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The Effect of Process Parameters on Electro-Coagulation Treatment of Paint Industrial Effluent

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Abstract

Number of electrodes, processing time and power supply were used as process parameters. The study conducted by preparing three electro-coagulation cells each having a volume of 1,800.0 mL, 6, 12, 18 aluminum electrodes (anode and cathode) with a respective dimension of 8.0 cm, 9.0 cm and 2.0 mm of width, height and thickness, power supply of 5.0, 7.5, 10.0 V and 20.0, 40.0, 60.0 minutes of processing time. The distance between each plate of the anode and cathode electrodes were uniform for the three electro-coagulation cells. Between 20 and 60 minutes of processing time and increased supply of power from 5 to 12.5 V found to have a removal of 78.9% to 99.5% of white paint pigment Titanium Dioxide (TiO_2); the anode and the power consumptions increased from 1.54 g/m to 4.32 g/m^3 and 3.07 to 21.61 Wh/m^3 respectively. The result obtained from response surface model was observed that the processing time, the power supply and their combined effect were significant on the removal percentage of white paint pigment TiO_2; on the other hand, the number of electrodes did not have significant effect. Based on the combined effect of treatment time and power consumptions, 99.44% of white paint pigment TiO_2 removal was recorded at a lower power and anode consumption of 3.25 Wh/m^3 and 1.63 g/m^3 respectively, and with optimized parameters of 12 aluminum electrodes, power supply of 5 V and 60 minutes of processing time. Beside the successful removal efficiency of the white color pigment TiO_2, COD, BOD_5 and TSS were 98.01%, 96.97% and 95.68 % respectively; hence these values were below the permissible limit of Federal Environmental Protection Authority (FEPA).

Keywords: Electro-coagulation, Paint Industry wastewater, Electrode, Effluent

1. Introduction

Every day, two million tons of sewage and other effluents drain into the world's waters [1]. In developing countries, 70 % of industrial waste is dumped untreated, polluting the usable water supply [2]. Paints generally consist of organic and inorganic pigments and dyestuffs, extenders, cellulosic and non-cellulosic thickeners, latexes, emulsifying agents, anti-foaming agents, preservatives, solvents and coalescing agents [3]. The wastewater from paint industries contains large proportion and is generated primarily due to cleaning operations of mixers, reactors, blenders, packing machines and floors [4-6]. The paint wastewater contains appreciable concentrations of chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), suspended solids (SS), toxic compounds and color [4, 6].

Electro-coagulation is a process that does not require the addition of any chemical coagulants; the coagulation - flocculation process is very similar to chemical coagulation, except that the coagulant is generated in-situ through the dissolution of sacrificial anodes that are connected to an electric current [7, 8]. Cat-ions were generated in situ through the electrolytic dissolution of sacrificial anodes, usually iron or aluminum plates are used [9].

White paint pigment TiO_2 based paint pigments pose treat to the aquatic photosynthetic plant which indirectly impart a negative impact on other microorganisms, since the amount of DO decreases with the decrease of photosynthetic plants in the aquatic environment. They also have higher rate of water pollution mainly due to higher dosage of COD, BOD_5 and SS, which resulted in depletion of DO in receiving water body [6, 10, 11]. According to the report by [12] there is sufficient evidence in experimental animals for the carcinogenicity of white color pigment TiO_2. However, there is inadequate evidence on carcinogenicity of white paint pigment TiO_2 in humans, but in large concentration it is possibly carcinogenic.

Assessment of the effect of process parameters such as process time, power supply and number of electrodes on electro-coagulation process for treatment of paint factory effluents. Electro-coagulation is a system where multiple electrochemical reactions occur simultaneously at the anodes and cathodes resulting to the generation of coagulant metal ions in situ by dissolving sacrificial anodes [7, 8].

In this study, electro-coagulation cells having an effective sample volume of real paint wastewater 1,800.00 mL was prepared. Power supply of 5.0, 7.5, 10.0 and 12.5 V and processing time of 20, 40 and 60 minutes were used for the removal of white paint pigment TiO_2. Chemical oxygen demand (COD), biological oxygen demand (BOD_5) and total suspended solids (TSS) removal values were determined for the best operating conditions.

2. Materials and Methods

In the electro-coagulation system, there are multiple and interdependent electrochemical reactions occurring simultaneously at the electrodes where the generation of coagulants takes place. Elimination of contaminants by the electro-coagulation process takes place through several steps: first, electro-oxidation of the anode and release of metallic cat-ions in solution takes place, then electro-migration and electrophoresis, which are the movements of charged ions and colloids, respectively, in the direction of electrodes of opposite charge resulting in destabilization of charges in solution. Then coagulation was formed due to the collisions and interactions between moving particles, which resulted in adsorption of the solids, colloids and other contaminants on the coagulated particles, forming bigger aggregates to be separated by settling [8].

The choice of material plays an important role in determining the overall cost. Aluminum and Iron electrodes or combination of them were used in most studies. In this study, Aluminum electrode was used as sacrificial anode and the cathode electrode to prevent corrosion and high consumption of the anode and cathode [9, 13, 14].

Three electro-coagulation cells with effective volume of 1,800 mL, hot plate Magnetic stirrer, DC power supply, multimeter, 100 and 1,000 mL beaker, 10 mL pipette, stopwatch, three support stands, refrigerator were used for the experimental process and sample collection. For this study, 24 experimental trials were conducted at Addis Ababa Science and Technology University industrial chemistry laboratory and 72 samples were taken for analysis. The characterization of untreated wastewater sample and treated samples for pH, COD, BOD_5, TSS, TDS and conductivity at selected maximum removal values were made at Addis Ababa Environmental Protection Authority laboratory after absorbance measurement of all samples using UV/VIS spectrophotometer.

2.1. Wastewater Sample Collection

Paint wastewater samples from Bright paint factory were taken for analysis. The current daily paint production capacity of the factory was about 5,000 – 6,500 kg/day of quartz, 3,500 – 4,200 lit/day of interior and exterior purpose paints and 1,170 – 1,400 lit/day enamel paints. For cleaning and washing of equipment the factory consumes about 20 - 40 lit of water per batch of barrel. The factory's treatment plant handles 3.33 m^3 of wastewater per day and uses aluminum sulfate as a chemical coagulant for the treatment of its wastewater.

Composite wastewater sample of 70 L were collected by mixing discrete samples of 5 L from each batch of production four times a day. Since the factory operates at batch process, individual samples were collected after each successive batch of production from the effluent outlet (discharging pipe). A cleaned plastic barrel was used for sample collection and transporting to Addis Ababa Science and Technology University laboratory in which the analysis was conducted. The samples were preserved below 4°C to avoid/minimize any biological degradation. The wastewater parameters and their corresponding testing methods were indicated in table 1.

2.2. Experimental Setup and Design

The dimensions of the electrodes and the electro-coagulation vessel were determined based on the volume of wastewater and amount of samples required for analysis [15, 16]. A rectangular glass vessel with dimensions of 16.0 cm × 10.0 cm × 13.0 cm and with working volume of 1,800.0 mL were used. Aluminum plate electrodes with dimensions of 8.0 cm, 9.0 cm and 2.0 mm of width, height and thickness respectively were used. The aluminum electrodes were connected each other by plastic pipe and heating stove wire in a mono-polar parallel mode. The electrodes distance between each plate of the anode and cathode were uniform for the three cells and the number of aluminum electrodes were 6, 12 and 18. The entire electrode assembly were put in the glass vessel. The assemblies were connected to DC power source. Magnetic stirrer was used to mix and uniformly distribute the wastewater sample throughout the electrode with a constant stirring speed of 100 rpm.

