Efficacy of the Electrocoagulation Treatment of Agricultural Drainage Water

Ahmed. A. El-Shafei[1,2], Hoda F. Zahran[3*], Mahmoud Nasr[4], Dina El Nozahy[2]

[1]Agricultural Engineering Department, College of Food and Agricultural Sciences, King Saud University, Riyadh 11451, Saudi Arabia

[2]Agricultural and Biosystems Engineering Department, Faculty of Agriculture, Alexandria University, Alexandria 21545, Egypt

[3]Pollution Management Department, Environment and Natural Materials Research Institute (ENMRI), City of Scientific Research and Technological Applications (SRTA-City), New Borg Al-Arab City 21934, Alexandria, Egypt

[4]Sanitary Engineering Department, Faculty of Engineering, Alexandria University, 21544, Alexandria, Egypt

ABSTRACT

Electrocoagulation is a promising treatment technique for agricultural drainage water, proposing an efficient removal of pollutants such as turbidity, nitrates (NO_3^-), dissolved solids (TDS), and salinity. The process utilizes the release of positively charged ions from electrodes to neutralize negatively charged pollutants, resulting in their coagulation and subsequent removal. The purpose of this study was to statistically characterize the relationships among the properties of agricultural drainage water (ADW) that has undergone electrocoagulation treatment (ECT). The unit was installed to treat samples of ADW collected from an agricultural experimental station in the Abis neighborhood of Alexandria, Egypt. The physicochemical characteristics were evaluated by testing various direct current (DC) values (A) and voltages (V). Specifically, the experiments included settings of 3 V at 0.45 A, 5 V at 0.45 A, 12 V at 0.01 A, and 12 V at 17 A. Treatment durations ranged from 10 to 60 min to identify optimal operational parameters for effective contaminant removal. Principal component analysis (PCA) was employed as a multivariate analysis technique to assess relevant data from complex datasets and determine the effectiveness of the electrocoagulation treatment unit. The PCA and PCACOV functions in MATLAB were utilized to estimate the principal components. The first three principal components (PC1, PC2, and PC3) all exhibited eigenvalues greater than 1, indicating that they could adequately characterize the functionality of the ECT system. The total dissolved solids (TDS), salinity, and nitrate (NO_3^-) parameters were found on the negative side of PC1, while the reaction time was positioned on the positive side. An increase in reaction time correlated with improved removal efficiencies for these parameters. Additionally, TDS, salinity, and electrical conductivity (EC) wastewater characteristics were aligned along the positive PC2 axis, suggesting a simultaneous increase in these parameters. The distribution of both reaction time and dissolved oxygen (DO) on the positive side of PC1 indicated that longer reaction times resulted in higher DO levels. It was determined that ADW could be effectively treated using the ECT procedure, demonstrating a statistically significant interaction between treatment performance and wastewater parameters.

Keywords: Agricultural drainage water; Electrocoagulation; Electrochemical analysis; Environmental sustainability; Multivariate analysis; Water quality improvement.

INTRODUCTION

Agricultural drainage water, a byproduct of irrigation and farming practices, presents significant environmental challenges. This water often contains a mixture of fertilizers, pesticides, and other agrochemicals, and its uncontrolled discharge can lead to the contamination of nearby water bodies, adversely affecting aquatic ecosystems and biodiversity. Consequently, the challenge of managing agricultural drainage water has become increasingly urgent in recent years, driven by the dual imperatives of environmental sustainability and agricultural productivity. The World Health Organization (WHO) has reported that approximately 40,000 people worldwide die daily due to the consumption of polluted water. Therefore, it is imperative to assess the water quality and pollution status (Omar *et al*., 2023). Effective management strategies are essential to mitigate the negative impacts of this drainage water while ensuring the continued viability of agricultural practices.

The inadequate rate of progress in water and sanitation highlights the urgent need to explore potential solutions through partnerships and cooperation, especially as global water demand is expected to rise dramatically. This issue of collaboration for water management is examined in relation to agri-culture, the environment, human settlements, industry, health, and climate change across various regions. Over the next 20 years, water demands in sectors such as industrial, residential, and agricultural uses are projected to increase significantly (WWAP, 2018 and 2023). In fact, these demands have increased six fold over the past century (Wada *et al*., 2016), with a consistent growth rate of approximately 1% per year (AQUASTAT, 2017). As a result, the patterns of global

_____

* Corresponding author e-mail: hfzahran@gmail.com

water consumption are expected to shift upward. Therefore, it is essential to expand water resources and address the various types of wastewater generated over the past several decades (Sallam, 2017).

Agricultural drainage water is a significant comp-onent of the wastewater management field, defined as the removal of excess water from the surface or subsurface of an area (Sallam, 2017). This drainage can have beneficial environmental effects on soil solute transport, water flow, and plant growth, although it may also introduce contaminants such as pesticides, nutrients, organic wastes, and trace elements, which can contribute to soil degradation (Brendan *et al*., 2018; Nouri *et al*., 2013;). In the agricultural sector, utilizing agricultural drainage water can play a crucial role in alleviating water scarcity by providing an additional resource for irrigation, thereby addressing one of the significant challenges faced by farmers (WAHBA, 2017).

