

PROCESS OPTIMIZATION AND ENHANCING THE PERFORMANCE OF ELECTROCOAGULATION IN BATCH AND CONTINUOUS MODES OF OPERATION

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**DEPARTMENT OF CHEMICAL ENGINEERING
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**PROCESS OPTIMIZATION AND ENHANCING THE
PERFORMANCE OF ELECTROCOAGULATION IN BATCH
AND CONTINUOUS MODES OF OPERATION**

by

Vinod Kumar Jaiswar

Submitted in fulfilment of the requirements for the degree of

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to the



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To my Family and Friends – by Birth and by Choice.

CERTIFICATE

This is to certify that the thesis entitled, **“Process optimization and enhancing the performance of electrocoagulation in batch and continuous modes of operation”** being submitted by **Mr. Vinod Kumar Jaiswar** to the Indian Institute of Technology Delhi for the award of **Doctor of Philosophy** is a record of bonafide research work carried out by him under my guidance and supervision in conformity with the rules and regulations of Indian Institute of Technology Delhi.

The research report and results presented in this thesis have not been submitted, in part or in full, to any other university or institute for the award of any degree or diploma.

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Vinod Kumar Jaiswar

ABSTRACT

The textile industries are highly water-intensive, generating large volumes of wastewater containing salts, dyes, and heavy metals, along with high biological oxygen demand (BOD) and chemical oxygen demand (COD). Therefore, the effluent must undergo adequate treatment to prevent environmental contamination before discharge into the aquatic environment. Several conventional and advanced wastewater treatment technologies have been employed to remove dyes from textile effluent. Among them, electrocoagulation (EC) has emerged as a promising method for treating domestic and industrial wastewater. In EC, coagulants are generated in situ through the electrochemical dissolution of a sacrificial anode on applying an electric current across the metal electrodes.

The performance of EC is influenced by several operational parameters, including applied current, inter-electrode distance, electrode shape and geometry, electrode configuration (connection mode), and the mode of operation (batch or continuous). In the present study, the effect of electrode geometry, specifically, electrodes with punched holes of varying number and diameter, along with key operating parameters and electrode configurations (bipolar, monopolar series, and monopolar parallel), has been investigated in batch mode. The performance of EC was assessed based on color removal efficiency (CRE), electrical energy consumption (EEC), and operating cost (OC). A commercially available Reactive Orange 4 dye was used to prepare the synthetic dye solution for the experiments.

It was observed that the punched-holed electrodes resulted in higher color removal efficiency, along with reduced energy consumption and operating cost, compared to the plane electrodes. A color removal efficiency of 96.50% was obtained using punched-hole electrodes under the optimized conditions: current of 0.05 A, inter-electrode distance of 1.0 cm, and an initial dye

concentration of 100 ppm. The EEC and OC were found to be 2.058 kWh/m³ and 0.649 US \$/m³, respectively, under these conditions. The effect of punched-hole electrodes on the treatment of real dye effluent was also studied, and the punched-hole electrodes resulted in a COD removal of 78.79%, compared to 69.30% with plane electrodes. The corresponding EEC and OC were 0.5 kWh/m³ and 0.424 US \$/m³ for the punched-hole electrodes.

Furthermore, the influence of electrode geometry and configuration was studied using four electrodes arranged in bipolar (BP), monopolar series (MP-S), and monopolar parallel (MP-P) connection modes. It was observed that both electrode shape and configuration significantly affected the rate of color removal, CRE, EEC, and OC. The highest rate of color removal was observed for the BP configuration, followed by MP-S, and the lowest for MP-P. The EEC values for BP, MP-S, and MP-P modes were found to be 4.22, 3.31, and 1.86 kWh/m³, respectively, while the operating costs were 1.192, 0.966, and 0.712 US \$/m³, respectively.

Electrocoagulation was also carried out in continuous mode of operation, which offers several advantages over batch operation, including consistent effluent quality, the ability to treat larger volumes of wastewater, and lower operational costs. A response surface methodology (RSM) using a full factorial central composite design (CCD) was employed to study the interactive effects of operating parameters, applied current, solution flow rate, and treatment time, on the performance of continuous EC. The selected parameter ranges were: current (0.1–0.3 A), flow rate (10–30 mL/min), and treatment time (60–180 min). It was found that the CRE improved with increasing current and decreasing flow rate. The highest CRE of 86.24% was obtained at 0.2 A current, 3.182 mL/min flow rate, and 120 min treatment time. Conversely, the lowest CRE of 39.69% was obtained at 0.032 A current, 20 mL/min flow rate, and 120 min treatment time. Additionally, according to operating conditions obtained using the optimization tool in RSM, a

maximum CRE of 91.89% was found under the conditions: current of 0.2493 A, flow rate of 3.18 mL/min, and treatment time of 192.368 min.