In all stages, a total of 36 samples from all electro-coagulation cells were taken at different operating conditions i.e. 20, 40 and 60 min processing time and 5.0, 7.5, 10.0 and 12.5 V power supply for a single run. 72 samples were collected from the first and second experimental processes. Analysis of these samples were made for

determining the removal efficiency of white color pigment (TiO$_2$), COD, BOD$_5$, TDS, TSS, pH and conductivity. Initially, absorbance measurement for determining TiO$_2$ removal efficiency were made three times and average values were taken and from the average values, five samples with a maximum removal efficiency were selected and then analysis of COD, BOD$_5$, TSS, pH and conductivity were made.

Initially the wastewater sample was placed in a refrigerator and allowed to stay for 24 hours for settlement. The pH of the untreated wastewater sample was measured using a HANNA HI 207 digital pH meter and it was 6.04. It was in the desired range for electro-coagulation process [17, 18]. The conductivity of the untreated wastewater samples was measured using a digital BANTE instrument 950 conductivity. TDS was measured by salinity meter and it was 302 µS which is not in the desired range and hence it was adjusted using Sodium Chloride (1g/L). This was because when conductivity is low, the current passing at the fixed voltage applied was very low. In this case, the solid/liquid separation or floc settling process slow down considerably, which in turn increased the retention time needed in the settling tanks [19]. To increase the amount of current passing through the system, several screening tests were conducted to observe the effect of adding sodium chloride salt on conductivity.

After each run, the electrodes were washed with water and were dipped for 5 min in 10% acetone solution to clean the surface and remove impurities on the aluminum electrode and were made ready for the next run. After each experiment the used anode and cathode plate were interchanged for effective electrode utilization. 100 mL of samples were taken at an interval of 20 min in a beaker using a 10 mL pipette. For the measurement of absorbance/transmittance of samples, Optizen POP UV/VIS spectrophotometer with 10 mm open-topped rectangular cell (cuvette) were used. The determination of the maximum absorbance wavelength was made by preparing different dilutions of 0.2 g/L of TiO$_2$ (5 to 90 mL dilution water was added) and wavelengths of 320 – 380 nm were used. Finally, 345 nm was found the maximum absorbance wavelength.
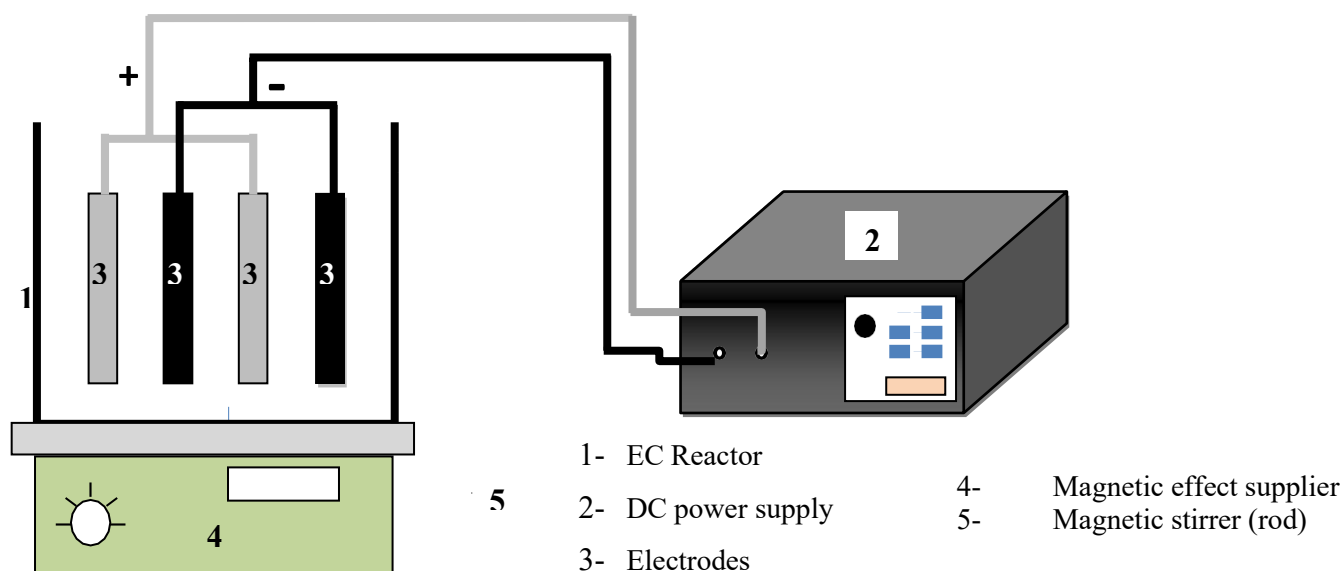

1- EC Reactor
2- DC power supply
3- Electrodes
4- Magnetic effect supplier
5- Magnetic stirrer (rod)

Figure 1 - A schematic diagram of experimental set-up

Table 1. Parameters of white paint Pigment TiO$_2$ wastewater and their corresponding testing methods

S. No	Parameters	A specific method for each parameter
1	pH	HANNA HI 207 digital pH meter
2	Pigment	Optizen POP UV/VIS spectrophotometer
3	COD	APHA 5220 B, Open reflux method
4	pH	Hach HQD field case Model 58,258-00
5	BOD$_5$	APHA 5210 B, 5-days BOD test
6	TSS	APHA 2540 D. Total suspended solids dried at 103–105 °C
7	TS	APHA 2540 B, Total solid dried at 103–105 °C
8	EC	Digital BANTE instrument 950 conductivity
9	TDS	Salinity meter

Colorimetry and/or absorptivity, based on Beer's law, is the rate of decreasing the intensity of radiation observed with the thickness of the medium is proportional to the intensity of the radiation and concentration   of the solute.

$$A = \varepsilon Cl \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots [1]$$

Where;

A - Absorbance

l – Absorbing cell (cuvette) length

ε − the absorptivity coefficient

C – Concentration

3.   Results and Discussion

3.1.   Determination of Maximum Absorption Wavelength for TiO$_2$

Initially 20 mg of pure reagent grade TiO$_2$ was taken and dissolved with 100 mL of distilled water to make a dispersion solution with 0.2g/L concentration. Then the 0.2 g/L sample was diluted in to 11 different samples by successively adding 5 to 90 mL of distilled water in different containers. Absorbance measurement for all diluted samples were made by UV/VIS spectrophotometer at different wavelengths between 320 and 380 and the maximum absorption wavelength were determined and found to be 345 nm as shown in table 2. At this wavelength, the absorption measurements of the diluted samples were made and by using excel, standard curve was plotted for checking the linearity of the results obtained for concentration vs. absorbance.