To evaluate and determine characteristics of agri-cultural drainage for reuse, several parameters are selected, such as: pH, salinity, electrical conductivity (EC), total suspended solids (TSS), total dissolved solids (TDS) and nitrates (NO_3^-) (Mahmoud and Hoda, 2015). For adequate remediation, chemical, physical and biological techniques such as ion exchange, rev-erse osmosis, microalgal-bacterial treatment, solar ponds, microalgal-bacterial treatment, volatilization and biological precipitation may be used for agricu-ltural drainage (Kravchenko *et al*., 2002). As an example of agricultural drainage, the agricultural drain-age stream of agricultural experimental station of Alexandria University in Abis region, Alexandria gov-ernorate, Egypt. This station concerns with both plant and animal production Departments researches. So, the agricultural drainage of this station is already polluted with several organic pollutants come from researches.
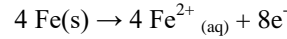
The electrocoagulation technique (ECT) is a pro-mising wastewater treatment method that utilizes an electrical current to treat contaminants without the need for additional coagulation chemicals (Nawarkar and Salkar, 2019; Allam and Negm, 2013). This technique is not only versatile but also environmentally compati-ble, making it an effective, cost-efficient, and straight-forward electrochemical method for the rem-oval of various pollutants from wastewater (Khan *et al*., 2023; Bharath *et al*., 2018). ECT has been shown to effect-tively reduce contaminants such as heavy metals, suspended solids, and organic matter, thus contributing to the improvement of water quality (Das *et al.,* 2022).

The concept of this process involves passing an electric current through a simple circuit composed of metallic electrodes (anode and cathode) submerged in a reactor, which generates *in-situ* coagulants that desta-bilize suspended pollutants in an aqueous solution. In the cathodic area, hydrogen gas is produced, aiding in the flotation of these pollutants (Hashim *et al*., 2019). The type of coagulant generated can be influenced by factors such as cost, availability, and oxidation poten-tial of the electrodes. Iron and aluminium are the most common and effective materials used for electrodes.
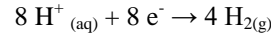
Several studies have demonstrated the mechanism of pollutant removal using electrocoagulation with iron electrodes, as described by Lopez-Guzman *et al*. (2021) in the following equations:
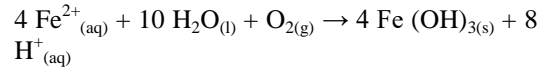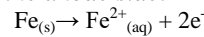
Mechanism I
On the anode:
$$4\ Fe(s) \rightarrow 4\ Fe^{2+}\ _{(aq)} + 8e^-$$
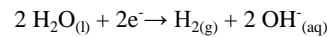*On the cathode:*
$$8\ H^+\ _{(aq)} + 8\ e^- \rightarrow 4\ H_{2(g)}$$
In the solution:
$$4\ Fe^{2+}\ _{(aq)} + 10\ H_2O_{(l)} + O_{2(g)} \rightarrow 4\ Fe\ (OH)_{3(s)} + 8\ H^+\ _{(aq)}$$

Mechanism II
On the anode side:
$$Fe_{(s)} \rightarrow Fe^{2+}\ _{(aq)} + 2e^-$$
On the cathode:
$$2\ H_2O_{(l)} + 2e^- \rightarrow H_{2(g)} + 2\ OH^-\ _{(aq)}$$
In solution:
$$Fe^{2+}\ _{(aq)} + 2\ OH^-\ _{(aq)} \rightarrow Fe\ (OH)_{2(s)}$$
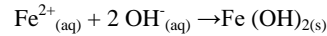
In aqueous media, metal ions produced at the anode react with hydroxide ions produced at the cathode to produce various hydroxide species such as $Fe\ (OH)_2$, $Fe\ (OH)_3$, $Fe\ (OH)_2+$ and $Fe\ (OH)_4$ depending on the pH. The iron-hydroxides coagulate and precipitate to the bottom of the system.

In this study, to determine the efficacy of ECT in improving agricultural drainage water, multivariate analysis such as principal component analysis (PCA) was applied to acquire useful information from complex datasets (Gupta *et al*., 2018). Some recent studies revealed that PCA helped to effectively reduce the number of physicochemical parameters that may assist in the description of drainage water quality (Nasr and Zahran, 2016). By considering physicochemical parameters such as pH, DO, turbidity, TDS, hardness, calcium ions, chloride ions, BOD and sulfate groups, PCA was applied to classify the different water reso-urces into different categories. This useful classifi-cation enables planners and field engineers to perform advanced ameliorative measures for preventing water resource contamination (Eaton *et al*., 2005). Therefore, this study aimed to investigate the efficacy of the electrocoagulation technique in treating agricultural drainage water. Principal component analysis was performed to evaluate the quality of the water, enabling its recycling and reducing its environmental pollution impact.

MATERIALS AND METHODS

Water sampling

Composite water samples were collected from an agricultural drainage stream at the Agricultural exper-imental station of Alexandria University in Abis (Latitude 31° 12′ 41.25″ North and Longitude 29° 59′ 16.54″ East), Alexandria, Egypt. Figure (1) shows the location map of this station. According to the standard methods for the examination of water and wastewater (Eaton *et al*., 2005), samples were collected in 20 L polyethylene containers and preserved in an icebox at 4°C during transportation to the laboratory.

Figure (1): Location map of the agricultural experimental station of Alexandria University in Abis.

