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Nitrogen and phosphorus removal from synthetic aquaculture water through electrocoagulation

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ABSTRACT

In this research, we utilized multivariate analysis to evaluate the efficient removal of nitrogen and phosphorus from synthetic aquaculture water using the electrocoagulation process. The elimination of nitrogen and phosphorus is a critical issue in various wastewater treatment plants and aquaculture systems, especially in instances of intensive or super-intensive cultivation. To avert the buildup of pollutants in the water, be it within internal recirculation systems or bodies of water receiving effluents from rearing tanks, it is imperative to employ treatment methodologies designed to effectively eliminate nitrogen and phosphorus nutrients. These nutrients have the potential to induce eutrophication in aquatic ecosystems. However, conventional biological treatment technologies can be ineffective, as they often only remove one pollutant or the other. Furthermore, the individual operations for these systems are complex and require substantial space. Electrocoagulation is a compact and promising technology for treating aquaculture water and effluents for raw nutrient removal. In this context, our findings showcase the simultaneous removal of both nitrogen and phosphorus through the electrocoagulation method. The best treatment was verified for the highest electrical current density (74 A. m^{-2}), the shortest distance between electrodes (4 cm), and the lowest electrolysis time (50 min). In these conditions, the efficiency removal in ammonia nitrogen and total phosphorus were 30.5% and 100% respectively.

Keywords: electrochemical treatment, eutrophication, water pollution control.

Remoção de fósforo e nitrogênio de água sintética de aquicultura por meio da eletrocoagulação

RESUMO

Neste estudo, empregamos a análise multivariada para avaliar a eficiência da remoção de nitrogênio e fósforo da água sintética de aquicultura por meio do processo de eletrocoagulação. A preocupação com a remoção desses elementos é crucial na aquicultura, independentemente do sistema de cultivo ser extensivo, intensivo ou superintensivo, uma vez que esses nutrientes podem propiciar o crescimento excessivo de algas e o desenvolvimento de microrganismos que degradam a matéria orgânica, resultando em eutrofização. Esse fenômeno, por sua vez, aumenta a demanda bioquímica de oxigênio, modifica o pH, libera toxinas e, potencialmente, causa a morte de peixes. As abordagens convencionais de tratamento biológico, muitas vezes, revelam-se ineficazes, focando apenas na remoção de um tipo específico de poluente. Além disso, esses sistemas demandam operações individuais complexas e ocupam considerável espaço. Por outro lado, a eletrocoagulação se destaca como uma tecnologia compacta e promissora para o tratamento de água na aquicultura, visando a remoção eficaz de nutrientes brutos. Os resultados obtidos indicam uma notável remoção simultânea de nitrogênio e fósforo por meio da eletrocoagulação. O tratamento mais eficaz foi observado com a maior densidade de corrente elétrica (74 $A.m^{-2}$), a menor distância entre os eletrodos (4 cm) e o menor tempo de eletrólise (50 min). Nessas condições, as eficiências na remoção de nitrogênio amoniacal e fósforo total alcançaram respectivamente 30,5% e 100%.

Palavras-chave: controle da poluição na água, eutrofização, tratamento eletroquímico.

1. INTRODUCTION

The aquaculture sector is of paramount importance in the current scenario of Brazilian livestock, both for generating income through the sale of various products from this activity and for creating jobs for the country's population. Aquaculture allows the cultivation of different aquatic species under controlled conditions. This control contributes to minimizing the environmental impacts caused by the production process, allowing for better productivity (Bernal-Higuita *et al.*, 2023).

In 2020, worldwide fishing and aquaculture produced 214 million tons, reflecting a 3% increase in volume compared to the previous year. However, this modest growth can primarily be attributed to a 4.4% decline in catches, particularly driven by reduced yields of pelagic fish, such as Peruvian anchoveta, coupled with diminished Chinese activity and the global repercussions of the Covid-19 pandemic (FAO, 2022).

Aquaculture can be carried out in four different production systems: extensive, semi-intensive, intensive, and super-intensive. Each system has its own management practices, and productivity varies according to stocking rates and feeding. Furthermore, aquaculture can be conducted in marine environments or in continental areas, known as freshwater aquaculture. In freshwater aquaculture, natural bodies of water such as lakes and rivers can be used, as well as constructed bodies of water like reservoirs or dams (USSEC *et al.*, 2022).

