



Dunaliella salina Harvesting Using Spiral Electrocoagulation and Parameters Optimization Using Response Surface Method

H. Hadiyanto^{a,b}, M. Christwardana^{c,d}, W. Widayat^e, P. Purwono^a, M. A. Budihardjo^f

^a Department of Environmental Sciences, School of Postgraduate Studies, Diponegoro University, Semarang, Indonesia

^b Center of Biomass and Renewable Energy (CBIOR), Chemical Engineering Department, Diponegoro University, Semarang, Indonesia

^c Department of Chemistry, Faculty of Science and Mathematics, Diponegoro University, Semarang - Indonesia

^d School of Postgraduate Studies, Diponegoro University, Semarang - Indonesia

^e Department of Chemical Engineering, Faculty of Engineering, Diponegoro University, Semarang - Indonesia

^f Department of Environmental Engineering, Faculty of Engineering, Diponegoro University, Semarang - Indonesia

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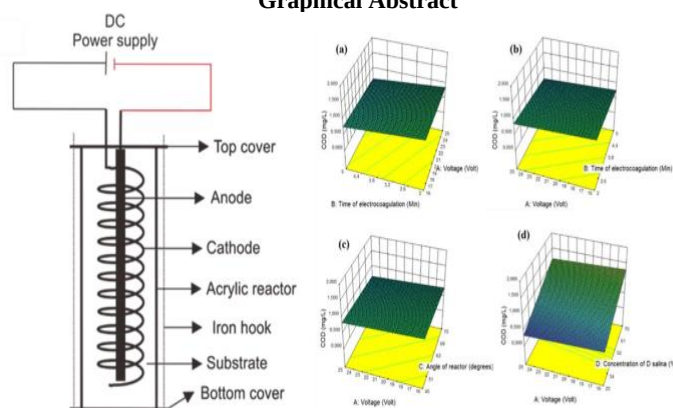
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ABSTRACT

Dunaliella salina has advantages over other microalgae species, including rapid growth, high salt concentration, simple growth requirements, and fast production. However, the harvesting process of *D. Salina* requires a particular harvesting method due to its tiny size. This research aims to develop an effective *D. Salina* harvesting method using spiral electrocoagulation (SEC). Optimization of operating parameters including initial *D. Salina* concentration, voltage, reactor slope, and electrocoagulation time is carried out using response surface methodology (RSM) to maximize the *D. Salina* harvesting process analysis of wastewater quality produced shortly after the harvesting process. The results showed that the optimum operation for *D. Salina* harvest until a harvesting efficiency of 85.77% was achieved required 25 V; 4.17 min as a time of electrocoagulation; 68.39 degrees as the angle of the reactor; and 25% initial concentration of *D. Salina*. The variable voltage, time, and initial concentration of *D. Salina* significantly affect harvesting efficiency, while the reactor angle has an insignificant impact. Based on the Central Composite Design (CCD) design, the minimum COD concentration is 3.36 mg/L when SEC operations use a voltage of 25V, time of electrocoagulation 5 min, angle of reactor 75-degree, and concentration of *D. Salina* 70% of the initial concentration. The concentration of nutrients (nitrate, phosphate, ammonia) produced after the harvesting process varies depending on variations in voltage, time, angle of reactor, and initial concentration of *D. salina*.

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Graphical Abstract



*Corresponding Author Email: hadiyanto@live.undip.ac.id, marcelinus@lecturer.undip.ac.id (H. Hadiyanto, M. Christwardana)

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NOMENCLATURE			
SEC	Spiral electrocoagulation	COD	Chemical Oxygen Demand
<i>D. salina</i>	<i>Dunaliella salina</i>	V	Volt
RSM	Response surface methodology	°	Degree
CCD	Central Composite Design		

1. INTRODUCTION

Microalgae biomass is a sustainable biological resource that can be used for various applications, such as fuel, food, pharmaceuticals, feed, and other bio-based products (1, 2). Biotechnological applications are of great interest to *D. Salina* due to its protein growth characteristics, composition, and production capacity. *D. Salina* can be cultivated on an industrial scale to produce β -carotene which is of great interest to humans. *D. Salina* has advantages over other microalgae species, namely rapid growth, high salt concentration (3).

The production process of microalgae biomass involves several techniques, especially cultivation, harvesting, drying, and pollution control. Efficient microalgae harvesting is crucial for sustainable biofuel production (4). Microalgae grown in culture media must be harvested for processing into final products (5). Microalgae is more challenging to collect and requires special harvesting methods. This is because microalgae are more dispersed in the culture medium, making it more difficult to separate from the medium. In addition, *D. Salina* has a low biomass concentration (< 1 g/L), small cell size (10–12 μ m), and similar density to the culture medium (6).

