

Figure 1. Pareto diagram for hypochlorite production.

Baydum and Sarubbo (2022) reported that chloride concentration in the system increases disinfectant production using an 8-liter electrolyte (Baydum and Sarubbo, 2022). Current intensity was investigated by Hsu et al. using titanium electrodes coated in a 12-liter solution, concluding that intensity has a direct relationship with active chlorine generation (Hsu et al., 2015). In 2012, Salem evaluated the effect of time in an 8-liter electrochemical reactor, obtaining higher hypochlorite concentrations after 50 minutes and after 3 hours this variable is no longer relevant in the process (Saleem et al., 2012).

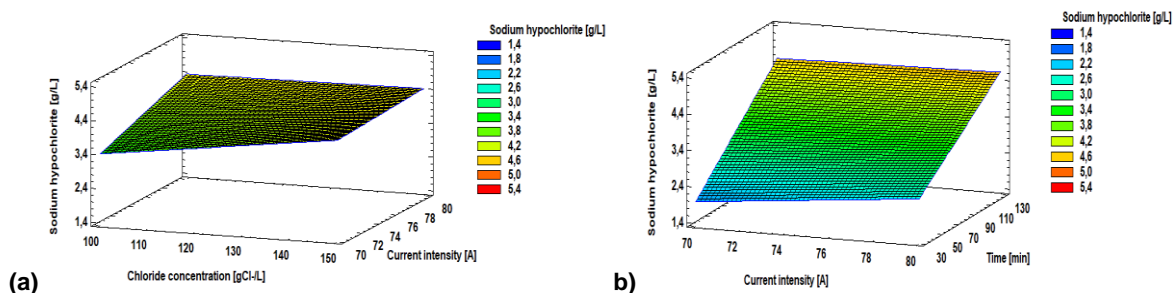


Figure 2: Response surface for hypochlorite production a) As a function of concentration and time. b) As a function of current intensity and time.

Fitted mathematical model for hypochlorite production:

$$\text{Sodium hypochlorite } [g.l^{-1}] = -1.92175 - 0.01257X_1 + 0.0266X_2 - 0.12535X_3 + 0.000297333X_1X_2 + 0.00122333X_1X_3 + 0.00198667X_2X_3 - 0.0000163111X_1X_2X_3 \quad (3)$$

Figure 2 describes the behavior of hypochlorite production as a function of concentration and time; in addition, the current intensity versus time. The analysis indicates that the maximum concentration reached by the system is produced at 80 Amperes, an initial chloride concentration of 150 g Cl<sup>-</sup>.l<sup>-1</sup> and an electrolysis time of 120 minutes, obtaining 4.46 g.l<sup>-1</sup> of hypochlorite solution.

The response surface analysis indicates that the disinfectant obtained is significantly favored at high chloride concentrations, high current intensities and prolonged times. In addition, the mathematical model has a 99.99% fit and describes the hypochlorite production as a function of the variables proposed in the factorial design of experiments 2<sup>3</sup>, it is possible to compare the performance of the prototype with other electrochemical systems, such as that of Baydum, who was able to generate 3.5% m/m of hypochlorite, in 1 hour, with an initial concentration of 4% m/m of chlorides (Baydum and Sarubbo, 2022), In Varigala's research, 120 mg.l<sup>-1</sup> of active chlorine was obtained in a 22-liter electrolysis cell with recirculation, the conductivity of the system was 2000 μS cm<sup>-1</sup> (Varigala et al., 2021). Hsu et al., used a volume of 12 liters and 10 Volts, achieved 9 g.l<sup>-1</sup> of disinfectant (Hsu et al., 2015), while, Salem obtained 6 g.l<sup>-1</sup> of hypochlorite in a volume of 8 liters (Saleem et al., 2012).

Graphite proved to be efficient in the production of oxidizing solutions, compared to other materials, in the study of graphite electrodes with cerium oxide 0.3 g.l<sup>-1</sup> of hypochlorite was produced (Alvarado-Ávila et al., 2022), in diamond electrodes the residual concentration of chlorine was 1.6 g.l<sup>-1</sup> (Lacasa et al., 2013).

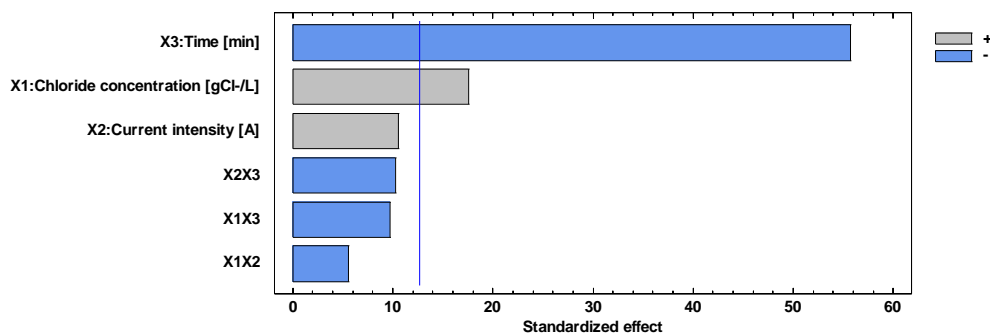


Figure 3. Pareto diagram, energy efficiency in the production of hypochlorite by the prototype.

In the analysis of energy efficiency, the Pareto result rules out the combined interaction of the three variables; however, the variable with the highest interaction in energy efficiency is time  $X_3$ , followed by current intensity  $X_2$  (Figure 3).

