Enhanced Phosphorus Removal Using Electrocoagulation in a UASB-Type Reactor

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Highlights

- UASB-EC reactor removed up to 80% of phosphate without chemical additives.
- Current density and electrolysis time strongly influenced phosphate removal.
- UASB-EC is a scalable, sustainable option for phosphorus removal in wastewater.

Introduction

Nutrients such as nitrogen and phosphorus are essential for the growth and development of microbial cells. However, when excessively discharged into an aquatic environment, these elements can contribute to the eutrophication process, characterized by the proliferation of undesirable aquatic species, depletion of dissolved oxygen, and increased aqutic organisms (METCALF & EDDY, 2016).

Several strategies are available for wastewater treatment; nonetheless, applying a single technique is often insufficient to ensure effective nutrient removal. As such, the integration of multiple treatment processes is commonly required. Anaerobic treatment is a well-established technology recognized for its operational simplicity, resilience to environmental fluctuations, efficient removal of organic matter, and capacity to produce renewable energy in biogas. However, its performance in removing nutrients, particularly nitrogen and phosphorus, remains limited, necessitating complementary post-treatment processes to achieve compliance with environmental regulations (CAMPOS, 2019; SANTOS et al., 2021).

Electrocoagulation (EC) emerges as a promising post-treatment alternative, characterized by the *in situ* generation of coagulants through the electrolytic oxidation of iron or aluminum electrodes. This process enhances pollutant removal by combining the mechanisms of coagulation, flotation, and electrochemical interactions, proving effective for eliminating organic compounds, nutrients (e.g., phosphorus), and heavy metals.

In light of the advantages offered by both technologies, a novel configuration was developed, consisting of an Upflow Anaerobic Sludge Blanket (UASB) reactor integrated with an electrochemical system equipped with four iron (Fe) electrodes, herein referred to as the UASB-EC reactor. This study aims to assess the influence of the electrochemical process on phosphorus removal efficiency during the treatment of synthetic wastewater under a hydraulic retention time (HRT) of 8 hours.

Material and Methods

The UASB-EC reactor was built in plexiglass with dimensions of 1.00 m in height, 0.18 m in width, and 0.17 m in length, yielding a useful volume of 25.1 L. An electrolytic cell was installed at the bottom of the reactor, below the three-phase separator (gas-solid-liquid). It consisted of four cylindrical iron (Fe) electrodes spaced 1.5 cm apart and connected in series to a direct current (DC) power supply. Each electrode measured 17.8 cm in length and 1.59 cm in diameter, with a submerged surface area of 84 cm^2.

The UASB-EC reactor was inoculated with 4 L of anaerobic flocculent sludge, corresponding to approximately 16% of the reactor volume. The sludge was obtained from a full-scale Upflow anaerobic sludge blank (UASB) reactor treating sanitary sewage in Curitiba, Paraná State, Brazil.

Synthetic wastewater simulating sanitary sewage was prepared according to the formulation described by Torres (1992). The solution was stored in a 210 L reservoir and fed into the system using a Prominent electromagnetic diaphragm metering pump (model gamma/X), operating at a flowrate (Q) of 7.6 L h^{-1}.

The UASB-EC reactor was operated continuously for 195 days with a hydraulic retention time (HRT) of 8 h, flowrate (Q) of 3.13 L h^{-1}, upflow velocity of 0.1 m h^{-1}, and volumetric organic loading rate of 1.0 kgCOD m^{-3} d^{-1}. Physicochemical analyses were performed in duplicate and according to the procedures described in the Standard Methods for Examination of Water and Wastewater (APHA, 2023) samples of the influent and effluent.

The effects of current density (*j*) and electrolysis time (*t*) on phosphate (PO_4^{-3}) removal efficiency were investigated using a 2^2 central composite rotational design (DCCR), which included three central points and four axial points. All samples were collected and analyzed 4 hours after the application of electrolysis in the reactor. Table 1 shows the experimental design.

