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Parameterization Of Electrolysis For The Thickening Of Sludge From Wastewater Treatment Plant: Taguchi Method Approach

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Abstract – The buildup of sludge is a significant issue for wastewater treatment facilities, and this study focuses on thickening it by electrolysis. The main objectives are to identify the factors influencing the sludge characteristics and to determine the optimal levels of these factors for efficient thickening. The Taguchi method with an L8(2^4) orthogonal array was used to conduct the tests, which showed that electrolysis is effective in thickening the sludge, as evidenced by the increase in dryness rate from 2.97% to 34.37% and the mass loss of 0.23 kg or 2.3%. Analyses of the carbon, chlorine, nitrogen, and sodium levels indicate that the process does not pose significant environmental risks. Minitab analysis identified the most influential factors: the electrolytic additive (NaOH) and the settling effect (without settling) for sludge thickening, the current intensity (12.6 A) for sludge quality, and the concentration of the electrolytic additive (0%) for energy consumption and electrolysis efficiency. This data is crucial for optimizing the electrolytic parameters, thereby enhancing the process efficiency and minimizing environmental and energy impacts.

Keywords – Sustainable Sludge Management, Taguchi Method, Environmental Protection, Electrolysis Optimization, Electrolytic Factors.

I. INTRODUCTION

Environmental degradation and destruction are primary consequences of industrial development [1]. Greenhouse gas emissions, natural resource depletion, and various forms of pollution are the major contributors to environmental degradation [2]. To ensure the well-being of future generations, it is essential to re-evaluate our development models to reconcile industrial progress and environmental preservation [3].

This study focuses on the tannery industry in Madagascar, which produces waste including leather scraps, soles, and wastewater. Wastewater is the primary source of water pollution [4]. In particular, tannery wastewater contains high concentrations of pollutants [5]. To obtain decontaminated water that can be safely released into the environment, this wastewater was treated through decantation. However, this process generates sludge that contains organic and inorganic materials, chemical contaminants, microorganisms, and other pollutants that cannot be directly discharged into the environment. Therefore, additional treatment of the sludge is required. Because treatment can take a long time, contaminated sludge accumulates and clogs treatment plants. Given these challenges, optimizing the management and treatment methods for sludge is essential [6].

Sewage sludge treatment is particularly critical for environmental safety because it reduces the volume of sludge and improves the quality of water discharged into the environment by eliminating impurities such as heavy metals [7]. Once these impurities are removed, the treated sludge can be utilized in various fields, such as agriculture and fertilizer production [8].

There are a variety of techniques for treating sludge, including anaerobic and aerobic digestion, mechanical dehydration, and thermal drying [9]. In this study, the electrolysis process was investigated, as it is a promising method for treating waste sludge owing to its numerous advantages [6]. This process effectively dehydrates sludge, reduces its volume, and simplifies its handling for disposal or resource recovery [10]. Additionally, it significantly decreases total solids and volatile solids and reduces disposal costs and energy consumption compared to conventional methods [11]. It can also be utilized to degrade metal complexes in electroplating sludge, thereby facilitating the removal of organic matter and valorization of precious metals in accordance with sustainable development principles [12].

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The potential of electrolysis to manage and valorize sludge resources from wastewater treatment plants has been examined in various contexts. Vijayaraghavan et al. [10] studied the electrolytic treatment of wastewater from beer breweries, whereas the Marc-André Bureau [13] investigated the stabilization and electrochemical treatment of municipal and industrial sewage sludge. Electrochemical processes, such as electrodehydration, have shown promise in effectively reducing sludge volume and recovering valuable substances [10]. Furthermore, the combination of electrochemical oxidation with traditional treatment processes such as the anoxic/oxic (A/O) process has shown significant effects on sludge reduction and effluent quality improvement [13]. New electrochemical methods have been developed to decompose sludge structures in alkaline environments [14]. Additionally, electrolysis has been utilized to recover aluminum from alum sludge, which exhibits high recovery efficiency and chemical oxygen demand (COD) removal rates [11]. In summary, these studies demonstrated that electrolysis can effectively disinfect sludge and recover resources [15].

The objective of this study was to enhance the electrolysis process with respect to mass loss, dryness rate, mineralization, conductivity, and the concentrations of sodium, nitrogen, carbon, chromium, and chlorine. To achieve this, the static Taguchi method was applied. Developed by Dr. Genichi Taguchi, this method aims to optimize product or process performance by minimizing the variability around the target value through robust design principles [16]. It utilizes orthogonal arrays [17] to simplify the experimental design, and signal-to-noise ratios to assess the effects of factors on performance [18]. This approach combined regression and quality control to create predictive models.

The Taguchi method was chosen because it offers several advantages over other process-optimization approaches. This method helps identify the optimal conditions for multiple factors affecting a process, thereby improving its overall performance. Studies on the adsorption of indigo dye onto iron oxide nanoparticles [19] have demonstrated the effectiveness of this method in reducing the dimensional deviations. Furthermore, the method effectively identifies the main effects of process optimization factors [20] and provides optimal parameters for the process factors, minimizing experimental testing, and making the process robust to noise factors [21]. Additionally, the Taguchi method helps determine the importance of each factor in the process, allowing for a focus on the most influential factors. Finally, the ability of the Taguchi method to accurately predict outcomes and efficiently optimize processes makes it a valuable tool for improving productivity and quality in various areas of research and industry.

Furthermore, it is essential to note that this research contributes to the broader field of water treatment, specifically focusing on desalination of seawater and brackish water. Considering that electrolysis could be a viable solution, examining its quantitative and qualitative effects on heavily polluted and high-salinity water, such as sludge from sewage treatment plants, represents a significant advancement for future research.

II. LITERATURE REVIEW

2.1. Principles of electrolysis and its application in sludge treatment

The utilization of electrolysis for the treatment of wastewater and sludge has several advantages. Electrolytic methods, including electrocoagulation and electrolysis, employ an electric current to break down pollutants in water into less harmful substances. Electrocoagulation creates metal coagulants that neutralize pollutant loads, resulting in flocs that can be removed through filtration or sedimentation, thus reducing the chemical oxygen demand (COD) and enhancing water quality. Two primary approaches are used for the treatment of sludge: stabilization, volume and odor reduction, and electrochemical treatment, which breaks down both organic and inorganic components. Electrolysis controls the pH, desorption, and mobilization of pollutants, effectively oxidizing organic matter, and specific techniques such as vortex electrolysis allow for metal recycling and environmental protection.

However, electrolysis poses several challenges. These include understanding the appropriate salt concentration in high-salinity wastewater and addressing gaps in the research on this process. It is necessary to comprehend the operational parameters or factors, study by-products, and enhance process efficiency. A thorough assessment is essential for industrial scale-up. Therefore, integration of electrochemical methods with biological processes for sludge treatment should be explored.

As per the literature, this approach has been proven to be a reliable and efficient solution for the treatment of both municipal and industrial sludge, resulting in improved sludge quality and wastewater while also mitigating their adverse environmental impact [24].