The recirculation system can be managed according to these production systems, and through water recirculation, sustainable aquaculture can be ensured if properly managed, always including a water treatment system. The 2030 Agenda (UN, 2015) that fulfills the Sustainable Development Goals (SDGs) is essential and urgent for the development of sustainable aquaculture worldwide. Closed production systems concentrate nutrients, mainly phosphorus and nitrogen, and if the water is not treated it can lead to eutrophication of the environment, increased anaerobic activity, and reduced dissolved oxygen, resulting in animal mortality and thus harming production (Dzulqornain *et al.*, 2018; Moyo and Rapatsa, 2021).

While various water treatment techniques exist, many of them require a significant amount of energy from non-renewable sources, leading to high carbon dioxide emissions (Boinpally *et al.*, 2023). This study proposes an alternative, electrocoagulation, to address this issue efficiently. In comparison to traditional methods, electrocoagulation demonstrates notable advantages. It can effectively remove both nitrogen and phosphorus from aquaculture system effluents, critical limiting factors in recirculating aquaculture. Furthermore, electrocoagulation generates less secondary pollution, produces less sludge, has a simplified operation, and offers greater control (Hashim *et al.*, 2020; Hashim *et al.*, 2021). This treatment system uses electric current to induce oxidation, typically employing aluminum or iron as electrode materials. These release ions that facilitate the coagulation, flotation, and/or sedimentation of organic matter and various nutrients (Xu *et al.*, 2021). Therefore, the underlying comparison highlights the potential benefits of electrocoagulation over traditional methods, emphasizing its environmental and operational effectiveness.

Electrocoagulation is a technology conceived in the 19th century, with the first patents filed by Eugene Hermine in England and France in 1887 (Wiendl, 1998). Despite its historical roots, its utilization in the treatment of aquaculture effluent is not widespread, and operational parameters considering the efficiency of nitrogen and phosphorus removal have not been well established (Boinpally *et al.*, 2023).

While prior research has predominantly used response surface analysis or univariate analysis to discuss their findings, contemporary references still tend to favor response surface analysis for result interpretation (Dubey *et al.*, 2023). In contrast, our study employed multivariate analysis to elucidate the relationships between the examined parameters and treatments.

Multivariate analysis empowers us to uncover correlations, interactions, and associations among the assessed parameters and applied treatments. In the realm of environmental monitoring, this analytical approach illuminates the intricate interplay of various pollutants and their repercussions on ecosystems (Ayoubi and Bahmani, 2023). These associations span from the specific co-occurrence of pollutants to more nuanced patterns of environmental influence, offering a comprehensive and intricate understanding of the relationships among different environmental variables.

Considering the potential of electrocoagulation technology in treating wastewater within aquaculture systems, we employed Principal Component Analysis (PCA) to evaluate the operational conditions that yield optimal nitrogen and phosphorus removal in treating synthetic water resembling aquaculture effluents.

2. MATERIAL AND METHODS

This study was carried out using synthetic aquaculture water (SAW) (Figure 1) prepared with research data on shrimp (*Farfantepenaeus* spp.) and trout (*Oncorhynchus mykiss*) wastewater, managed in an internal recirculation system (Table 1). Such a system can result in a high concentration of nutrients and thus represent a more critical system in terms of water pollution. Producing synthetic water allowed us to optimize variables. We proved the validity of this water by means of references on the characteristics of real aquaculture wastewater from internal recirculation systems (Lin *et al.*, 2005; Fontenot *et al.*, 2007; Sharrer *et al.*, 2010; Davidson *et al.*, 2019; Tejido-Nuñez *et al.*, 2019).

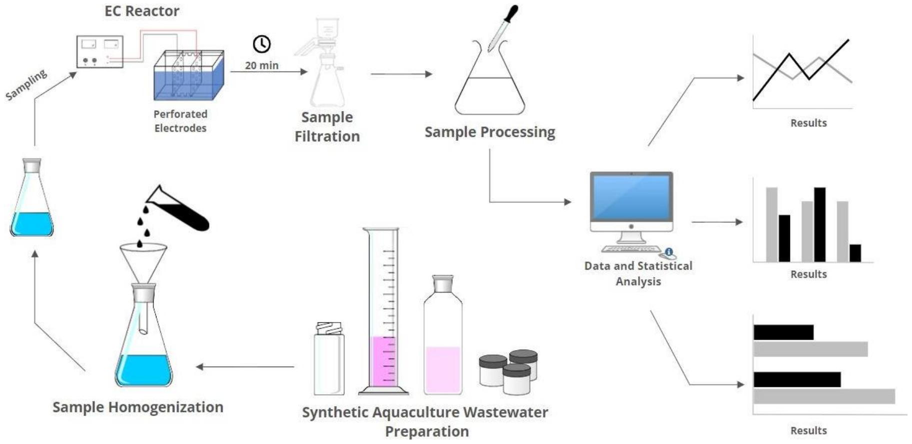

Figure 1. Diagram of the experimental setup.

