

Advanced technological integration for swine wastewater: Enhancing treatment with photo-Fenton and electrocoagulation

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ABSTRACT

The increase in pork consumption and its reputation as one of the best sources of protein has led to growth in this industry, however, its production generates a significant amount of swine wastewater (SWW). Conventional biological treatment methods are typically used to treat SWW. However, their applicability in small and medium sized enterprises (SMEs) in the swine industry is limited due to their high space requirements. Therefore, advanced oxidation processes (AOPs) such as photofenton (PF) and electrocoagulation (EC) represent a potential alternative for SWW treatment due to their lower space requirements. The aim of this study was to treat SWW by integrating the PF process followed by EC as a technological couple to optimize the removal efficiency of pollutants present in SWW. Experiments were conducted in a 2 L batch reactor, examining the effects of hydrogen peroxide (H₂O₂) concentration (0.5, 2.5, 5.0 g L⁻¹) and current density (10, 50, 90 A m⁻²) on pH, organic matter, nutrients, and germination index (GI). The results showed that the optimum process conditions correspond to 2.6 g L⁻¹ H₂O₂ and a current density of 41 A m⁻². Under these conditions, an effluent is obtained with pH values of 7.8, TSS of 385 mg L⁻¹, COD of 254 mg L⁻¹, BOD₅ of 139.8 mg L⁻¹, TN of 190.4 mg L⁻¹ and GI of 117 %. The results showed that the effluent complies with the Colombian standards. From a cost perspective, the use of Photo-Fenton to treat wastewater under these conditions would be US\$ 0.7 per liter.

1. Introduction

The increasing global demand for protein has led to an increase in livestock and poultry production, with the pork sector accounting for 38 % of global meat production [1,2]. Pork production has an average water footprint of between 3000 and 9000 L of water per kilogram of meat, generating a significant amount of swine wastewater (SWW) [3]. It is also recognized that the situation is critical for small-scale pig farms, as they can generate approximately 1300 L of SWW per year, which is equivalent to between 4 and 8 L of SWW per day [4]. Furthermore, it is predicted that SWW generation will increase in the future due to the expected growth in meat production by 2050 [5].

SWW are characterized by values of pH between 6.7 and 8.9, turbidity between 360 and 4350 NTU, chemical oxygen demand (COD)

between 910 and 19,380 mg L⁻¹, between 2000 and 30,000 mg L⁻¹ biological oxygen demand (BOD₅), total nitrogen (TN) between 200 and 2055 mgL⁻¹, ammonia nitrogen (NH₄⁺-N) between 110 and 2200 mg L⁻¹, total phosphorus (TP) between 10 and 918 mg L⁻¹ [2,6,7]. The high organic content in SWW is also due to the presence of color-forming compounds such as long-chain chloroorganics (i.e., fulvic acid, humic acid, and melanoidin) and chromophoric compounds [8]. This means that discharging dyed wastewater into the environment may have an impact on the ecosystem due to its lack of biodegradability and persistence. In addition, SWW has a high microbiological load (i.e., *Escherichia coli* and *Salmonella* sp) and the presence of refractory compounds such as heavy metals, antibiotics, and hormones [2,9]. In developed countries, SWW is used as fertilizer for irrigation in agricultural soils, but it represents a source of pollution that contributes to eutrophication due to

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the high concentration of nutrients [10,11].

The treatment of SWW is adapted to the size of the facility, its proximity to agricultural land, its geographical location and the local regulations in force [1]. Therefore, biological treatment technologies such as anaerobic digestion, aerobic lagoons, activated sludge systems, or solid-liquid phase separation systems have been proposed as treatment methods for SWW. However, although these systems are economical, they face the challenge of reducing the hydraulic retention time and thus the volume required for the reactors [12,13]. Similarly, anaerobic systems require post-treatment [14], and high contaminant loads in SWW can affect its treatment efficiency [15], making it difficult to meet increasingly strict discharge standards [16]. In addition, due to overproduction of pork, it is possible to find antibiotics and hormones in SWW that cannot be removed by conventional treatment [2,17]. Low-cost wastewater treatment technologies are also needed, especially for small-scale pig farms that cannot afford high-efficiency treatment facilities [18]. This situation is of high concern since in countries such as Colombia there are approximately 14000 pig farms with a capacity to raise more than 1.7 million pigs, of which 3388 are considered technified farms and the rest are small or SME (i.e., rearing or complete cycle of less than 10 females; or less than 40 pigs) that do not have the land for a conventional treatment system [19].

Advanced Oxidation Processes (AOPs) are emerging as an alternative for wastewater treatment due to their efficient removal of organic matter and refractory compounds, shorter treatment time compared to biological processes, and the absence of biological sludge [1]. These technologies include photocatalysis, electrolysis or oxidative degradation, Fenton, Photo-Fenton (PF), chemical coagulation (EC) or a combination of technologies. PF is an AOP used to remove organic compounds from liquid effluents [20]. This process is considered to be simple, fast, and inexpensive, requiring only hydrogen peroxide (H_2O_2) and iron source [12,20]. PF is a technology that generates short-lived free radicals, such as hydroperoxide and hydroxyl radical ($\bullet OH$), to rapidly and non-selectively oxidize organic and inorganic pollutants in wastewater, converting them to CO_2 , water or biodegradable products [21]. This technology reduces the toxicity of the effluent, improves its biodegradability and increases the efficiency of subsequent treatments [22]. During the PF, hydroxyl radicals interact with H_2O_2 and an iron catalyst (Fe^{2+}) in an acidic environment. This iron catalyst is constantly regenerated between Fe^{3+} and Fe^{2+} states under UV-vis light irradiation, which increases the reaction rate for the oxidation of organic pollutants [23]. Equations (1)–(4) describe the PF process.



It is recognized that H_2O_2 concentration is a key parameter to optimize because low concentration or excess of hydroxyl ions affects the efficiency of the PF process. Process [24]. For example, Domingues et al. [12], evaluated the PF process for SWW with 750 mg L^{-1} H_2O_2 and $FeSO_4$ and concluded that the process is an adequate method to remove 72 % of COD and water toxicity with *Aliivibrio fischeri* at 65 %. They also highlight that the articulation of the PF followed by a biofiltration process increased and COD removal to 91 %. Similarly, Park et al. [25], conducted a 60-min reaction using Fe^{2+} concentrations of 3685.8 mg L^{-1} (0.066 M) and 558.5 mg L^{-1} (0.01 M), along with H_2O_2 concentrations of 6802.9 mg L^{-1} (0.2 M) and 3401.5 mg L^{-1} (0.1 M). They achieved a COD removal of 70–79 % with Fe^{2+}/H_2O_2 molar ratios ranging from 0.3 to 0.1. Similarly, Toor et al. [13], indicate that the dose of 800 mg L^{-1} $FeSO_4$ and 5207 mg L^{-1} H_2O_2 showed 76.7 % removal for total organic carbon (TOC) and 98 % color from SWW with a reaction time of 120 min. Other

authors have reported experiences indicating that concentrations of H_2O_2 between 5.0 and 5.2 g L^{-1} and Fe between 0.1 and 1.0 g L^{-1} are suitable for the PF process [12]. Other research indicates that the efficiency of PF is affected by the concentrations of H_2O_2 and the iron source used [22]. Although COD removal efficiencies range between 70 % and 80 %, there is still a need for process optimization. However, there is no consensus on the optimal operating conditions, especially regarding the concentrations of H_2O_2 and $FeSO_4$, for SWW treatment.

This process consists of the generation of hydroxides by passing an electric current through sacrificial electrodes that allow the removal of contaminants through charge neutralization, adsorption, complex formation, and precipitation [26–28]. In addition, unlike conventional methods, EC does not require the addition of chemical inputs to destabilize the particles [29]. EC with aluminum electrodes is modelled by Equation (5) and Equation (6).