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2.2. Application of the Taguchi method to the optimization of sludge treatment

Various studies have investigated the use of this technique for the treatment of sludge and wastewater. Potassium ferrate was employed using the Taguchi method to optimize the purification of highly contaminated tannery wastewater, resulting in a noteworthy reduction in multiple parameters [25]. Additionally, it has been applied ato optimize the electrocoagulation process for tannery wastewater treatment, focusing on aspects such as initial pH, current density, electrolysis time, air flow, and electrode surface, which effectively remove pollutants [26].

Using this method, electrolysis parameters, including the electrolyte composition ratio, current density, and temperature, were systematically adjusted and assessed to identify the most influential parameters [27]. The outcomes, including the analysis of variance and signal-to-noise ratio, provide insights into the impact of various factors on the electrolysis process [28]. These results enabled the identification of optimal conditions [29] [30] and the best combinations of electrolysis parameters, thereby enhancing the efficiency, yield, and overall performance of the process [31].

III. MATERIALS AND METHODS

3.1. Treatment of sludge from wastewater treatment plants by electrolysis

The wastewater examined in this study was sourced from a tannery industry located in Antananarivo.

3.1.1. Thickening by electrolysis of wastewater treatment plant sludge

In this study, electrolysis thickening was explored for the treatment of sewage treatment plant sludge.

Electrolysis is an electrochemical phenomenon that involves the decomposition of water into dihydrogen and dioxygen in the presence of an electrolyte and an electric charge [32].

The effects of electrolysis on species in solution can be either direct or indirect [6].

During electrolysis, electrons are exchanged exclusively on the electrode through the direct action of electric current. Consequently, there was a direct impact on the species present in the solution. The process involves several physicochemical mechanisms, such as anodic oxidation and cathodic reduction of impurities, destabilization and coagulation of particles owing to the action of the electric field, and flotation of particles through the action of gas bubbles (O_2 and H_2) generated on the electrodes.

Indirect electrolysis involves the electrochemical creation of an oxidant that interacts with pollutants.

Electrolysis occurs in an electrolyzer, a device that facilitates the dissociation of water molecules into hydrogen and oxygen through a combination of two electrochemical half-reactions occurring on the electrodes (cathode and anode) [32]. The electrolyzer comprises an electrolyte, electrodes, and current source. The electrolyte disintegrates in the body, allowing cations to flow towards the cathode and anions towards the anode [6].

In this study, the duration of electrolysis was set at 120 minutes.

3.1.2. Design of a wastewater treatment plant sludge thickening system

As part of this study, a system was designed to thicken the sewage sludge from treatment plants. The system comprises the following components.

- The electrolyte, which is formed by sewage sludge and contains mobile ions, such as Na^+, Cl^-, OH^-, H^+, Cr^{3+}, and other ions, is contained in a polyester tank (Figure 1). This tank has several properties, including toughness up to 80°C, resistance to diluted acids and alkalis, resistance to breakage, impact, and transparency of colors to visualize the release of hydrogen and oxygen, as well as the evolution of the pressure of these gases in the electrolyzer.
- The electrode was a bipolar stainless-steel electrode containing 11 plates connected in series (Figure 2). One plate was connected directly to the positive terminal and another to the negative terminal, whereas the other nine plates acted as both the cathode and anode, located between the two plates mentioned previously. This electrode was selected because of its large active surface area, which has a considerable impact on gas production.
- The current supply system comprises a variable voltage generator (Figure 3), which includes a transformer, a rectifier, a capacitor, and a voltage regulator.

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- For each test, the quantity of sludge to be thickened was set to 10 kg to ensure that the electrodes were completely immersed in the solution.

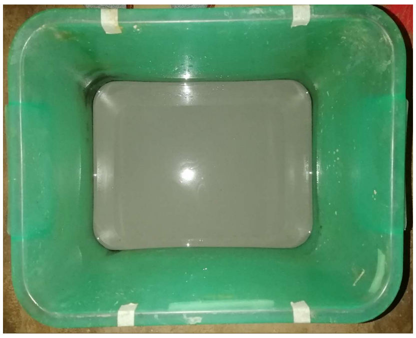

Figure 1: Polyester tank

Figure 2: Stainless steel electrode

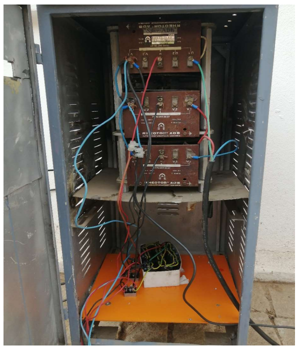

Figure 3: Variable voltage generator

3.2. Application of the Taguchi method to the electrolysis of wastewater treatment plant sludge

3.2.1. Establishment of the experimental plan

To implement the Taguchi method for analysis, the following stages were delineated based on the research context. Initially, we formulated an experimental design using the Taguchi approach to regulate data acquisition effectively [33]. Next, we optimized the procedure and assessed the problems with and without constraints for robust design [34][35]. Finally, we examined the impact of these factors on the process performance [36].

To develop the experimental plan, the following seven steps must be undertaken [6].

Step 1: The effectiveness of the product to be developed can be measured by selecting the most appropriate indicator to analyze the response during the experiment. The primary objective of this research was to thicken the sludge from a sewage treatment plant (WWTP) through electrolysis. The parameters that can be used to assess the efficacy of the method are the dryness rate and mass loss, which are attributable to the conversion of water into HHO gas, a mixture of H_2 and O_2.

Step 2: Identify the various parameters that affect the outcomes.

In this research, four key factors are under consideration:

- 1. An electrolytic additive to enhance the electrical conductivity of the mud.
- 2. The type of electrolyte additive used, according to Kohlrausch's law [37], significantly affects the conductivity of the electrolyte.
- 3. The electrical parameter, which is a critical factor during electrolysis, and in this study, current intensity was chosen as a fixed factor.
- 4. The accelerated settling phenomenon achieved using $Ca(OH)_2$ lime at a concentration of 10g/l.

Step 3: The factors being investigated in this study are defined as follows:

- 1. Electrolyte additive: In this study, sodium chloride (NaCl) and caustic soda (NaOH) were chosen as electrolyte additives because they are inexpensive and allow good gas production, with pure HHO production ranging between 95% and 100%.
- 2. Concentration of the electrolytic additive: Taking into account Kohlrausch's law, the values to be studied for this factor were 0% and 10%.
- 3. Electrical parameter: For this factor, the minimum intensity value chosen was 6.2A. This value was determined through a salt-water electrolysis test, during which it was observed that electrolysis began to produce gas with a current density of

0.041 A/cm^2 at this intensity. According to Michael Faraday, electrolysis cells can withstand a current density of up to 0.084 A/cm^2 without overheating [6]. Therefore, the maximum current value for this factor was 12.6A.

- 4. Accelerated settling: This factor includes two levels: accelerated settling and no accelerated settling.