Performance of the electrocoagulation set

Schematic design for the electrocoagulation unit

Figure (2) shows a schematic diagram of the electrocoagulation unit established by the authors of this work and used experimentally with the following specifications: width: length: height of 40: 30: 50 cm and 12 Fe/Fe electrodes connected in monopolar parallel mode with an inert distance of 2 cm. These electrodes were used as anodes and cathodes and each electrode has dimensions of 27×14 cm. This unit was powered by a CS - 300 V- C`S cleaver Scientific LTd, UK power supply for variable DC current and voltage values. For recording water samples as electrolytes, this unit was supplied with a multiprobe meter (model Aquaprobe AP-7000, England).

Application of the designed electrocoagulation unit

By using the last designed electrocoagulation unit on the captured water samples and by testing different values of DC (Am) and voltage (V) (3 V- 0.45A, 5 V- 0.45 A, 12 V- 0.01 A and 12 V- 17 A) a suitable pollutant removal efficiency was reached, which was translated into a decrease of water parameter measure-ements. Starting at 10 min and possibly up to 60 min, parameters were determined by using a multipara-meter water quality meter (Aquaprobe AP-7000, England) which were listed as follows: Temp°C, oxidation reduction potential (ORP mv), pH, dissolved oxygen (DO) mg/l, EC µs/cm, TDS mg/l, salinity %, NO_3^- mg/l and turbidity NTU. Zero-time analysis of the water samples before treatment was considered as control measure.

Application of the designed electrocoagulation unit

By using the last designed electrocoagulation unit on the captured water samples and by testing different values of voltage (V) and DC (Am) including: 3 V- 0.45A, 5 V- 0.45 A, 12 V- 0.01 A and 12 V- 17 A. Suitable pollutant removal efficiencies were achieved, as indicated by a decrease in the measured water qua-lity parameters. Measurements were taken at intervals starting from 10 mins and extending up to 60 mins. The parameters were assessed using a multiparameter water quality meter (Aquaprobe AP-7000, England) and included the following: temperature (°C), oxidation-reduction potential (ORP, mV), and pH, dissolved oxy-gen (DO) mg/l, EC µs/cm, TDS mg/l, salinity %, NO_3^- mg/l and turbidity NTU. Zero-time analysis of the water samples before treatment was considered as control measure.

Statistical analysis

Principal component analysis (PCA) shows the correlation structure of a data matrix X, approximating it by a matrix product of lower dimension (T × P'), called the principal components (PCs), plus a matrix of residuals (E) (Costa *et al.*, 2009). This procedure can be formulated by the following equation:

$$X = (1 \times x') + (T \times P') + E$$

Where, T is a matrix of scores that summarizes the X-variables (scores) and P is a matrix of loadings that indicates the effect of the variables on each score. The term $(1 \times x`)$ represents the variable averages. The second term, the matrix product (T×P`), models the structure. The third part, E, includes the deviations between the original values and the projections. PCA was conducted using the following procedures: (a) the correlation matrix was calculated, (b) the eigenvectors and eigenvalues were estimated, (c) the eigenvalues were sorted in descending order and (d) the eigenvector with the highest eigenvalue was considered the most dominant principal component of the dataset; i.e., PC1
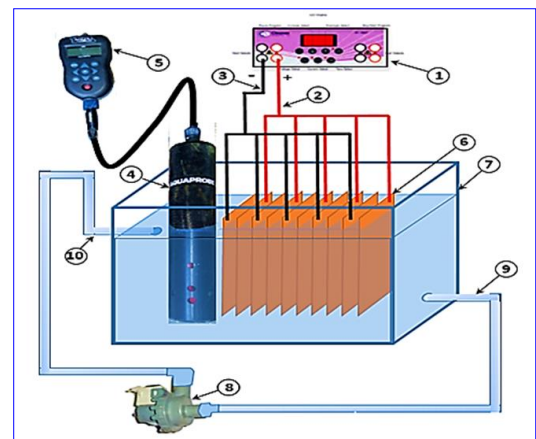

Figure (2): Schematic diagram of the designed and used Electrocoagulation unit for water treatment. 1, Power supply; 2, Anode; 3, Cathode; 4, Aqua probe apparatus; 5, Recorder; 6, Iron plates; 7, Glass jar; 8, Pump; 9, Outlet; 10, Inlet.

and (e) PC2 were computed under the constraint of being orthogonal to PC1 and having the second largest variance (Awolusi et al., 2018).

The functions PCA and PCACOV in MATLAB software were used to perform the PCA and to estimate the PC coefficients. Basically, PCA rotates the set of records around their mean to form a new and orthogonal coordinate system, known as the principal component (PC) and it also means ordinations according to the studied water parameters. The first principal component (PC1) is the new axis that describes the highest possible variance in the dataset (Mackiewicz and Ratajczak, 1993).

The second principal component (PC2) accounts for the direction perpendicular to PC1 and it corresponds to the next highest variance. Correlation analysis is another statistical technique that can be employed to understand the performance of an electrode (ECT) (Nasr and Zahran, 2016). The Pearson correlation coefficient is an estimation of the linear correlation between two variables. It provides a value between +1 and -1, where 1 is a total positive correlation, 0 is no relationship and -1 is a total negative correlation (Gupta et al., 2018).

RESULTS

Evaluating the designed electrocoagulation unit for water sample treatment

Results obtained from Table (1, i, ii, iii and iv) well declare variations in Temp (°C), ORP (mv), pH, DO (mg/l), EC (µS/cm), TDS (mg/l), Sal % and Turbidity (NTU) under different values of voltage (V) and DC (Am). Table (1, i and ii) show a decrease in salinity, ORP, EC, and TDS values over the course of the test in descending order. Table (1, iii and iv) demonstrated sharply rising DO values throughout the course of the experiment. The last four ECT unit application trials have demonstrated the effectiveness of ECT- designed units in eliminating pollutants from agricultural drainage water.