EC efficiency is affected by several variables such as electrode type, electrode spacing, mono or bipolar configuration, among others [16], but it is recognized that current density (j) is the most important variable in the process [30]. Mores et al. [30], investigated the feasibility of using different values of current density (i.e., j between 163 and 575 A m^{-2}) for turbidity removal using aluminum electrodes and reported efficiencies of 91 % and 93 % for total phosphorus (TP). On the other hand, Chen et al. [16], found that 300 A m^{-2} , no agitation, an initial pH of 6.3 and a reaction time of 35 min removed 50.6 % of COD and 10 % of BOD_5 for high-strength SWW. Likewise, Sandoval et al. [31], they evaluated different current densities ($j = 100, 200$ and 300 A m^{-2}) and indicated that the most efficient corresponded to 200 A m^{-2} . Other studies report the use of current densities ranging from 5 to 1500 A m^{-2} [32,33], so the literature on CE is extensive.

The combination of PF and EC can help to improve the removal efficiency of organic and recalcitrant substances present in SWW, as well as to reduce their toxicity for subsequent reuse in the circular economy. Although this coupling has been successfully tested with wastewater from the dairy industry [34], there is little evidence of its use in SWW. Therefore, in this type of combined processes, the optimization of parameters is an important aspect to determine the optimal conditions in terms of pollutant removal [13]. This is important because the combination of different operating conditions, such as H_2O_2 concentration and current density, can have synergistic or antagonistic effects on effluent quality. In addition, PF or EC studies are often limited to one-variable-at-a-time (OVAT) analysis, which may not capture non-linear relationships between the factors studied and affect the response variables [13,22]. The definition of operational conditions can be carried out with the integration of statistical methods with experimental basis and empirical models. In this context, the Response Surface Methodology (RSM) allows to obtain models that serve this purpose and provide information for process optimization [35,36].

This research evaluates the joint effects of operating parameters such as hydrogen peroxide concentration and current density on various response parameters (i.e., pH, TSS, COD, BOD_5 , TN, and GI) to improve SWW water quality. For this purpose, a technological coupling between PF and EC was implemented. The study allows to determine the main operational parameters affecting the process efficiency and the quality of the treated SWW. For this purpose, the process is monitored and optimization tools such as response surface are used to reveal the effects of individual factors as well as a possible autocorrelation between the studied factors. To the authors' knowledge, there are few studies that integrate PF with EC, especially applied to the treatment of wastewater from swine SME. Likewise, there are few studies that analyze the interaction of H_2O_2 concentration and current density for PF and EC, respectively, and define a range where the removal of the different pollutants is maximized; furthermore, the operating conditions are

optimized, allowing their use within the framework of the circular economy.

2. Materials and methods

2.1. Wastewater samples collection

The wastewater was collected from a stabilization pond of a pig farm located in the village of La Renta, in the municipality of Lebrija, Colombia. This company operates an integrated pig farm with a capacity of 700 pigs. The collected wastewater comes from the pig houses and consists of a mixture of excrement from these animals at all stages of development, as well as water used to clean the housing facilities, straw, and remnants of feed. The SWW is gradually discharged to the ground through infiltration fields. The wastewater was collected in airtight 30 L containers and transported to the laboratory for analysis. Samples were stored at 4 °C to avoid reactions and contamination. Triplicate samples of 5 L were collected. The wastewater samples were characterized in terms of physicochemical and microbiological parameters such as pH, oil and grease, total alkalinity, total suspended solids (TSS), COD, BOD₅, total organic carbon (TOC), total nitrogen (TN), ammonia nitrogen (NH₄⁺), sulfate (SO₄²⁻), chlorides, total phenolic content, total coliforms (TC), and fecal coliforms (TF). Each of the parameters was measured in accordance with [37]. The parameters were measured 3 times and the mean value, and its standard deviation are reported.

2.2. Experimental setup

The experiments were performed on a laboratory scale set-up in batch mode. The tests were done in a Plexiglas reactor. For the PF test, a plexiglas photoreactor with a capacity of 2 L was used inside a vessel to which a UV irradiation system (UV-C, Puriplus) was attached at the top 30 cm from the reactor. The photoreactor was placed on a magnetic stirrer (model 752 A, Fisatom) at 190 rpm [25]. Fig. 1 shows a representation of the reactors and their constituents. Peroxide (H₂O₂, 35 % v/v) and iron sulfate (Fe₂SO₄·7H₂O, 30 % v/v) were used in the Photo-Fenton reactions HCl (35 % v/v) was used to set the pH to 4 [38, 39]. The PF effluent was piped to a 3 L capacity rectangular plexiglas reactor for the EC process. A UNI-T UTP1306 DC power supply was used in the range of 0–6 A and 0–30 V for current and voltage, respectively. Rectangular Al electrodes with dimensions of 12.7 cm × 8.8 cm and 2 mm thickness with an effective area of 111.8 cm² were used. The number of electrodes in the reactor depended on the applied current

density. In addition, the electrode arrangement was of the parallel monopolar type (MP-P) and they were separated by 1 cm [40], with this distance maintained by a horizontal plate that did not allow contact between the electrodes. To reduce passivation of the electrodes, their polarity was reversed every 15 min [39]. The electrodes were washed with ethanol and distilled water to remove surface contaminants before each experiment [41]. On the other hand, the reactor had a sludge accumulation zone with its corresponding purge valve. The sludge zone had a volume of 0.51 L, where the formed flocs sedimented by gravity.

2.3. Analytical methods

The pH was measured by the potentiometric method (pH meter: WTW Model 315i, Wissenschaftlich-Technische Werkstätten GmbH, Weilheim, Germany) in a 20 mL sample. Fats and oils were measured by method 5520 B SM by liquid-liquid extraction with gravimetric participation. Alkalinity was determined by method 2320 B SM. TSS concentration was determined gravimetrically by passing the wastewater sample through a glass fiber filter. The filter was dried at 105 °C to constant weight according to method 2540 D SM. COD was measured spectrophotometrically with a Merck NOVA 400 UV spectrometer using the closed reflux method with potassium dichromate as oxidant. BOD₅ was determined with the 5-day incubation method optical electrode/SM 5210 B SM 4500-OH. TOC was quantified by combustion of the samples at 680 °C using a non-dispersive IR source (Tekmar Dohrmann Apollo 9000). TN was determined as Kjeldahl total nitrogen. Ammoniacal nitrogen (NH₄) was measured using the SM 4500 method. Chlorides, sulfates, and phenols were measured using methods 4500 Cl-B, 4500 SO42-E, and 5530, respectively. Fecal and total coliforms were measured according to method SM 9921. All parameters were measured in triplicate to calculate the standard deviation.

2.4. Experimental design

A central composite design was performed to define the optimal operating conditions for SWW treatment. H₂O₂, (g L⁻¹) and electric current density (A m⁻²) were considered as independent factors. These factors were considered due to their incidence in PF and EC as reported in the literature [21,29]. Specifically, was selected due to its incidence in the release of OH radicals that affect the efficiency of the treatment, while the current density was selected due to its effect on the generation of hydroxyl ions that promote the removal of contaminants through charge neutralization, adsorption, complex formation and precipitation

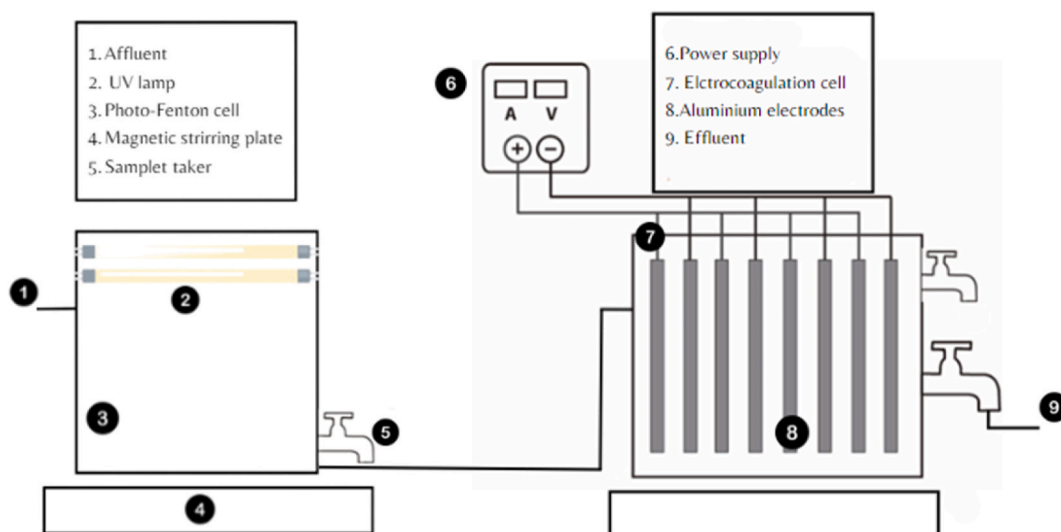


Fig. 1. Experimental configuration.