Step 4: The selection of an appropriate experimental plan, contingent upon the multifarious factors, plethora of values (levels), and myriad potential interactions between the aforementioned factors. In this particular investigation, we considered the luxury of four factors, each exhibiting two levels of magnitude. Hence, the application of Taguchi's experimental design was deemed the most suitable.

Step 5: Undertake examinations pertaining to changes in the aspects and degrees proposed by the software.

Step 6: Undertake an in-depth examination and interpretation of the findings (employing specialized software for conducting analysis of variance and linear regression calculations).

Step 7: Model the response based on all parameters.

Table 1 summarizes these factors and their respective levels during the experiment.

Table 1: Factors with their respective levels

Factors	Levels	
Electrolyte additive	NaCl	NaOH
Additive concentration	0% of the mass of the solution	10% of the mass of the solution
Electrical parameter (current intensity)	6.2A	12.6A
Decantation	Without decantation	With decantation

The experimental plan according to the Taguchi method (Table 2) was then created using Minitab software.

Table 2: Taguchi Map

Number of tests	Electrolyte additive	Concentration	Intensity (A)	Decantation
1	NaCl	0%	6.2	Without
2	NaCl	0%	12.6	With
3	NaCl	10%	6.2	With
4	NaCl	10%	12.6	Without
5	NaOH	0%	6.2	With
6	NaOH	0%	12.6	Without
7	NaOH	10%	6.2	Without
8	NaOH	10%	12.6	With

Based on Table 2, the Taguchi method suggests an L8(2^4) experimental design.

3.2.2. Answers studied

The examination of various responses in this study is of paramount importance for comprehending the consequences and outcomes of the procedures under investigation.

➢ ***Dryness rate and mass loss***

Dryness rate and mass loss are crucial indicators of sludge thickening, as identified in this study [13]. These responses play a vital role in characterizing the physicochemical transformations in mud and offer valuable insights into its behavior [6]. The dryness rate

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signifies the influence of drying on the sludge, whereas the mass loss corresponds to the quantity of gases evaporated during electrolysis.

Mass loss was measured by calculating the difference between the initial and final masses of the sludge sample following electrolysis treatment.

The dryness rate is the percentage of dry matter relative to the weight of the sludge sample or dry matter content of the sludge. The measurement method consisted of placing the sludge sample in an oven at 105°C until a constant mass was obtained. The dryness rate (TS) was determined using formula 1:

Let M_1 be the mass of the wet sample, and M_2 be its mass after drying. The dry matter content was calculated using the following formula:

$$TS = \frac{M2*100}{M1} \quad (1)$$

With, M_1: mass of the wet sample

M_2: mass of the sample after drying

Note that before electrolysis, the dryness rate of the sludge was 2.97%.

➢ ***Conductivity and mineralization***

Given that this research makes use of electrolysis as a sludge treatment process, it is of paramount importance to study sludge conductivity [3 8]. A key component of this research is the relationship between conductivity and mineralization, as conductivity reflects the mineralization of an aqueous solution [39].

To quantify conductivity and mineralization, a conductivity meter was utilized.

➢ ***Carbon, chlorine and nitrogen levels***

A comprehensive investigation of the components including carbon, chlorine, and nitrogen is vital for predicting the potential emission of gaseous substances such as CO_2, Cl_2, and N_2. This is particularly relevant during electrolysis, as the analysis of these gases enables an evaluation of the environmental implications of the procedure. [6].

- The carbon content of the sludge was measured using an analytical method for soil analysis. The process is as follows:

- Approximately 0.5 g of the sludge was weighed and the exact weight was recorded. It was then transferred to a 250mL Erlenmeyer flask.
- 10mL of a 1N potassium dichromate solution was added to the Erlenmeyer flask and the sludge was dispersed in the solution by swirling the flask.
- Concentrated sulfuric acid was then added to the flask and the mixture was swirled and vigorously shaken for 1 min.
- The mixture was left to rest for 30 minutes.
- 200mL of distilled water was then added to the flask, followed by 4 drops of orthophenanthroline and the solution was titrated with 0.5 N $FeSO_4$.
- A blank test was also performed under the same conditions (control solution) to ensure accuracy.
- The quantity of carbon in the sludge was calculated using the following formula:

$$Quantité\ de\ carbone = (Nred\ Vred)\ tem - (Nred\ Vred)ech]\frac{0,39}{P.E} \quad (2)$$

Where Nred is the normality of the ferrous sulfate reducer (tem: of the control solution; ech: of the sample) and Vred is the volume of the reducer (tem: of the control solution; ech: of the sample solution). In this context, PE refers to the test portion.

- The chlorine content of the sludge was determined using the Charpentier-Volhard method.
- The following procedure was adopted to determine the quantity of nitrogen in the sludge: A sample of mud was dried in an oven at a temperature of 103 °C until all water content was eliminated. The dried sample was then mineralized by adding concentrated sulfuric acid (approximately 15mL) and two catalyst pellets (copper sulfate). The mineralized product was subsequently placed in a distiller, followed by the addition of 50 mL concentrated NaOH (400g/l). The amount of nitrogen in the sludge was calculated using the following formula:

$$Quantité\ d'azote = \frac{N*M*Cb*1000}{P.E} \quad (3)$$

Where N is the normality of H_2SO_4 in mg/l (0.105), M the molar mass of nitrogen, Cb the Cruet fall, and PE the test sample

➢ ***Chromium and sodium levels***

The analysis of the chromium content of tannery sludge is of significant importance in this research, particularly in light of the tanning process involving chromium-based products [40]. Accurate knowledge of Cr levels is essential to ensure the quality of the final product and minimize any potential environmental risks. Furthermore, the chromium levels in the treated thickened sludge underscores the importance of responsible waste management and the potential for valorizing these residues, highlighting the sustainability of our approach, which allows for the recovery of by-products while reducing environmental impacts.

In addition, the sodium index (Na) was studied in relation to the use of sodium chloride (NaCl) or caustic soda (NaOH) to increase conductivity. Measuring the sodium concentration in the solution is critical for achieving optimal electrical conductivity. Chromium and sodium levels were determined using atomic absorption spectrophotometry.

In conclusion, the analytical results contribute to a comprehensive understanding of the processes under investigation and provide a solid foundation for informed decisions and sustainable practices.

3.2.3. Optimization of the thickening of wastewater treatment plant sludge using the Taguchi method

The primary goal of optimizing sludge thickening through the application of the Taguchi method is to identify factors that can minimize response variability. To accomplish this, it is essential to measure the signal-to-noise ratio (S/N) of various responses generated by the process.

In the context of the Taguchi method, the term "signal" refers to the desired (controllable) aspect, while "noise" refers to the undesired (non-controllable) aspect [42]. By measuring the S/N ratio, it is possible to evaluate the overall performance of the process and enhance its robustness and resistance to noise factors [43]. Additionally, this method enables the identification of the key factors that influence a specific response and the optimization of the process [6].