Table 1 Matrix of the 2^2 factorial design, efficiency of phosphate removal obtained through the design and the desirability of the UASB-EC system

Independent variables	Coded and real levels of independent variables				
	-1.414	-1	0	1	1.414
j (mA cm^{-2})	1.78	2.31	3.58	4.85	5.36
t (min)	20	26	40	54	60
	Variables coded		Variables decoded		Removal (%)
Samples	*j*	*t*	*j*	*t*	PO_4^{-3}
1	-1	-1	2.31	26	19%
2	1	-1	4.85	26	35%
3	-1	1	2.31	54	27%
4	1	1	4.85	54	75%
5	-1.414	0	1.78	40	26%
6	1.414	0	5.36	40	63%
7	0	-1.414	3.58	20	26%
8	0	1.414	3.58	60	72%
9	0	0	3.58	40	51%
10	0	0	3.58	40	44%
11	0	0	3.58	40	38%
12*	1.2148	1.0293	5.13	55	80%

Note: * Optimal condition obtained by desirability

It is worth noting that, at the end of each experimental run, the electrodes were rinsed with tap water and subsequently immersed in a 3 mol L^{-1} hydrochloric acid (HCl) solution for 30 minutes to remove the passivation layer formed on their surfaces. This procedure was essential to maintain electrode activity and ensure consistent performance in subsequent experiments.

The experimental results were statistically evaluated using analysis of variance (ANOVA), which was employed to estimate relevant statistical parameters and assess the adequacy and predictive capability of the proposed mathematical model.

Results and Discussion

The results of the phosphate removal efficiency obtained from the factorial design experiments are shown in Table 1, and Table 2 displays the analysis of the estimated effects used to assess the influence of the parameters *j* and *t* on the PO_4^{-3} removal efficiency. Statistically significant factors at the 95% significance level are highlighted.

Table 2 Effects of variables and regression analysis

	Effect	Standard error	T	p-value
Average/Intercept	44.33499	4.405409	10.06376	0.000166
Current density (L)	29.08389	5.395909	5.38999	0.002966
Current density (Q)	-3.96163	6.423244	-0.61676	0.564387
Electrolysis time (L)	27.55816	5.395909	5.10723	0.003747
Electrolysis time (Q)	1.54003	6.423244	0.23976	0.820036
Current density x Electrolysis time	16.00000	7.630392	2.09688	0.090110

Note: (L) - Linear; (Q) – Quadratic; T – t *Student*.

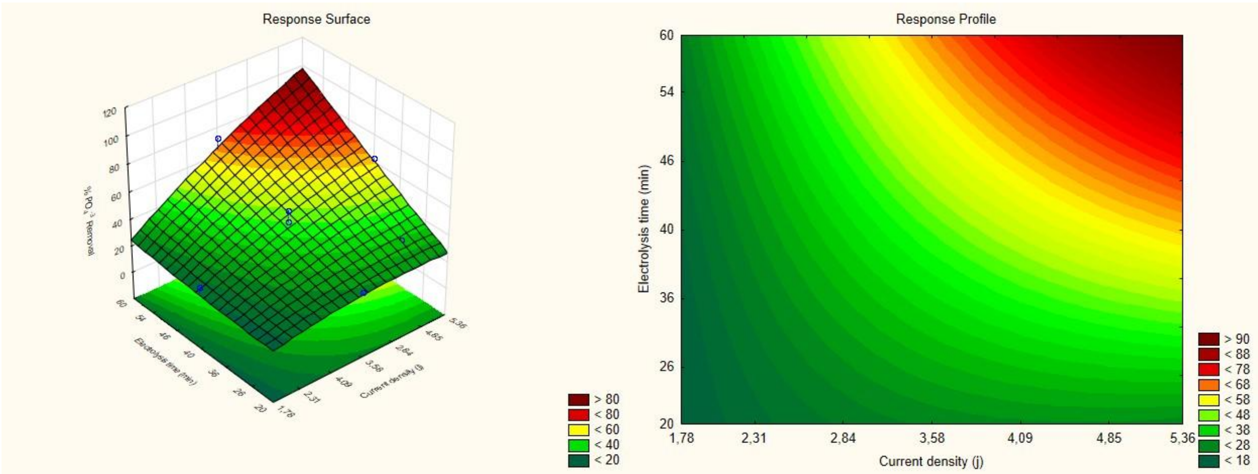
Based on the significant variables, an analysis of variance (ANOVA) was conducted, as presented in Table 3. The coefficient of determination (R^2) obtained was 0.84, indicating that the model is statistically significant, as 84% of the variability in the response can be explained by the proposed model.

