneous impact of both modifications on the reduction of COD value is indicated by an R-square value of 94.7% in the multiple models. Consequently, it can be inferred that the impact of electric voltage and the quantity of plates on the reduction of COD value is 94.7%, while 5.3% of the COD value is affected by other variables. Additionally, individual t-tests demonstrated that both electrical voltage ($p < 0.005$) and the number of plates ($p < 0.005$) significantly impacted COD reduction. The negative coefficients for these variables indicate that an increase in electrical power and the number of plates reduced COD. The remaining 5.3% of the variation in COD may be attributed to other unmeasured factors. The following regression equation can be seen below:

$$Y\ (COD) = 546.667 - 12.483X_1 - 20X_2 \quad (11)$$

The relative contributions of electrical voltage and the number of plates to COD reduction can be inferred from their respective R-squared values in Table 4. Electrical voltage accounted for 67% of the variation in COD, while the number of plates contributed an additional 27.5%. This suggests that both factors significantly influenced COD reduction, as corroborated by Figure 3, which shows a clear trend of decreasing COD with increasing numbers of plates. Variations V2T3 and V3T3 attained COD levels of 188.5 mg/L and 137 mg/L below the Indonesian regulatory threshold for cattle slaughterhouse wastewater.

Analysis parameter of biological oxygen demands

Figure 2b illustrates that augmenting both voltage and the quantity of electrode plates

Table 4. Multivariate analysis of the effects of electrical voltage and electrode plates on chemical oxygen demand reduction

Model		Unstandardized coefficients		Standardized coefficients	t	Sig.	R Square
		B	Std. Error	Beta			
1	Constant	546.667	32.668		16.734	0.000	0.947
	Electrical voltage (X1)	-12.483	1.437	-0.819	-8.686	0.000	0.670
	Electrode pairs's quantity (X2)	-20.000	3.593	-0.525	-5.566	0.001	0.275

Note: Analysis of 2024.

improves BOD elimination. The initial biological oxygen demand of the effluent was 1487.5 mg/L, which was reduced to 49.68 mg/L, thereby complying with the discharge criteria for slaughterhouses (<100 mg/L). This enhancement is probably attributable to the augmented dissolved oxygen levels resulting from aeration in the electroflotation process. Microbes employ dissolved oxygen to oxidize and break down organic materials, providing energy and facilitating reproduction (Scully et al., 2003)

Figure 3 illustrates that the effectiveness of BOD removal escalates with increasing voltage and the number of electrode plates, achieving peak efficiency (96.6%) at V3T3. The fundamental mechanism is bacteria employing dissolved oxygen to oxidize and degrade organic materials (Scully et al., 2003).

As illustrated in Table 5, multiple linear regression analysis revealed a highly significant ($p < 0.05$) relationship between the dependent variable, BOD reduction, and the independent variables, electrical voltage and number of plates. The highly substantial constant term confirmed the model's overall significance ($p < 0.005$). Furthermore, individual t-tests indicated that both electrical voltage ($p < 0.005$) and the number of plates ($p < 0.005$) exerted a significant influence on BOD reduction. The negative coefficients for these variables suggest that increasing both electrical voltage and the number of plates led to a decrease in BOD. The following regression equation can be seen below:

$$Y\ (BOD) = 610.910 - 21.598X_1 - 29.191X_2 \quad (12)$$

The data in Table 5 indicates an R-square value of 0.846, signifying an 84.6% influence of electric voltage and the number of electrodes on the reduction of BOD value. This indicates that electrical voltage and the number of plates significantly influenced BOD elimination. Fifteen-point four percent of the variance can be ascribed to other unmeasured components. Moreover, individual R-squared values indicated that electrical voltage explained 65.4% of the variance, while the number of plates contributed an additional 19.2%, affirming their substantial impact on BOD reduction. Variations V1T3, V2T3, and V3T3 attained BOD levels of 99.33 mg/L, 50.57 mg/L, and 49.68 mg/L, respectively, all below the regulation threshold for cattle abattoir wastewater.