Correlation analysis

The correlation matrix of the measured parameters provides valuable insights into the relationships between various water quality parameters (Table 2) which demonstrates that the measured temperature and dissolved oxygen (DO) showed perfect positive correlation (1.0). This result indicates that as temperature increases, dissolved oxygen levels also increase. This is somewhat counter intuitive, as higher temperatures typically decrease DO solubility; however, this may reflect specific conditions or data collection methods under the studied environment. In addition, highly positive correlations (1.0) were detected between EC and both TDS and salinity. Meanwhile, the strong negative correlation (-0.96) recorded, between temperature and pH, suggests that as temperature rises, pH levels tend to decrease (Table 2). Similar strong negative correlation (-0.91 and -0.90) of nitrate concentrations (NO_3^-) were associated with lowering temperature and DO, respectively. EC and pH

also: recorded strong negative correlation (-0.80) in which as conductivity increases, often a sign of higher ion concentrations pH tends to decrease. Furthermore, positive strong correlations were observed between time and both of ORP and DO (0.74 and 1.0, respectively). Week correlations were recorded between pH and either EC, TDS or salinity (0.46, 0,45 and 0.44, respectively). Nitrate concentration was also recorded week correlations with EC, TDS and salinity (0.47, 0.45 and 0.46, respectively). In general, turbidity reported weak correlations with most parameters, including temperature (0.31), ORP (0.00), and TDS (-0.12).

Principal component analysis (PCA)

The data in the box plots (Figure 3) illustrates the standardized distribution of the parameters used for the PCA of the electrocoagulation unit. Standardizing the data to a mean of 0 and a standard deviation of 1 ensures all variables, including time (min), DO (mg/L), and temperature in (°C), contribute equally to the PCA, preventing dominance by parameters with larger scale values. Figure (3) illustrates the parameters used to develop the PCA for the tested electrocoagulation unit. The median values for most parameters were centered around zero, confirming the effectiveness of the standardization process. Parameters such as ORP and pH exhibit narrower interquartile ranges, indicating lower variability, while turbidity and temperature display wider distributions, reflecting greater variability in these metrics. Generally, greater variability in parameters like turbidity, time, and temperature can have a significant impact on the principal components' loadings and their interpretation.

Table (3) indicates that the first three principal components (PCs) explained 97.62% of the total variance. The Eigenvalues PC1, PC2 and PC3 were greater than 1, indicating that the first three PCs could describe the EC system. PC1 explained 67.43% of the total variance and had high loadings on time (0.36), temp. (0.36), ORP (0.34), pH (-0.35), DO (0.36) and NO_3^- (-0.33). PC1 was affected by the operational conditions of the EC experimental setup. PC2 explained 20.24% of the variance and had high loadings on EC (0.44), TDS (0.44) and salinity (0.45). PC2 was influenced by the wastewater characteristics and the EC performance. PC3 explained 9.94% of the variance and had high loadings on NO_3^- (0.32) and turbidity (0.86).

PC3 described the turbidity removal efficiency. Additionally, Table (3) illustrates that the reaction time was distributed on the positive side of PC1, whereas, TDS, salinity, and NO_3^- were located on the -PC1. Hence, an increase in reaction time improved the removal efficiencies of TDS, salinity and NO_3^-. ORP was positioned on +PC1, whereas, NO_3^- and TDS were located on -PC1. An increase in ORP suggested that more positively charged ions from the EC electrodes were released into the solution and interacted with the negatively charged pollutants. Therefore, the neutralization mechanism was responsible for pollutant removal. Similarly, turbidity was located in the +PC2.

4

Table (1): Evaluation of dynamic changes in water quality parameters of the electrocoagulation unit with varying voltage (V) and direct current (Am): A Comparative Analysis.

	Time (min)	Temp (°C)	ORP (mv)	pH	DO (mg/l)	EC (µs/cm)	TDS (mg/l)	Salinity (%)	NO₃ (mg/l)	Turbidity (NTU)
i. At 3 V and 0.45 Am	0	28.8	438.5	4.41	4.97	1744	1132	0.86	-	144
	10	28.9	264.6	4.24	4.97	1619	1054	0.80	-	272
	20	28.9	-111.6	5.13	4.97	1512	982	0.74	-	198
	30	28.9	-284.4	6.63	4.97	1502	975	0.71	-	185
	40	28.9	-185	6.68	4.97	1431	932	0.68	-	247
	50	28.9	-280	6.79	4.97	1484	962	0.7	-	275
	60	29	-368	7.18	4.97	1478	961	0.7	-	225
ii. At 5 V and 0.45 Am	0	29.6	206.6	8.35	4.98	467	303	0.15	-	-
	10	29.6	96.7	8.53	4.98	464	301	0.15	-	-
	20	29.7	-479	8.97	4.98	430	227	0.14	-	-
	30	29.7	-513.2	9.4	4.98	413	267	0.13	-	-
	40	29.8	-502.3	9.11	4.98	419	271	0.13	-	-
	50	29.8	-539.3	9.38	4.98	404	262	0.13	-	-
	60	29.9	-569.7	9.56	4.98	416	258	0.13	-	-
i. At 12 V and 0.01 Am	0	28.6	127.4	7.55	4.96	319	207	0.1	-	157
	10	29.1	-20.6	7.43	4.97	274	178	0.09	-	79.0
	20	29.6	-30.6	7.43	4.98	255	163	0.08	-	57.6
	30	30.0	-46.0	6.93	4.98	252	163	0.08	-	26.9
	40	30.4	-50.4	6.78	4.99	242	161	0.08	-	72.8
	50	-	-	-	-	-	-	-	-	-
	60	-	-	-	-	-	-	-	-	-
ii. At 12 V and 17 Am	0	29.1	-1.3	8.48	4.96	1387	891	0.65	4.87	257
	10	30.4	19.1	8.44	4.98	1161	754	0.55	5.19	281
	20	31.6	21	8.39	5.0	1060	689	0.5	2.6	130
	30	32.6	22.6	8.41	5.01	1047	680	0.5	3.0	59.4
	40	33.6	23.5	8.36	5.03	1099	715	0.52	2.25	91.4
	50	34.6	24.6	8.32	5.04	1241	811	0.59	1.61	117
	60	35.1	23.2	8.25	5.05	1072	692	0.51	1.9	859