In conclusion, electrocoagulation is a viable technique for treating wastewater in batch and continuous modes of operation. The electrode shape and configuration are significant in determining CRE, EEC, and OC. The BP connection mode resulted in the highest CRE. However, the MP-P connection mode resulted in the lowest operating cost. The continuous mode of operation was used to effectively treat the wastewater.

सार

कपड़ा उद्योग में पानी की अत्यधिक खपत होती है, जिससे बड़ी मात्रा में लवण, रंग, भारी धातु, और उच्च जैविक ऑक्सीजन मांग और रासायनिक ऑक्सीजन मांग युक्त अपशिष्ट जल उत्पन्न होता है। अपशिष्ट जल को जलीय वातावरण में छोड़े जाने से पहले उचित उपचार करना आवश्यक है ताकि पर्यावरणीय प्रदूषण को रोका जा सके। कपड़ा अपशिष्ट जल से रंगों को हटाने के लिए कई पारंपरिक और उन्नत अपशिष्ट जल उपचार तकनीकों का उपयोग किया गया है। इन तकनीकों में, इलेक्ट्रोकोगुलेशन, घरेलू और औद्योगिक अपशिष्ट जल के उपचार के लिए एक उभरती हुई प्रभावी विधि के रूप में सामने आई है। इस प्रक्रिया में, धातु इलेक्ट्रोड में विद्युत धारा प्रवाहित करके बलिदानी एनोड के विद्युत रासायनिक विघटन के माध्यम से कोएगुलेंट्स को मौके पर उत्पन्न किया जाता है।

इलेक्ट्रोकोगुलेशन की कार्यक्षमता कई प्रचालनात्मक मापदंडों जैसे कि प्रवाहित विद्युत धारा, इलेक्ट्रोड्स के बीच की दूरी, इलेक्ट्रोड का आकार और ज्यामिति, इलेक्ट्रोड का संयोजन और संचालन का तरीका (खेप या निरंतर) पर निर्भर करती है। वर्तमान अध्ययन में, इलेक्ट्रोड ज्यामिति के प्रभाव, विशेष रूप से, अलग-अलग संख्या और व्यास के छिद्रित छिद्रों वाले इलेक्ट्रोड, साथ ही प्रमुख परिचालन मापदंडों और इलेक्ट्रोड संयोजन (द्विध्रुवीय, एकध्रुवीय श्रृंखला, और एकध्रुवीय समानांतर) की खेप प्रणाली में जांच की गई है। इलेक्ट्रोकोगुलेशन की कार्यक्षमता का मूल्यांकन रंग हटाने की दक्षता, विद्युत ऊर्जा खपत, और परिचालन लागत के आधार पर किया गया था। प्रयोगों के लिए व्यावसायिक रूप से उपलब्ध प्रतिक्रियाशील नारंगी 4 डाई का उपयोग कृत्रिम डाई घोल बनाने के लिए किया गया था।

यह पाया गया कि साधारण समतल इलेक्ट्रोड्स की तुलना में छिद्रित इलेक्ट्रोड के कारण रंग हटाने की दक्षता अधिक थी, और साथ ही ऊर्जा की खपत और परिचालन लागत भी कम थी। अनुकूलित स्थितियों (0.05 A की विद्युत धारा, 1.0 सेमी की अंतर-इलेक्ट्रोड दूरी और 100 ppm की प्रारंभिक डाई सांद्रता) के तहत छिद्रित इलेक्ट्रोड का उपयोग करके 96.50% की रंग हटाने की दक्षता प्राप्त की गई। इन स्थितियों के तहत विद्युत ऊर्जा की खपत और परिचालन लागत क्रमशः 2.058 kWh/m³ और 0.649 US \$/m³ पाए गए। वास्तविक डाई अपशिष्ट जल के उपचार पर छिद्रित इलेक्ट्रोड के प्रभाव का भी अध्ययन किया गया और छिद्रित इलेक्ट्रोड के परिणामस्वरूप 78.79% रासायनिक

ऑक्सीजन मांग निष्कासन हुआ, जबकि समतल इलेक्ट्रोड्स के साथ यह 69.30% था। छिद्रित इलेक्ट्रोड के लिए संबंधित विद्युत ऊर्जा की खपत और परिचालन लागत 0.5 kWh/m³ और 0.424 US \$/m³ थे।