IV. RESULTS AND DISCUSSIONS

4.1. Results and discussions of the analyzes of the responses during each test

Table 3 provides a comprehensive summary of the various responses assessed in the laboratory. The analyses for this study were performed at the CNRE laboratory, which is situated in Tsimbaza Antananarivo and operates under the auspices of the National Center for Environmental Research.

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Table 3: Summary of responses for each test

No. of tests	Dryness rate (%)	Mass loss (kg)	Mineralization (g /l)	Conductivity (mS/cm)	N / A (g /100g)	Cl (g /100g)	NOT (mg /l)	VS (%)	Cr (g /100g)
1	3.67	0.06	12.56	15.79	1.08	0.98	749.51	0.07	0.07
2	5.05	0.09	14.44	14.44	0.51	0.34	1234.80	0.10	0.05
3	13.22	0.05	90.20	88.40	3.35	4.39	1352.40	0.14	0.03
4	13.17	0.05	80.40	87.10	3.59	4.53	2028.50	0.16	0.07
5	6.50	0.08	13.96	16.95	0.66	0.25	867.31	0.11	0.10
6	34.37	0.23	13.30	16.15	0.45	0.48	1675.80	0.11	0.06
7	17.48	0.09	331.10	228.00	5.23	ND	441.02	0.05	0.01
8	3.01	0.13	326.70	202.60	8.46	ND	823.20	0.09	0.04

According to Table 3, the descending order of the tests in terms of their dryness rate is as follows: test 6 (34.37%), test 7 (17.48%), test 3 (13.22%), test 4 (13.17%), test 5 (6.50%), test 2 (5.05%), test 1 (3.67%), and test 8 (3.01%).

With regard to the loss of mass in 10 kg of treated sludge, the descending order of the tests was as follows: test 6 (0.23 kg), test 8 (0.13 kg), tests 7 and 2 (0.09 kg), test 5 (0.8 kg), test 1 (0.06 kg), and tests 3 and 4 (0.05 kg).

In both instances, test 6 had the highest values. For mass loss, 0.23 kg corresponds to 2.3% of the initial mass of the treated sludge (10 kg) during 2 hours.

The relationship between mineralization and conductivity is closely linked. The descending order of the tests based on mineralization and conductivity values were identical, with the following readings: test 7 (331.10 g/l; 228.00 mS/cm), test 8 (326.70 g/l; 202.60 mS/cm), test 3 (90.20 g/l; 88.40 mS/cm), test 4 (80.40 g/l; 87.10 mS/cm), test 2 (14.44 g/l; 14.44 mS/cm), test 5 (13.96 g/l; 16.95 mS/cm), test 6 (13.30 g/l; 16.15 mS/cm), and test 1 (12.56 g/l; 15.79 mS/cm). This demonstrates that the conductivity reflects the level of mineralization, and these results confirm that the experiments and measurements were conducted accurately.

With regard to sodium (Na), an increase in its value was observed in tests 3 and 4 with the addition of NaCl. This was also evident in tests 7 and 8, in which NaOH was added. A negative sign indicates slight variation in sodium levels, although this remains within acceptable limits [6]. The decrease in chlorine levels indicates the release of Cl_2 gas during the reaction, which can be attributed to the addition of NaCl, as confirmed by tests 3 and 4. ND means "not detected" and indicates that chloride ions were not detected using the analytical methods employed.

The oxidation of complex organic molecules, which serve as a source of carbon and energy, in the presence of oxygen leads to the release of CO_2 and the formation of other inorganic substances, such as nitrogen compounds (e.g., NH_3), by the transfer of their electrons to oxygen. Oxygen acts as the final electron receptor and is reduced to water (H_2O). This explains the increase in the amount of nitrogen observed in Tests 3, 4, and 6. As the concentration of cyanate ions in the solution increases, these ions undergo increased oxidation to carbonates and nitrogen gas, which explains the decrease in nitrogen in tests 1, 5, 7, and 8 [6].

All values for carbon are positive and relatively low (0.05 to 0.16%), which indicates that there is no dangerous CO_2 release.

The significant variation in the analysis results demonstrates that the nature of the electrolytic additive, its concentration, current intensity, and presence or absence of settling have a significant impact on the measured responses.

4.2. Results and discussions of analyzes using the Taguchi method

- Taguchi analysis: The dryness rate as a function of the electrolytic additive (AE) and its concentration (C/tion), the current intensity (I), and the settling effect (ED).

The outcomes of the dryness trials for each test are shown in Table 4.

Table 4: Dryness rate values

No. of tests	Electrolyte additive	Concentration	Intensity (A)	Decantation	Dryness rate (%)
1	NaCl	0%	6.2	Without	3.67
2	NaCl	0%	12.6	With	5.05
3	NaCl	10%	6.2	With	13.22
4	NaCl	10%	12.6	Without	13.17
5	NaOH	0%	6.2	With	6.50
6	NaOH	0%	12.6	Without	34.37
7	NaOH	10%	6.2	Without	17.48
8	NaOH	10%	12.6	With	3.01

Data analysis was conducted using the Taguchi method, and the outcomes are presented in Tables 5 and 6, as well as Figures 4 and 5.

Table 5: Response table for signal-to-noise ratios

Prefer the larger ones

Level	AE	C/tion	I	ED
1	17.53	18.02	18.67	22.29
2	20.29	19.80	19.15	15.53
Delta	2.77	1.77	0.49	6.76
Rank	2	3	4	1

Table 6: Table of responses for Means

Level	AE	C/tion	I	ED
1	8,826	12,161	10,334	17,186
2	15,770	11,935	13,762	6,910
Delta	6,444	0.226	3,429	10,276
Rank	2	4	3	1

As shown in Tables 5 and 6, decantation was the most significant factor influencing the dryness rate, followed closely by electrolytic additive. In contrast, the additive concentration and current intensity have relatively minor effects. These findings imply that maximizing the dryness rate necessitates the optimization of decantation and selection of an appropriate electrolytic additive, with a preference for NaOH.

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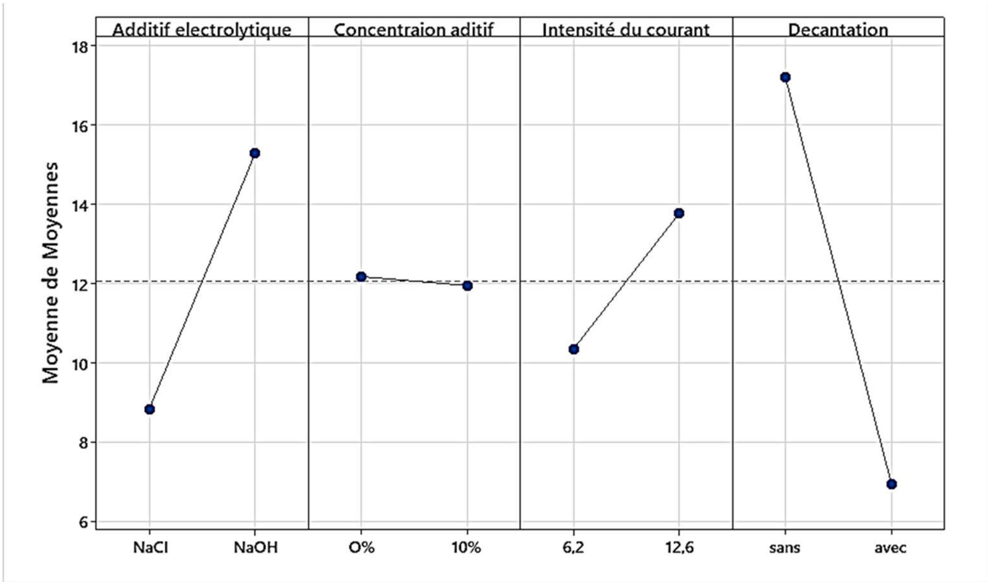