(Full table grouped under **Electrocoagulation unit (water system)** and header **Measured parameters**)

-, Not detected.

Table (2): Pearson correlation matrix among the designed electrocoagulation unit parameters.

Parameters	Time	Temp.	ORP	pH	DO	EC	TDS	Salinity	NO₃⁻	Turbidity
Time	1.00									
Temp.	0.99*	1.00								
ORP	0.74	0.79	1.00							
pH	-0.96*	-0.94*	-0.68	1.00						
DO	1.00*	1.00*	0.77	-0.95*	1.00					
EC	-0.47	-0.50	-0.80	0.46	-0.47	1.00				
TDS	-0.45	-0.49	-0.77	0.45	-0.45	1.00*	1.00			
Salinity	-0.44	-0.48	-0.78	0.44	-0.44	1.00*	1.00*	1.00		
NO₃⁻	-0.89	-0.91*	-0.70	0.85	-0.90*	0.47	0.45	0.46	1.00	
Turbidity	0.40	0.31	0.00	-0.56	0.34	-0.09	-0.12	-0.09	-0.10	1.00

*Strong correlation.

direction, while, ORP was positioned on the–PC2 axis. The negative correlation between the ORP and turbidity revealed that an increase in ORP (more +ve charge) caused a decrease in the solution turbidity, which is referred to as the neutralization process. Both reaction time and turbidity were distributed on the +PC1 axis, suggesting that as time increased, turbidity also increased. The wastewater characteristics of TDS, salinity, and EC were located on the +PC2 axis, indicating that these parameters increased together Both reaction time and DO were distributed on +PC1, suggesting that an increase in reaction time caused an increase in DO.
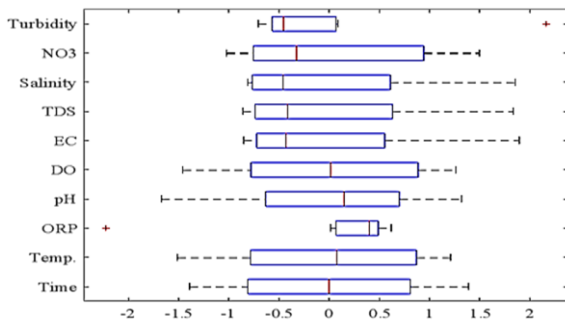

Figure (3): Standardized box plots of parameters used in principal component analysis of electrocoagulation unit performance

Table (3): Eigenvalues, variances and loadings for the first three principal components from PCA of the designed electrocoagulation unit parameters at 12 V and 17 A

| Parameters	PC1	PC2	PC3
Time	0.36	0.26	-0.05
Temp	0.36	0.22	-0.13
ORP	0.34	-0.18	-0.21
pH	-0.35	-0.28	-0.14
DO	0.36	0.25	-0.11
EC	-0.29	0.44	-0.13
TDS	-0.29	0.44	-0.17
Salinity	-0.29	0.45	-0.14
NO_3^-	-0.33	-0.18	0.32
Turbidity	0.12	0.29	0.86
Eigenvalue	6.74	2.02	0.99
Variance (%)	67.43	20.24	9.94
Cumulative (%)	67.43	87.67	97.62

DISCUSSION

From table (1, i and ii) decreasing in salinity, ORP, EC, and TDS values   may be resulted by a decrease in the positive charged ions that were produced by the electrodes of the ECT designed unit. However, DO remains a steady figure but in table (1, iii and iv) this increasing in DO values may be because some water molecules dissociated, releasing oxygen gas into the electrolyte, which would enhance the oxidation process for the ECT unit's anode electrodes (Moneer *et al*., 2016).

As pollutants have been minimized via application of this ECT; it was found in other studies, an ECT unit equipped with Fe electrodes demonstrated a high removal efficiency of heavy metals such as Cu, with a percentage value that may eventually reach 100%

(Moneer *et al*., 2016). In terms of correlation analysis, the linear relationship between two variables is quantified by Pearson product moment correlation analysis (Mackiewicz and Ratajczak, 1993). The established correlation coefficient is the strength of the association in the same direction (positive values) or the opposite direction (negative values), and it ranges from negative to positive (Khambete and Christian, 2014).