[26–28]. Each factor was examined at three levels for a total of nine treatments. Each treatment was replicated twice. The peroxide concentrations were 0.5, 2.5 and 5.0 g L⁻¹, while the current densities considered were 10, 50 and 90 A m⁻². The levels studied were defined according to those reported in the literature, for H₂O₂ between 5 and 5.2 g L⁻¹ and for current density values between 5 and 1500 A m⁻² [12, 14,32]. For the PF process, the dose of FeSO₄·7H₂O was set at 0.7 g L⁻¹ [12] and the reaction time for both PF and EC the reaction time was 60 min. These conditions were established in preliminary experiments. Table 1 shows the treatments resulting from the experimental design.

All runs were performed at room temperature of 25 ± 1 °C. The response variables considered were pH, reduction of the TSS, COD, BOD₅, TN, TC and CF compared to those measured in the influent. In addition, GI was considered as an indicator of effluent phytotoxicity. Other variables were not considered due to their low concentration in the wastewater. The percentage of pollutant removal (Re) was also quantified using Equation (7) [12].

$$Re = (C_0 - C / C_0) * 100 \quad \text{Equation 7}$$

Where Re is the removal efficiency of parameter *i*, C₀ is the concentration of parameter *i* in the influent and C is the concentration of parameter *i* in the effluent. To evaluate the toxicity of the treated effluent, seeds of *Raphanus sativus*, a species sensitive to the presence of contaminants, were used. This procedure consisted in diluting the sample in distilled water (i.e. 1:10 w/v ratio) and was calculated using Equation (8) [42]. GI values below 50 % indicated the presence of phytotoxic substances, while those between 50 % and 80 % indicated a moderate presence. On the other hand, GI values above 80 % showed positive effects, and biostimulatory effects were observed when GI values exceeded 120 %.

$$GI = \frac{RSG * RRE}{100} \quad \text{Equation 8}$$

Where GI is germination index; RSG is relative seed germination, and RRE is relative root elongation.

2.5. Statistical analysis, mathematical modeling and validation of the optimal Profile

To determine the incidence of the independent factors on the responses, a two-way ANOVA with a 5 % significance level was used. The experimental data were used in an exploratory approach to define the optimal operating conditions using RSM. For this purpose, the data for the variables pH, TSS, COD, BOD₅, TN and GI were fitted to empirical statistical models with the general form presented in Equation (9).

$$Y = \beta_0 + \sum_j \beta_j q_j + \sum_j \beta_j q_j^2 + \sum_{i < j} \beta_{ij} q_i q_j + \varepsilon \quad \text{Equation 9}$$

Where, Y corresponds to the response variable, β_0 is a coefficient, β_i β_j are linear coefficients, β_{ij} represents the interactive effect of the independent factors q_i and q_j ; k is the number of independent variables;

Table 1
Treatments resulting from the experimental design.

Treatment	H ₂ O ₂ Coded factor	Current density Coded factor	H ₂ O ₂ [g L ⁻¹]	Current density [A m ⁻²]
T1	-1	-1	0.5	10
T2	-1	0	0.5	50
T3	-1	+1	0.5	90
T4	0	-1	2.5	10
T5	0	0	2.5	50
T6	0	+1	2.5	90
T7	+1	-1	5.0	10
T8	+1	0	5.0	50
T9	+1	+1	5.0	90

and ε is the experimental error. The optimal conditions were determined by superimposing the different response surfaces [36]. For this purpose, constraints were considered with the following maximum permissible values: pH between 7 and 9, TSS < 400 mg L⁻¹, COD < 900 mg L⁻¹, BOD₅ < 450 mg L⁻¹. These restrictions were defined in accordance with Colombian discharge regulations. Additionally, TN < 200 mg L⁻¹, and GI > 80 % conditions were considered. Once the optimal operating condition had been determined using the RSM, a new test was performed to validate the results obtained.

2.6. Cost analysis of the combination of the technologies

The cost of combining PF with EC was estimated to be US\$ per liter of SWW treated. For PF, the methodology of Trigueros et al. [34] was used, which considers the cost of electrical energy and the purchase of inputs according to the Colombian context. In the case of H₂O₂, a value of US\$ 3.86 per L of 35 % H₂O₂ was used, for iron sulfate heptahydrate US\$ 4.1 per kg of Fe₂SO₄·7H₂O, for hydrochloric acid US\$ 79.04 per L of 37 % HCl and for electrical energy US\$ 0.07 per kWh. For the CE process, the electrical energy consumption cost ENC (Equation (10)) was considered according to the literature [43,44]. On the other hand, the apparent faradaic yield (Equation (11)) was estimated to determine the amount of electrode mass dissolved from the anode during the reaction (MEC) as shown in Equation (12). This element was used to estimate the total cost of CE (Equation (13)).

$$ENC(kwh / m^3) = \frac{j^*s^*V^*t}{1000^*V_s} \quad \text{Equation 10}$$

$$\phi = \frac{z_{Al}^*F^*\Delta COD^*V_s}{i^*t^*M} \quad \text{Equation 11}$$

$$MEC = \frac{\phi^*j^*s^*t^*M}{z_{Al}^*F^*\Delta COD^*V_s} \quad \text{Equation 12}$$

$$OC \left(\frac{USD\$}{m^3} \right) = (ENC^*EEP) + (MEC^*EMP) \quad \text{Equation 13}$$

Where *j* is the current density (A m⁻²), V is the voltage (V), S is the electrode area (m²), F is the Faraday constant (96,486 C mol⁻¹), t is the time (h); Δ COD is the amount of COD removed (mg L⁻¹), V_s is the volume of effluent solution (m³), M is molecular mass of Al (26.98 g mol⁻¹), z is the valence number of Al (z = 3), EEP is the price of the electric energy (US\$ 0.07 per kWh), and EMP is the price of the aluminum electrode material (US\$ 3.28 per m³).

3. Results and discussion

3.1. Characterization of wastewater and removal of contaminants

Table 2 shows the characteristics of the SWW and the different discharge limits adopted by various countries. The pH values were neutral (7.1 ± 0.3) and in agreement with those reported by Yang et al. [18] para SWW (7.0 ± 0.15) and by Castellanos-Rivera [45] for municipal slaughterhouse water (6.88 ± 0.15). In addition, they are within the permissible discharge limits according to World Bank guidelines, European standards and those of countries such as the USA, China and Colombia. However, it is not suitable for the PF process and requires conditioning to a pH of 4 [25,46]. The oil content was low and lower than the maximum allowed by Colombian regulations. Total alkalinity was higher than that reported in another study (222.3 ± 210.2) [45]. Total suspended solids (TSS) were similar (1705 ± 39 mg L⁻¹) to those reported by Sandoval et al. [31], (16276 ± 6064.6 mg L⁻¹). However, it is not suitable for discharge according to international discharge standards. Regarding COD and BOD₅, these had lower values than those found by Yang et al. [18] and Castellanos-Rivera [45], who reported COD values of 16276 ± 6064.6 mg L⁻¹ and 9718 ± 1716 mg

Table 2

Physicochemical and microbiological characteristics of SWW.