Table 2 - UV/VIS spectrophotometer absorbance measurement for determination of maximum wavelength at 0.2 g/L solutions of TiO_2

mL of distilled water added to 10 mL of sample	Wavelength (λ)							
	320	**330**	**340**	**345**	**350**	**360**	**370**	**380**
0	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000
5	2.983	2.991	3.000	3.000	2.952	2.870	2.771	2.701
10	2.659	2.702	2.855	2.862	2.811	2.647	2.754	2.659
15	2.213	2.259	2.356	2.410	2.443	2.255	2.177	2.114
20	1.877	1.834	1.596	2.095	1.960	1.861	2.071	1.861
30	1.466	1.660	1.659	1.861	1.264	1.301	1.439	1.259
40	1.191	1.177	1.276	1.227	1.201	1.145	1.103	1.113
50	1.173	1.202	1.200	1.213	1.205	1.150	1.149	1.101
60	0.933	0.876	0.913	0.889	0.852	0.818	0.824	0.801
70	0.721	0.770	0.791	0.820	0.796	0.713	0.705	0.701
80	0.516	0.527	0.546	0.557	0.563	0.514	0.502	0.511
90	0.402	0.410	0.425	0.433	0.431	0.419	0.421	0.416

From the table 2, the maximum absorptions were obtained between the values of 340 and 350 nm wavelengths, of which most of these values were observed at a wavelength of 345 nm. Therefore, this value was taken as a maximum absorption wavelength. Absorbance measurements were made to determine the absorptivity coefficient at a wavelength of 345 nm.

Volume of distilled water for 10 mL sample, in mL	Absorbance	Concentration, in g/L
90	0.541	0.032

$C_2 = C_1 V_1 / V_2 = (0.032*100)/10 = 0.32$ g/L

Triplicate analyses were made for pH, conductivity, COD, BOD_5 and TDS. TSS was analyzed twice. Excel regression method were used to determine the concentration of each sample by plotting a standard curve as indicated in figure 2 from known concentration of TiO_2 suspension. Using this standard curve the concentrations of unknown samples were determined by the relation;

Concentration = TREND ([Known y's], [Known x's], [New x's], [Const^n])...................... [2]

Where;

Known y's – the concentrations of TiO_2 suspension prepared to plot the curve

Known x's – measured absorbance of TiO_2 suspension prepared

New x's – measure absorbance of treated samples

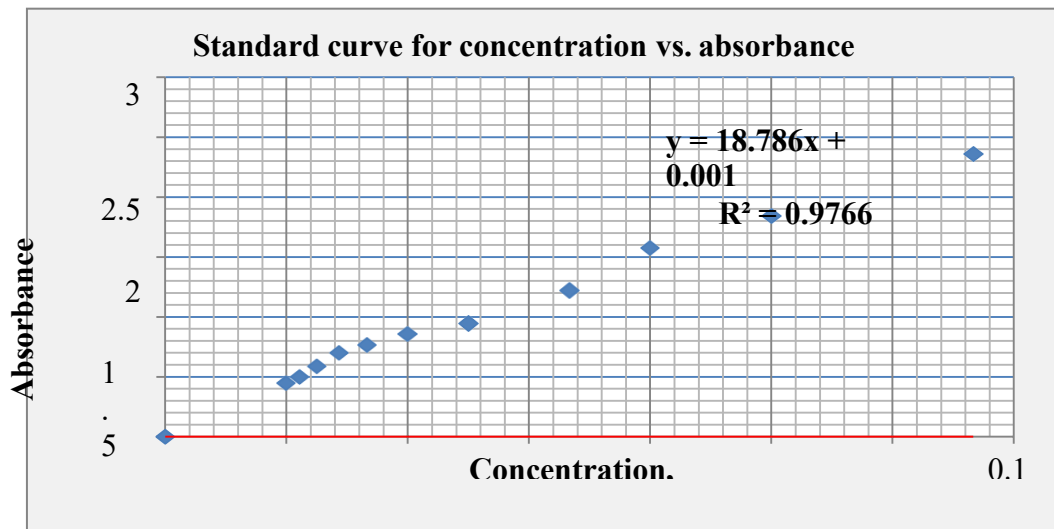Const^n – the value of the slope of the curve

Figure 2 - Standard curve for concentration vs. absorbance

From the equation that relates absorbance and concentration (eqn. 1)

$$A = \varepsilon lC \qquad \text{So, } A = 18.786 \, C \qquad \text{Since } \varepsilon l = 18.786$$

The value of this slop was used for subsequent absorbance measurements to determine the concentration of the untreated and treated wastewater samples and the values were summarized in table 4. It was difficult to calculate the initial concentration of the untreated wastewater sample by making direct absorbance measurement since the concentration of the wastewater was beyond the detection range of the equipment and hence absorbance measurement was made after dilution.

3.2. *Characterization of Treated and Untreated Wastewater*

Table 3 - Comparison of untreated wastewater with FEPA's industrial effluent standard

S.No	Parameters	Units	Average Value	FEPA limit value	Remarks
1	pH	-	6.0	6.0-9.0	In range
2	TDS	mg/L	155.0	3000.0	In range
3	TSS	mg/L	4,880.0	100.0	Not in range
4	BOD$_5$	mg/L	132.0	80.0	Not in range
5	COD	mg/L	10,400.0	250.0	Not in range
6	Absorbance of TiO$_2$	-	0.541	-	-
7	E-Conductivity	µS	302.0	-	-

* Source: [20]

As it is shown in table 3, except the value of TDS, all other parameters were beyond the FEPA's industrial effluent discharge limit. The biodegradability index (BI) is the degree of biodegradability of the wastewater comparing the ratio of BOD_5 to COD. BI from 0.3 to 0.6 indicated fairly degradable and conventional biological treatment can be effective whereas the BI values less than 0.3 is very challenging to degrade. The BI of this study was 0.013 and biological (conventional) process cannot be successful. Therefore, finding proper treatment method with a reasonable operating cost, simple operation and minimal treatment time like advanced oxidative treatment (electro-coagulation) was mandatory. This paint wastewater has a high potential to create environmental pollution.

The concentrations of TiO_2 (white paint pigment) for each samples of wastewater taken at different time intervals were determined from the results of UV/VIS spectrophotometer absorbance measurement and calculating it using Beer's – Lambert equation (eqn. 2).

The concentration of the samples after dilution was calculated by: $C_1V_1 = C_2V_2$

$$C_2 = \frac{C_1V_1}{V_2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{[2]}$$

Where;

C_1 = initial concentration (g/L), C_2 = concentration of sample after dilution

V_1 = initial volume of sample taken, V_2 = volume of sample after dilution

Table 4 – Absorbance and concentration of samples taken at different conditions

Voltage supply (V)	No. of electrodes	Absorbance of samples at time t			Concentration of samples at time t, in g/L		
		20 min	40 min	60 min	20 min	40 min	60 min
	E6	0.637	0.193	0.156	0.0298	0.0041	**0.0020**
5.0	E12	0.197	0.173	0.152	0.0044	0.0030	**0.0018**
	E18	0.742	0.167	0.150	0.0359	0.0027	**0.0017**
	E6	0.634	0.387	0.200	0.0297	0.0154	**0.0046**
7.5	E12	0.737	0.204	0.154	0.0356	0.0048	**0.0019**
	E18	0.517	0.375	0.360	0.0229	0.0145	**0.0138**
	E6	0.578	0.240	0.222	0.0264	0.0069	**0.0058**
10.0	E12	0.653	0.302	0.148	0.0308	0.0105	**0.0016**
	E18	0.359	0.353	0.223	0.0138	0.0134	**0.0059**
	E6	1.290	0.831	0.374	0.0676	0.0411	**0.0146**
12.5	E12	1.099	0.466	0.240	0.0566	0.0200	**0.0069**
	E18	1.077	0.760	0.297	0.0553	0.0370	**0.0102**

Sample codes E6/5V/3, E12/5V/3, E18/5V/3, E12/7.5V/3 and E12/10V/3 represented an electrocoagulation cell with 6, 12, 18, 12, 12 plate electrodes, 5 V, 5 V, 5 V, 7.5 V, 10 V power supply respectively and the last 3 for 60 min.