Table 1. Reagents used to prepare SAW.

Reagent	Molecular formula	Concentration (mg L^{-1})
Sodium bicarbonate	$NaHCO_3$	653.5
Ammonium chloride	NH_4Cl	69.8
Calcium chloride	$CaCl_2.2H_2O$	158.3
Tripotassium phosphate	K_3PO_4	36.0
Calcium hydroxide	$Ca(OH)_2$	126.3
Potassium nitrate	KNO_3	112.5
Calcium sulfate	$CaSO_4.2H_2O$	147.8
Magnesium sulfate	$MgSO_4.7H_2O$	143.9
Potassium sulfate	K_2SO_4	291.5

Source: Adapted from Lin *et al.* (2005); Fontenot *et al.* (2007); Sharrer *et al.* (2010); Davidson *et al.* (2019); Tejido-Nuñez *et al.* (2019).

2.1. Experimental Design

We optimized the independent variables current density, application time and distance between electrodes, as these variables influence the electrochemical treatment. We therefore used a 2^3 factorial design of eight main treatments with three replicates, which combined the independent variables and the variation levels (Table 2).

Table 2. Factorial design treatments carried out with independent variables and the variation levels.

Treatments	Current density ($A.m^{-2}$)	Distance between the electrodes (cm)	Time (min)
T1	74	4	50
T2	59	4	50
T3	74	6	50
T4	59	6	50
T5	74	4	60
T6	59	4	60
T7	74	6	60
T8	59	6	60
T9	67	5	55

The electrocoagulation tests were performed using a 1.5 L acrylic electrolytic cell with a 240 cm^2 surface area and two aluminum plates (anode and cathode), arranged in monopolar mode, with dimensions 10 × 9 × 0.3 cm (length × width × thickness) and 20 holes 3 mm in diameter distributed along its length to improve the mass transport and the release of the gasses generated. No isolation was done to the electrodes, and the anode and cathode contact area corresponds to 134.85 cm^2 each. The intensity of the electric current was controlled by a stabilized switching source with direct current (30V 5A 120W). A support made of 0.40 cm acrylic sheet, placed at the bottom of the glass container, positioned vertically and parallel to its four walls, was used to support the electrodes and their position at the distances determined in the factorial experimental design. At the end of each test, the electrodes were removed, washed under running water and immersed in 1% HCl for 1 minute to eliminate any impurities present on their surfaces. The treated samples were allowed to stand in the reactor for 15 minutes and were subsequently filtered using a qualitative filter paper with a diameter of 15 cm and a pore size of 25 µm to separate the liquid phase from the solids.

2.2. Operating cost analysis (OCA)

The OCA of the electrocoagulation process includes the cost of energy consumption, the dissolved electrode, and the cost of adding any chemical reagents (to increase the conductivity of the solution, or to change its pH) (Khandegar and Saroha, 2013). As no chemical reagent was added in this study, the operating cost was determined according to Equation 1 (Mollah *et al.*, 2004).

$$OC = aC_{energy} + bC_{electrode} \tag{1}$$

Where:

a: price of electricity, US$/ kWh;

b: price of the electrode, US$/ kg;

C_{energy}: electricity consumption, kWh/ m^3;

$C_{electrode}$: mass of the consumed electrode, kg/m^3.

Power consumption in a batch electrocoagulation reactor was calculated by Equation 2 [21]:

$$E = \frac{U\, I\, Tec}{1000} \tag{2}$$

Where:

E: electric energy, kWh;

U: applied electric voltage, V;

I: applied electric current, A;

Tec: time of current application, h.

The mass of the consumed electrode (M_E) is directly related to the applied current and was calculated by Equation 3 (Mollah *et al.*, 2004).

$$M_E = \frac{I\, t\, M}{F\, n} \tag{3}$$

Where:

M_E : Mass of the electrode that has been consumed, mg;

I: applied electric current, A;

t: Treatment duration, s;

M: molar mass of the primary element comprising the electrode, mg/mol;

F: Faraday constant, 96,500 C/mol;

n: total number of electrons involved in the oxidation reaction occurring at the anode.