Parameter	Unit	Value	World Bank ^a [49]	European Union ^b [50]	US EPA ^c [51]	Chinese Standards ^d [52]	Colombian standards ^e [53]
pH		7.1 ± 0.3	6–9	N. A.	6–9	6–9	7–9
Oil and grease	mg L ⁻¹	<10.00*	10	N. A.	N. A.	N. A.	20
Total Alkalinity	mg CaCO ₃ L ⁻¹	500 ± 56	N. A.	N. A.	N. A.	N. A.	A & R
TSS	mg L ⁻¹	1705 ± 39	50	35–60	20–30	20–30	400
COD	mgO ₂ L ⁻¹	1351 ± 54	125	125	N. A.	100–300	900
BOD ₅	mgO ₂ L ⁻¹	717 ± 57.4	30	25	16–26	20–100	450
TOC	mg TOC L ⁻¹	196 ± 14	N. A.	N. A.	N. A.	20–60	N. A.
TN	mg L ⁻¹	334 ± 37	10	10–15	4–8	15–20	N. A.
Ammonia nitrogen	mg L ⁻¹	319 ± 18	N. A.	N. A.	N. A.	N. A.	N. A.
Sulfate	mg L ⁻¹	10 ± 1.0	N. A.	N. A.	N. A.	N. A.	N. A.
Chlorides	mg L ⁻¹	237 ± 45	N. A.	N. A.	N. A.	N. A.	N. A.
Total phenolic content	mg L ⁻¹	0.6 ± 0.1	N. A.	N. A.	N. A.	N. A.	N. A.
Total coliforms (TC)	NPM/100 mL	2x10 ⁸	400	N. A.	N. A.	N. A.	N. A.
Fecal coliforms (TF)	NPM/100 mL	21x10 ⁷	N. A.	N. A.	N. A.	N. A.	N. A.

Note: TOC is total organic carbon. N. A.: Does not apply; A & R: Analysis and Report. * out of detection limit.

^a Environmental, Health, and Safety (EHS) Guidelines: Wastewater and Ambient Water Quality.^b Urban wastewater treatment directive 91/271/EEC.^c Effluent limitations guidelines and new source performance standards for the meat and poultry products point source category.^d Discharge standard of water pollutants for meat packing industry GB 13457-92.^e Resolution 631 of 2015 Whereby the parameters and maximum permissible exposure limits in specific discharges to surface water and public sewer systems and other provisions are established.

L⁻¹, respectively. This result evidenced that SWW is heterogeneous and depends on the washing and feeding practices carried out in the SMEs. On the other hand, the BOD₅/COD ratio of 0.5 indicated the presence of biodegradable material and other compounds, such as phenols, which can hinder the biological degradation process [22]. As a matter of fact, the phenol concentration was higher than the limit of 0.20 mg L⁻¹ set by Colombian regulations. This result highlights the importance of research on synergistic processes, such as the PF process combined with EC, and is in line with what has been reported in other research with SWW [31]. Therefore, the discharge of untreated SWW may pose a health risk according to the World Bank guidelines. The TOC and TN contents are higher than those reported in other studies of SWW [47,48], and higher than the maximum values allowed by Chinese standards (20–60 mg L⁻¹).

Regarding the concentration of NH₄⁺-N, it was found to vary between 110 and 2200 mg L⁻¹, similar to those reported in other works [2, 6,7], while the chlorides (237 ± 45 mg L⁻¹) were higher than those reported by Sandoval et al. [31], for pig slaughterhouse wastewater. The phenol content was low, and the concentrations of TC and TF were high.

In terms of environmental regulatory restrictions, parameters such as TSS, COD, BOD₅, TOC, TN, ammonia nitrogen, and TC and TF represent a potential risk if SWW is discharged untreated to soil or water [54].

Table 3 shows the results of the effluent obtained from the PF and EC process for each treatment are presented. All effluents from the PF process exhibited pH values below the initial values, which is indicative of the release of salt ions (i.e., Cl⁻ y SO₄²⁻) and acids during the reaction [55]. Similarly, in all treatments, there was a reduction in TSS and OM indicator parameters. This is since Fe²⁺, in addition to reacting with •OH, acted as a coagulant through the formation of hydroxyls and polyhydroxides that contribute to the coagulation of macromolecules present in the wastewater [33]. However, the results varied depending on the dose of H₂O₂. Similar results are reported by San Juan-Garisado et al. [22] in the PF process. The lowest dose of hydrogen peroxide (0.5 g L⁻¹) resulted in a low removal efficiency, with TSS, COD, and BOD₅ removal efficiencies of 36.8 %, 72.1 %, and 67.6 %, respectively. The COD removal results were similar to those reported by Domingues et al. [12] who evaluated the PF process for SWW at 750 mg L⁻¹ H₂O₂. This was attributed to the fact that H₂O₂ was the limiting reagent, which affected

Table 3

The characteristics of the effluent obtained from the PF and EC processes for each treatment.

Treatment	PF Effluent				EC Effluent						
	pH	TSS	COD	BOD ₅	pH	TSS	COD	BOD ₅	TN	TC (NPM/100 mL)	FC NPM/100 mL)
		(mg L ⁻¹)	(mg L ⁻¹)	(mg L ⁻¹)		(mg L ⁻¹)	(mg L ⁻¹)	(mg L ⁻¹)	(mg L ⁻¹)		
T1	3.2 ± 0.3	976 ± 63.7	372 ± 53.9	219 ± 17.3	7.4 ± 0.6	673 ± 85.1	240 ± 26.9	141 ± 35.4	95.1 ± 1.5	1600	920
	3.8 ± 0.1	1101 ± 51.5	413 ± 44.5	252 ± 14.8	8.4 ± 0.2	715 ± 26.3	260 ± 18.5	168 ± 11.2	80.3 ± 7.9	150	43
T3	3.9 ± 0.3	1156 ± 94.2	347 ± 37.2	226 ± 23.6	8.5 ± 0.7	826 ± 38.5	231 ± 49.2	148 ± 23.5	66.4 ± 12.4	840	330
	3.4 ± 0.2	900 ± 56.2	283 ± 61.8	158 ± 15.1	7.3 ± 0.2	600 ± 51.7	195 ± 32.6	99 ± 8.9	60.0 ± 19.4	1.6 x10 ³	9.2x10 ²
T5	3.7 ± 0.5	803 ± 75.8	179 ± 23.4	153 ± 18.2	8.5 ± 0.5	384 ± 36.4	122 ± 12.9	94 ± 15.7	65.1 ± 7.2	45	0
	3.5 ± 0.1	837 ± 96.6	293 ± 46.7	156 ± 13.4	8.6 ± 0.1	523 ± 19.5	180 ± 26.3	104 ± 18.3	54.9 ± 12.1	4.5x10 ³	0
T7	3.3 ± 0.4	1200 ± 105.3	481 ± 88.6	307 ± 36.7	7.4 ± 0.1	750 ± 63.1	290 ± 20.8	186 ± 46.1	70.2 ± 5.5	5.4x10 ⁵	7.9 x10 ⁴
	3.9 ± 0.2	1096 ± 81.4	477 ± 59.3	281 ± 49.7	8.6 ± 0.3	685 ± 87.3	300 ± 43.1	190 ± 10.9	60.6 ± 3.9	1.6x10 ⁶	9.2x10 ⁵
T9	3.9 ± 0.1	1193 ± 79.9	515 ± 72.1	301 ± 19.2	8.4 ± 0.2	760 ± 24.7	320 ± 19.7	194 ± 38.2	78.5 ± 7.6	3.7x10 ³	1.8x10 ³

the formation of the hydroxyl radical and, consequently, the oxidation of the pollutants. On the other hand, the presence of the chloride anion could also affect the degradation of the contaminants and reduce the efficiency of the process. Chloride ions generate Cl^- radicals, which are less reactive than $\bullet\text{OH}$ and other radicals such as Cl_2^- , ClOH^- , and $\text{HClOH}\bullet$, and react with Fe^{3+} to form $\text{Fe}(\text{Cl})^{2+}$, which affects the distribution and reactivity of iron ions [56]. When the H_2O_2 concentration was 5.0 g L^{-1} , the removal efficiencies were 31.8 % for TSS, 63.6 % for COD and 58.7 % for BOD_5 . In this case, the presence of an excess of H_2O_2 may have been a contributing factor, which likely facilitated the formation of $\bullet\text{O}_2\text{H}$ radicals with a lower oxidation potential ($E^\circ = 1.42 \text{ V/SHE}$ at 25°C) than $\text{OH}^\bullet$ [34]. In addition, the added H_2O_2 may have consumed $\text{OH}^\bullet$ and initiated secondary reactions (see Eq. (14) through 16), which may have limited the oxidation of the contaminants.