When microalgae are harvested, wastewater will be produced that contains excess nutrients such as nitrates and phosphorus. These nutrients come from macronutrients (nitrogen and phosphorus) and micronutrients (iron, zinc, manganese, copper, and cobalt) used for microalgae growth (7). Excess nitrates and phosphorus can cause eutrophication of water bodies, resulting in algae and aquatic plants experiencing overgrowth (8, 9). These nutrients, mainly nitrogen and phosphorous, could cause eutrophication of water bodies (rivers, lakes, and oceans) and ecosystem degradation if discharged directly without proper treatment (10). Therefore, we need an effective *D. Salina* harvesting method to minimize the pollutant content in *D. Salina* harvesting wastewater.

Centrifugation and membranes are used in *D. Salina* harvesting (11, 12). Membrane system increase harvesting efficiency and reduce cell damage. Flocculation technique using sodium hydroxide is effective to harvest *D. Salina* effectively (13), and another study utilized *Spirulina* culture wastewater to agglomerate *D. Salina* under high pH conditions (14). However, centrifugation and membrane filtration methods require complex maintenance. Therefore,

further research is needed to simplify the maintenance process and reduce harvesting costs, without reducing the speed of harvesting (15).

Electrocoagulation (EC) is a harvesting technique that requires an external electric current that causes flocculation and sedimentation. This method is very effective for microalgae harvesting and has several advantages over other techniques, such as ease of operation, minimal environmental impact, fast harvesting, and environmental friendliness (16). EC can be used for various microalgae species and adapted to suit different growing conditions (17). In addition, the EC method was found to be more cost-effective and achieve high harvest efficiency (greater than 95%) under various conditions while also producing biomass suitable for human consumption (iron content < 4 mg/g) (18).

Krishnamoorthy et al. [17] conducted experiments using electrodes Fe, Al, Mg, Steel, Boron-doped diamond-Al, Al-IrO₂/TiO₂, Nickel, Carbon, Stainless steel, and Al-Graphite. The power used is 3 to 40 V, electrolysis time is 1.32 min to 60 min, and stirring speed is 100 rpm. Types of microalgae harvested include *Chlorella vulgaris*, *Scenedesmus acuminatu*, *Desmodesmus subspicatus*, *Mixed microalgae*, *Chlorella sp.*, *Tetraselmis sp.*, *Scenedesmus quadricauda*, *Dunaliella salina*, *Phaeodactylum tricornutum*, *Nannochloropsis sp.*, *Scenedesmus obliquus*, *Dunaliella viridis*. The results showed that electrochemical techniques are exclusively suitable for biofuel production since they positively affect the amount of lipids and pigments present in microalgae.

Harvesting *Chlorella vulgaris* using electrocoagulation was carried out using Pb, Mg, Al, and Zn electrodes. Voltage 10 V, 20 V, 30 V, electrolysis time 20 minutes, and stirring speed 20 rpm (19). The highest to lowest flocculation efficiency, the results are as follows: Cu, Zn, Mg, Al, and Pb at 10 V; Mg, Zn, Cu, Al, and Pb at 20 V; and Mg, Zn, Al, Cu, and Pb at 30 V. The experimental process needs to minimize the use of chemicals/test materials and cost efficiency. Response surface methodology (RSM) is an empirical statistical modeling approach investigating the relationship between independent and dependent parameters. The main advantage of RSM is that it reduces the number of experimental trials and chemical consumption (20). RSM is also used to optimize the bio-flocculation of *Chlorella vulgaris* using filament pellets of *Aspergillus niger fungus* to increase harvest efficiency (21). Response surface methodology (RSM) is used for the evaluation of

Chlorella sp harvesting using bio-flocculants (22). RSM is also used to determine optimal operating conditions such as cost, current density, pH, and operating time (23). The EC system using rectangular-shaped Fe anodes has a harvesting efficiency of <85% with an operating time of 3 hours and a precipitation time of 4 hours (24). Until now, spiral electrocoagulation (SEC) has not attracted significant attention from researchers as a method of harvesting *D. salina*. The use of spiral-shaped electrodes in electrocoagulation for biomass separation does offer several benefits, including a significant increase in surface area for more effective flotation, the formation of small bubbles for increased floc formation, and a reduction in power consumption and an increase in electrode life. Therefore, this research aims to develop an effective *D. Salina* harvesting method using spiral electrocoagulation (SEC). Optimization of operating parameters, including the initial concentration of *D. salina*, voltage, angle of reactor, and electrocoagulation time, using response surface methodology (RSM) to maximize the *D. Salina* harvesting process analysis of wastewater quality produced shortly after the harvesting process.

2. MATERIALS METHOD

2. 1. Electrocoagulation Reactor and Operation Condition

The research was located in the CBIORE laboratory, an integrated laboratory of Diponegoro University. The *D. Salina* harvesting process used a 1600 mL capacity reactor made of acrylic, so researchers can directly observe the process that occurs during *D. Salina* harvesting using SEC. The SEC reactor used cylindrical acrylic with a diameter of 12 cm. The top and bottom caps use polyurethane material with a thickness of 3 cm. The reactor cap is given a circular hole according to the diameter of the acrylic and the outer side of the cap is linked using iron with a diameter of 0.8 cm and a length of 20 cm. The top cap had sample inlet hole, gas outlet, cathode hole, and anode hole. The distance between the holes is arranged in such a way that the holes do not interfere with each other. Each hole is installed in the faucet except the cathode and anode holes. The reactor scheme is shown in Figure 1.