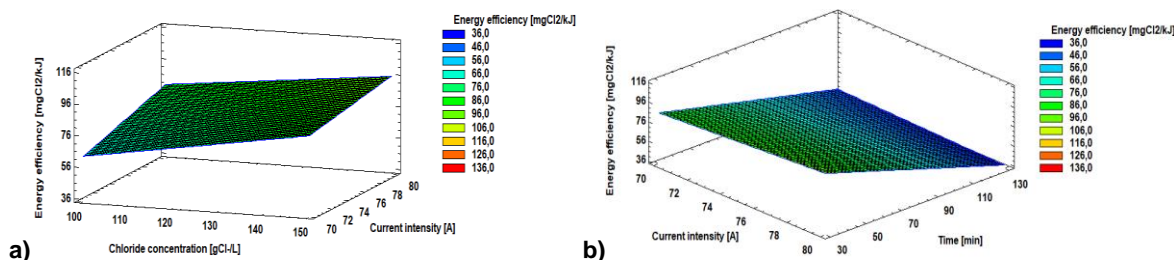


Figure 4: Response surface of energy efficiency in hypochlorite production, a) As a function of concentration and current intensity. b) As a function of current intensity and time.

The response surface (Figure 4) shows that the energy efficiency is significantly affected in relation to time and current intensity. The highest efficiency obtained was  $96.25 \text{ mgCl}_2 \cdot (\text{kJ})^{-1}$  at 30 minutes, 80 Amps and  $150 \text{ g Cl} \cdot \text{l}^{-1}$ , this is due to the fact that in the shortest operation time a higher efficiency is generated because the energy consumption is reduced. However, the maximum hypochlorite concentration is not achieved, for 30 minutes the concentration was  $2.52 \text{ g} \cdot \text{l}^{-1}$  of disinfectant agent.

Mathematical model of energy efficiency for hypochlorite production in the prototype:

$$\text{Energy efficiency [mgCl}_2 \cdot \text{kJ}^{-1}] = -257.017 + 1.64987X_1 + 3.89367X_2 + 1.13856X_3 - 0.0157X_1X_2 - 0.00302222X_1X_3 - 0.0159222X_2X_3 \quad (4)$$

The mathematical model obtained in Equation 4 describes the behavior of the energy efficiency of the prototype as a function of the three variables manipulated in the process, the adjusted mathematical model has an  $R^2$  of 99.97%. It is comparable with results of Hsu, Naderi and Nasseri and Khalid, established that by increasing the operation time and the electric potential (proportional to the current intensity) the energy efficiency is reduced (Hsu et al., 2017; Khalid et al., 2020; Naderi and Nasseri, 2020).

The maximum efficiency obtained for Hsu was  $45 \text{ mg Cl}_2 \cdot (\text{kJ})^{-1}$  at 200 min and 6 Volts (Hsu et al., 2017). Similar results have been obtained using a 200 ml system, at conditions of  $63.42 \text{ g} \cdot \text{l}^{-1}$  chlorides, 15.73 Volts and 15 minutes, where the energy efficiency was  $42 \text{ mg Cl}_2 \cdot (\text{kJ})^{-1}$  (Naderi and Nasseri, 2020). The current efficiency evaluated in 1.7 liter anodic and cathodic cells was 4.08 % using titanium electrodes, at 0.68 Amps and 5 Volts (Khalid et al., 2018), indicating that it can achieve higher efficiency with increasing current intensity.

Energy consumption as a function of residual total oxidants (TRO) has been used as an indicator of electrolysis efficiency. In the research of Jung et al. a 300 ml cell and coated titanium electrodes were used, under conditions of  $200 \text{ mA} \cdot (\text{cm}^2)^{-1}$  and  $5 \text{ g} \cdot \text{l}^{-1}$  chlorides, the energy consumption of was  $5 \text{ E}10^{-3} \text{ Wh/TRO}$  (Jung et al., 2016) indicating that the amount of energy required for the production of a disinfectant solution is low enough to produce a disinfectant solution. The results obtained allow establishing that electrolytic reactors can respond to the growing need for water disinfection in resource-poor areas due to their low energy consumption and high production yield.

#### 4. Conclusions

The evaluation of the effect of the variables in the production of hypochlorite in a 22 liter reactor, built with graphite electrodes, concludes with the significant statistical correlation between the current intensity and chloride concentration in the medium, allowing to establish that the maximum concentration of hypochlorite was 4.46 g.l<sup>-1</sup>, at conditions of 120 minutes, 80 amperes and 150 g.l<sup>-1</sup> of initial chlorides.

The energy efficiency analysis showed that the equipment during its maximum efficiency of 96.25 mgCl<sub>2</sub>.(kJ)<sup>-1</sup>, during 30 minutes was not able to obtain the maximum concentration, thus foreseeing the need to study the optimization of energy efficiency in electrolysis equipment with graphite electrodes.

#### Nomenclature

A – amperes, A	
cm <sup>2</sup> – square centimeters, cm <sup>2</sup>	mg.l <sup>-1</sup> -milligram per liter
Cl <sub>2</sub> – molecular chlorine	ml – milliliters
Cl <sup>-</sup> – chloride ion	min – minutes
ClO <sub>2</sub> – chlorine dioxide	mm – millimeter
g.l <sup>-1</sup> – grams per liter	NaClO – sodium hypochlorite
gCl <sup>-1</sup> – grams of chlorides per liter	TRO - oxidantes totales residuales
H <sub>2</sub> – hydrogen molecular	Wh - watts-hour
HClO –hypochlorous acid	X <sub>1</sub> - chloride concentration in the medium, gCl <sup>-1</sup>
kJ – energy consumed	X <sub>2</sub> – current intensity, A
l – liter of cell electrolysis	X <sub>3</sub> – time, min
mgCl <sub>2</sub> .(kJ) <sup>-1</sup> – milligrams of free chlorine per kilojoule	μS.cm <sup>-1</sup> – microsiemens per centimeter

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