The best treatment for a reaction time of 60 min was found to correspond to a dose of H_2O_2 of 2.5 g L^{-1} (i.e. 54.3 % of TSS, 81.4 % for COD and 78.3 % of BOD_5). The COD removal found was higher than that found with the application of 0.5 and 5.0 g L^{-1} of H_2O_2 , indicating the effect of this independent factor. The result was higher than that obtained by Park et al. [25], who reported efficiencies between 70 and 79 % for concentrations of 3.4 and 6.8 g L^{-1} . The difference between the studies is attributed to the variability of SWW in each case. The observed removal efficiencies are comparable to those reported by Trigueros et al. [26] for dairy wastewater treated with the same system. Although the removal efficiency of TSS, COD and BOD_5 is high under the condition of 2.5 g L^{-1} of H_2O_2 , the concentrations found for TSS ranged from 803 to 900 mg L^{-1} , COD from 179 to 293 mg L^{-1} , and BOD_5 from 153 to 158 mg L^{-1} , which do not meet the maximum allowable values of the World Bank standards [49] (TSS of 50 mg L^{-1} , COD of 125 mg L^{-1} , BOD_5 of 125 mg L^{-1} , COD of 125 mg L^{-1} , BOD_5 of 30 mg L^{-1}) or the Chinese standards [52] (TSS between 20 and 30 mg L^{-1} , COD between 100 and 300 mg L^{-1} , BOD_5 between 20 and 100 mg L^{-1}) or the Colombian standards [53] (TSS of 400 mg L^{-1} , BOD_5 of 450 mg L^{-1}). The results highlighted the need to articulate PF with technologies such as CE to improve the quality of wastewater discharged into a water source or soil to minimize the potential risk of environmental degradation (i.e., eutrophication, consumption of dissolved oxygen and favoring anoxic environments, presence of antibiotics and persistent pollutants, as well as changes in soil biota) [54,57].

PF effluent was affected current density demonstrated a significant effect on the process ($p < 0.05$) during the CE process. At low current densities (i.e., 10 A m^{-2}), regardless of the peroxide dose, the average removal efficiency was 46.7 % for TSS, 35.2 % for COD and 37.5 % for BOD_5 . This result indicated that the applied current density was not sufficient for the formation of hydroxyl ions to favor the neutralization or absorption process and then precipitate the pollutants [58]. The effluent of the lower current density PF effluent does not meet the World Bank [49], European [50] or Colombian standards [53] except for pH and COD. At the intermediate current density value (i.e. 50 A m^{-2}), the average removal efficiency was 48.5 % for TSS, 55.5 % for COD and 54.7 % for BOD_5 . This result is related to the fact that, in addition to the higher current density, the pH values were closer to 4, which could favor acid/base equilibrium reactions, complexation, and dissolution/precipitation of the electrode in the medium [35]. In addition, under these conditions, it was possible to promote the formation of hydrogen bubbles that bind to the contaminants, reduce their specific gravity and improve the flocculation process [26–28]. The results reported here are also in agreement with those obtained in other studies carried out on SWW [30]. In terms of effluent quality, the results indicate that T2 and T8 do not meet international standards except for pH

and COD. In contrast, T5 meets the regulatory standards of China [52] and Colombia [53]; however, its high TN content suggests a potential use for agricultural purposes within a circular economy framework [59]. This result is attributed to the enhanced sweeping mechanism facilitated by the alkaline pH, which promoted the formation of denser flocs, aiding in the sedimentation of contaminants and the removal of COD, BOD_5 , and TN. Conversely, at a current density of 90 A m^{-2} , the average values for TSS, COD, and BOD_5 were 34.1 %, 35.8 %, and 33.4 %, respectively. This could be related to possible resuspension of contaminants due to increased formation of hydrolysis products (hydroxometallic species) and increased water temperature (70°C), which could have increased the solubility of $\text{Al}(\text{OH})_3$, leading to the formation of $\text{Al}(\text{OH})_4^-$, which is less effective in wastewater treatment [60]. In terms of effluent quality, T3, T6 and T9 are limiting in terms of TSS, COD and BOD_5 to meet the standards in Table 2.

3.2. Interactive effect of independent factors on effluent pH, TSS and OM

The concentration of H_2O_2 and current density were statistically significant with respect to the removal of TSS, COD, and BOD_5 ($p < 0.05$). The models describing the effect of the factors on the response variables are presented in Table 4. It is highlighted that all models were significant and had a high F-value, indicating the importance of each variable in the model. Moreover, all models exhibited R^2 values exceeding 0.8, indicating a robust explanatory capacity for the effect of the factors on the response variables. Regarding pH, the linear model exhibited the greatest fit to the experimental conditions. In contrast, for TSS, COD, and BOD_5 , the models were of the second order and were significant ($p < 0.05$). The individual terms of each factor in the pH, TSS, COD, and BOD_5 models exhibited a positive influence on the removal percentages, as indicated by a positive sign. Conversely, a negative sign indicated the opposite situation.

Fig. 2a shows the pH response surface. Current density was the most influential factor in the process ($p = 0.002$), while H_2O_2 concentration affected pH to a lesser extent ($p = 0.7$). This result is mainly attributed to the EC process resulting from the chemical reactions due to the release of aluminum species at the sacrificial electrodes. Regardless of the operational conditions of H_2O_2 concentration and under current density between 10 and 40 A m^{-2} , the pH values were between 6 and 7.5, with insignificant differences ($p < 0.05$). In this case, the pH increased due to the electrochemical reactions of the buffer effect of the hydroxo-aluminum species [36]. Conversely, when the current density increased to values above 50 A m^{-2} , the pH was above 7.6 up to 8.5, which also indicated a higher sludge generation [44]. This also showed that current density was the main factor affecting effluent pH and that H_2O_2 was negligible. Similar pH values are reported by Emerick et al. [61], for pig slaughterhouse effluent with EC (8.8), but lower than those with EC with ultrasound (9.2).

In the case of TSS, H_2O_2 concentration was the most significant ($p =$

Table 4
Models for response variables pH, TSS, COD and BOD_5 .

Model	R^2	p-value	F	Equation
$\text{pH} = 6.796 + (0.0413 \cdot \text{H}_2\text{O}_2) + (0.05057 \cdot j) - (0.0006 \cdot \text{H}_2\text{O}_2^2) - (0.000350 \cdot j^2) - (0.000525 \cdot j \cdot \text{H}_2\text{O}_2)$	0.98	0.006	42.42	Equation 17
$\text{TSS} = 48.8 + (14.04 \cdot \text{H}_2\text{O}_2) + (0.267 \cdot j) - (2.731 \cdot \text{H}_2\text{O}_2^2) - (0.00345 \cdot j^2) + (0.02136 \cdot j \cdot \text{H}_2\text{O}_2)$	0.88	0.01	4735	Equation 18
$\text{COD} = 76.55 + (7.95 \cdot \text{H}_2\text{O}_2) - (0.091 \cdot j) - (1.547 \cdot \text{H}_2\text{O}_2^2) - (0.00071 \cdot j^2) - (0.0084 \cdot j \cdot \text{H}_2\text{O}_2)$	0.91	0.008	5.42	Equation 19
$\text{BOD}_5 = 75.64 + (9.61 \cdot \text{H}_2\text{O}_2) - (0.0569 \cdot j) - (1.955 \cdot \text{H}_2\text{O}_2^2) + (0.000465 \cdot j^2) - (0.00046 \cdot j \cdot \text{H}_2\text{O}_2)$	0.97	0.015	21.67	Equation 20