2. 2. Sample The sample of this study was *substrate D. Salina* from the CBIORE laboratory, an integrated laboratory of Diponegoro University. *D. Salina* seeds were checked morphologically using a microscope to ensure that the type of microalgae was *D salina*. The morphology of *D. Salina* seedlings photographed using an optical microscope is shown in Figure 1(c).

One liter of *D. Salina* seedlings was cultured by adding aquadest, salt mix, and Guillard F2 media of 1.5 L each, 3 g, and 1 mL. The place of cultivation uses

Erlenmeyer placed on shelves equipped with lighting and aeration. The light source comes from an 8-watt LED lamp (Philips) with a luminance of 1500 lux. The eagle tip connected to the aerator (BS-410, Amara, Shanghai, China) is inserted into the base of the Erlenmeyer, and the air discharge is regulated at 3.5 L/min. This air serves as a source of carbon for photosynthesis and stirs *D. Salina* so that they do not precipitate (25). Researchers added F2 Guillard 1 mL/L every three days during the cultivation process. The growth of *D. Salina* is known from the optical density (OD) value. According to Lu et al. (26) the method of assessing microalgal biomass that utilizes optical density is precise and efficient. A spectrophotometer is used to carry out an automatic scan of the maximum wavelength (27). OD was measured using a UV-Vis spectrophotometer (Genesys 150, Thermo Fisher Scientific, USA) at a wavelength of 442 nm.

2. 3. Experimental Setup and Optimization of *D. Salina* Harvesting Using RSM

The *D. Salina* culture is fed into the SEC reactor until it is full, then closed by rotating a 17 mm screw. The SEC reactor is laid on board, allowing it to be rotated to a slope of 30°, 45°, 60°, 75°, and 90° as shown in Figure 2. The ends of the cathode and anode were connected to a DC power source. The adapter converts AC to DC so that the operational voltage can be set at 11.5V, 16V, 20.5V, 25V, and 29.5V. Operation conditions were carried out for 30 times treatment according to the Central Composite Design (CCD) design. Researchers have conducted

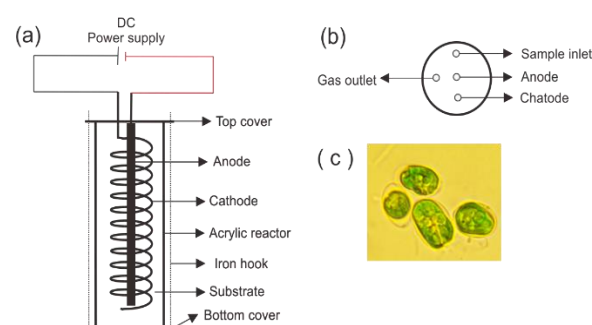


Figure 1. (a) SEC reactor scheme (b) Top cover of SEC reactor used to harvest *D. salina* (c) Morphology of *D. Salina* photographed using an optical microscope

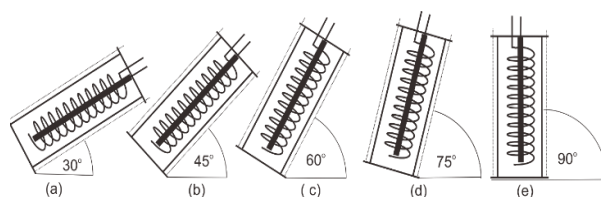


Figure 2. The angle of SEC reactor (a) 30°, (b) 45°, (c) 60°, (d) 75°, (e) 90°

preliminary studies to determine the effect of voltage variations, electrocoagulation time. Operating conditions that produce the highest harvesting efficiency were used as reference data to determine the range of variation in central composite design (CCD) (Table 1). Based on preliminary data, the best voltage was 20 V and the electrocoagulation time was 5 minutes. While variations in *D. Salina* concentration and angle of reactor follow central composite design (CCD) data. The electrocoagulation time was performed between 0.5 min, 2 min, 3 min, 5 min, and 6.5 min. During SEC operation, *D. Salina* was stirred at 400 rpm using a stirrer (DLAB Digital Magnetic Stirrer MS-PA, USA). When the operational condition has been completed, the adapter is turned off by pressing the on-off button. The sample was removed from the SEC reactor and allowed to stand for 30 minutes for settling. 50 mL of samples, such as pH, temperature, TDS, salinity, and DHL, were taken for in-situ analysis. Nitrate, Phosphate, Ammonia, COD, and Fe parameters were analyzed in the laboratory. The sample testing process was not completed in one day, so the sample must be preserved by inserting it into a cooler <2°C. Sample testing was carried out in duplicate.

The Design Expert program, namely version 10.0.1, was utilized throughout this investigation's testing. Each treatment was based on a central composite design (CCD). The significance value of each variable is known from the ANOVA test. The F-test is used to determine the significance of the overall model. A low p-value of the F-test indicates that the model condition is significant, meaning that the independent variable in the model has a significant influence on the dependent variable.