2.3. Data analysis

For both raw and treated samples subjected to electrochemical treatment, we measured the following parameters: pH (X1), electrical conductivity (X2), ammoniacal nitrogen (X3), nitrate (X4), nitrite (X5), total nitrogen (X6), and total phosphorus (X7) in accordance with the Standard Methods for the Examination of Water and Wastewater 21st edition (APHA *et al.*, 2005). We commenced our analysis by employing the Tukey test to compare parameter means across different groups, considering assumptions such as homogeneity of variances, normality of residuals, and identification of outliers. All analyses were conducted using the complimentary version of SAS Studio. The Tukey Test unveiled noteworthy distinctions among the parameters studied, providing essential insights into the efficacy of nutrient removal across diverse operational conditions in the electrocoagulation process. Upon identifying the most efficient treatment, we calculated its operational cost for electrocoagulation to treat 1.5 L of wastewater, assuming a price of US$ 0.10 per kWh and aluminum electrodes costing $ 9.90 per kg. Subsequently, PCA and discriminant analysis were also conducted.

3. RESULTS AND DISCUSSION

Electrocoagulation proves to be a promising treatment technology for the removal of nutrients, as demonstrated in Table 3. Tukey's test revealed significant differences in all parameters analyzed, except for electrical conductivity and total nitrogen. The operational conditions of electrocoagulation typically depend on the chemistry and composition of the aqueous medium, including the presence of specific chemical species. pH plays a critical role in electrocoagulation, as it influences the solution's conductivity, zeta potential, and electrode dissolution (Moussa *et al.*, 2017).

The initial pH of the raw sample was 8.01, due to the typical composition of synthetic aquaculture water, and no significant variations were observed between the samples. The pH of the influent directly impacts the efficiency of electrocoagulation and the solubility of metallic hydroxides (Mohammed *et al.*, 2018). Enhanced pollutant removal is typically achieved in alkaline pH conditions (Chen, 2004). In our study, after the electrochemical treatment, the pH has remained consistently alkaline. Alkaline solutions generally exhibit higher conductivity, facilitating the flow of electric current during the electrocoagulation process and promoting coagulation. Additionally, in an alkaline environment, aluminum electrodes tend to dissolve at a slower rate. This can be advantageous, as it extends the lifespan of the electrodes and enhances the effectiveness of coagulation.

As shown in Table 3, high percentages of nitrate removal were observed regardless of the pH value. In an alkaline medium, which is the case for all treatments in this study, the formation of aluminum hydroxides is favored (Thirugnanasambandha *et al.*, 2015). The chemical reaction involved in the formation of aluminum hydroxides is represented as:

$$2Al_{(s)} + 6H_2O_{(l)} + 2OH^-_{(aq)} \rightarrow 2Al(OH)_4{}^-_{(aq)} + 3H_{2(g)}$$

In the pH range of 9 to 10.5, nitrate ions can undergo reduction to form ammonia when aluminum electrodes are used. The reduction of nitrate ions with aluminum electrodes is described by the following reactions (Murphy, 1991).

$$3NO_3{}^-_{(aq)} + 2Al_{(s)} + 3H_2O_{(l)} \rightarrow 3NO_2{}^-_{(aq)} + 2Al(OH)_{3(aq)}$$

$$NO_2{}^-_{(aq)} + 2Al_{(s)} + 5H_2O_{(l)} \rightarrow NO_3{}^-_{(aq)} + 2Al(OH)_{3(aq)} + OH^-_{(aq)}$$

$$2NO_2{}^-_{(aq)} + 2Al_{(s)} + 4H_2O_{(l)} \rightarrow N_{2(g)} + 2Al(OH)_{3(aq)} + 2OH^-_{(aq)}$$

$$3NO_3{}^-_{(aq)} + 6Al_{(s)} + 12H_2O_{(l)} \rightarrow NH_{3(aq)} + N_{2(g)} + 6Al(OH)_{3(aq)} + 2OH^-_{(aq)}$$

Table 3. Concentration and efficiency in nutrient removal (%) found in each treatment.