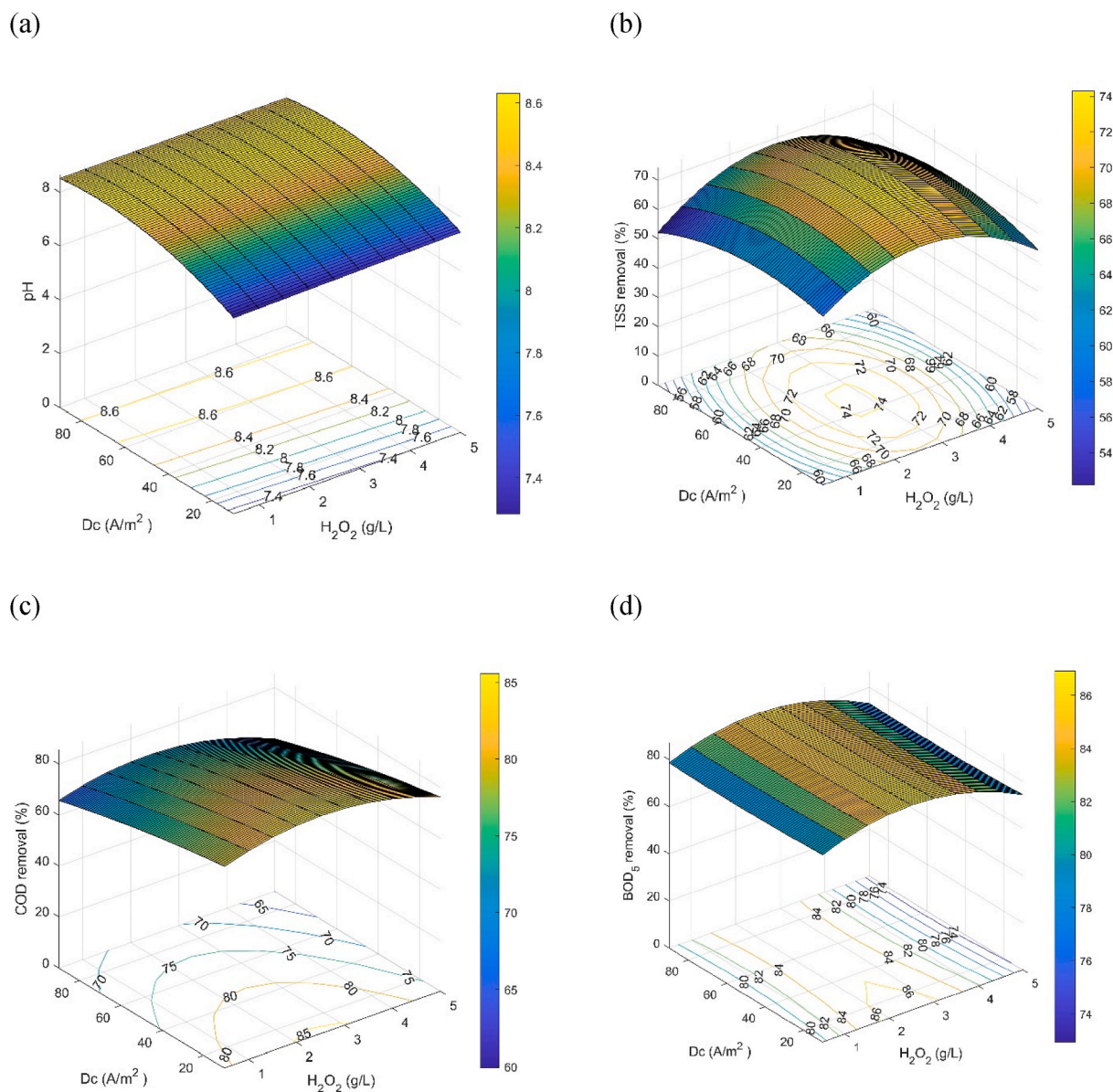


Fig. 2. Response Surface plot for: (a) pH. (b) TSS removal. (c) COD removal. (d) BOD₅ removal.

0.033) and its effect was significantly higher with respect to current density ($p = 0.29$) on TSS removal. The result indicated that the pollutant removal process was mainly developed during PF. In this process, the macromolecules present in SWW were mineralized and degraded into smaller intermediates, which could then be more easily removed in the EC stage [62]. The results of the RSM for TSS are presented in Fig. 2b. The results indicated that H₂O₂ concentration between 2.0 and 3.7 A m⁻² and a current density in the range of 40–80 A m⁻² resulted in overall removal efficiencies in the order of 68–74 % for TSS. This result is likely due to the greater availability of highly reactive ·OH radicals and the presence of aluminum ions, which act as coagulants, facilitating the formation of flocs between contaminants. Consequently, a reduction in TSS concentration was observed. This result is associated with two factors: (i) the self-decomposition of H₂O₂ into peroxy, which also decomposes H₂O and O₂ [45], less reactive species; and (ii) the destabilization of OM due to the probable predominance of hydroxo-aluminum species. Furthermore, under these conditions, the water temperature increased to 70 °C due to the elevated current density values, which destabilized the metal dissolution reactions and hydrogen production, thereby affecting the removal of TSS.

Fig. 2c and d show the response surface plots for COD and BOD₅. It is evidenced that both responses are affected in a non-linear manner. For both COD and BOD₅, the H₂O₂ concentration was more influential on the removal process ($p = 0.03$ and $p = 0.005$, respectively) compared to the current density ($p = 0.47$ and $p = 0.49$, respectively). However, it is highlighted that the EC process was important in improving the effluent quality despite its lower contribution to pollutant removal. The interactive effect was also observed with H₂O₂ concentration between 2 and 3 g L⁻¹ with current density values between 10 and 45 A m⁻², where the efficiency was higher than 80 % for COD (Fig. 2c). The COD reduction is ultimately attributed to the hydroxyl radicals and hydroperoxides formed during the Fenton reaction [62]. These results agree with those reported by Riaño et al. [39], who evaluated the Fenton process applied to biologically pretreated pig manure with a COD removal efficiency of 78 %. Compared to conventional technologies for wastewater treatment, the efficiency of COD removal was below the reported by Chen et al. [63], for membrane bioreactors presenting efficiencies above 90 %. Nevertheless, its efficiency is similar to that reported by Nagarajan et al. [64], for constructed wetlands achieving percentages above 80 %. Compared to other AOPs, the efficiency of removal of COD is similar to

that reported in another study for EC with aluminum electrodes for the treatment of pig slaughterhouse wastewater [31]. Thus, as the H_2O_2 dose and current density increase, the COD removal initially increases until it reaches an optimum value, after which it gradually decreases. This behavior was observed at high concentrations of H_2O_2 (i.e., 3 g L^{-1}) and current density (i.e., higher than 45 A m^{-2}), at which the removal decreased (i.e., less than 75 %). In this respect, an excess of H_2O_2 and current density can result in low pollutant degradation efficiency, increased sludge formation, and increased COD in the effluent [22,34]. Therefore, the results suggest that the optimal operating conditions correspond to the range of H_2O_2 concentration between 1.5 and 3.2 g L^{-1} with current density between 40 and 55 A m^{-2} for SWW. On the other hand, it was found that with H_2O_2 concentrations between 2 and 4 g L^{-1} with a maximum current density of 40 A m^{-2} the removal of BOD_5 ranged between 84 and 86 %. When the current density increases, the reaction efficiency is reduced to 80 %. Less ideal conditions were found when the H_2O_2 concentration was between 0.5 and 1 g L^{-1} and between 4 and 5 g L^{-1} (i.e., 74–80 %) regardless of the current density used. The removal mechanism of COD that could be developed during PF and CE is presented in Equations (21)–(32).