In contrast, a high p-value indicates that the term is insignificant and can be removed from the model. R^2 and R^2 adjusted mean how well the model fits the data and how reliable the predictions are. The parameters voltage, time of electrocoagulation, angle of the reactor, and concentration of *D. Salina* pH, as well as their interactions, are found to be significant model terms based on their F and p values.

TABLE 1. The independent variables and level of model code used in this study are based on Central Composite Design (CCD) experiments

Code	Independent variable	Level				
		- α	-1	0	1	+ α
A	Voltage, V	11,5	16	20,5	25	29,5
B	Time of electrocoagulation, min	0,5	2	3,5	5	6,5
C	Angle of reactor, degree	30	45	60	75	90
D	Concentration of <i>D salina</i> , %	2,5	25	47,5	70	92,5

2. 4. Analytical Method OD measurement using a spectrophotometric method using UV-Vis spectrophotometer (Genesys 150, Thermo Fisher Scientific, USA) at Wavelength 442 nm. Analysis of operational parameters, nutrients, and wastewater (pH, temperature, TDS, salinity, DHL, nitrate, phosphate, ammonia, COD, and Fe) refers to Standard water and wastewater (28). COD measurement using closed reflux method, 2.5 mL sample, digestion solution, and catalyst solution. The digestion solution is made from a mixture of 2.6 g $K_2Cr_2O_7$, 8.33 g $HgSO_4$, and 42 mL H_2SO_4 (concentrated), then diluted to a total volume of 250 ml with aquadest. The catalyst solution is prepared by adding 5.06 g of Ag_2SO_4 to 500 mL of H_2SO_4 (concentrated). The mixture is heated using a thermoreactor at 150°C for 120 min. The absorbance value was measured using a UV-Vis spectrophotometer (Genesys 150, Thermo Fisher Scientific, USA). Measurement of dissolved Fe using atomic absorption spectrophotometer (AAS) (VGP 210, Buck Scientific, USA). We used Origin 2022 to perform tabular and graphical representations of research data.

3. RESULT AND DISCUSSION

3. 1. Characteristic of *D. Salina* culture before Harvested

The growth media *D. Salina* follows previous research using Guillard's F/2 medium (29, 30), although other media can be used, such as Johnson's modified medium, Erdschreiber's medium, modified ASP medium, and enriched seawater. The characteristics of *D. Salina* culture before harvesting are shown in Table 2. Before harvest, the initial *D. Salina* culture has the characteristics of Optic density, pH, temperature, salinity, and TDS of 0.213 each; 7.710; 24.8 °C; 3.09 mg/L and 3940 mg/L. Other parameters such as DHL,

TABLE 2. Characteristics of *D. Salina* culture before harvested

No.	Parameters	Unit	Result
1	OD	-	0.213
2	pH	-	7.710
3	Suhu	°C	24.8
4	TDS	ppm	3940
5	Salinitas	ppm	3.09
6	DHL	mS	5.64
7	Nitrate	mg/L	9.70
8	Fosfat	mg/L	1.44
9	Ammonia	mg/L	0.450
10	COD	mg/L	49.57
11	Fe terlarut	mg/L	0.41

nitrate, phosphate, ammonia, COD, and Fe each amounted to 5.64 mS, 9.70 mg/L, 1.44 mg/L, 0.450 mg/L; 49.57 mg/L; and 0.41 mg/L.

3. 2. Optimization of Operational Parameters on Harvesting Efficiency of *D. Salina* Using RSM

In this study, RSM was used to optimize the harvesting efficiency of *D. salina*. The optimization objective uses the Response Surface Methodology (RSM) method to find optimal operational conditions for the *D. Salina* harvesting process as well as wastewater treatment produced after *D. Salina* is harvested. RSM involves collecting data on the optic density (OD) used to calculate *D. Salina* harvesting efficiency and then using statistical analysis to identify optimal conditions for *D. Salina* harvesting. We have conducted preliminary research to determine the range of voltage values, time of electrocoagulation, reactor angle, and *D. Salina* concentration. The RSM results of this study will predict the exact conditions of the influence of the independent variable on the dependent variable. The independent variables in this study were voltage (11.5-29.5 V), time of electrocoagulation (0.5-6.5 min), angle of the reactor (30-90 degrees), and concentration of *D. Salina* (2.5-92.5%). The dependent variables in this study were the efficiency of *D. Salina* harvesting, nutrient removal (nitrate, ammonia, and phosphate), and dissolved COD & Fe as wastewater parameters resulting from the *D. Salina* harvesting process.

In previous studies, RSM was used to optimize the bio-flocculation of *Chlorella vulgaris* using filament pellets of the fungus *Aspergillus niger* to improve harvest efficiency. The results showed that a harvest efficiency of 98% has been achieved under optimal conditions: pH 8, cationic inducer concentration of 0.06 mM, bio-flocculant dose of 3.5% w/v, and agitation at 160 rpm [21]. Response surface methodology (RSM) was used for the evaluation of *Chlorella sp.* harvesting. using bio-flocculants [22]. Optimum conditions were achieved at dosage, pH and mixing rate of bio-flocculation process of 30 mg/L, pH seven and rpm 125, respectively with a harvest efficiency of 97.2%. Microalgae harvesting using a new ozone-air flotation method and evaluating its effect on biomass recovery and biocomponents (lipids, carbohydrates, proteins). The best processing conditions were established using response surface methodology (31).