Table 3 Analysis of variance (ANOVA) for the statistical model of phosphate removal

	Source of variation	SQ	GL	MQ	Fcal	Ftab	Fcal/ Ftab
Removal Efficiency (%)	Regression (model)	3210.165	2	1895.364	26.480	4.459	5.938
	Residue	572.609	8	71.576			
	Total	3790.727	10				

Note: (SQ) sum of squares; (GL) degrees of freedom; (MQ) sum average of squared errors; (Fcal) calculated Fisher distribution; (Ftab) Fisher distribution tabulated with 5% probability.

Analysis of the response surface plots (Figure 1) for the response variable PO_4^{-3} removal efficiency revealed the optimal combination of current density and electrolysis time. The best operational region of for the response variable for phosphate removal was identified within the range of approximately 46 to 60 minutes of electrolysis and a current density between 3.58 to 5.36 mA cm^{-2}, where the highest removal efficiencies were achieved.



(a) (b)

Figure 1 Response surface (a) and response profile (b) for phosphate removal efficiency as a function of current density and electrolysis time.

Therefore, it is noteworthy that increasing the levels of both variables, current density and electrolysis time, may lead to an overall improvement in process efficiency. Table 4 summarizes the physicochemical parameters of the treated effluent under optimal operating conditions (j = 5.13 mA cm^{-2} and t = 55 min), including pH, temperature, chemical oxygen demand (COD), volatile fatty acids (VFAs), alkalinity, turbidity, conductivity, total phosphorus, and iron concentration.

Table 4 Characterization of the effluent after treatment in optimal operating condition

Parameter	Average		SD		Minimum		Maximum	
	inf	effl	inf	effl	inf	effl	inf	effl
pH	6.6	7.5	0.5	0.1	6.2	7.4	7.0	7.5
Temperature (ºC)	20.1	20.5	0.6	0.5	19.6	20.1	20.5	20.8
Turbidity (NTU)	20	29.5	1.0	1.4	19.2	28.5	20.7	30.5
Total alkalinity (mgCaCO$_3$ L^{-1})	99.8	121,6	15.0	6.3	89.2	117.13	110.4	126.0
Volatile Acids (mgHac L^{-1})	46.5	42.4	12.7	10.5	37.5	34.9	55.5	49.8
Conductivity (µS cm^{-1})	915.9	968.5	157.2	154.9	804.7	859	1027	1078
COD (mg L^{-1})	319.2	58.5	59	17.9	277.5	45.84	361	71.1
COD Removal (%)	–	81.7	–	–	–	–	–	–
Total phosphorus (mg L^{-1})	14.9	3.0	0.4	0.2	14.6	2.84	15.2	3.1
Total phosphorus Removal (%)	–	80	–	–	–	–	–	–
Iron (mg L^{-1})	-	3.3	-	0.1	-	3.2	-	3.3

The model was validated under optimal conditions using the desirability function approach. The optimal point was identified at coded variable values of 1.2148 for current density and 1.0293 for electrolysis time. These correspond to real values of 5.13 mA cm^{-2} and 55 minutes, respectively, achieving a phosphate removal efficiency of approximately 80% (as shown in Table 1).

Conclusion

Electrochemical systems employing iron electrodes integrated into UASB-type reactors have demonstrated the capability to efficiently remove phosphate from synthetic wastewater simulating sanitary sewage, with the UASB-EC reactor achieving removal efficiencies of up to 80%.

Both current density and electrolysis time were found to significantly influence phosphate removal performance. Variations in these parameters directly affect the system's efficiency, either enhancing or reducing the removal rates.

Overall, it can be concluded that the UASB-EC reactor is an effective configuration for maximizing phosphate removal from synthetic wastewater without the addition of chemical reagents. The integration of electrocoagulation within the reactor not only enhances contaminant removal but also represents a simple, practical, and scalable technology with high potential for application in advanced wastewater treatment systems targeting phosphorus removal.

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