Analysis parameter of total suspended solid

The initial TSS concentration in the cattle slaughterhouse wastewater was measured at 280 mg/L, as seen in Figure 2 (c). The initial TSS concentration decreased to 8.33 mg/L, meeting the stipulated discharge standards for cattle slaughterhouse wastewater wastewater (< 100 mg/L). Ledoh et al. (2022) asserted that prolonged electrolysis allows particles in wastewater to adhere to gas bubbles generated during the electrolysis process (Ledoh et al., 2022). The electrolysis process decomposes organic molecules in wastewater into ions, facilitating an oxidation-reduction reaction that generates gas, contributing to total suspended solids reduction in the electroflotation process. Oxygen atoms will generate negatively charged ions (OH^-), while hydrogen atoms will produce positively charged ions (H^+). The H^+ ion at the anode will be drawn to the negatively charged cathode, resulting in its union at the cathode. Hydrogen atoms will generate hydrogen gas in gas bubbles that ascend. The OH^- ions similarly converge at the anode, emitting oxygen gas in bubble form, as delineated in Equations 11, 12, and 13.

$$2H_2O\ (l) = O_2\ (g) + 4H^+\ (aq) + 4e^- \quad (13)$$

$$2H^+\ (aq) + 2e^- = H_2\ (g) + OH^- \quad (14)$$

$$2H_2O\ (aq) = 2H_2\ (g) + O_2\ (g) \quad (15)$$

Table 5. Multivariate analysis of the effects of electrical voltage and electrode plates on biological oxygen demand removal

Model		Unstandardized coefficients		Standardized coefficients	t	Sig.	R Square
		B	Std. Error	Beta			
1	Constant	610.910	97.092		6.292	0.001	0.846
	Electrical voltage (X1)	-21.598	4.271	-0.809	-5.056	0.002	0.654
	Electrode Pairs's quantity (X2)	-29.191	10.679	-0.438	-2.734	0.034	0.192

Note: Analysis of 2024.

Figure 3 indicates that total suspended solids removal efficiency increases with increasing applied voltage. TSS removal is also observed when varying the number of electrode pairs. The most significant percentage of TSS removal efficiency occurs at V3T3 (97.2%), while the lowest is at V1T1 (79.17%). All variations tested in this study met the TSS discharge standard for cattle abattoir wastewater. The continuous generation of hydrogen and oxygen gas bubbles sustains the flotation process over the specified duration. The main distinction is found in the gas production rate. Higher voltages and a more significant number of electrode pairs lead to an increase in the production of hydrogen and oxygen bubbles. The adsorption and adhesion properties of small hydrogen and oxygen gas bubbles enhance the flotation of suspended particles in abattoir wastewater. Xing & Lin (2011) explain that separating colloidal and suspended particles in sewage is based on the electroflotation mechanism, and specifically, suspended particles in the wastewater come into direct contact with the gas bubbles generated at the cathode and anode, subsequently rising to the surface to form a layer (Xing & Lin, 2011).

Table 6 indicates a significance value of 0.000 for the constant, leading to the rejection of H0 and acceptance of H1, as 0.000 < 0.05, corresponding to a 5% tolerance level. It may be inferred that electrical voltage and the number of plates concurrently affect the reduction of the TSS value. The multiple linear regression analysis generates the equation that can be seen below:

$$Y(TSS) = 102.963 - 2.778X_1 - 5.556X_2 \quad (16)$$

The impact of electric voltage and the number of plates on the reduction of TSS value is evidenced by the R-square value for electric voltage (X1) and the number of plates (X2) presented in Table 21. The R-square value indicates that electric voltage accounts for 55.6% of the variance. This relationship is further illustrated in Figure 3 and Table 6, which shows that the reduction in TSS value is directly proportional to the increase in electric voltage. The influence of the number of plates is 35.6%, indicating that the number of plates affects the reduction in TSS values. This is further illustrated in Figure 3, which shows that an increase in the number of plates corresponds to a more significant decrease in TSS values. All variations in this study effectively lowered the TSS concentration to below the quality standard for the V3T3 variation of cattle abattoir wastewater exhibited the most substantial reduction, measuring 8.33 mg/L.

Analysis parameter of oil and grease

Figure 2d illustrates that augmenting the applied voltage and the quantity of electrode pairs significantly influences the oil and fat content. The abattoir wastewater's initial oil and fat content was 1251.50 mg/L, subsequently reduced to 20 mg/L. However, this value still exceeds the stipulated discharge standards for cattle wastewater. Arly et al. (2018) suggest that the reduction in oil and grease during flotation is attributed to the aeration process, which introduces air bubbles that attach to grease particles and carry them to the surface (Arly et al., 2018). Ji et al. (2015) further elaborate that electroflotation ionizes OH^- and H^+ ions through the electrolysis of wastewater, and the oil aggregates adhere to the electrolytically generated oxygen and hydrogen bubbles (Ji et al., 2015).