Table 5 – Analysis of ANOVA Result for Response Surface Model

Source	Sum of Squares	DF	Mean Square	F-value	P-value	
Model	749.20	6	124.87	12.44	< 0.0001	significant
A	1.7800	1	1.7800	0.180	0.67660	
B	224.72	1	224.72	22.38	< 0.0001	
C	464.90	1	464.90	46.31	< 0.0001	
AB	5.6100	1	5.6100	0.560	0.46090	
AC	5.5500	1	5.5500	0.550	0.46330	
BC	46.640	1	46.640	4.650	0.03960	

As shown in table 4, increasing the supply voltage and the processing time has decreased the absorbance value and concentration of the wastewater. After the supply voltage increased to more than 10 V, the absorbance and concentration values increased which implied that the degradation capability of the electrodes and the supply voltage couldn't play a critical role after the supply voltage became 12.5 V. In addition, the concentration decreased rapidly than the absorbance as the processing time increased from 20 min to 60 min.

From the values obtained after absorbance measurement, five parameter combinations with minimum concentrations selected and they were E6/5V/3, E12/5V/3, E18/5V/3, E12/7.5V/3 and E12/10V/3.

Table 6 - Summary of parameters analyzed for selected five best conditions

Parameters Analyzed	E6/5V/3	E12/5V/3	E12/7.5V/3	E12/10V/3	E18/5V/3
pH	6.210*	6.820*	6.140*	6.980*	5.850
TDS (mg/L)	2251*	2657*	2319*	2197*	2250*
TSS (mg/L)	550.0	310.0	403.0	211.0	247.0
BOD$_5$ (mg/L)	4.000*	8.400*	10.800*	12.400*	9.200*
COD (mg/L)	342.0	579.0	367.0	207.0*	360.0
Absorbance of TiO$_2$	0.156	0.152	0.154	0.148	0.150
E-Conductivity (μS)	419.2	422.5	439.4	416.0	444.0

* *Represents values that are in a permissible limit of FEPA*

The significance of the factors that contributed to the overall removal of the white color pigment TiO_2 was analyzed using Response Surface Method by Design Expert software. The Model's F-value of 12.44 implied that the model was significant. Values of "P-value" less than 0.05 indicated that the model terms were significant. In this case B, C, BC are significant model terms. Values greater than 0.1 indicated the model terms were not significant. A ratio of adequate precision greater than 4 is desirable. Therefore, the ratio of 12.869 found from the design expert shown an adequate signal.

COD, BOD_5, TSS, pH and conductivity was analyzed for the five selected samples to examine the removal efficiency of the electro-coagulation cell. As depicted in table 6, after 60 min processing time, 5 V and 7.5 V power supply in an electro-coagulation cells and 6, 12 and 18 plate electrodes, the values of pH, TDS and BOD_5 were in the allowable FEPA's industrial effluent discharge limit but, TSS and COD were beyond the permissible limit. On the other hand, the electro-coagulation cell having 12 electrodes and 10 V power supply, the value of pH, TDS, COD and BOD_5 were in the allowable FEPA's industrial effluent discharge limit and only TSS was beyond the limit.

3.3. *Determining Best Operating Efficiencies*

Percentage removal was calculated using the following equation:

$$\% \text{ Removal } = \frac{\text{Initial concentration} - \text{Final concentration}}{\text{Initial concentration}} * 100 \quad .... [3]$$

As shown in table 7, a significant amount of reduction of BOD_5 were achieved for all the treated wastewater samples and the maximum removal efficiency of 96.97% BOD_5 were recorded for the wastewater sample code E6/5V/3. And also COD, TSS and TiO_2 had degradation of all the wastewater samples and their maximum removal efficiencies of COD (98.01%), TSS (95.68%) and TiO_2 (99.5%) were successfully achieved for the sample code E12/10V/3.

Equation in Terms of Coded Factors: %R = +94.33–0.27A-3.35B+4.40C+0.65AB-0.59AC+1.87BC

Equation in Terms of Actual Factors: %R = +102.205-0.011A-2.237C+0.061B+0.029AC-4.906A-0.003AB+0.024CB

3.4. *Effect of Processing Time and Number of Electrodes on Power Supply and Anode Consumption*

Energy consumption was calculated using:

$$C_{electrode} = \frac{ItM_W}{zFv} \quad .... [4]$$

$$C_{energy} = \frac{UIt}{v} \quad .... [5]$$

Where:

$C_{electrode}$ - mass of the anode consumed (g/m³)

C_{energy} - Energy consumed (Wh/m³)

U - Voltage applied (V)

I - current passing through (A)

Mw - molecular weight of the electrode material (27 g/mol for Aluminum),

z - Valence number of electrons transferred by the anode (3 for Al^{+3})

t - Operating time (seconds),

v - Volume of water treated (m^3), and F - Faraday's constant (C/mole)

C – Coulomb (C = Q/U = It/U)

Table 7 – Summery on removal efficiency of BOD_5, COD, TSS and white paint pigment TiO_2

Sample code	BOD of untreated wastewater (mg/L)	BOD of treated wastewater (mg/L)	% Removal
E6/5V/3	132.00	4.00	96.97
E12/5V/3	132.00	8.40	93.64
E12/7.5V/3	132.00	10.80	91.82
E12/10V/3	132.00	12.40	90.61
E18/5V/3	132.00	9.20	93.03
Sample code	**COD of untreated wastewater (mg/L)**	**COD of treated wastewater (mg/L)**	**% Removal**
E6/5V/3	10,400.00	342.00	96.71
E12/5V/3	10,400.00	579.00	94. 43
E12/7.5V/3	10,400.00	367.00	96.47
E12/10V/3	10,400.00	207.00	98.01
E18/5V/3	10,400.00	360.00	96.54
Sample code	**TSS of untreated wastewater (mg/L)**	**TSS of treated wastewater (mg/L)**	**% Removal**
E6/5V/3	4,880.00	550.00	88.73
E12/5V/3	4,880.00	310.00	93. 65
E12/7.5V/3	4,880.00	403.00	91.74
E12/10V/3	4,880.00	211.00	95.68
E18/5V/3	4,880.00	247.00	94.94
Sample code	**Concentration of TiO_2 in untreated wastewater (mg/L)**	**Concentration of TiO_2 in treated wastewater (mg/L)**	**% Removal**
E6/5V/3	0.32	0.0020	99.38
E12/5V/3	0.32	0.0018	99. 44
E12/7.5V/3	0.32	0.0019	99. 40
E12/10V/3	0.32	0.0016	99.50
E18/5V/3	0.32	0.0017	99. 47

Table 8- Amounts of anode and energy consumption using E6, E12 and E18

Operating time (min)	Anode consumption at different power supply (g/m³) for E6				Energy consumption at different power supply (Wh/m³) for E6			
	5 V	7.5 V	10 V	12.5 V	5 V	7.5 V	10 V	12.5 V
20	0.576	0.864	1.153	1.441	1.024	2.304	4.097	6.401
30	1.153	1.729	2.305	2.882	2.048	4.609	8.194	12.803
60	1.729	2.593	3.458	4.322	3.072	6.913	12.291	19.204
Operating time (min)	Anode consumption at different power supply (g/m³) for E12				Energy consumption at different power supply (Wh/m³) for E12			
	5 V	7.5 V	10 V	12.5 V	5 V	7.5 V	10 V	12.5 V
20	0.544	0.816	1.089	1.361	1.085	2.440	4.338	6.778
30	1.089	1.633	2.177	2.722	2.169	4.880	8.676	13.556
60	1.632	2.449	3.266	4.082	3.254	7.320	13.014	20.334
Operating time (min)	Anode consumption at different power supply (g/m³) for E18				Energy consumption at different power supply (Wh/m³) for E18			
	5 V	7.5 V	10 V	12.5 V	5 V	7.5 V	10V	12.5 V
20	0.512	0.768	1.025	1.281	1.152	2.593	4.609	7.202
30	1.025	1.537	2.049	2.562	2.304	5.185	9.218	14.404
60	1.537	2.305	3.073	3.842	3.457	7.778	13.828	21.605

As shown in table 8, the anode and energy consumption were increasing as the processing time and applied voltage were increased using the three sets of electrodes (6E, 12E and 18E). As the number of electrodes, processing time and the supply voltage increased, the energy consumption became more than three times to five times higher than the anode consumption.