3. 2. 1. Application of SEC to Harvest *D. Salina*

Microalgae harvesting technology needs to be developed intensively in order to obtain harvesting technology that is simple, fast, high efficiency, and easy to maintain, one of which is electrocoagulation (EC) [16]. In this study, we are using a spiral cathode, starting now referred to as spiral electrocoagulation (SEC). Significant SEC operations to consider include electrical voltage, initial

microalgae concentration, and electrocoagulation time (18, 32). The operational conditions of *D. Salina* harvesting using SEC based on central composite design (CCD) cause changes in several parameters, including optic density (OD), pH, temperature, TDS, salinity, DHL, nitrate, phosphate, ammonia, COD, and dissolved Fe. The OD value used to calculate the harvesting efficiency of *D. Salina* refers to the research of Lu et al. [26]. Figure 3 is a three-dimensional representation illustrating the effect of electrical power, electrocoagulation time, angle of SEC reactor, and *D. Salina* concentration on *D. Salina* harvesting efficiency using SEC.

The results showed that the maximum harvesting efficiency was 88.73% when SEC operations used a voltage of 20.5 V, time of electrocoagulation of 3.5 min, angle of reactor 60 degrees, and concentration of *D. Salina* 2.5% of the initial concentration. Minimum harvesting efficiency of 38.97%, when SEC operations use voltage 16 V, time of electrocoagulation 2 min, angle of reactor 45-degree, concentration of *D. Salina* 70% of initial concentration.

Harvesting efficiency =

$$+32,799+2,226*A+7,469*B+0,3085*C-0,9339*D-0,0734*A*B-3,912E-004*A*C+3,1588E-003*A*D+3,7819E-003*B*C+0,1592*B*D+6,1728E-004*C*D-0,0181*A^2-1,18045*B^2-2,4148-003*C^2-1,3052E-003*D^2$$

where A is Voltage, V; B is the time of electrocoagulation, min; C is the reactor's degree angle; D is the concentration of *D. salina*, %.

Post-analysis is used to determine the optimum composition between voltage, electrocoagulation time, reactor angle, and *D. Salina* concentration. The results of harvesting efficiency optimization using the RSM method are shown in Figure 4. Optimization of harvesting efficiency is carried out using Expert Design software to find specific points that maximize harvesting efficiency (33). Harvesting *D. Salina* until a harvesting

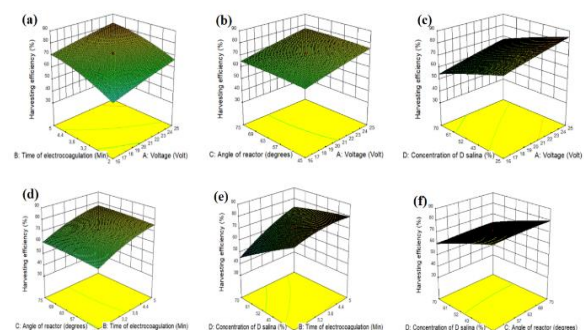


Figure 3. A three-dimensional representation illustrating the effect of electrical power, electrocoagulation time, reactor tilt, and *D. Salina* concentration on *D. Salina* harvesting efficiency using SEC

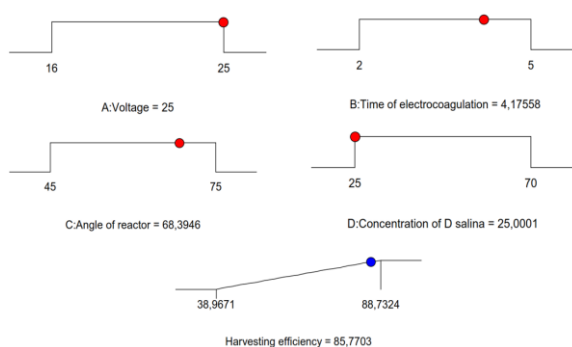


Figure 4. Solution SEC parameters to achieve maximum harvesting efficiency

efficiency of 85.7703% is achieved requires 25V, 4.1 minutes as the time of electrocoagulation, 68.3946 degrees as the angle of the reactor, and a concentration of *D. Salina* of 25.001%. Variable voltage, time, and initial concentration of *D. Salina* significantly affect harvesting efficiency, while the reactor angle has an insignificant effect. Changes in reactor angle in the electrocoagulation process can indeed have an impact on flow patterns and turbulence, further affecting sedimentation efficiency and particle sedimentation rate (34, 35). However, factors such as current density, electrode type, and electrolysis time significantly affect the performance of the electrocoagulation process (36). Based on ANOVA analysis, voltage variation, time of electrocoagulation, concentration of *D. Salina* each yielded a p-value of < 0.0001. This indicates that these three variables significantly affect the efficiency of *D. Salina* harvesting. While the variation in the angle of reactor produces a p value of 0.2540 which means that the angle of reactor has an insignificant effect on the efficiency of the harvester *D. Salina*.