Figure 3 shows that the amount of oil and fat decreases as the number of plates increases. It is crucial to remember that even if the processing procedure drastically lowers the amount of fat and oil concentrations, the final levels remain above the established limits for slaughterhouse wastewater. Oil and grease characteristics escalate with an increase in electric voltage. Conversely, eliminating fatty oils also transpires with an increase in the

Table 6. Multivariate analysis of the impact of electrical voltage and electrode plates on total

Model		Unstandardized coefficients		Standardized coefficients	t	Sig.	R Square
		B	Std. Error	Beta			
1	Constant	102.963	10.170		10.124	0.000	0.913
	Electrical voltage (X1)	-2.778	0.477	-0.746	-6.206	0.001	0.556
	Electrode Pairs's quantity (X2)	-5.556	1.675	-0.597	-4.967	0.003	0.356

Note: Analysis of 2024.

number of plates. The V3T3 version achieved the maximum oil removal effectiveness at 91.77%. The minimum was seen in the V1T1 variant at 54.49%. Nonetheless, in all variants implemented in this investigation, the fat oil produced using electroflotation has failed to meet the requirement of 15 mg/L for fat oil characteristics. This occurs because the naturally generated flocculants are insufficient to bind oil and fat at a high value effectively. Tong et al. (2021) indicated that reactive hydroxyl ions arise when the pH is at an acidic level of 5. The ineffectiveness of fat oil binding is attributed to the elevated pH conditions observed during the electroflotation investigation. The fat reduction effectiveness is highly effective, achieving a decrease of up to 91.77% thanks to the flotation process, which facilitates the binding of oil and the adsorption and adhesion of bubbles to the wastewater surface. The implementation of grease trap technology as a preliminary unit to diminish the concentration of oil and fat in wastewater is a viable alternative when electroflotation is utilized as the primary method in the cattle slaughterhouse business.

$$Y(oil\ \&\ grease) = 1063.778 - \\ - 20.617X_1 - 72.125X_2 \quad (17)$$

Table 7 reveals that the significance value for the constant is 0.000. This results in the dismissal of H0 and the endorsement of H1, as 0.000 is less than 0.05, with a tolerance level set at 5%. Thus, it can be assumed that electric voltage and the number of plates simultaneously influence the decrease in oil and grease parameters. In Table 7, it is also known that the significance value for electric voltage (X1) is 0.004 < 0.05, which assumes that electric voltage significantly affects the decrease in the oil and grease parameter of -20.617. In addition, the significance value for the number of plates is 0.001 < 0.05, which assumes that the number of plates significantly affects the decrease in the oil and grease parameter of -72.125. Therefore, the following equation is obtained from multiple linear regression analysis results.

The combined influence of electrical voltage and the number of plates on the reduction of oil and grease concentration was substantial, as indicated by the multiple R-squared value of 0.907. This implies that 90.7% of the oil and grease reduction variation could be attributed to these two factors, while other unmeasured variables may explain the remaining 9.3%. The contributions of electrical voltage and the number of plates to the reduction in oil and grease were analyzed through their respective R-squared values presented in Table 7. Electrical voltage explained 30.6% of the variance, and Figure 3 illustrates a direct positive correlation between increasing voltage and decreasing oil and grease concentration. The findings reveal that the quantity of plates accounts for 60.1% of the explained variance, reinforcing the hypothesis that an increased number of plates improves oil and grease removal.

Analysis parameter of ammonia

Figure 3 also illustrates this trend, demonstrating that increasing the number of plates resulted in a corresponding decrease in ammonia. Variations V3T2 and V3T3 achieved the most significant ammonia reductions, with final concentrations of 11.202 mg/L and 10.481 mg/L, respectively. These values are well below the regulatory limit of 25 mg/L for ammonia in slaughterhouse wastewater.

The magnitude of the influence of electric voltage and the number of plates on the decrease in ammonia value can be seen from the R-square value of electric voltage (X1) and the number of plates (X2) in Table 8. From the R-square value, the influence of electric voltage is 51.5%. This can also be seen in Figure 3, where the decrease in ammonia value is directly proportional to the increase in electric voltage. Likewise, the influence given

Table 7. Multivariate analysis of the impact of electrical voltage and electrode plates on oil and grease removal

Model		Unstandardized coefficients		Standardized coefficients	t	Sig.	R Square
		B	Std. Error	Beta			
1	Constant	1063.778	105.207		10.111	0.000	0.907
	Electrical voltage (X1)	-20.617	4.628	-0.554	-4.454	0.004	0.306
	Electrode Pairs's Quantity (X2)	-72.125	11.571	-0.775	-6.233	0.001	0.601

Note: Analysis of 2024.