When the coefficient is nearer the absolute value of one, a strong positive or negative link is found. A weak or nonexistent link between two variables is shown by coefficients that are closer to zero. As shown in table 2, plausible bivariate relationships were found by applying Pearson product moment correlation analysis to each pair of proposed electrocoagulation unit parameter datasets. While correlation analysis is a valuable technique for classifying the relationships between two variables, its ability to evaluate the relationships between multiple variables at once yields restricted findings (Rastogi and Sinha, 2011). However, PCA can be performed to study the interrelationships between a broad collection of variables (Lebart *et al*., 1979).

PCA is a useful method for reducing a large number of initially associated variables to a small number of uncorrelated variables. Through this dimension reduction process, the derived components of this dimension reduction procedure represent the information of the entire dataset (Alberto *et al*., 2001). As much of the variation that cannot be explained by the former component is captured by each of the components that are obtained. This methodology has been effectively implemented for water and wastewater data across multiple research domains (Lee *et al*., 2006). According to PCA as well, the electrolytic dissociation of water molecules, which may result in tiny bubbles of oxygen gasses, could be the cause of DO readings rising with time as explained in the following equation:

$$2H_2O \rightarrow 4H^+ + O_2(g) + 4e^-$$
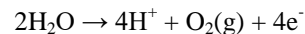
The advantages of O_2 gas are threefold: (a) it improves pollutant removal *via* flotation mechanisms, (b) it prevents the anaerobic (or septic) conditions of wastewater and (c) it enhances the oxidation process. The ORP and temperature were both on +PC1, which may be because a higher temperature promoted electrode dissociation, which resulted in the release of additional +ve charges and an increase in ORP (Rastogi and Sinha, 2011).

Furthermore, the concentration of hydrogen ions H^+ in water is expressed by the pH value. Because it regulates the kind and speed of reactions between various pollutants in water, pH is a crucial water quality measure. This study's rising pH average values, particularly at 3V and 5 V, are resulted by the electrolysis reaction's ongoing process, which alters the electrolyte's composition and raises pH. This could be because of the release of H^+, as Equation 7 states, or it could be because of the release of OH^- and H_2 gas,

depending on the electrode material (Rusdianasari *et al.*, 2021).

Since operation time is important for the ECT process, this study found that the optimal time was about 40 min, which had the highest removal efficiency for TDS at 5 V and 0.45 A. However, other studies found that the optimal time was 30 min, and that an additional 30 min of treatment time had negligible improvements in the removal efficiency for the parameters under study (Saleem *et al.*, 2011). Recent findings showed that increasing of voltage causes increasing of ECT removal efficiency of NO_3^- (Rusdianasari *et al.*, 2021), which appeared in current work at 12V that NO_3^- average values decreased by approximately 60% at the end of the experiment. Other researches proved that increasing electrode inert spacing may minimize ECT efficiency (Bukhari, 2008). (Saleem *et al.*, 2011) found that efficiency of ECT in turbidity removal increased as the electrode inert spacing decreased from 8 cm to 5 cm, which is proved at this study, the spacing between electrodes was 2 cm which pushes towards high efficiency which appeared in decreasing turbidity average values at trail of 12 V and 0.01 A.

CONCLUSIONS

In this study, principal component analysis (PCA) was effectively applied to evaluate the interrelationships among physicochemical parameters of agricultural drainage water treated using electrocoagulation technology (ECT). The analyzed parameters included temperature, oxidation-reduction potential (ORP), pH, dissolved oxygen (DO), electrical conductivity (EC), total dissolved solids (TDS), salinity, nitrate (NO_3^-), and turbidity. PCA results demonstrated strong positive correlations between operational conditions (DO and time, temperature and ORP) and water quality metrics (EC and TDS, EC and salinity, TDS and salinity), emphasizing the interconnected nature of these parameters in the treatment process. Conversely, strong negative correlations were observed between time and NO_3^-, ORP and TDS, in addition to ORP and salinity, highlighting the inverse relationships that influence pollutant removal efficiency. The PCA findings revealed an organized relationship between pollutants, providing insights into their behavior during electrocoagulation treatment. This study underscores the efficacy of ECT in removing agricultural drainage water pollutants and demonstrates PCA as a robust analytical tool for understanding and optimizing water treatment processes.

FUNDING

REFERENCES

ALBERTO, W. D., DEL PILAR, D., AME, M., FAB-IANA, P., HUED, A. AND ANGELES, B. 2001. Pattern recognition techniques for the evaluation of spatial and temporal variations in water quality. A case study: suquía river basin (Cordobae Argentina). Water Research, 35(12):2881-2894.

ALLAM, A. AND NEGM, A. 2013. Agricultural Drainage Water Quality Analysis and its Suitability for Direct Reuse in Irrigation: Case Study: Kafr El-Sheikh Governorate, Egypt, Seventeenth International Water Technology Conference Proceedings, IWTC17. November 2013 Istanbul, 5-7

AWOLUSI, O., NASR, M., KUMARI, S. AND BUX, F. 2018. Principal component analysis for inter-action of nitrifiers and wastewater environ-ments at a full-scale activated sludge plant. International Journal of Environmental Science and Technology, 15(7):1477-1490, https://doi:10.10-07/s13762-017-1506-9.

BHARATH, M., KRISHNA, B. AND MANOJ, K. 2018. A Review of Electrocoagulation Process for Wastewater Treatment. International Journal of Chem Tech Research, 11(3):289-302.