As it is seen in figure 3, the TiO_2 concentration was inversely proportional to the anode and power consumed in the treatment process with increasing the processing time and keeping constant the number of electrodes and the supply voltage. The TiO_2 concentration was highly decreasing except for 12E and 5 V as the processing time increased. The anode and power consumption were very high for 12E and 5 V and the consumption for other set of electrodes and supply voltage were low especially for 6E and 5 V, 12E and 7.5 V, 18E and 5 V.

As it can be seen from figure 3, minimum power and electrode consumptions were achieved for samples at 20 min of processing time. However, the removal efficiencies at these points were minimal. As the number of electrodes increased from 6 to 18 a regular increase in removals were observed only by a supply of 5 V. But for a power supply of 7.5, 10 and 12.5 V larger removal values were obtained for an electro-coagulation cell with 12 electrodes.

For an electro-coagulation cell with 6 electrodes and 5 V, at a process time of 20 min reduced concentration of 29.9 mg/L was achieved with a power consumption of 1.024 Wh/m^3 and anode consumption of 0.576 g/m^3. Further reduction of 4.2 mg/L was achieved with a power consumption of 2.048 Wh/m^3 and anode consumption of 1.153 g/m^3 as the process time increase to 40 min. Furthermore, the concentration reduced to 2 mg/L when the treatment time increased to 60 min with 3.072 Wh/m^3 and 1.729 g/m^3 of power and anode consumptions respectively.

Similarly, for an electro-coagulation cell with 12 electrodes and 5 V, at processing time of 20 min significant reduction of 4.4 mg/L was achieved with a power consumption of 1.085 Wh/m^3 and anode consumption of 0.544 g/m^3. Further reduction of 3 mg/L was achieved with a power consumption of 2.169 Wh/m^3 and anode consumption of 1.089 g/m^3 as the processing time increased to 40 min and then the concentration reduced to 1.8 mg/L when the treatment time increased to 60 min with 3.254 Wh/m^3 and 1.632 g/m^3 of power and anode consumptions respectively.

On the other hand, for an electro-coagulation cell with 18 electrodes and 5 V, at processing time of 20 min reduction of 35.9 mg/L was achieved with a power consumption of 1.152 Wh/m^3 and anode consumption of 0.512 g/m^3. Further reduction of 2.7 mg/L was achieved with a power consumption of 2.304 Wh/m^3 and anode consumption of 1.025 g/m^3 as the process time increased to 40 min and the concentration reduced to 1.7 mg/L when the treatment time rose to 60 min with 3.457 Wh/m^3 and 1.537 g/m^3 of power and anode consumptions respectively.

For electro-coagulation cells with 6 electrodes and a power supply of 5 V, it was found that maximum value of 99.37% removal of the white color pigment was achieved at 60 min of processing time and a power and anode consumption of 3.072 Wh/m^3 and 1.729 g/m^3 respectively. In addition, for an electro-coagulation cell with 12 electrodes and 60 min of process time comparably higher removal values i.e. 99.44%, 99.41% and 99.5% were obtained with the applications of 5, 7.5 and 10 V power supply and 1.632 g/m^3, 2.449 g/m^3 and 3.266 g/m^3 and 3.254 Wh/m^3, 7.32 Wh/m^3 and 13.014 Wh/m^3 anode and power consumption respectively.

Finally, for an electro-coagulation cell with 18 electrodes and 60 min of processing time larger removal efficiency of 99.47% was obtained with minimal anode consumption of 1.537 g/m^3 and larger power consumption of 3.457 Wh/m^3 at a power supply of 5V. From these values, as the number of electrodes increased, the power consumption also increased but the anode consumed decreased and vice versa. And hence, higher removal values with a minimum value of power consumption were achieved at a power supply of 5 V.
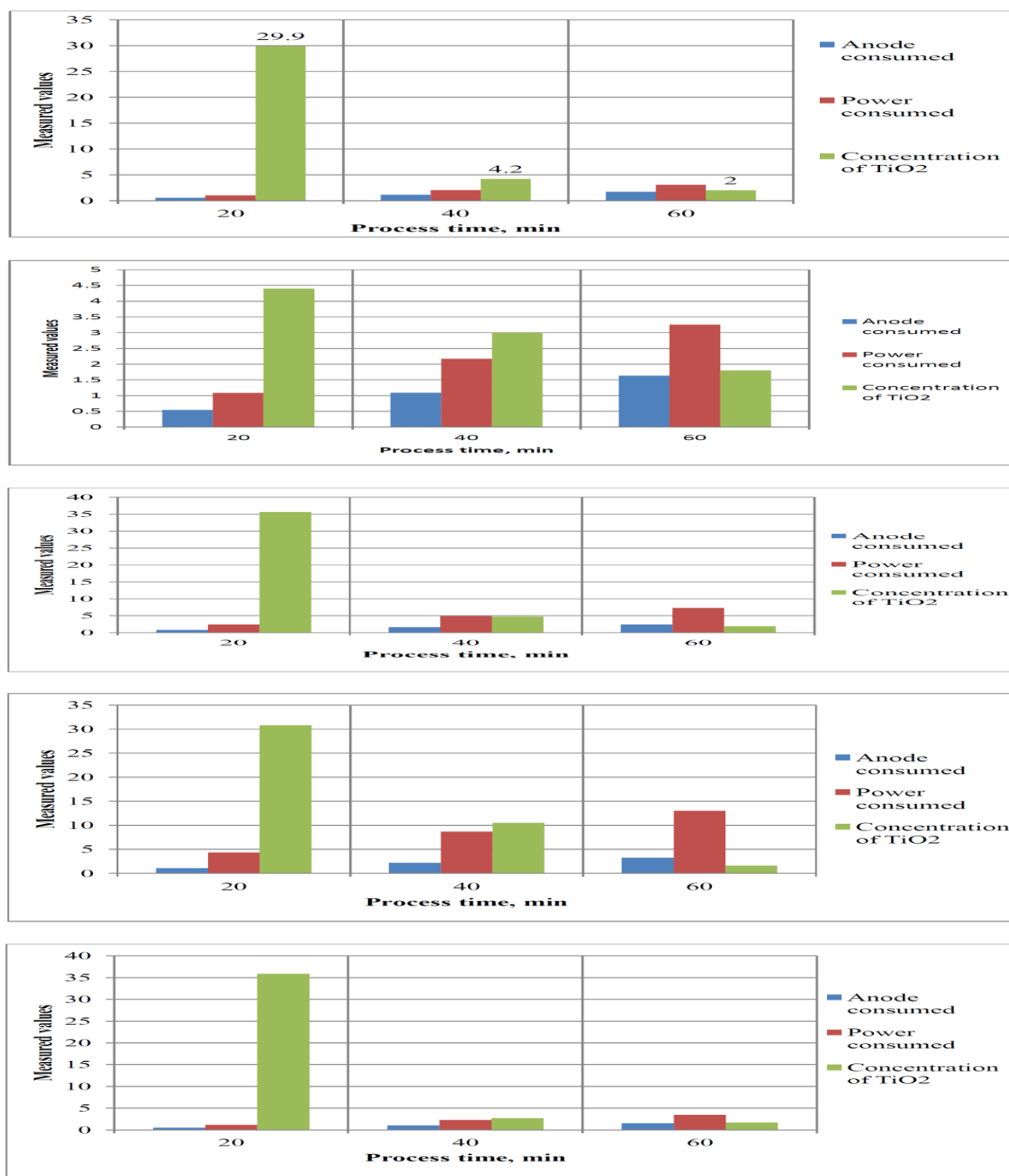
Figure 3 – TiO₂ concentration, anode and power consumption for constant values of 6E and 5 V, 12E and 5 V, 12E and 7.5 V, 12E and 10 V and 18E and 5 V respectively and increasing processing time.