Table 8. Multivariate analysis of the impact of electrical voltage and electrode plates on ammonia removal

Model		Unstandardized coefficients		Standardized coefficients	t	Sig.	R Square
		B	Std. Error	Beta			
1	Constant	123.723	15.229		8.124	0.000	0.865
	Electrical voltage (X1)	-3.210	0.670	-0.718	-4.791	0.003	0.515
	Electrode Pairs's quantity (X2)	-6.613	1.675	-0.592	-3.948	0.008	0.350

Note: Analysis of 2024.

by the number of plates is 35%. This assumes that the number of plates also affects the decrease in the amount of ammonia value, which can also be seen in Figure 3, where the more significant the variation in the number of plates, the higher the decrease in ammonia value. From Figure 3, it can be seen that in this case, a significant decrease occurred in the V3T2 and V3T3 Variations, which were under the cattle slaughterhouse wastewater quality standards for ammonia 25 mg/L, namely 11.202 mg/L and 10.481 mg/L, respectively.

Figure 2(d) demonstrates that fluctuations in electric voltage and the number of plates utilized affect the ammonia value. The initial concentration of ammonia in cattle abattoir effluent was recorded at 69.057 mg/L, which decreased to 10.481 mg/L after electroflotation treatment. The ultimate concentration post-treatment met the quality standard of 25 mg/L. The chlorine gas generated during the electrolysis process could reduce ammonia concentration, as the wastewater contains an adequate concentration of chloride ions (Huang et al., 2016). Chlorine (Cl_2) can oxidize ammonia, organic compounds, nitrite ions, hydrogen sulfide, and other chemical compounds susceptible to oxidation, leading to flotation. The reaction that transpires during electroflotation is electrolysis, as follows:

$$2Cl^- \rightarrow Cl_2 + 2e^- \quad (18)$$

$$NH_4^+ + HOCl = NH_2Cl + H_2O + H^+ \quad (19)$$

$$NH_2Cl + 2HOCl = NH_2Cl \uparrow + 2H_2O \quad (20)$$

$$NHCl_2 + HOCl = NCl_3 \uparrow + H_2O \quad (21)$$

$$NH_3 + HOCl = NH_2Cl + H_2O \quad (22)$$

$$NH_2Cl + NHCl_2 + HOCl = N_2O + 4HCl \quad (23)$$

$$2NH_2Cl + HOCl = N_2 + H_2O + 3HCl \quad (24)$$

The analysis revealed that chloride ion concentration in wastewater was 1084.81 mg Cl-/L, suggesting that the constituents were adequate for decomposing organic compounds during the electroflotation process, as illustrated in the preceding reaction. However, levels up to 1500 mg/L are not detrimental to human health (Herlambang et al., 2011).

On the one hand, it is concerning that chloride ions and chlorine gas interact with dissolved organic molecules to generate trihalomethanes, which are toxic and carcinogenic. Trihalomethane is a chemical compound derived from methane (CH_4). It is created by replacing three hydrogen atoms with halogens, namely chlorine (Cl), bromine (Br), and iodine (I), which are recognized as carcinogenic. Murphy asserts that not all dissolved organic matter indicators, including BOD and COD, correlate with trihalomethane production (Murphy et al., 2010). Trihalomethanes may occur when chloride ions and chlorine gas mix with either total organic carbon or UV254 chromophore dissolved organic matter and dissolved organic carbon (Murphy et al., 2010). Consequently, the presumption that trihalomethane is generated is exceedingly minimal unless re-evaluated with more associated dissolved organic matter. The theory posits that organic substances act as precursors for the synthesis of trihalomethanes. Consequently, the effectiveness of electroflotation in diminishing trihalomethanes can be evaluated by its capability to degrade the precursors of their synthesis, particularly organic molecules.

Furthermore, chloride ions are converted into hypochlorous acid, a strong oxidant that can oxidize ammonia, nitrite, and nitrate—common organic pollutants in wastewater—by the increased electric field created by rising voltage. This technique successfully removes ammonia, as it does total suspended solids. The electrolysis of wastewater containing chloride produces chlorine gas, which can oxidize various substances, including organic debris, ammonia, and reduced sulfur species, hence promoting their eventual flotation, per the findings of (Huang et al., 2016).