Variables	Raw	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
pH**	8.0b	8.2b	8.5a	8.6a	8.4b	8.6a	7.7b	8.5a	8.2b	7.9b
Conductivity mS/cm	3.32a	2.83a	2.69a	2.67a	2.71a	2.71a	2.53a	2.73a	2.80a	2.30a
NH_3-NH_4, mg/L	19.75e	13.72a	16.15cde	15.59cde	16.98d	16.24cde	14.56ab	15.12abc	16.00cd	16.33cd
NH_3-NH_4, %removal		30.5	18.2	21.1	14.0	17.8	26.3	23.4	18.8	17.3
NO_3^-, mg/L	17.00c	14.67bc	9.33abc	0.00a	0.00a	2.00a	4.33ab	2.00a	0.33a	0.00a
NO_3^-, %removal		13.7	45.1	100.0	100.0	88.2	74.5	88.2	98.1	100.0
NO_2^-, mg/L	6.30c	5.03bc	2.90ab	2.20a	3.90abc	4.43abc	13.03d	3.77abc	3.90abc	3.60ab
NO_2^-, %removal		20.2	54.0	65.1	38.1	29.7	*	40.2	38.1	42.9
P Total, mg/L	1.22b	< 0.01a	0.01a	< 0.01a	< 0.01a	< 0.01a	0.05a	< 0.01a	< 0.01a	0.02a
P total, %removal		100.0	99.6	100.0	100.0	100.0	96.1	100.0	100.0	98.6

Different letters indicate there was a significant difference at 0.05 probability.
* nitrite concentration increased by 106.35%.
** From the letter "a" we have the results with higher values for pH.

High concentrations of ammonia nitrogen in water can have a significant impact on the dynamics of dissolved oxygen in the medium. For instance, during biological nitrification, approximately 4.3 mg of O_2 is required to oxidize 1.0 mg of ammonium ion.

Moreover, under basic pH conditions, ammonia nitrogen is present predominantly as free ammonia (NH_3), which is toxic to aquatic organisms (Elazzouzi *et al.*, 2019). A reduction in ammoniacal nitrogen values was demonstrated in the course of this study on feeding practices; the highest removal efficiency was observed in Treatment 1 (1 A, 4 cm electrode distance, and 50 minutes), reaching 30.5% (Table 3). Under alkaline conditions, similar to those consistently maintained throughout the electrocoagulation process, nitrate (NO_3^-) is reduced to nitrite (NO_2^-) and even further to ammonia (NH_3). This phenomenon elucidates the removal of nitrogen from SAW in this study. Díaz *et al.* (2011) found that using a current density of 5 A/m² for approximately 120 minutes did not result in significant ammoniacal nitrogen removal. In contrast, when applying a current density of 50 A/m² for 45 minutes, complete removal of ammoniacal nitrogen was achieved.

In biological nitrification, in the presence of oxygen, ammonia undergoes conversion into nitrate facilitated by nitrifying bacteria. This nitrification process is mediated by Nitrosomonas bacteria, which convert ammonia into nitrite, and Nitrobacter bacteria, which further convert nitrite into nitrate (Kubitza, 1998). Nitrate, in excess, can be associated with environmental contamination and certain diseases (Von Sperling, 1996). Examples of diseases linked to elevated nitrate levels include methemoglobinemia, a condition often referred to as "blue baby syndrome," which can affect infants; and certain cancers, where the formation of nitrosamines, a byproduct of nitrate metabolism, has been investigated for its potential association with gastric, colorectal, and other cancers. However, it's crucial to note that research in this area is ongoing, and the direct causal relationship between nitrate and specific diseases is complex and may involve various factors. Regular monitoring of nitrate levels in water sources and adherence to recommended safety standards are important to mitigate potential health risks.

After applying the treatments, the results for nitrate showed a reduction, with Treatments 3 (74 A/m², 6 cm electrode distance, and 50 minutes), 4 (59 A/m², 6 cm electrode distance, and 50 minutes), and 9 (67 A/m², 5 cm electrode distance, and 55 minutes) exhibiting 100% efficiency in removing this variable (Table 3).

Nitrite represents an intermediate phase of nitrogen between ammonia (reduced form) and nitrate (more oxidized form) (Davis, 1995). Its presence indicates active biological processes influenced by organic pollution (Bosma and' Verdegem, 2011). Concentrations of nitrite were observed in Treatment 6, while the other treatments showed a reduction. The lowest concentrations were found in Treatment 2 (59 A/m², 4 cm electrode distance, and 50 minutes) and Treatment 3 (74 A/m², 6 cm electrode distance, and 50 minutes), with removal efficiencies of 54% and 65.1%, respectively (Table 3).

Excessive phosphorus concentration can lead to eutrophication in aquatic environments, negatively impacting algae proliferation and oxygen deficits due to consumption (Li *et al.*, 2019). All treatments studied resulted in a reduction of phosphorus, with Treatments 1 (74 A/m², 4 cm electrode distance, and 50 minutes), 3 (74 A/m², 6 cm electrode distance, and 50 minutes), 4 (59 A/m², 6 cm electrode distance, and 50 minutes), 5 (74 A/m², 4 cm electrode distance, and 60 minutes), 7 (74 A/m², 6 cm electrode distance, and 60 minutes), and 8 (59 A/m², 6 cm electrode distance, and 60 minutes) exhibiting 100% phosphorus removal efficiency.