In addition to the technical benefits of improving the quality of SWW by combining the PF and EC processes, Domingues et al. [1] pointed out that one of the environmental benefits of using PF is the reduced production of iron sludge compared to the conventional Fenton process. This is due to the formation of hydroxyl radicals, enhanced by UV radiation, which act non-selectively by degrading organic contaminants, resulting in less sludge volume along with carbon dioxide, water, inorganic ions and less toxic by-products. This is important because in the conventional Fenton process, the main drawback is the formation of iron-rich sludge, which requires further treatment due to the presence of Fe^{3+} [65]. In this study, during the CE process, the Fe^{3+} generated in the PF can be reduced to Fe^{2+} at the cathode, which contributes to improved organic removal efficiency without producing large amounts of sludge that could cause secondary pollution [65]. However, despite this advantage, the sludge produced may contain aluminum phosphate (AlPO_4), nitrogen compounds, and aluminum hydroxide ($\text{Al}(\text{OH})_3$). The latter requires proper treatment for removal, as excessive amounts can be harmful if discharged into water or soil. On the other hand, although in this study it was not possible to estimate the mineralization of organic matter in both the SWW and the sludge generated, the need to address these aspects in future research is highlighted.

3.3. Interactive effect of the independent factors on TN removal and effluent phytotoxicity

The models describing TN and GI are shown in Table 5. In both cases, H_2O_2 concentration was the most significant ($p = 0.032$ and $p = 0.021$ respectively), but less pronounced than in the case of COD and BOD_5 , with EC having a greater relevance ($p = 0.25$ and $p = 0.15$ respectively). The results indicate that H_2O_2 dose had the most significant effect on TN removal. For TN, the H_2O_2 and current density dose terms were negative, indicating a negative relationship between the response and the factors. In contrast, for GI, the linear and interactive terms were positive, indicating a synergistic effect on this parameter.

Fig. 3a shows the response surface plot for TN removal. The effect of H_2O_2 concentration from 2 to 4 g L^{-1} and current density of 40 in the range of $35\text{--}95 \text{ A m}^{-2}$ corresponded to the least optimal operating conditions (i.e., efficiency between 57 and 78 %). It can be noted that at low concentrations of H_2O_2 (i.e., $0.5\text{--}1.0 \text{ g L}^{-1}$), the removal efficiency increases from 75 to 93 %. Regarding the phytotoxicity of the treated effluent (Fig. 3b), the GI was higher than 80 % in all cases, indicating that the effluent can be used for agricultural purposes. However, the effect can be enhanced under conditions of H_2O_2 concentration of 10 and 15 g L^{-1} and current density of 40 % and 60 %.

From the RSM of each response (Fig. 4), it was found that the process is optimized by using 2.6 g L^{-1} of H_2O_2 and 41 A m^{-2} the treated SWW would have a pH of 7.8, TSS removal of the order of 68.3 % (1164.5 mg L^{-1}), the COD of 87.5 % (1182.1 mg L^{-1}), the BOD_5 of 86.8 % (622.3 mg L^{-1}), TN with 59.7 % (198.4 mg L^{-1}) and a GI of 121 %. The desirability function (d) was 0.77. These results show that the treated wastewater could be used for agriculture due to the TN content that would provide nutrients to the soil, provide OM that was not removed to the soil and with low toxicity according to the estimated GI that would not generate inhibition to plant growth. However, it is highlighted the need to address this aspect in future research, considering other parameters such as electrical conductivity, cation exchange capacity, phosphorus and trace elements.

3.4. Validation of operational conditions

The test performed with the optimized conditions showed similar results to those of the multicriteria optimization. After validating the composite optimization, it was found that the treated water had pH values (7.8), TSS removal of 77.4 %, COD of 81.2 %, BOD_5 of 80.5 %, TN of 43 % and GI of 117 %, which are equivalent to concentrations in the effluent of 3.92 mg L^{-1} , 254 mg L^{-1} , 139.8 mg L^{-1} , 190.4 mg L^{-1} respectively. This result complies with Colombian and Chinese standards. Moreover, this result shows that the experimental data met the minimum requirement estimated by the model, thus confirming the validity of the predictive model and the effectiveness of the optimized treatment condition. This result showed that the model error with the optimized treatment is less than 10 %, so the model of the optimized condition manages to adequately represent the process response.

which met the minimum requirement estimated by the model, thus confirming the validity of the predictive model and the effectiveness of the optimized treatment condition. This result showed that the model

Table 5
Models for response variables TN and GI.

Model	R ²	p-value	F	Equation
$\text{TN} = 110.5 - (24.84 \cdot \text{H}_2\text{O}_2) - (0.513 \cdot j) + (3.16 \cdot \text{H}_2\text{O}_2^2) + (0.00136 \cdot j^2) + (0.1013 \cdot j \cdot \text{H}_2\text{O}_2)$	86.3	0.15	3.78	Equation 33
$\text{GI} = 54.3 + (40.71 \cdot \text{H}_2\text{O}_2) + (0.97 \cdot j) - (7.27 \cdot \text{H}_2\text{O}_2^2) - (0.00071 \cdot j^2) - (0.00906 \cdot j^2) + (0.0119 \cdot j \cdot \text{H}_2\text{O}_2)$	90.3	0.09	5.56	Equation 34

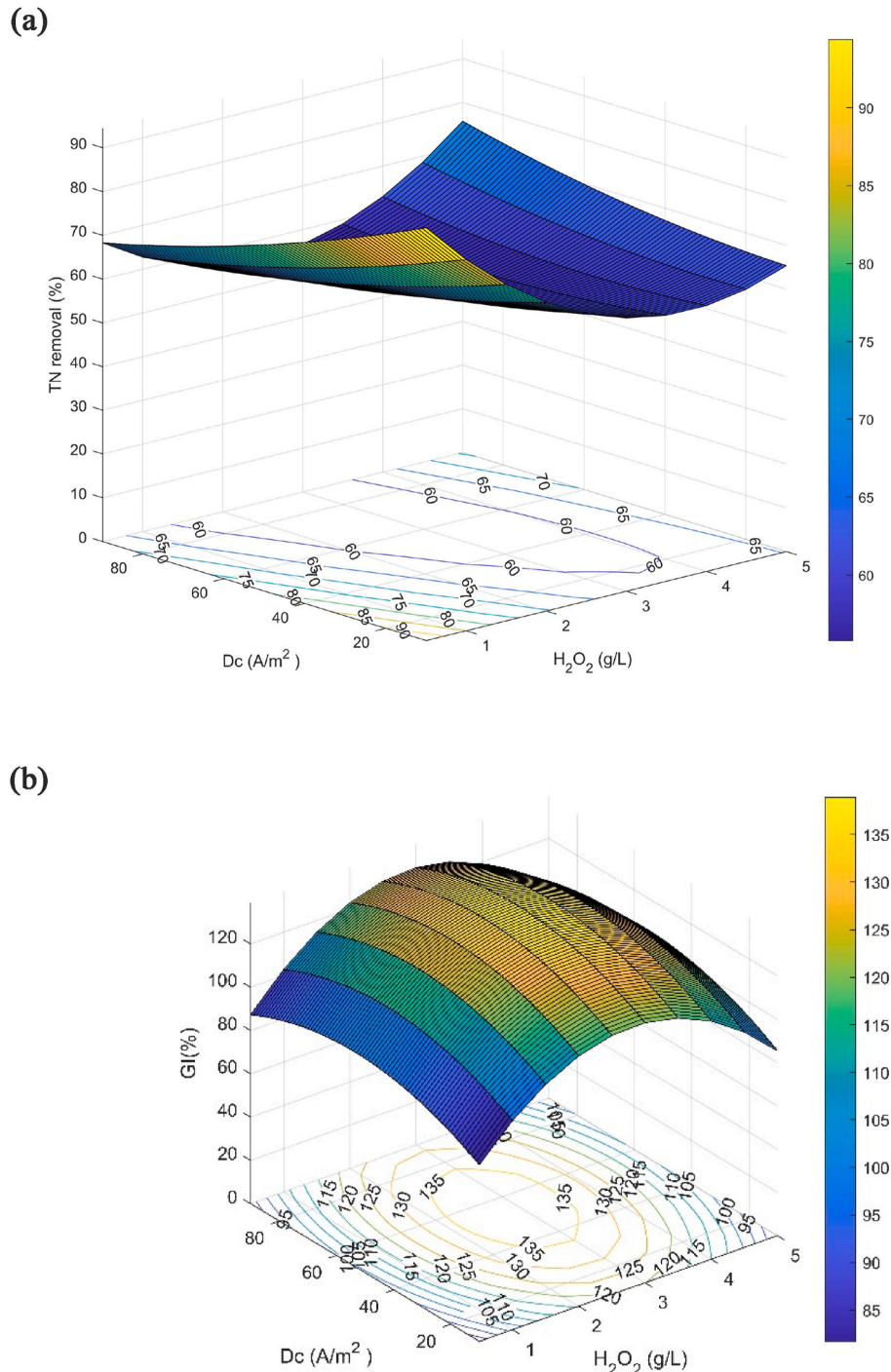


Fig. 3. Response Surface plot for: a) TN removal. (b) GI.