Table 8 demonstrates that multiple linear regression analysis indicated a significant ($p < 0.05$) relationship between the dependent variable, ammonia reduction, and the independent variables, electrical voltage and number of plates. The significant constant term ($p < 0.05$) validated the overall significance of the model. Additionally, individual t-tests revealed that both electrical voltage ($p < 0.005$) and the number of plates ($p = 0.008$) significantly affected ammonia reduction. The negative coefficients for these variables indicate that an increase in electrical voltage and the number of plates reduced ammonia concentration. The subsequent regression equation was derived from these findings.

$$Y(\text{amonnia}) = 123.723 - 3.210X_1 - 6.613X_2 \quad (25)$$

Moreover, the model explained 86.5% of the total variation in ammonia reduction, suggesting that electrical voltage and the number of plates were strong predictors of ammonia removal. The remaining 13.5% of the variance may be attributed to other unmeasured factors. Table 8 shows that the contributions of electrical voltage and the number of plates to ammonia removal were analyzed further through their respective R-squared values in Table 8. The analysis demonstrates that electrical voltage accounts for 51.5% of the explained variance.

Figure 3 demonstrates a positive correlation between applied voltage and ammonia removal efficiency. Furthermore, increasing the number of electrode pairs also enhanced ammonia removal. The highest removal efficiency of 84.823% was achieved at variation V3T3, while the lowest efficiency of 8.879% was observed at variation V1T1. The elevated electric field generated by increasing voltage facilitates the conversion of chloride ions into hypochlorous acid, a potent oxidant capable of oxidizing ammonia, nitrite, and nitrate, common organic contaminants in wastewater. Ammonia is efficiently eliminated via this process, akin to total suspended solids. The electrolysis of chloride-containing wastewater produces chlorine gas, which oxidizes various compounds such as ammonia, organic matter, and reduced sulfur species, thereby facilitating their flotation, consistent with the findings of (Huang et al., 2016)

Effect of voltage and number of electrode pairs on generating gas rate

In the electroflotation reaction, specifically electrolysis, H_2 and O_2 gases are generated during the reaction phase. According to Zhang et al. (2020), hydroxide ions travel toward the anode and are oxidized to O_2, while hydrogen ions flow toward the cathode and are reduced to H_2. The current study pointed out that the generation of H_2 and O_2 gases in electroflotation is affected by the number of plates, electric current, and duration of electrolysis (Table 9). As reported by Chang & Zenyuk (2023), at a specific current intensity (proportional to voltage), the quantity (mass) of O_2 and H_2 gases increases with the duration of the redox reaction (Chang & Zenyuk, 2023). Similarly, O_2 and H_2 gases increase with increasing current intensity for a given reaction time. This indicates that the gases' moles represent the bubble production in electroflotation. As shown in Table 9, increasing the electric current and current density, which is influenced by the number of plates, results in a higher number of moles of electrons. For example, variation V1T1 produced 0.0145 moles of electrons, while variation V3T3 produced 0.1362.

Table 9. Electric voltage, current density, and moles of electrons from variations in electric voltage and number of plates

Variables	Electric voltage (A)	Current density (mA/Cm^2)	Time (second)	Moles of electrons (moles)
V1T1	1.56	7.61	900.00	0.0145
V1T2	4.63	22.58		0.0432
V1T3	7.20	33.90		0.0672
V2T1	3.00	10.98		0.0280
V2T2	7.60	27.83		0.0709
V2T3	10.25	37.54		0.0956
V3T1	4.25	20.73		0.0396
V3T2	9.50	46.43		0.0886
V3T3	14.60	71.22		0.1362

Note: Analysis, 2024

The study involved the generation of hydrogen and oxygen bubbles at the cathode and anode. Electroflotation processing would be more efficient when all hydrogen gas from electrolysis forms bubbles (Chen, 2000; Comninellis & Chen, 2010). Understanding this facet of the electroflotation process is crucial, especially for producing hydrogen gas bubbles that ascend and capture contaminants in wastewater. The oxygen evolution reaction commences with the adsorption of hydroxide ions, producing OH groups on the surface, producing oxygen anions that are ultimately released as oxygen atoms (Zhang et al., 2020).