We determined through unilateral statistical analysis using Tukey's method that Treatment 2 (current density of 59 A/m², electrode distance of 4 cm, and 50 minutes of treatment) and Treatment 3 (current density of 74 A/m², electrode distance of 6 cm, and 50 minutes of treatment) are the most effective treatment in reducing the pollutants responsible for eutrophication, namely nitrogen and phosphorus.

Using Pearson's correlation coefficient, it becomes evident that the closer the values are to the extremes of the interval, the stronger the correlation, whereas closer to the center of the interval (zero), the correlation is weaker. The results highlight numerous variables that exhibit significant correlations with each other. Notably, the correlations between electrical conductivity and phosphorus, as well as between pH and nitrite, are particularly strong. It's worth noting that electrical conductivity represents the medium's ability to conduct electrical current, and it is directly proportional to the concentration of conductive ions present in the liquid. Furthermore, the efficiency of pollutant removal and operational costs are closely tied to conductivity (Symonds *et al.*, 2015). This information justifies the observed correlation between electrical conductivity and total phosphorus. As electrochemical treatment progresses, electrical conductivity decreases, leading to the precipitation of phosphorus.

We can observe that the variable electrical conductivity is positively correlated with nitrate, indicating that as conductivity increases, nitrate concentration also increases. Variable pH, on the other hand, is negatively correlated with nitrite, meaning that as pH levels increase, nitrite concentration decreases. Variable phosphorus shows positive correlations with variables electrical conductivity and ammoniacal nitrogen, implying that as ammoniacal nitrogen and total phosphorus concentrations increase, electrical conductivity also rises. This correlation can be explained by the fact that electrical conductivity creates a favorable environment for oxidation-reduction reactions during the electrochemical treatment process, thereby enhancing nitrification reactions and total phosphorus removal (Attour *et al.*, 2014; Mahvi *et al.*, 2011). Consequently, ammoniacal nitrogen, nitrate, and total phosphorus concentrations are also reduced. However, the percentages of phosphorus removal are higher than those for nitrogenous species, as the removal mechanisms for these two pollutants differ (Mahvi *et al.*, 2011).

The discriminant function (CAN1) derived from the raw canonical coefficients in the MANOVA is expressed by Equation 4 and illustrates the interaction among the variables nitrogen, phosphorus, and pH in the synthetic aquaculture water. The function obtained through canonical discriminant analysis using Tukey's test reveals that higher concentrations of total phosphorus and ammoniacal nitrogen result in lower pH (X1) values, and conversely, lower concentrations of total phosphorus (X7) and ammoniacal nitrogen (X3) lead to higher pH values.

$$CAN1 = 47.72X7 + 1.54X3 - 4.62X1 \tag{4}$$

The raw, Treatment 9 (67 A/m^2; 5 cm; 55 min) and Treatment 1 (74 A/m^2; 4 cm; 50 min) groups had significant differences at 95% confidence level, with Treatment 1 showing the greatest difference (Figure 2).

The untreated sample (Raw) differs significantly from all treatments, as it exhibits high values for phosphorus and ammoniacal nitrogen, along with low values for pH. Consequently, after the application of electrochemical treatment, there is a reduction in the concentration of total phosphorus and nitrate, and an increase in pH which is a result of the redox reactions occurring in the reactor. Treatment 9, on the other hand, stands out as distinct from all other treatments.