इसके अतिरिक्त, चार इलेक्ट्रोड्स को तीन विभिन्न संयोजनों, द्विध्रुवीय, एकध्रुवीय श्रृंखला, और एकध्रुवीय समानांतर में उपयोग करके इलेक्ट्रोड ज्यामिति और विन्यास के प्रभाव का अध्ययन किया गया। यह देखा गया कि इलेक्ट्रोड आकार और विन्यास दोनों ने रंग हटाने की दर, रंग हटाने की दक्षता, विद्युत ऊर्जा की खपत, और परिचालन लागत को महत्वपूर्ण रूप से प्रभावित किया। रंग हटाने की उच्चतम दर द्विध्रुवीय विन्यास के लिए देखी गई, उसके बाद एकध्रुवीय श्रृंखला और एकध्रुवीय समानांतर के लिए सबसे कम। द्विध्रुवीय, एकध्रुवीय श्रृंखला और एकध्रुवीय समानांतर संयोजनों के लिए विद्युत ऊर्जा की खपत मान क्रमशः 4.22, 3.31 और 1.86 kWh/m³ पाए गए, जबकि परिचालन लागत क्रमशः 1.192, 0.966 और 0.712 US/m³ थी।

इलेक्ट्रोकोगुलेशन को संचालन के निरंतर मोड में भी किया गया था, जो खेप संचालन प्रक्रिया की तुलना में कई लाभ प्रदान करता है, जिसमें निरंतर स्थिर जल गुणवत्ता, अधिक मात्रा में अपशिष्ट जल उपचार की क्षमता, और कम परिचालन लागत शामिल है। एक पूर्ण फैक्टोरियल केंद्रीय समग्र डिजाइन का उपयोग करके एक प्रतिक्रिया सतह पद्धति का उपयोग निरंतर इलेक्ट्रोकोगुलेशन के प्रदर्शन पर परिचालन मापदंडों, लागू विद्युत, प्रवाह दर और उपचार समय के इंटरैक्टिव प्रभावों का अध्ययन करने के लिए किया गया था। चुने गए मापदंडों की सीमा थी: विद्युत (0.1-0.3 A), प्रवाह दर (10-30 मिलीलीटर प्रति मिनट), और उपचार समय (60-180 मिनट)। यह पाया गया कि बढ़ती विद्युत और घटती प्रवाह दर के साथ रंग हटाने की दक्षता में सुधार हुआ। 86.24% का उच्चतम रंग हटाने की दक्षता 0.2 A विद्युत, 3.182 मिलीलीटर प्रति मिनट प्रवाह दर और 120 मिनट उपचार समय पर प्राप्त किया गया था। इसके विपरीत, 0.032 A विद्युत, 20 मिलीलीटर प्रति मिनट प्रवाह दर और 120 मिनट उपचार समय पर 39.69% की सबसे कम रंग हटाने की दक्षता प्राप्त हुई। इसके अतिरिक्त, प्रतिक्रिया सतह पद्धति में अनुकूलन उपकरण का उपयोग करके प्राप्त परिचालन स्थितियों के अनुसार, 91.89% की अधिकतम रंग हटाने की दक्षता निम्नलिखित स्थितियों में पाई गई: 0.2493 A का विद्युत, 3.18 मिलीलीटर प्रति मिनट की प्रवाह दर और 192.368 मिनट का उपचार समय।

निष्कर्ष में, इलेक्ट्रोकोॅगुलेशन एक प्रभावी तकनीक है जिसे खेप और निरंतर संचालन मोड में अपशिष्ट जल के उपचार के लिए लागू किया जा सकता है। इलेक्ट्रोड का आकार और विन्यास रंग हटाने की दक्षता, विद्युत ऊर्जा की खपत, और परिचालन लागत निर्धारित करने में महत्वपूर्ण है। द्विध्रुवीय कनेक्शन मोड के परिणामस्वरूप उच्चतम रंग हटाने की दक्षता प्राप्त हुआ। हालाँकि, एकध्रुवीय समानांतर कनेक्शन मोड के परिणामस्वरूप सबसे कम परिचालन लागत हुई। अपशिष्ट जल के प्रभावी उपचार के लिए निरंतर संचालन मोड का उपयोग किया गया।

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ABBREVIATION

AOPs	:	Advanced oxidation processes
BOD	:	Biological oxygen demand
BP	:	Bipolar
CCD	:	Central composite design
CD	:	Current density
CHC	:	Chemical consumed
COD	:	Chemical oxygen demand
CRE	:	Color removal efficiency
EC	:	Electrocoagulation
EEC	:	Electrical energy consumption
ELC	:	Electrode consumed
FAU	:	Formazin Attenuation Unit
HRT	:	Hydraulic retention time
IDC	:	Initial dye concentration
IED	:	Inter-electrode distance
MP-P	:	Monopolar parallel
MP-S	:	Monopolar series
NTU	:	Nephelometric turbidity unit
OC	:	Operating cost
Ppb	:	Parts per billion
ppm	:	Parts per million
rpm	:	Rotation per min

RSM : Response surface methodology

S/V : Surface area to volume

TDS : Total dissolved solids

Temp : Temperature

TOC : Total organic carbon

TS : Total solids

TSS : Total suspended solids

NOMENCALTURE

C_0 : Initial concentration

D : Diameter of hole

I : Current

N : Number of holes

T : Treatment time

X_0 : Initial value of X

X_t : Value of X at time t