A decrease in total suspended solids also influences the reduction in the concentration of organic contaminants, including BOD, COD, and ammonia, due to the presence of particular constituents of total solids that are organic contaminants. The decrease in concentration is also affected by the adsorption process and degradation by flotation. The decomposition of organic compounds occurs when the oxygen produced during electroflotation combines with chloride ions to form a strong oxidant capable of breaking down organic compounds in wastewater, forming a low-density monolayer. Consequently, the gas bubbles generated in the electroflotation process carry these organic pollutants to the surface, along with the bubbles that adsorb pollutants in the slaughterhouse wastewater. In flotation systems, solid mixtures can be separated through the selective attachment of hydrophobic solid particles to gas bubbles (air bubbles) while other hydrophobic substances remain in the water. The density difference between air bubbles and water provides buoyancy, lifting the hydrophobic solid particles to the surface, where they are retained in the foam (Albijanic et al., 2010).

According to Table 10 and Figure 4, the V3T3 variation yields the highest quantity of moles,

Table 10. Number of moles and volume of H_2 and O_2 gas formed at variations in electric voltage and number of plates

Variables	Mol H_2 (moles)	Mol O_2 (moles)	Volume H_2 (L/s)	Volume O_2 (L/s)
V1T1	0.007	0.003	0.163	0.081
V1T2	0.022	0.011	0.484	0.242
V1T3	0.034	0.017	0.752	0.376
V2T1	0.014	0.007	0.313	0.157
V2T2	0.035	0.018	0.794	0.397
V2T3	0.048	0.024	1.071	0.535
V3T1	0.020	0.010	0.444	0.222
V3T2	0.044	0.022	0.992	0.496
V3T3	0.068	0.034	1.525	0.763

Note: Analysis, 2024

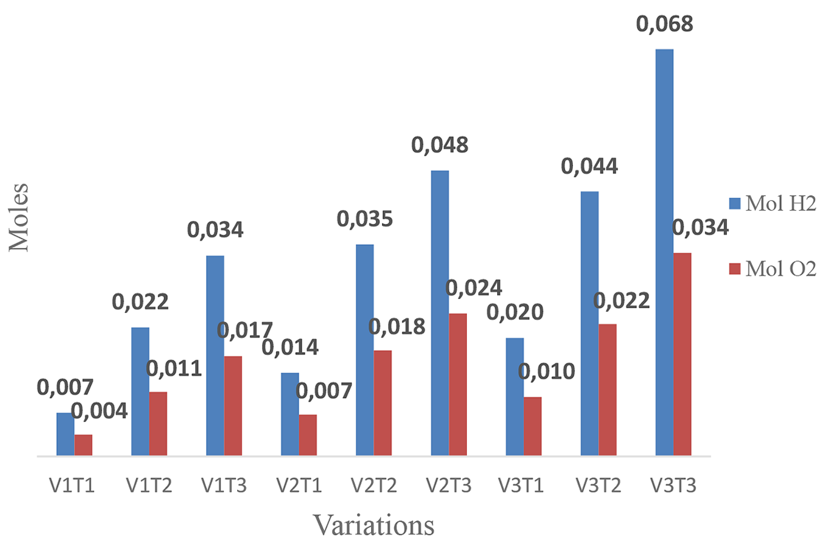


Figure 4. The amount of moles of H_2 and O_2 gas produced

totaling 0.068, corresponding to a hydrogen gas volume of 1.525 L under standard conditions (STP). This suggests that an increase in electric voltage and the number of plates influences hydrogen gas generation during the electrolysis process in electroflotation, resulting in bubble formation. Table 10 depicts the most significant O_2 moles produced in the V3T3 variation, resulting in 0.034 moles. Under standard conditions (STP), this yields an oxygen gas volume of 0.763 L, suggesting that the escalation of electric voltage and the number of plates influences the generation of oxygen gas during the electrolysis process in electroflotation, resulting in bubble formation.

CONCLUSIONS

The study concludes that the variables employed influence the reduction of pollutant concentrations in cattle slaughter effluent. The optimal pollutant reduction efficacy is achieved with a voltage fluctuation of 15 V and five pairs of electrode plates (10 plates). The reduction efficiencies are as follows: COD at 94.2%, BOD at 96.6%, TSS at 97.02%, ammonia at 84.82%, and oil and fat at 91.77%. An augmentation in electric power and the quantity of plates is associated with reduced COD, BOD, TSS, oil and fat concentrations, and ammonia levels. This indicates an enhanced level of elimination efficiency. The greater the O_2 and H_2 gas production, the more bubbles are generated. This suggests that electroflotation is more effective in diminishing pollutants in wastewater from the livestock abattoir.

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