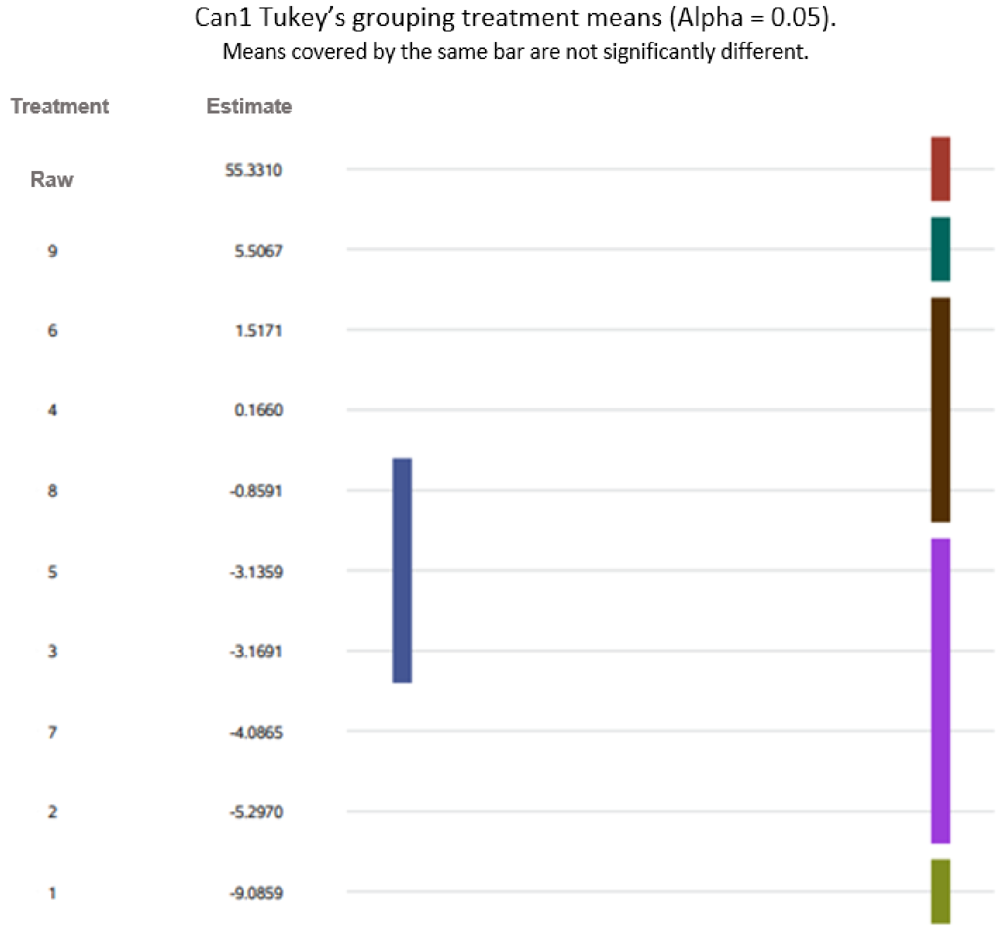

Figure 2. Comparison of means by Tukey's test using canonical variables at 0.05 probability level.
Bars of different colors indicate differences between treatment means.

Since the first principal component explains 76.32% of the data variance, we utilized the second principal component, accounting for 17.53%, to collectively explain 93.85% of the total variance in the variables. The main component's function was calculated using Equations 5 and 6:

$$PC1 = 0.986X4 + 0.104X6 \tag{5}$$

$$PC2 = 0.978X5 \tag{6}$$

In Figure 3, a robust correlation is depicted among the parameters ammoniacal nitrogen (X3), electrical conductivity (X2), and phosphorus (X7), evident by the closely clustered arrows on the graph, with X2 displaying greater variance. Conversely, negative correlations are observed for variables pH (X1) with nitrate (X4), nitrite (X5), and total nitrogen (X6). Moreover, variable X5 demonstrates a higher variance, as evidenced by the arrows associated with this variable. Regarding the treatments, it is evident that both samples, raw and Treatment 6 are distant from the analyzed parameters, indicating a lack of correlation. Treatments 2 and 4 have median values of X1, indicating a balance in relation to the average, which is why they align with the arrow. In contrast, Treatments 7 and 8 exhibit lower median values for X5. It's worth noting that Treatment 1 displayed low nitrite concentrations and achieved a 100% phosphorus removal rate (Table 3). This suggests that a higher current density, shorter electrode distance, and reduced application time led to significant pollutant removal percentages. The impact of electrode spacing on the technology's efficiency can be elucidated by the fact that electric fields, contingent on electrode distance, decline as this factor increases (Hakizimana *et al.*, 2017).