The maximum pH is 7.97 when SEC operations use a voltage of 16 V, time of electrocoagulation 5 min, angle of reactor 75 degrees, concentration of *D. Salina* 70% of the initial concentration. The minimum pH is 7.278 when SEC operations used a voltage of 25 V, time of electrocoagulation 5 min, angle of reactor 75 degrees, and concentration of *D. Salina* 25% of the initial concentration. The pH value has an effect on floc formation. Based on research conducted by Lucakova et al. (18) the pH range between 3 and 7 is the optimal condition for floc formation. The pH of a solution will affect the electrode dissolution, the distribution of Fe^{3+} ions, and the solubility of amorphous hydroxide (37). The pH level also influences the ratio of positive ions to negative ions, which play a crucial role in neutralising the negative charge on the surface of the cell.

The maximum temperature was 36.30 °C when SEC operations used a voltage of 29.5 V, time of electrocoagulation 3.5 min, angle of reactor 60-degree, and concentration of *D. Salina* 47.5% of the initial

concentration. The maximum TDS was 3.040 when SEC operations used a voltage of 20.5 V, time of electrocoagulation 3.5 min, angle of reactor 60 degrees, and concentration of *D. Salina* 92.5% of the initial concentration. The maximum salinity was 2.6 ppt when SEC operations used a voltage of 16 V, time of electrocoagulation 2 min, angle of reactor 75 degrees, and concentration of *D. Salina* 70% of the initial concentration. The minimum salinity was 0.26 ppt when SEC operations used a voltage of 20.5 V, time of electrocoagulation 3.5 min, angle of reactor 60 degrees, and concentration of *D. Salina* 2.5% of the initial concentration. DHL maximum of 4.43 mS, when SEC operations used voltage 20.5 V, time of electrocoagulation 3.5 min, angle of reactor 60-degree, concentration of *D. Salina* 92.5 % of initial concentration. DHL minimum was 0.546 mS when SEC operations used voltage 20.5 V, time of electrocoagulation 3.5 min, angle of reactor 60-degree, concentration of *D. Salina* 2.5% of initial concentration.

3. 2. 2. Quality Nutrient Wastewater Produced from *D. Salina* Harvesting Using SEC

After harvest, microalgae generate nutrient-rich (nitrogen and phosphate) effluent. If not treated properly, these contaminants can eutrophicate rivers, lakes, and seas and destroy ecosystems (8, 9).

Table 3 shows the equations of nutrient removal using spiral electrocoagulation (SEC) at optimum conditions. The operational requirements of *D. Salina* harvesting using SEC based on central composite design (CCD) resulted in a maximum nitrate concentration of 11.35 mg/L when SEC operations used a voltage of 25 V, time of electrocoagulation 2 min, angle of reactor 75-degree, concentration of *D. Salina* 70% of the initial concentration. The minimum nitrate is 3.43 mg/L when SEC operations used a voltage of 25 V, time of electrocoagulation 5 min, angle of reactor 75 degrees, and concentration of *D. Salina* 70% of the initial concentration. The assessment of denitrification using the electrocoagulation process suggests that the detection of ammonium concentrations, equivalent to 50% of total nitrogen, may be attributed to an extra mechanism of nitrate reduction on the cathode (38). This reduction process likely converts nitrate to nitrogen gas, contributing to the observed decrease. Electrolyzing water generates hydrogen and oxygen gas, along with nitrogen gas derived from nitrate ions (39).

More Fe^{3+} is released from the cathode with longer electrocoagulation times. These ions coagulate negatively charged colloids and create flocs and sediment. Electrocoagulation can lower wastewater nitrate by forming flocs (40).

The maximum phosphate was 1.87 mg/L when SEC operations used a voltage of 16V, time of electrocoagulation 2 min, angle of reactor 45 degrees,

TABLE 3. The equations of nutrient removal using spiral electrocoagulation (SEC) at optimum condition

Parameters (mg/L)	Model	Equations of nutrient removal using spiral electrocoagulation (SEC) at optimum condition
Nitrate	Linear	$=+3,7511-0,03749*A-0,09097*B-2,2083E-003*C+3,32407E-003*D$ $=+0,09708648963521$
Ammonia	Quadratic	$-6,23319224963263E-003*A$ $-0,01647116775961*B$ $+3,57351770485600E-004*C$ $+6,18432363144659E-004*D$ $+4,61808441858317E-004*A*B$ $-2,19908781837294E-005*A*C$ $-2,05248196381475E-005*A*D$ $-3,95835807307127E-005*B*C$ $-2,37501484384277E-004*B*D$ $+5,71762832776963E-006*C*D$ $+1,33166984557028E-004*A^2$ $+2,05614711017870E-003*B^2$ $-5,49771954593222E-007*C^2$ $+7,08594963697946E-006*D^2$
Fosfat	Linear	$=+0,84466-0,013921*A-0,074255*B-6,01582E-003*C+0,018540*D$
COD	Linear	$=+0,84466-0,013921*A-0,074255*B-6,01582E-003*C+0,018540*D$