3.5.   *Effect of Processing Time on Removal Efficiency of TiO2*

Processing time is a significant factor for electro-coagulation process. As clearly indicated in figure 4, the concentrations of the color pigment TiO_2 decreased with an increase in processing time in all electro-coagulation cells with a supply of different voltage. To compare the results of the samples taken at different processing time, classification was made as the first, second and third session of treatment to represent the degradation at 20, 40 and 60 minutes respectively. The TiO_2 removal was from 0.32 g/L to 0.0044 g/L (98.23%) and this degradation value increased further to 0.003 g/L (99.06%) and 0.0018 g/L (99.44%). This record was at the second and third sessions of the treatment. The values obtained during the second session was higher change in concentrations.
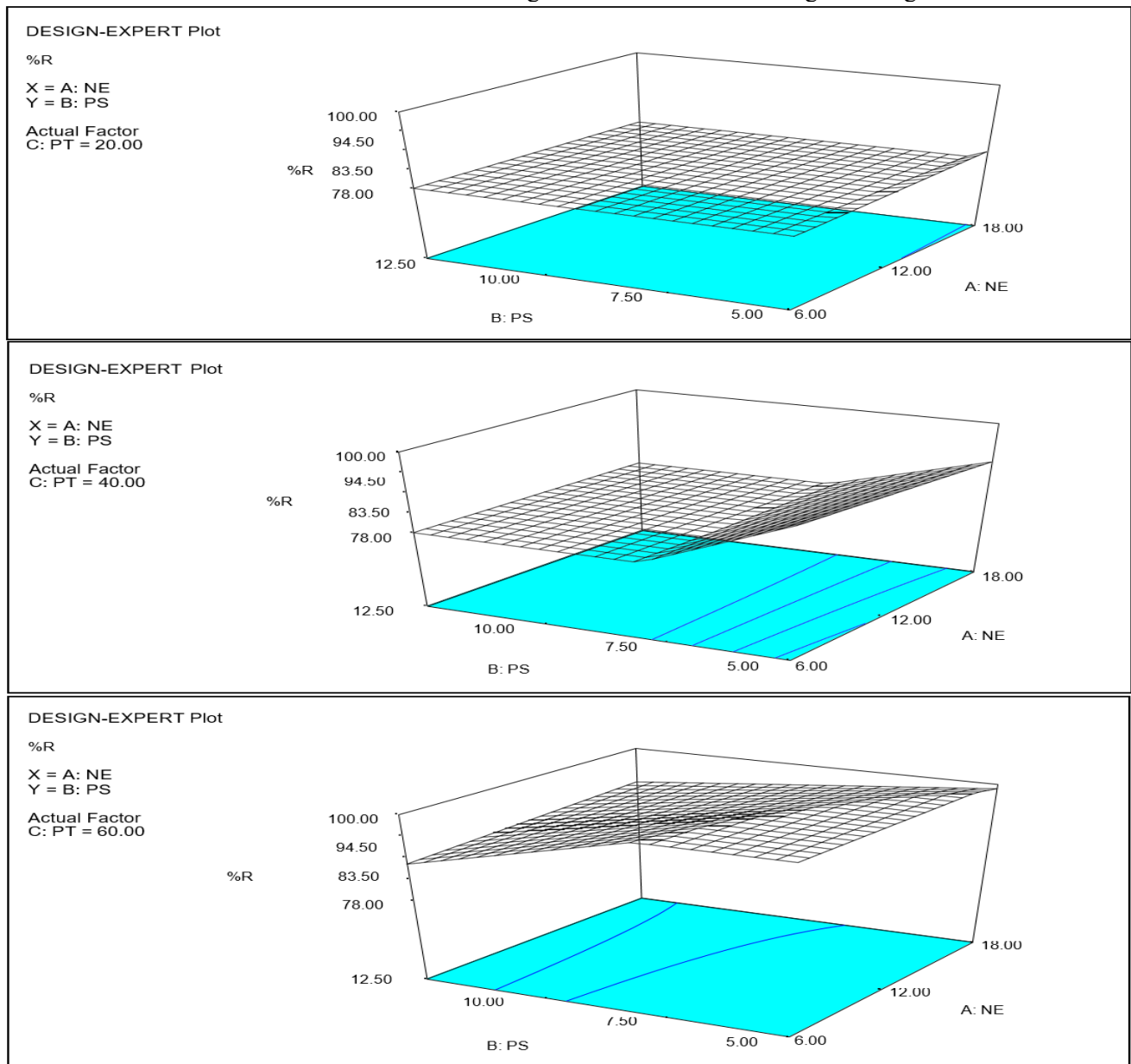

Figure 4 - Effect of varying processing time on removal efficiency of white color pigment

Keeping the number of electrodes and power supply constant, the removal efficiency was increased by increasing the processing time. From the experimental process and graph of design expert plot, it was observed that the removal efficiency during the first session showed no significant variations among all electro-coagulation cell with application of 5, 7.5, 10 and 12.5 V power supply. An increase in the removal of the wastewater samples for all electro-coagulation cells were observed during the second and third session of treatment process. Increasing process time further to 70 and 80 min resulted in a breakdown of flocs with 6 and 12 electrodes for a power supply of 5 and 7.5 V. On the other hand an electro-coagulation cell with 18 electrodes showed no significant change. This phenomenon was taken as an indication to the completion of the process and 60 min was taken as a best operating process time.