Figure 4: Main effects plot for Signal-to-Noise Ratios (dryness rate)

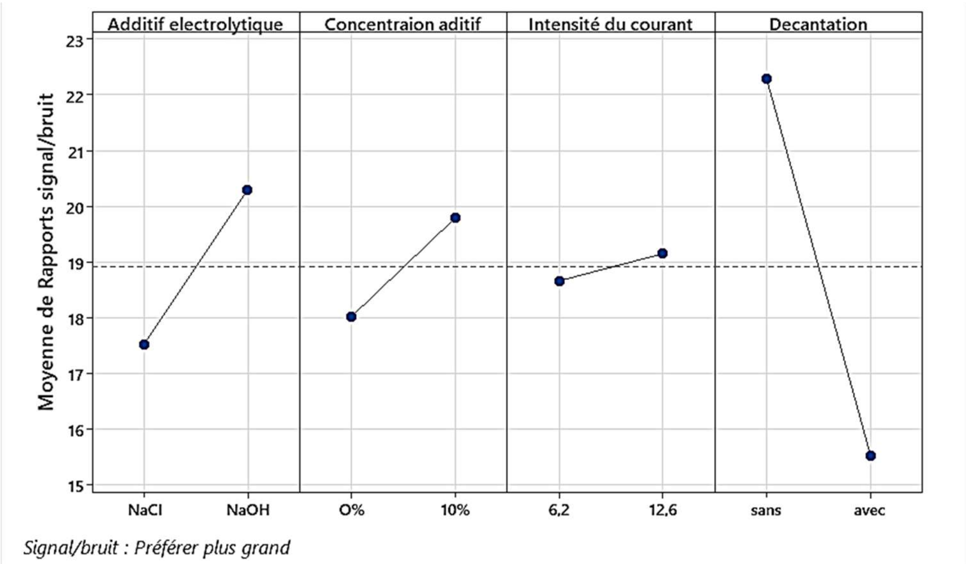

Figure 5: Main effects plot for Means (dryness rate)

According to the information presented in Figure 4, the average impact of each factor on the dryness rate signal-to-noise ratio can be summarized as follows:

- The NaOH electrolyte additive demonstrated a superior signal-to-noise ratio compared to that of NaCl.
- The concentration of the additive, which ranged from 0 to 10%, exhibited a moderate effect.
- The current intensity, ranging from 6.2 to 12.6, displayed a weak effect.
- The presence of decantation significantly degraded the signal-to-noise ratio.

According to Figure 5, the average impact of each factor on the average dryness rate is as follows:

- The transition from NaCl to NaOH resulted in an increased dryness rate.
- The concentration of the additive, which ranged from 0 to 10%, exhibited a moderate effect.

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- The current intensity, ranging from 6.2 A to 12.6A, demonstrated a moderate effect.
- The absence of settling significantly improved the dryness rate.

Thus, to optimize the dryness rate, the factors with the most significant effects and their optimal levels in descending order are as follows:

Rank 1: settling effect - absent

Rank 2: electrolytic additive - NaOH

Rank 3: concentration of the additive - 0%

Rank 4: current intensity - 12.6A

➢ The Taguchi analysis: mass loss as a function of the electrolytic additive (AE), its concentration (C/tion), current intensity (I), and settling effect (ED).

The mass loss values for each test are presented in Table 7.

Table 7: Mass loss values

No. of tests	Electrolyte additive	Concentration	Intensity (A)	Decantation	Mass loss (kg)
1	NaCl	0%	6.2	Without	0.06
2	NaCl	0%	12.6	With	0.09
3	NaCl	10%	6.2	With	0.05
4	NaCl	10%	12.6	Without	0.05
5	NaOH	0%	6.2	With	0.08
6	NaOH	0%	12.6	Without	0.23
7	NaOH	10%	6.2	Without	0.09
8	NaOH	10%	12.6	With	0.13

These data were analyzed using the Taguchi method, and tables 8–12 present the results.

Table 8: Response table for signal-to-noise ratios

Prefer the larger ones

Level	AE	C/tion	I	ED
1	-24.22	-19.99	-23.11	-21.37
2	-18.24	-22.48	-19.35	-21.09
Delta	5.98	2.49	3.76	0.27
Rank	1	3	2	4

Table 9: Table of responses for means

Level	AE	C/tion	I	ED
1	0.06350	0.11500	0.0715	0.09000
2	0.13350	0.08200	0.1255	0.10700
Delta	0.07000	0.03300	0.0540	0.01700
Rank	1	3	2	4

Table 10: Estimated model coefficients for means

Term	coefficient	Coef ErT	T	P
Constant	0.098500	0.01592	6,188	0.009
AE: NaCl	-0.035000	0.01592	-2,199	0.115
C/tion: 0%	0.016500	0.01592	1,036	0.376
I: 6.2 A	-0.027000	0.01592	-1,696	0.188
ED: With	-0.008500	0.01592	-0.534	0.630

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Table 11: Model Summary

S	R square	R squared (adjusted)
0.0450	75.15%	42.01%

Table 12: Analysis of variance for means

Source	D.L.	SomCar seq	SomCar adjustment	CM adjustment	F	P
Electrolyte additive	1	0.009800	0.009800	0.009800	4.83	0.115
Concentration	1	0.002178	0.002178	0.002178	1.07	0.376
Intensity	1	0.005832	0.005832	0.005832	2.88	0.188
Effect of decantation	1	0.000578	0.000578	0.000578	0.29	0.630
Residual error	3	0.006082	0.006082	0.002027		
Total	7	0.024470				

According to Tables 8 and 9, the "electrolytic additive" factor has the most significant impact on the mass loss and signal-to-noise ratio values, followed by the current intensity. However, the factors "additive concentration" and "settling effect" had a relatively smaller influence. These findings suggest that to optimize mass loss, it is essential to choose the appropriate electrolyte additive, such as NaOH, and the current intensity, which was found to be 12.6 A.

Table 10 lists the levels of each factor, allowing the maximum mass loss to be achieved. For the "electrolytic additive" factor, the coefficient associated with NaCl was negative (-0.035), indicating a reduction in mass loss compared to other electrolytic additives. For the "concentration" factor, the coefficient associated with the 0% level was positive (0.0165), suggesting an increase in mass loss compared to higher concentrations. With respect to the "current intensity" factor, its coefficient associated with 6.2A was negative (-0.027), indicating a reduction in mass loss compared to higher current intensities. Lastly, for the "settling effect" factor, the coefficient related to the presence of settling was negative (-0.0085), which means that there was a reduction in mass loss compared to the absence of settling.