BUKHARI, A.A. 2008. Investigation of the electro-coagulation treatment process for the removal of totalsuspended solids and turbidity from municipal wastewater. Bioresour. Technol. 99(5): 914-921

COSTA, J. C., ALVES, M. AND FERREIRA, E. 2009. Principal component analysis and quantitative image analysis to predict effects of toxics in anaerobic granular sludge Bioresource Technology,100: 1180- 1185.

DAS, P.P., SHARMA, M. AND PURKAIT M.K. 2022. Recent progress on electrocoagulation process for wastewater treatment: A review. Separation and Purification Technology, 292(1):121058. https://doi.org/10.1016/j.seppur.2-022.121058.

EATON, A, CLESCERI L. AND GREENBERG, A. 2005. Standard methods for the examination of water and wastewater. 21st ed. Washington: American Public Health Association/American Water Works Association.

GUPTA, S.K., ANSARI, F., NASR, M., CHAB-UKD-HARA, M. AND BUX, F. 2018. Multivariate analysis and health risk assessment of heavy metal contents in foodstuffs of Durban, South Africa. Environmental Monitoring and Assessment, 190 (3): 151.

HASHIM, K.S., ALKHADDAR, R., JASIM, N., SH-AW, A., PHIPPS, D., KOT, P., ORTONEDA-PEDROLA, M., ALATTABI, A.W., ABDULRE-DHA, M.A. AND ALAWSH, R. 2019. Electrocoagulation as a green technology for phosphate removal from river Water. Separation and Purification Technology,210: 135– 144.

KHAN, SAIF ULLAH, MOHAMMAD K., KHALID H., MEHDI HASSANVAND JAMADI, MILAD MOUSAZADEH, FARRUKH B., AND IZHARUL H. FAROOQI. 2023. Efficacy of Electrocoagulation Treatment for the Abatement of Heavy Metals: An Overview of Critical Processing Factors, Kinetic Models and Cost Analysis Sustainability 15 (2): 1708. https://doi.org/10.3-390/su1-5021708.

KHAMBETE, A. 2014. Statistical analysis to identify the main parameters to effecting WWQI of sewage treatment plant and predicting BOD. International Journal of Research in Engineering and Technology, 3(01):186-195.

KRAVCHENKO, A.N., BOLLERO, G. A., OMONODE, R.A. AND BULLOCK, D. G. 2002. Quantitative mapping of Soil drainage classes using topographical data and soil electrical conductivity. Soil Science Society of America Journal, 66 (1): 235–243.

LEBART, L., MORINEAU, A. AND FENELON, J. 1979. Traitement des donnees statistiques (methodes et programmes).

LEE, D. S., LEE, M., WOO, S. H., KIM, Y.J. AND PARK, J. M. 2006. Multivariate online monitoring of a full-scale biological anaerobic filter process using kernel-based algorithms. Industrial Engineering and Chemical Research, 45(12): 4335-4344.

LÓPEZ-GUZMÁN, M., FLORES-HIDALGO, M. A., & REYNOSO-CUEVAS, L. 2021. Electrocoagulation Process: An Approach to Continuous Processes, Reactors Design, Pharmaceuticals Removal, and Hybrid Systems-A Review. Processes, 9(10), 1831. https://doi.org/10.3390/pr910-1831.

MACKIEWICZ, A. AND RATAJCZAK, W. 1993. Principal components analysis (PCA). Computers & Geosciences, 19: 303-342.

MALONE, B., ALEX, B. M. AND MINASNY, B. 2018. Description and spatial inference of soil drainage using matrix soil colors in the Lower Hunter Valley, New South Wales, Australia. Peer Journal. 2018. 6: e4659

MONEER, A., EL-SHAFEI, A., ELEWA, M. AND NAIM, M. 2016. Removal of copper from simulated wastewater by electrocoagu-lation/floatation technique. Desalination and Water Treatment, 57 (48-49): 22824-22834.

NASR, M. AND ZAHRAN, H. 2015. Assessment of agricultural drainage water quality for safe reuse in irrigation applications-a case study in Borg El-Arab, Alexandria. Journal of Coastal Life Medicine, 3 (3): 241-244. 2015.

NASR, M. AND ZAHRAN, H. 2016. Perf-ormance evaluation of agricultural drainage water using modeling and statistical approaches. The Egyptian Journal of Aquatic Research, 42(2):141- 148

NAWARKAR, C. J. AND SALKAR, V. D. 2019. Solar powered Electrocoagulation system for municipal wastewater treatment. Fuel, 237(1): 222-226.

NOURI, H., BEECHAM, S., HASSANLI, A. M. AND INGLETON, G. 2013. Variability of drainage and solute leaching in heterogeneous urban vegetation environs. Hydrology and Earth System Sciences,17: 4339- 4347.

OMAR, B., ZALOUK, R., SOLIMAN, S., EL-GAMMAL, M. 2023. 'Controlling Disinfection By-Products using Chlorine Profile and CT Tables at EL-Nobarya Drinking Water Treatment Plant, Egypt', Catrina: The International Journal of Environmental Sciences, 27(1), pp. 33-43. https://doi: 10.21608/cat.2023.194317.1158

RUSDIANASARI, BOW, Y., SYAKDANI, A. AND MAYASARI, D.I. 2021.The Effectiveness of Electrocoagulation Process in Rubber Wastewater Treatment using Combination Electrodes.IOP Conf. Series: Earth and Environmental Science,709.