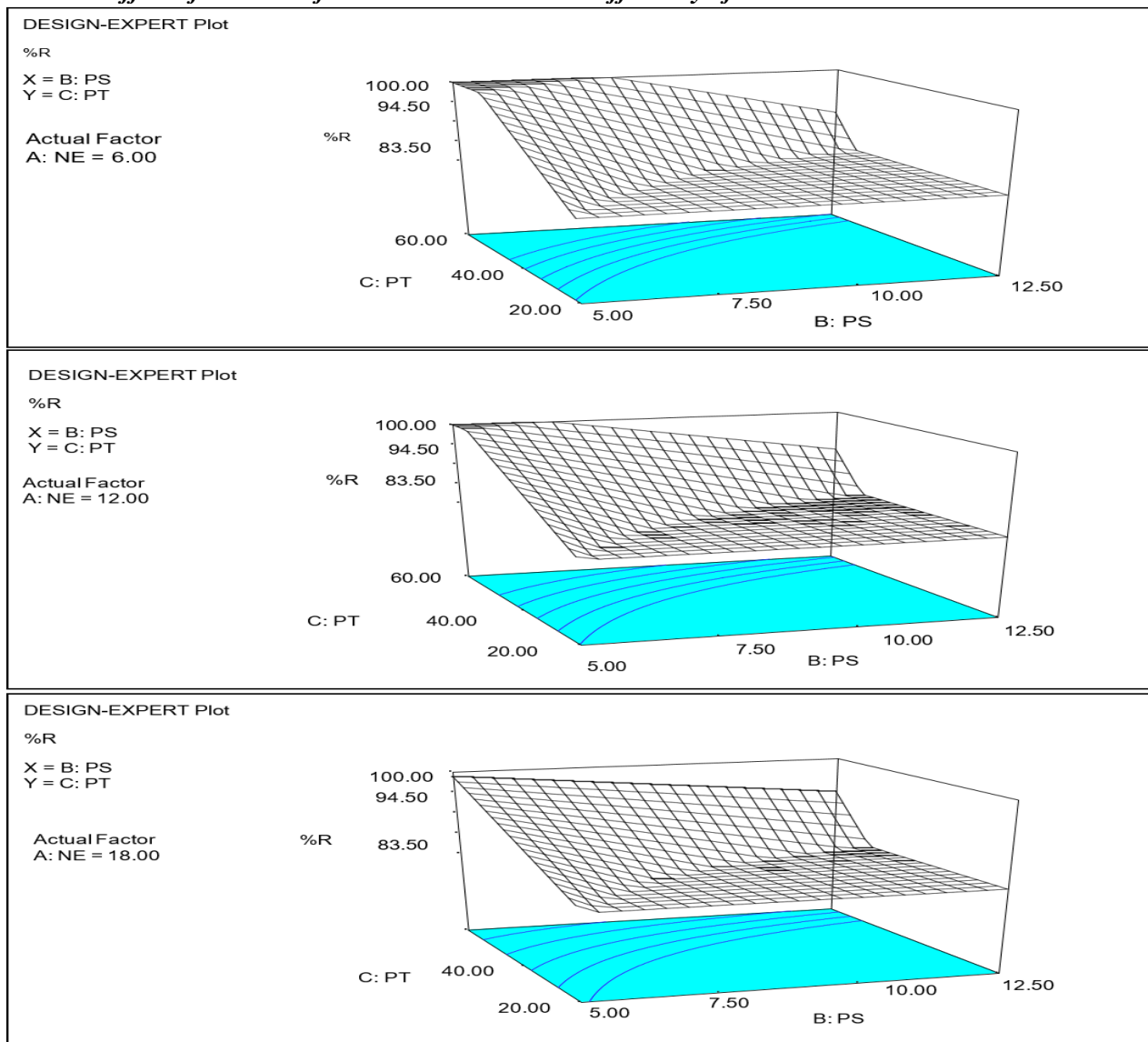### 3.6.   Effect of Number of Electrodes on Removal Efficiency of TiO2

Figure 5 - Effect of varying number of electrodes on removal efficiency of white color pigment

From Figure 5, At 60 min of processing time, removals of the color pigment TiO_2 for 6, 12 and 18 electrodes were found to be 99.38%, 99.44% and 99.47% for 5 V power supply, 98.56%, 99.41% and 95.69% for 7.5 V power supply, 98.19%, 96.81% and 98.16 % for 10 V power supply and 95.44%, 97.84% and 96.81% for 12.5 V power supply respectively. From these values it was observed that the effect of variation in number of electrodes was not significant.

3.7. *Effect of Power Supply on Removal Efficiency of TiO2*

As shown in figure 6, a decrease in removal efficiencies were observed as power supply increased and keeping the number of electrodes and processing time the same. For an electro-coagulation cell with 6 and 18 electrodes more than 99% removal were obtained with a power supply of 5 V and decrease to 95% as the power supply increased. An electro-coagulation cell with 12 electrodes showed that more than 99% removal for 5, 7.5 and 10 V power supply. In general as the power supply increased, a decrease in removal efficiency was observed. Depending up on the above observation 5 V power supply was taken as the best operating condition.

3.8. *Result Optimization*

Best operating conditions were determined based on three parameters namely, removal efficiency of the electro-coagulation cell, treatment time and power and electrodes consumption. Best processing time was chosen based on the relative amount of TiO_2 concentration after absorbance measurement. From the absorbance and concentration measurement, it was shown in table 4 that 60 min was the best operating time. Further treatment beyond 60 min resulted in destabilization and breaking of flocks formed.

Depending on the optimal points suggested by the design expert software, synthetic wastewater sample were prepared by dissolving 0.32 g/L of TiO_2 in water and treatment has been conducted to verify that the electro-coagulation cell works effectively at the proposed conditions. The values obtained were summarized in table 9 below.

As it is clearly shown in the table 9, the absorbance and TiO_2 concentrations were similar to the proposed conditions by the design expert.
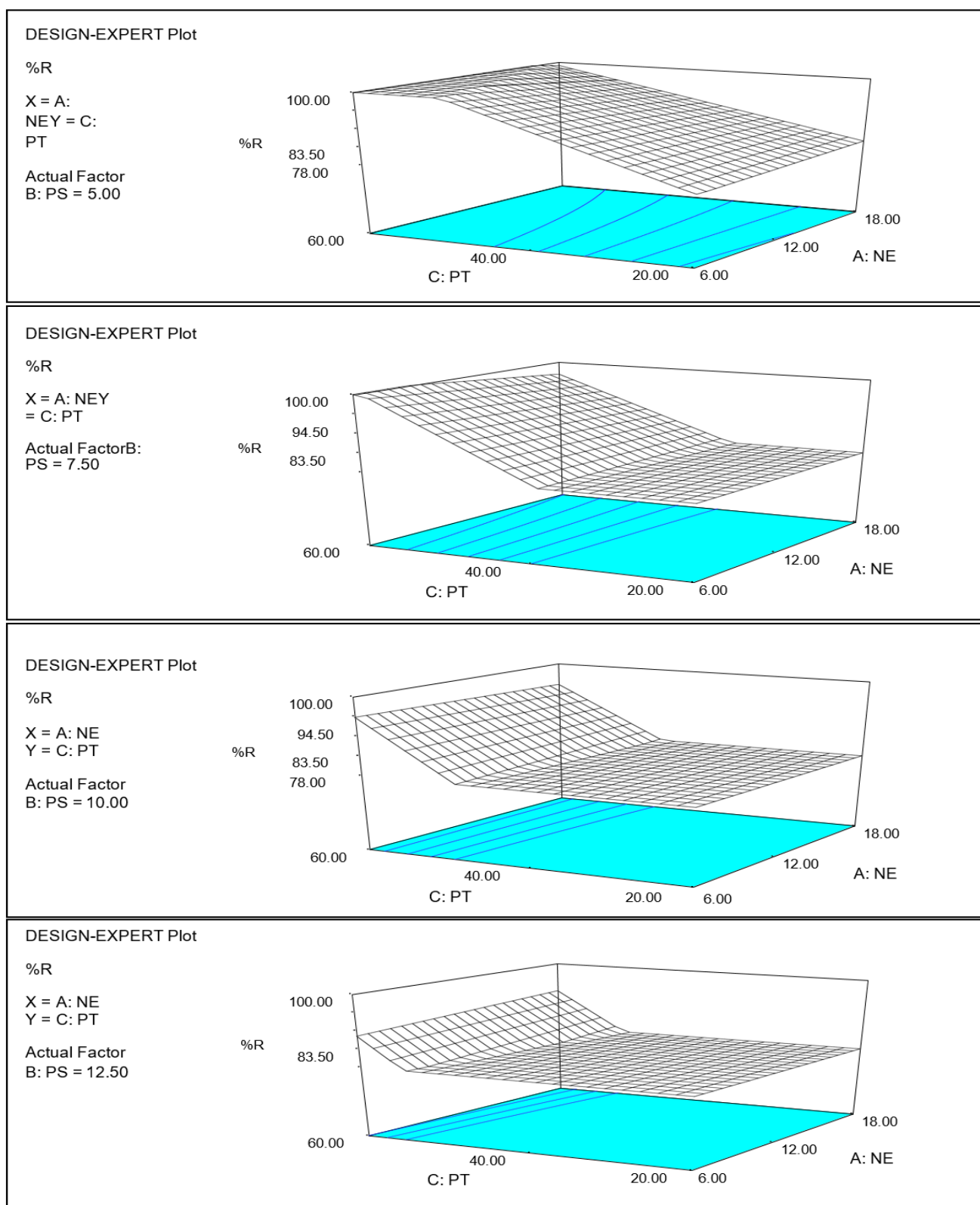
Figure 6 - Effect of varying power supply on removal efficiency of white color pigment