The factors that have the most significant impact on mass loss are ranked as follows:

Rank 1: Electrolytic additive - NaOH

Rank 2: Current intensity - 12.6A

Rank 3: Concentration of the additive - 0%

Rank 4: Stabilization effect - without

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Tables 11 and 12 present the results of the analyses performed by Minitab to determine the factors that had statistically significant effects on mass loss. The p value was greater than the significance threshold ($p > 0.05$). This indicates that the association was not statistically significant. The factors showed no statistically significant association with the response, suggesting that the results obtained were likely due to chance.

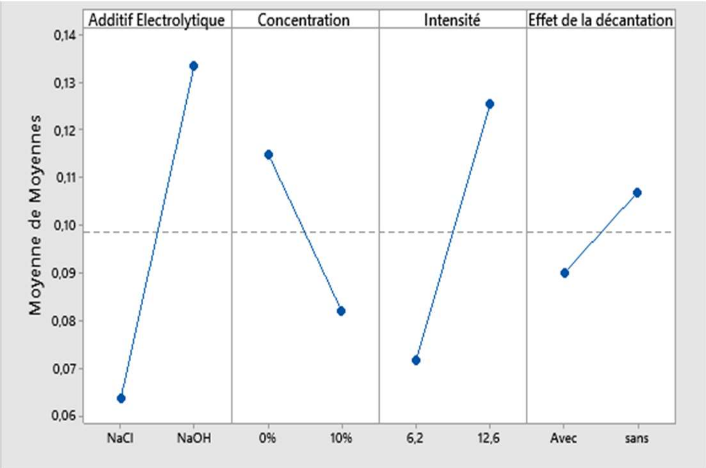

Figure 6: Graphs illustrating the main effects for Means (mass loss)

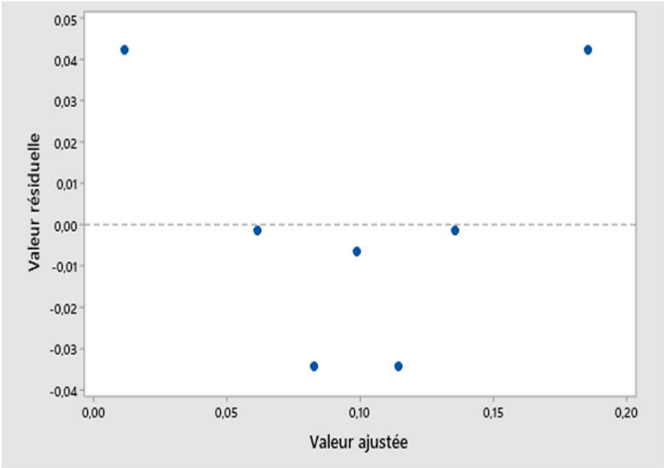

Figure 7: Graph displaying the residual values as a function of adjusted values (mass loss))

Figure 6 confirms the outcomes in Table 9 by exhibiting that the "electrolyte additive" factor has the most significant impact on the average of the responses. Figure 7 depicts that the distribution of residual values is balanced, that is, the model is appropriate, and the variance is constant.

- Taguchi analysis: carbon rate value as a function of the electrolytic additive concentration (C/tion), current intensity (I), settling effect (ED)

Carbon rates of each test are presented in Table 13.

The results demonstrated the impact of each variable on the carbon rate obtained for each test.

Table 13: Carbon rate values

No. of tests	Electrolyte additive	Concentration	Intensity (A)	Decantation	Carbon (%)
1	NaCl	0%	6.2	Without	0.05
2	NaCl	0%	12.6	With	0.08
3	NaCl	10%	6.2	With	0.12
4	NaCl	10%	12.6	Without	0.14
5	NaOH	0%	6.2	With	0.09
6	NaOH	0%	12.6	Without	0.09
7	NaOH	10%	6.2	Without	0.03
8	NaOH	10%	12.6	With	0.07

These data were analyzed using the Taguchi method, and Tables 14–18 present the results.

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Table 14: Response table for signal-to-noise ratios

Prefer the larger ones

Level	AE	C/tion	I	ED
1	-20.86	-22.45	-23.95	-21.09
2	-23.85	-22.26	-20.76	-23.62
Delta	2.98	0.18	3.20	2.53
Rank	2	4	1	3

Table 15: Response table for averages

Level	AE	C/tion	I	ED
1	0.09750	0.07750	0.07250	0.09000
2	0.07000	0.09000	0.09500	0.07750
Delta	0.02750	0.01250	0.02250	0.01250
Rank	1	3	2	4

Table 16: Estimated model coefficients for means

Term	coefficient	Coef ErT	T	P
Constant	0.083750	0.01533	5,464	0.012
AE: NaCl	0.013750	0.01533	0.897	0.436
C/tion: 0%	-0.006250	0.01533	-0.408	0.711
I: 6.2 A	-0.011250	0.01533	-0.734	0.516
ED: With	0.006250	0.01533	0.408	0.711

Table 17: Model Summary

S	R square	R squared (adjusted)
0.0433	35.85%	0.00%

Table 18: Analysis of variance for means

Source	D.L.	SomCar seq	SomCar adjustment	CM adjustment	F	P
Electrolyte additive	1	0.001513	0.001513	0.001513	0.80	0.436
Concentration	1	0.000313	0.000313	0.000313	0.17	0.711
Intensity	1	0.001013	0.001013	0.001013	0.54	0.516
Effect of decantation	1	0.000312	0.000312	0.000312	0.17	0.711
Residual error	3	0.005638	0.005638	0.001879		
Total	7	0.008788				

The results presented in Table 14 indicate that the "current intensity" factor has the most significant impact on the signal-to-noise ratio of the carbon rate. The "electrolyte additive" factor had a moderate effect, while the "concentration" and "settling effect" factors had weaker effects. Table 15 shows that the "electrolytic additive" factor had the greatest influence on the carbon rate values, followed by the "intensity" factor, and then the "concentration" and "settling effect" factors.

Table 16 illustrates the levels of each factor, which can be adjusted to optimize the carbon rate. For the "electrolytic additive" factor, the positive coefficient associated with the use of NaCl (0.08375) suggests that it increases the carbon rate compared with other types of electrolytic additives. The negative coefficient for the "concentration of the additive" factor linked to 0% (-0.00625) indicates a reduction in the carbon rate compared to higher concentrations. The negative coefficient for the "current intensity" factor linked to 6.2A (-0.01125) suggests that higher intensities result in a lower carbon rate compared to lower intensities. Lastly, the positive coefficient associated with the presence of settling for the "settling effect" factor (0.00625) indicates that it has a positive impact on the carbon rate compared to the absence of settling.