SALEEM, M., BUKHARI, A.A. AND AKRAM, M. N. 2011. Electrocoagulation for the treatment of wastewater for reuse in irrigation and plantation. Journal of Basic and Applied Sciences. 7(1): 11-20.

SALLAM, GEHAN. 2017. The Assessment of Egypt's Subsurface Drainage System. 10.1007/69-8_2017_45.

URASTOGI, G.K. AND SINHA, D. 2011. A novel approach to water quality management through correlation study Journal of Environmental Research and Development, 5 (4): 1029-1035.

WADA, Y., FLÖRKE, M., HANASAKI, N., EISNER, S., FISCHER, G., TRAMBEREND, S., SATOH, Y., VLIET, M., YILLIA, P., RINGLER, C., BUREK, P. AND WIBERG, D. 2016. Modelling global water use for the 21st century: The Water Futures and Solutions (WFaS) initiative and its approaches. Geoscientific Model Development, 9: 175–222.

WAHBA, M. 2017.Assessment of options for the sustainable use of agricultural drainage water for irrigation in Egypt by simulation modelling. Irrigation and Drain, 66:118–128.

WWAP: United Nations World Water Development Report 2018: Nature-Based Solutions for Water. UNESCO

WWAP: United Nations World Water Development Report 2023: partnerships and cooperation for water. UNESCO

فاعليــة المعالجــة بالتــخثير الكــهربى لمـياه الصرف الـزراعى

أحمد عبد الله الشافعى [1،2]، هدى فاروق زهران[3]، محمود نصر[4] ودينا النزهى[2]

[1] قسم الهندسة الزراعية، كلية علوم الزراعة والغذاء، جامعة الملك سعود، الرياض 11451، المملكة العربية السعودية

[2] قسم الهندسة الزراعية والنظم الحيوية، كلية الزراعة، جامعة الاسكندرية، 21545، الاسكندرية، مصر

[3] قسم التحكم فى التلوث، معهد بحوث البيئة والمواد الطبيعية، مدينة الأبحاث العلمية والتطبيقات التكنولوجية، برج العرب الجديدة 21934، الاسكندرية، مصر

[4] قسم الهندسة الصحية، كلية الهندسة، جامعة الاسكندرية، الاسكندرية, 21544، مصر

الملخـــــص العربي

تقنيــة التخثير الكهربي هو تقنية معالجة واعدة لمعالجة مياه الصرف الزراعي وهى تعتبرطريقة إزالة فعالة للملوثات مثل العكارة والنترات(NO_3^-) ، والمواد الصلبة الذائبة (TDS) والملوحة. ويتم فى هذه العملية إطلاق أيونات موجبة الشحنة من الأقطاب الكهربائية من أجل معادلة الملوثات سالبة الشحنة مما يؤدي إلى تخثرها وإزالتها. وكان الغرض من هذه الدراسة هو التوصيف الإحصائي للربط بين خصائص مياه الصرف الزراعي (ADW) التي خضعت للمعالجة بالتخثير الكهربى(ECT). ولقد تم انشاء وحدة تخثير كهربائي على المستوى المعملى لمعالجة عينات من مياه الصرف الزراعي التي تم جمعها من مزرعة تجريبية في حي أبيس في الإسكندرية - مصر. تم تقييم الخصائص الفيزيوكيميائية للعينات من خلال اختبار قيم مختلفة من التيار المستمر (أمبير) والجهد (فولت) (3 فولت - 0.45 امبير، 5 فولت - 0.45 امبير، 12 فولت - 17 أمبير) والفترات الزمنية للمعالجة التى تراوحت من 10 الى 60 دقيقة حتى تم تحقيق الأداء الأمثل للمعالجة. تم استخدام تحليل المكونات الرئيسية (PCA) كتقنية تحليل متعدد المتغيرات لتقييم البيانات ذات الصلة من مجموعات البيانات المعقدة وتحديد فعالية وحدة المعالجة بالتخثير الكهربي. حيث تم استخدام دالتي PCA و CACOV في برنامج MATLAB لتقدير المكونات الرئيسية. ولقد أظهرت المكونات الرئيسية الثلاثة الأولى (PC1, PC2,PC3) قيما أصلية أكبر من 1 مما يشير إلى أنها يمكن أن تميز وبشكل كافٍ خصائص هذه التقنية المذكورة. ولقد تم الحصول على المواد الصلبة الذائبة الكلية (TDS) والملوحة والنترات (NO_3^-) ت على الجانب السالب من PC1، بينما كان زمن التفاعل على الجانب الموجب. ولقد ارتبطت الزيادة في وقت التفاعل بتحسين كفاءة الإزالة. وبالإضافة إلى ذلك فانه كانت خصائص مياه الصرف الصحي مثل TDS والملوحة والتوصيلية الكهربائية (EC) تمت محاذاتهاعلى طول محور PC2 الموجب مما يشير إلى زيادة متزامنة في هذه الخصائص. وأشار توزيع كل من وقت التفاعل والأكسجين المذاب (DO) على الجانب الموجب من PC1 إلى أن أوقات التفاعل الأطول أدت إلى ارتفاع مستويات DO. ولقد ثبت أنه يمكن معالجة مياه الصرف الزراعى ADW بفعالية باستخدام تقنية ECT مما يدل على تفاعل ذو دلالة إحصائية بين أداء المعالجة ومؤشرات مياه الصرف الزراعى.