Table 9 - values of absorbance and concentration at optimal points

No. of electrodes	Abs 1	Conc^n 1	Abs 2	Conc^n 2	Abs 3	Conc^n 3	Ave. Conc^n
6	0.153	0.0018	0.153	0.0018	0.155	0.0019	0.0019
12	0.148	0.0015	0.148	0.0015	0.149	0.0016	0.0016
18	0.150	0.0017	0.152	0.0018	0.154	0.0019	0.0018
Untreated sample	1.872	0.1010	1.972	0.1070	1.938	0.1050	0.1043

6.00   18.00

NE = 12.13

5.00   12.50

PS = 5.85

20.00   60.00

PT = 59.78

78.88   99.5
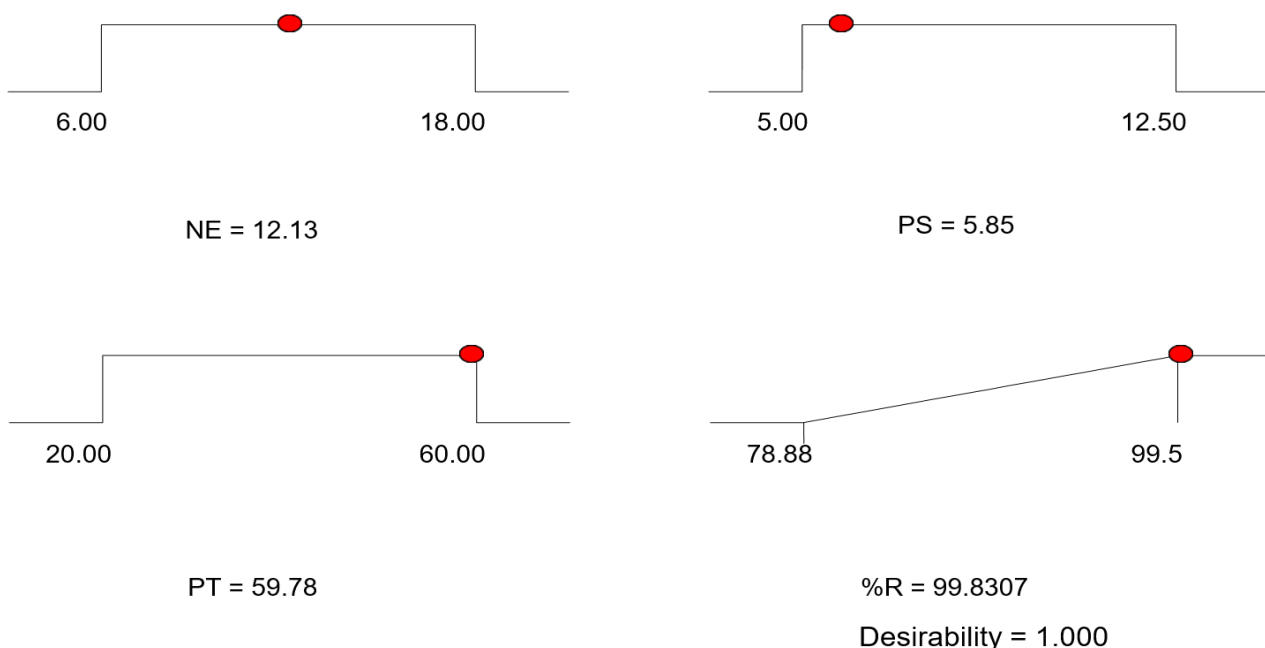
%R = 99.8307

Desirability = 1.000

Figure 7 - Design expert output for optimal points of the process

2.   Conclusions

Paint industry effluent treatment by electro-coagulation resulted in a significant reduction of pollutants. The percentage removal of TiO_2 obtained between 20 and 60 min of treatment time was 78.9% for electro-coagulation cell with 6 electrodes and application of 12.5 V power supply and 99.5% for electro-coagulation cell with 12 electrode and power supply of 5 V which were the minimum and maximum values respectively. On the other hand, 90.6% to 96.9% BOD_5, 94.4% to 98% COD and 88.7% to 95.7% TSS removals were achieved without addition of chemical coagulants.

In general, by increasing the processing time from 20 to 60 min the removal efficiency of TiO_2 was increased from 88.78% to 99.47%, 88.88% to 99.41%, 90.4% to 99.5% and 78.87% to 98.2% and the anode consumed was from 0.512 g/m^3 to 1.729 g/m^3, 0.768 g/m^3 to 2.593 g/m^3, 1.025 g/m^3 to 3.458 g/m^3 and 1.281 g/m^3 to 4.322 g/m^3,

power consumption also increased from 1.024 Wh/m^3 to 3.457 Wh/m^3, 2.304 Wh/m^3 to 7.778 Wh/m^3, 4.097 Wh/m^3 to 13.828 Wh/m^3 and 6.401 Wh/m^3 to 21.605 Wh/m^3 by applying 5, 7.5, 10 and 12.5 V power respectively. Some of the anode oxidized and released as cat-ion (Al^{3+}) to the solution during the process were reduced and adsorbed on the cathode and the remaining colloidal particles settle with the sludge.

Higher removal values were obtained for all electro-coagulation cells with a power supply of 5, 7.5, 10 and 12.5 V. However, the power consumptions increased significantly when power supply and number of electrodes increased, and hence it incurred higher operating cost. On the other hand, using less number of electrodes resulted in higher values of anode consumption and hence requires frequent replacement of electrodes and maintenance cost. At lower power supply and optimal numbers of electrodes, comparably higher TiO$_2$ reduction were obtained with optimal values of anode and power consumptions and hence the electro-coagulation process was operated well at lower power supply and moderate numbers of electrodes.

Conflict of interest: The authors declared that they have no conflict of interests.

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