To optimize the carbon rate, the most influential factors and their optimal levels are as follows:

Rank 1: electrolytic additive - NaCl

Rank 2: current intensity - 12.6A

Rank 3: concentration of the additive - 10%

Rank 4: stabilization effect - with

Table 17 and Table 18 illustrate the outcomes of the analyses performed by Minitab to identify factors that have a statistically significant impact on carbon levels. For average carbon values, $p > \alpha = 0.05$, the association was not statistically significant. These factors showed no statistically significant associations with carbon levels. Therefore, it is likely that the results were due to chance.

Figure 8 displays the graphs of the main effects of the average values (carbon rate). Figure 9 shows a graph of the residual values in relation to the adjusted values (carbon rate). Figure 8 confirms the results in Table 15 by demonstrating that the "electrolyte additive" factor has the most significant impact on the average response. Figure 9 indicates that the distribution of residuals is well balanced, which suggests that the model is suitable and that the variance is consistent.

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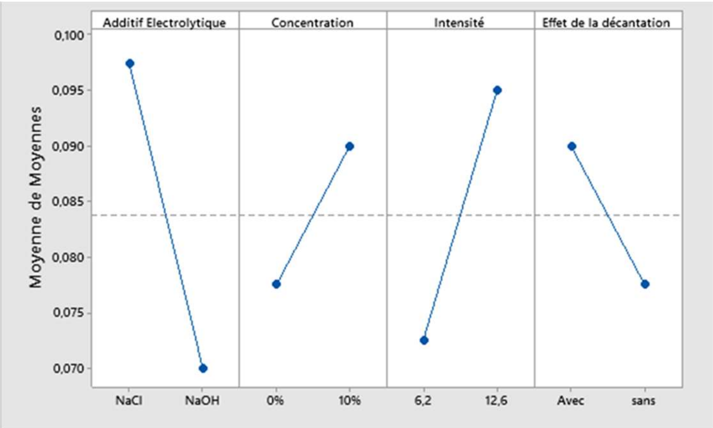

Figure 8: Graphs of main effects for Means (carbon rate)

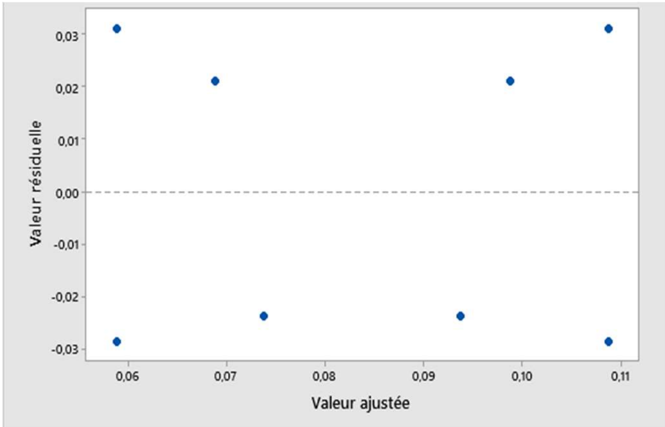

Figure 9: Graphs of residual values as a function of adjusted values (carbon rate)

Taguchi analysis of the other responses as a function of electrolytic additives (AE) and their concentration (C/tion), current intensity (I), and settling effect (ED).

Taguchi analysis was conducted on the remaining responses (dryness rate, conductivity, chlorine, nitrogen, chromium, and sodium). The results obtained from this analysis are presented in Table 19, which displays the rankings of the factors (and their respective levels) according to their importance in influencing the responses.

Table 19: Results of analyzes using the Taguchi method

Answers / Factors	Dryness rate		Loss of mass		Mineralization		Conductivity		C		Cl		N		Cr		Na	
	Rk	Level	Rk	Level	Rk	Level	Rk	Level	Rk	Level	Rk	Level	Rk	Level	Rk	Level	Rk	Level
AE	4	NaOH	1	NaOH	2	NaOH	2	NaOH	1	NaCl	4	NaOH	1	NaOH	2	NaOH	2	NaOH
C/tion	3	0%	3	0%	1	10%	1	10%	3	10%	3	0%	3	0%	1	10%	1	10%
I	2	12.6	2	12.6	3	6.2	3	6.2	2	12.6	2	12.6	2	12.6	3	6.2	3	6.2
ED	1	Without	4	without	4	With	4	Without	4	with	1	Without	4	without	4	With	4	without

In this context, Table 19 contains four ranks that indicate the relative effects of the different factors on the response. "Rk" signifies “Rank”? The ranking system is as follows.

Rank 1 signifies the highest effect,

Rank 2 signifies the second highest effect,

Rank 3 signifies the third highest effect, and

Rank 4 signifies the fourth highest effect.

- **Impacts of electrolysis factors on the quantitative responses (or characteristics) of sludge**

The results pertaining to the treated sludge were evaluated based on dryness rate and mass loss.

According to Table 19, the dryness rate was noticeably affected by the settling effect, with the optimal level being "without." The intensity of the current was the second most influential factor, with the best level being 12.6 A. The concentration of the electrolytic additive was the third most significant factor, with the best level being 12.6A. Lastly, the electrolytic additive was the least significant factor, with a best rate of 0%.

In terms of the mass loss, the most significant factor was the electrolyte additive, with the best level being NaOH. The second most significant factor was current intensity, with the best level being 12.6A. The concentration of the electrolyte additive was the third-most influential factor, with the highest rate of 0%. Lastly, the settling effect was the least significant factor, with the best rate being "without."

Hence, it can be observed that the optimal levels of each factor for maximizing the dryness rate and mass loss are identical.

- **Impacts of electrolysis factors on sludge qualitative responses**

The results of the sludge treatment process can be assessed using various parameters, including mineralization, conductivity, carbon content, chlorine content, nitrogen content, chromium content, and sodium content.

According to the data presented in Table 19, the influence of each factor on the two parameters of mineralization and conductivity was remarkably similar. This similarity is expected because mineralization serves as an indicator of conductivity [39]. The most significant factors affecting these parameters were the concentration of the electrolyte additive, with an optimal level of 10%, and the electrolyte additive itself, with the best level being NaOH. This is because the electrolytic additive enhances the conductivity of sludge by accelerating the reaction [6]. The third most influential factor is the current intensity, with the optimal level set at 6.2 A. Interestingly, the settling effect has the least impact on these two parameters, with the best level for optimization of mineralization being "with" and the best level for conductivity being "without."

The impact of these factors on the remaining responses, namely carbon, chlorine, nitrogen, chromium, and sodium levels, is not as consistent. Each parameter was influenced differently by these factors. However, for the "electrolyte additive" factor, the optimal level for all, except the sodium level, was NaCl. This is because the sodium content in the sludge originates from the use of NaOH as the electrolyte additive. For the "concentration" factor of the electrolytic additive, the optimal rate was 10%, except for the Cr rate. The "current intensity" factor has the best level set at 12.6 A, except for the chlorine rate. Finally, the "settling effect" factor has the best level set as "with," except for chlorine and nitrogen levels.