A is Voltage, V; B is the time of electrocoagulation, min; C is the angle of reactor, degree; D is the concentration of *D. Salina*, %.

and concentration of *D. Salina* 70% of the initial concentration. The minimum phosphate was 0.29 mg/L when SEC operations used a voltage of 20.5 V, time of electrocoagulation 3.5 min, angle of reactor 60 degrees, and concentration of *D. Salina* 2.5% of the initial concentration. Maximum ammonia of 0.070 mg/L when SEC operations used voltage 16V, time of electrocoagulation 2 min, angle of reactor 75-degree, concentration of *D. Salina* 70% of initial concentration. Minimum ammonia was 0.002 mg/L when SEC operations used voltage 25 V, time of electrocoagulation 2 min, angle of reactor 75 degrees, concentration of *D. Salina* 25% of initial concentration. The equations of nutrient removal using spiral electrocoagulation (SEC) at optimum conditions are summarized in Table 3.

3. 2. 3. COD and Fe Dissolved in Wastewater Resulting from *D. Salina* Harvesting Using SEC

The maximum COD was 14.10 mg/L when SEC operations used a voltage of 20.5 V, time of electrocoagulation 0.5 min, angle of reactor 60-degree, concentration of *D. Salina* 47.5% of the initial concentration. The minimum COD was 3.36 mg/L when SEC operations used a voltage of 25 V, time of

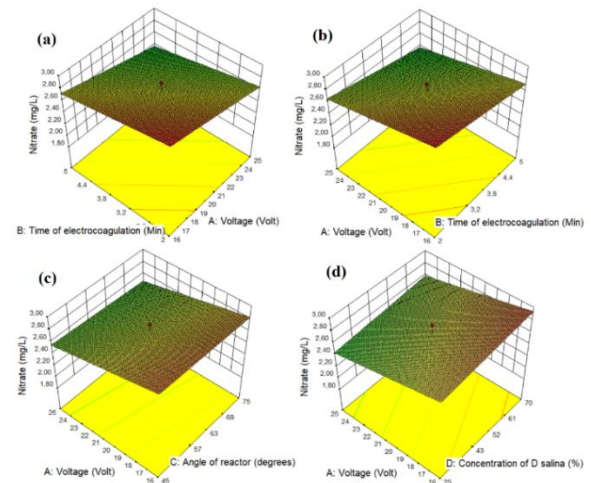


Figure 6. A three-dimensional representation illustrating the effect of electrical power, electrocoagulation time, reactor tilt, and *D. Salina* concentration on nitrate levels during the *D. Salina* harvesting process using SEC

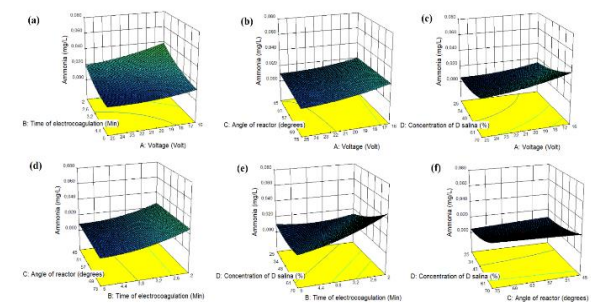


Figure 1. A three-dimensional representation illustrating the effect of electrical power, electrocoagulation time, reactor tilt, and *D. Salina* concentration on ammonia levels during the *D. Salina* harvesting process using SEC

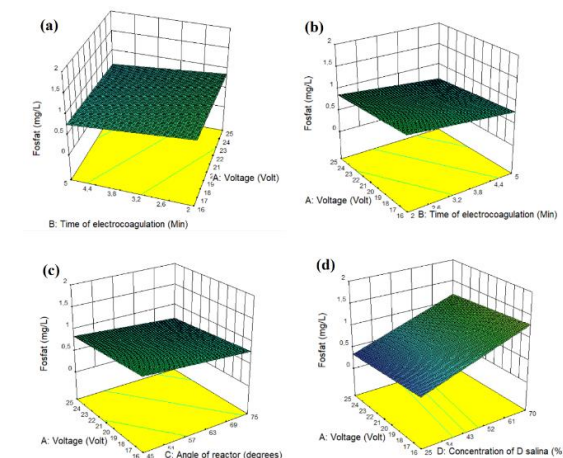


Figure 2. A three-dimensional representation illustrating the effect of electrical power, electrocoagulation time, reactor slope, and *D. Salina* concentration on phosphate levels during the *D. Salina* harvesting process using SEC