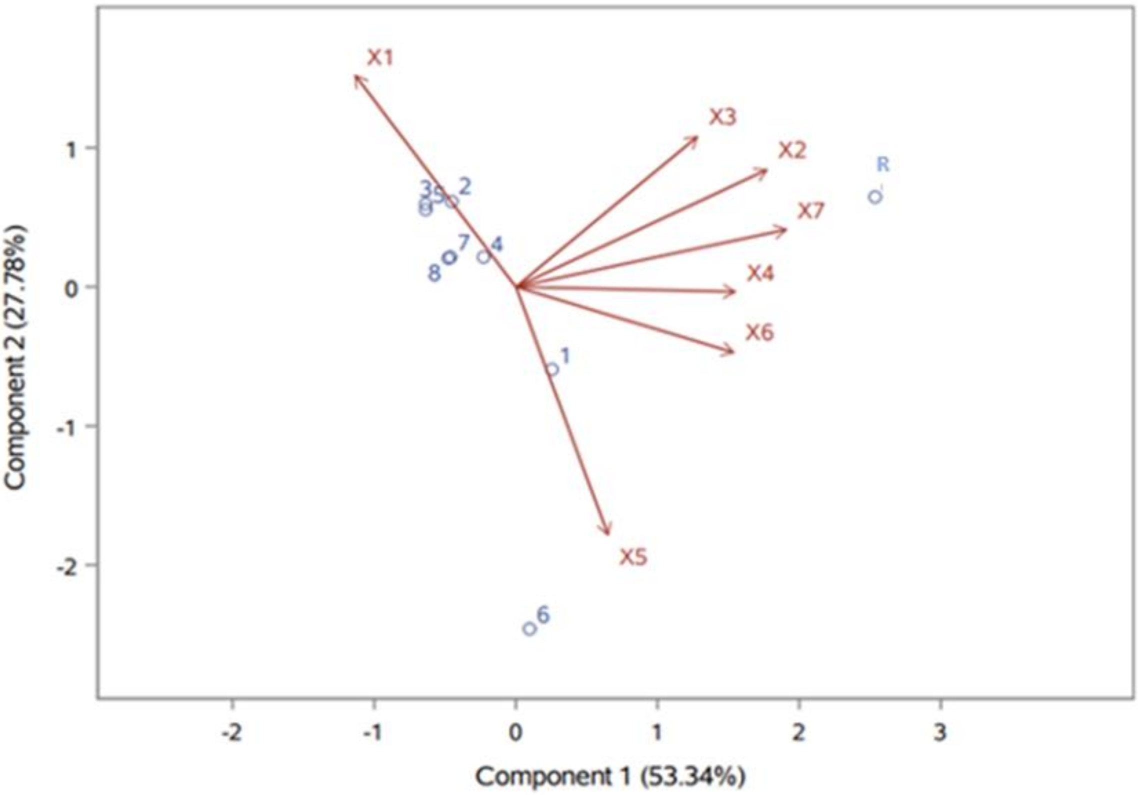

Figure 3. Biplot from characterization of treatment means using principal components. From X1 to X7 we have the evaluated parameters. R (raw) and 1 to 9 the treatments. pH (X1), electrical conductivity (X2), ammonia nitrogen (X3), nitrate (X4), nitrite (X5), total nitrogen (X6) and total phosphorus (X7).

As reported by Mohammed *et al.* (2018), a decrease in treatment time correlates with reduced electricity expenditure. The typical duration for electrochemical treatment to achieve maximum pollutant removal ranges from 15 to 60 minutes (Mohammadi *et al.*, 2017). Nevertheless, a study conducted by Jafari *et al.* (2023) achieved an impressive 98% pollutant removal efficiency with just 5 minutes of electrocoagulation. However, in Treatment 1, the energy consumption amounted to 0.0343 kWh/1.5m^3, and the electrode mass was reduced by 10.1 mg, resulting in an operational cost of US$ 0.0095/1.5m^3. Kushwaha *et al.* (2010) noted that costs associated with electricity consumption and electrode wear ranged from US$ 0.072/1.5m^3 to US$ 2.55/1.5m^3. These higher cost values are likely attributed to the extended experiment duration, which lasted up to 90 minutes for the electrochemical treatment. In this study, the most cost-effective treatments had an operation time of up to 15 minutes.

4. CONCLUSION

During laboratory-scale testing using synthetic aquaculture water, it was established that the optimal setup for a 240 cm^2 electrolytic cell required a current density of 74 A/m^2, an electrode spacing of 4 cm, and an application duration of 50 minutes. This specific configuration resulted in the effective removal of total phosphorus and the median ammonia nitrogen level, emphasizing the critical need for additional research to further improve technology efficiency.

5. RECOMMENDATIONS

The presented results suggest some key recommendations for future research. First, conducting pilot-scale studies beyond the laboratory level would enhance our understanding of electrocoagulation under more realistic conditions. Additionally, investigating the durability of electrodes over time is crucial. An environmental impact assessment, including life cycle analyses, is needed, and optimizing operational parameters for efficiency should be explored. Real aquaculture water should be incorporated for more practical insights, and a long-term cost-benefit analysis considering both immediate costs and equipment durability is essential. These recommendations aim to advance the understanding of electrocoagulation in aquaculture without undermining the existing work.

6. ACKNOWLEDGEMENTS

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