- **Combined effects of the factors “electrolyte additive”, “additive concentration” and “current intensity” on all responses**

Table 19 serves a vital function in determining the joint impact of the electrolyte additive, its concentration, and current intensity on the properties of the treated sludge.

- The combination of 0% NaOH and an intensity of 12.6 A appears to have a substantial influence on the mass loss and dryness rate.
- Similarly, the combination of NaOH at a concentration of 10% and intensity of 12.6 A appears to have a significant impact on mineralization and sodium levels.
- In the case of NaCl, when combined at a concentration of 10% and an intensity of 6.2 A, it seems to have a considerable effect on the conductivity and chlorine levels.
- Moreover, when NaCl was combined at a concentration of 10% and an intensity of 12.6 A, it appeared to have a substantial impact on the carbon and nitrogen levels.
- Finally, the combination of NaCl at a concentration of 0% and intensity of 12.6 A appears to have a significant influence on the chromium level.

- **Better factor levels to optimize the studied responses (or characteristics) of treated sludge**

The "electrolytic additive" factor has two levels: sodium hydroxide (NaOH) and sodium chloride (NaCl). NaOH has a higher conductivity (200-250 mS/cm) than NaCl (80-120 mS/cm) [6], and its use has a better effect on the mass loss, conductivity, mineralization, and sodium level. Thus, considering the lesser effect of NaCl on sludge electrolysis responses, the use of NaOH is preferable.

For the "concentration" factor, the two levels are 0% and 10%. The 10% level was the best level for responses, with the exception of the mass loss, dryness rate, and chromium rate. Considering the preference for NaOH as an electrolytic additive, a concentration

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of 0% was preferable for the dryness rate and mass loss. Thus, electrolytic additives are unnecessary for the latter, which are the responses most linked to the actual thickening of the sludge. However, a concentration of 10% is preferable for mineralization, conductivity, and sodium levels, which are essential for an optimal method of reducing the energy requirements of electrolysis [10].

For the "intensity" factor, its two levels are 6.2 A and 12.6 A. The 12.6 A level is preferable for the majority of responses, except for conductivity and mineralization. Therefore, the best level was 12.6 A.

The "settling effect" factor has two levels, with and without. The "without" level is preferable for mass loss, dryness rate, conductivity, chlorine rate, and nitrogen rate. This level achieved the best results.

These findings are consistent with those in Table 3, which displays the best results in test 6 (the greatest mass loss = 0.23 kg and the greatest dryness rate = 34.37%). The operating conditions of this test were as follows: electrolytic additive, NaOH; concentration, 0% (i.e., without additive); current intensity - 12.6 A, settling effect, without. This demonstrates that the variation in electrolysis factors significantly affected the responses.

From the analysis performed on Minitab, it appears that for almost all the factors examined, the associations do not display statistical significance for each response, as the p-value is greater than $\alpha = 0.05$. Consequently, it is impossible to determine the optimal combination of these factors.

A study by Bureau Marc-André [13] confirmed the effectiveness of electrolysis in wastewater treatment and the impact of electrolytic factors on the performance of the process. Bureau Marc André studied the treatment of urban and industrial wastewater by eliminating biosolids. Their study showed that electrolysis improved the filterability of biosolids, and the treatment was effective. According to the results, the electrochemical treatment increased the dryness rate by 5.5%, which increased the mass loss by 20 to 30%. This study also highlighted the impact of electrolytic parameters or factors on the characteristics of the treated sludge.

In conclusion, electrolysis has demonstrated noteworthy success in thickening sludge from tannery wastewater treatment facilities, as well as in addressing issues of plant saturation and clogging. The findings of this study offer beneficial information for additional research aimed at enhancing wastewater and sludge treatment procedures at wastewater treatment facilities.

V. LIMITATIONS AND PROSPECTS

During the course of the experiments, degradation of the electrolyzer plate was observed, which highlights the need for additional research on suitable materials. To enhance and optimize the electrolysis of sludge from wastewater treatment plants, further investigation into energy consumption and the utilization of Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) is necessary.

In this study, an optimal combination of factor levels was established to improve the characteristics of the treated sludge. As the p-value was greater than $\alpha = 0.05$, indicating the absence of statistical significance, it was essential to repeat each test (at least twice) to confirm that the results were not due to chance. The limited number of tests is dictated by the cost of the analysis.

The study outcomes focused on addressing the saturation challenges at tannery stations through sludge thickening. However, the effect of electrolysis on contaminant removal has not been thoroughly studied and should be further investigated in future research.

VI. CONCLUSION

Industrial development has led to an increase in industrial waste, which poses significant dangers to both human health and the environment. Several studies have explored the effectiveness of treatment methods. One such study focused on the tannery industry in Madagascar, where sludge buildup in sewage treatment plants often causes operational disruptions. This study aims to address this issue by investigating the thickening of sludge using electrolysis. Specifically, this study sought to determine the impact of electrolysis and various factors on the thickening and characteristics of the treated sludge, as well as to identify the optimal levels of electrolyte factors to maximize thickening efficiency.

The Taguchi method was implemented. This involved an orthogonal array L8(2^4), which entailed the execution of eight tests with varying levels of four factors: electrolytic additive and its concentration, current intensity, and settling effect. A thickening system was developed to conduct the tests. Among the eight tests, test 6, which lacked an additive and had a current intensity of 12.6 A and no decantation, demonstrated a significant increase in the amount of thickened sludge. The dryness rate of the sludge increased to 34.37%, compared to the 2.97% before treatment, and the mass loss was 0.23 kg or 2.3%. This indicates that electrolysis can be effective in thickening sludge and that the efficiency of the process depends on the importance of these factors. In addition, other responses were examined, including the levels of carbon, chlorine, sodium, and nitrogen, to assess the quality of the treated sludge and the environmental impact of the process. The results showed that treated sludge and electrolysis posed no threat to the environment, highlighting the potential of this process for the treatment of sludge from wastewater treatment plants. The study also examined mineralization and conductivity, as they can affect the energy consumption of electrolysis.

The findings of this research indicate that Minitab processing of the test results was used to determine the optimal levels of each factor and their influence on sludge characteristics. For the "electrolyte additive" factor, the most effective level was NaOH caustic soda, which had the greatest impact on mass loss. Regarding the "concentration" factor, the best level was 0% for mass loss and dryness rate, whereas 10% was more suitable for mineralization and conductivity. The "intensity" factor had its best level at 12.6 A, and it had the second most influence on mass loss and dryness rate, as well as the highest influence on nitrogen rate. Finally, the "settling effect" factor had the greatest impact on the dryness rate when set at "without". However, it was not possible to determine the best combination of factors as they did not show statistical significance.

This study demonstrates the advantages of using the Taguchi experimental method on Minitab to optimize sludge management processes. The results of this study provide practical insights into the potential benefits of electrolysis in the context of sludge management and highlight the need for continued research on optimization techniques in the field of environmental engineering. This study contributes to the development of sustainable sludge-management practices.

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