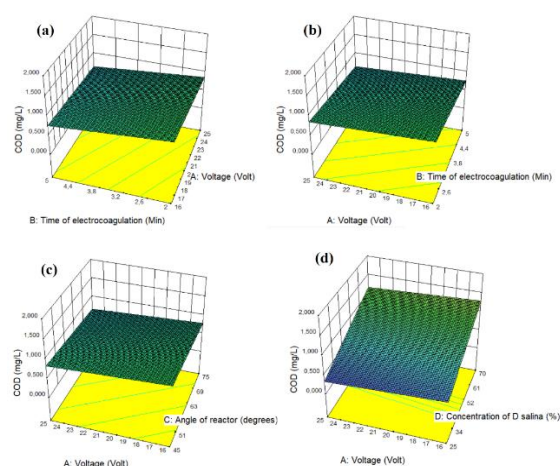


Figure 9. A three-dimensional representation illustrating the effect of electrical power, electrocoagulation time, reactor tilt, and *D. Salina* concentration on COD levels during the *D. Salina* harvesting process using SEC

electrocoagulation 5 min, angle of reactor 75 degrees, and concentration of *D. Salina* 70% of the initial concentration.

These results prove that each parameter's harvesting efficiency and concentration vary. This is likely due to changes in the chemical composition of *D. Salina* culture during the electrocoagulation process using SEC. The chemical composition of *D. Salina* culture changes due to an electrochemical phenomenon, namely the production of metal ions from the Fe anode (41). Metal ions released from the SEC anode are Fe^{3+} , then react with hydroxyl ions to form metal-hydroxide or polyhydroxide, which functions as a coagulant (42). These coagulants react with *D. Salina* and other contaminants, clumping together and forming larger, easier-to-harvest particles. According to Das et al. (16) microalgae harvesting in the SEC process involves three phenomena, namely adsorption, coagulation, and flotation.

5. CONCLUSION

Efforts to develop an effective *D. Salina* harvesting method using spiral electrocoagulation (SEC) have been made in this study. The results showed that the optimum operation for *D. Salina* harvest until harvesting efficiency of 85.77% was achieved required 25 V; 4.17 min as the electrocoagulation time; 68.39 degrees as reactor angle; and 25% initial concentration of *D salina*. Variable voltage, time, and initial concentration of *D. Salina* significantly affect harvesting efficiency, while the reactor angle has an insignificant effect. Based on the Central Composite Design (CCD) design, the minimum COD concentration is 3.36 mg/L when SEC operations

used a voltage of 25V, time of electrocoagulation 5 min, angle of reactor 75-degree, and concentration of *D. Salina* 70% of the initial concentration. The concentration of nutrients (nitrate, phosphate, ammonia) produced after the harvesting process varies depending on variations in voltage, time, angle of reactor, and initial concentration of *D salina*. Scale-up reactors allow for development, and the process is more applicable when SEC is applied in actual conditions. Industrial-scale reactors require careful design to accommodate higher flow rates, larger volumes, and longer residence times. Stable performance is maintained, and electrical systems must be adjusted for efficiency. Economic feasibility is determined through cost analysis, regulatory standards, and permits.

6. ACKNOWLEDGMENT

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Persian Abstract

چکیده

Dunaliella salina نسبت به سایر گونه های ریزجلبک مزایایی دارد که از جمله آنها می توان به رشد سریع، غلظت بالای نمک، نیازهای رشد ساده و تولید سریع اشاره کرد. با این حال، فرآیند برداشت *D. Salina* به دلیل اندازه کوچک آن نیاز به روش برداشت خاصی دارد. هدف این تحقیق توسعه یک روش موثر برداشت *D. Salina* با استفاده از انعقاد الکتریکی چرخشی (SEC) است. بهینه سازی پارامترهای عملیاتی از جمله غلظت اولیه *D. salina*، ولتاژ، شیب راکتور، و زمان انعقاد الکتریکی با استفاده از روش سطح پاسخ (RSM) برای به حداکثر رساندن تجزیه و تحلیل فرآیند برداشت *D. Salina* از کیفیت فاضلاب تولید شده در مدت کوتاهی پس از فرآیند برداشت انجام می شود. نتایج نشان داد که عملیات بهینه برای برداشت *D. Salina* تا زمانی که راندمان برداشت 77/85 درصد حاصل شود، نیاز به ولتاژ 25 دارد. 4.17 دقیقه به عنوان زمان انعقاد الکتریکی 68.39، درجه به عنوان زاویه راکتور 25 درصد غلظت اولیه *D. salina*، ولتاژ متغیر، زمان و غلظت اولیه *D. Salina* به طور قابل توجهی بر راندمان برداشت تأثیر می گذارد، در حالی که زاویه راکتور تأثیر ناچیزی دارد. بر اساس طراحی مرکب مرکزی (CCD)، حداقل غلظت 3.36 COD میلی گرم در لیتر است که در عملیات SEC از ولتاژ 25 ولت، زمان انعقاد الکتریکی 5 دقیقه، زاویه راکتور 75 درجه و غلظت 70٪ *D. Salina* استفاده می شود. از غلظت اولیه غلظت مواد مغذی (نیتрат، فسفات، آمونیاک (تولید شده پس از فرآیند برداشت بسته به تغییرات ولتاژ، زمان، زاویه راکتور و غلظت اولیه *D. Salina* متفاوت است.