error with the optimized treatment is less than 10 %, so the model of the optimized condition manages to adequately represent the process response.

3.5. Technology integration cost analysis

The cost of SWW treatment under the optimized conditions corresponds to an average of US\$ 0.7 per liter. However, due to the variation in the price of energy in Colombia, the range of variation in the cost of treatment under the scale considered was 0.57 and 0.85 US\$ per liter. Although this is a cost that must be borne by the SME pig farmers, it is a more attractive cost compared to the environmental risk that can cause

and by the retributive fee that they must pay for discharging SWW to a water source (US\$ 0.72 per liter), since many pig farmers currently do not have treatment systems. The value found is lower than that reported by Emerick et al. [61] for SWW treatment, who reported 1.031 \$/m³ and 0.745 \$/m³ for the EC and ECF processes with ultrasound using Al electrodes, respectively. This result also shows the benefits of combining the two processes. Also, the cost is lower than that found by San Juan-Garisado et al. [22] using PF (i.e., \$1.15 per liter) and supports the versatility of the proposed coupling for SWW treatment. On the other hand, the value found in this study is higher than that reported by Yi et al. [66], who used a coagulant of polysilicate aluminum ferric from foundry dusts (0.38 \$/m³ when treating SWW, considering only the cost

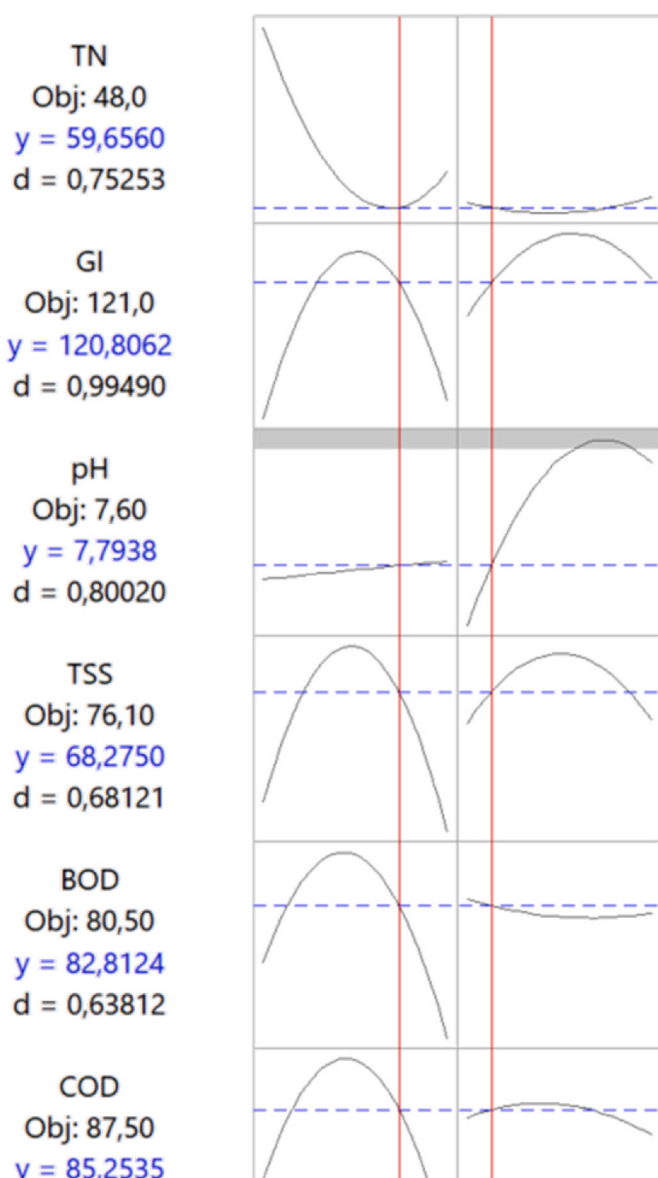


Fig. 4. Multi-Objective optimization for response variables.

of raw materials), costs not considered in their study could make the result competitive. Finally, the cost found by Trigueros et al. [34] using the same coupling for the treatment of dairy wastewater was \$40.24 per kg of COD removed. However, the differences are associated with a longer reaction time (180 min) required for the PF and a higher current density (i.e. 107.14 A m^{-2}). In addition, the pig farmers are willing to pay for the treatment, although they are aware that the value may change as the process is scaled up. Therefore, to minimize costs, it is also necessary to minimize energy consumption costs by incorporating renewable energy sources [67,68]. Therefore, a much more detailed economic analysis is required, considering operational and maintenance aspects on a larger scale.

4. Conclusions

The main conclusion of this study was as follow:

This study investigated the treatment of swine wastewater (SWW) using a combined Photo-Fenton (PF) and Electrocoagulation (EC) process. SWW samples from a pig farm were analyzed for physicochemical and microbiological parameters. Laboratory-scale batch reactor experiments optimized pollutant removal by varying hydrogen peroxide

(H_2O_2) concentrations and current densities, utilizing central composite design and response surface methodology. The results showed significant enhancements in organic matter, nutrient, and pollutant removal, with optimal conditions identified as $2.6 \text{ g L}^{-1} \text{ H}_2\text{O}_2$ and 41 Am^{-2} current density. Under these conditions, pollutant removal efficiencies reached 77.4 % (TSS), 81.2 % (COD), and 80.5 % (BODs), meeting Colombian regulatory standards with low phytotoxicity (germination index >100 %). While further optimization may be necessary for international regulations, this combined treatment method offers a promising, cost-effective solution for small and medium-sized swine industry enterprises, warranting further large-scale applications and economic analysis. In addition, it is necessary to evaluate in the future the use of renewable energy to reduce the electrical consumption of the coupling. It is also necessary to analyze the quality of the sludge and its potential for land application in the context of the circular bioeconomy.

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Data availability statement

All data generated or analyzed during this study are included within the article.

CRediT authorship contribution statement

Tatiana Luque: Writing – original draft, Methodology, Investigation, Formal analysis. **María Jimenez:** Writing – original draft, Methodology, Investigation, Formal analysis. **Anye Aguilar:** Writing – original draft, Methodology, Investigation, Formal analysis. **Brayan A. Parra-Orobio:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Jesús Alvarez:** Writing – review & editing. **Angelica Hernandez:** Writing – review & editing. **Cristian Mejia-Parada:** Writing – review & editing. **Viviana Mora-Ruiz:** Writing – review & editing. **Claudia Tavera -Ruiz:** Writing – review & editing, Conceptualization. **Jonathan Soto-Paz:** Writing – review & editing, Visualization, Supervision, Conceptualization.

Declaration of competing interest

Each of the authors confirms that this manuscript has not been previously published, and it is not currently under consideration by any other journal. Likewise, all named authors declare that they have no known competing financial interests or personal relationships that could appear to have influenced the work reported in this paper.

Data availability

Data will be made available on request.

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