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Harvesting of *Dunaliela Salina* at Low Concentrations using Spiral Electrocoagulation (SEC)

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Abstract: Harvesting of *Dunaliella salina* at low concentrations is more difficult to collect and requires special harvesting procedures. This is because the microalgae are more dispersed in the culture medium, making it harder to separate from the medium. When microalgae are harvested, it will produce wastewater that contains excess nutrients such as nitrate and phosphorus. Wastewater of microalgae harvesting should not contain microalgae and excess nutrients. These pollutants cause eutrophication of water bodies and ecosystem destruction when left untreated. The aims of the study were to analyze the harvesting efficiency of *D salina* at low concentrations and evaluation the nutrients in the wastewater produced from *D salina* harvesting. In this study, we used spiral electrocoagulation (SEC) with variations in voltage (16, 18, and 20 V) and electrolysis times (1, 3, and 5 min), a surface area of 88.13 cm-2, and a stirring speed of 400 rpm. The response surface method was utilized to optimize operating conditions that were CCD-randomized by five levels of two variables. Harvesting of *D salina* at low concentrations reached a maximum efficiency of 74.6% when voltage was set to 20 V for five minutes with surface area (Fe) 88.13 cm-2, stirring speed = 400 rpm, current intensity = 2.1 A. The power consumption required to harvest *D salina* at a low concentration, which is 0.426517 kWh/kg biomass, is higher compared to a higher microalgae concentration. Nutrients (nitrate and phosphate) in the wastewater were successfully reduced by 97 % using SEC within one minute under 20 volts applied.

Keywords: low concentrations; *Dunaliella salina*; nitrate; phosphate; harvesting

1. Introduction

Microalgae have been identified as a promising feedstock for renewable energy production and can be converted into various valuable products such as biofuels, animal feed, and pharmaceuticals [1)]. Microalgae-derived biodiesel is one biofuel source that has the potential to be environmentally friendly [2,3)]. The use of a photobioreactor is one way to improve the production of microalgae and reduce potential contamination [4,5)]. The production process of *microalgae Chlorella vulgaris* and *Spirulina platensis* can generate electricity using Microalgae-Microbial Fuel Cell (MmFC)[6)]. The microalgae grown in the culture medium must then be harvested for the subsequent recovery and extraction procedures [7)].

Microalgae harvesting poses challenges due to the small size of microalgae cells, their negative surface charge, and faster growth rate than land plants [8)]. These characteristics make it challenging to collect microalgae efficiently for industrial applications. Cost factors, environmental residues, and efficiency of microalgae harvesting methods remain a concern for many researchers [9)]. Further research is needed to optimize operational parameters, develop new methods, and improve microalgae harvesting techniques' efficiency, feasibility, and effectiveness.

At low concentrations, microalgae are more difficult to collect and requires special harvesting method. This is because the microalgae are more dispersed in the culture medium, making it harder to separate from the medium. Harvesting microalgae at low concentrations refers to the process of collecting the microalgae from a culture when the concentration of the microalgae is low. When microalgae are harvested, it will produce wastewater that contains excess nutrients such as nitrate and phosphorus. Microalgae need trace amounts of macronutrients

(nitrogen and phosphorus) for optimal growth and micronutrients (iron, zinc, manganese, copper, and cobalt [10]).

Excess nitrate and phosphorus can cause eutrophication of water bodies, which is a process where the water becomes enriched with these nutrients, leading to an overgrowth of algae and aquatic plants [11,12]. Meetiyagoda & Fujino states that it is essential to ensure that microalgae harvesting wastewater does not pollute water bodies [13]. Nutrients in microalgae harvesting wastewater may be recovered into useful products like struvite [14]. As a result, we require a more effective way of harvesting.

Techniques for the harvesting of microalgae have advanced significantly in recent years. Generally, microalgae harvesting uses centrifugation, coagulation, filtration, pH reduction, and ultrasonic techniques [15]. Techniques such as centrifugation and membrane filtering are the most often used harvesting methods for large-scale microalgae farms.

90% of the microalgae is recovered during the filtration-based harvesting method. The centrifugation technique is characterized by high harvesting speed and efficiency. However, centrifugation techniques can cause damage to microalgae cells [16]. Centrifugation and filtration of membranes require complex maintenance. Therefore, microalgae harvesting techniques require improvisation so that harvesting techniques are found that the maintenance process is easy, low cost without reducing the efficiency of harvesting and the purity of biomass [17].

Electrocoagulation (EC) is a harvesting technique that requires external electric currents that cause flocculation and sedimentation.This method has been found to be highly effective for microalgae harvesting and has several advantages over other techniques, such as ease of operation, minimal environmental impact, rapid harvesting, and environmental friendliness [18]. EC can be used for a variety of microalgae species and can be adjusted to suit different growth conditions [19]. Additionally, EC method was found to be more cost effective and achieved a high harvesting efficiency (greater than 95%) over a broad range of conditions while also producing biomass suitable for human consumption (iron content < 4 mg g-1) [20].

EC method using Fe anode has a harvest efficiency of <85% with 3 hours operating time and 4 hours settling time [21]. The electrodes are rectangular in shape used have an area of 24 cm-2 and a concentration of *D salina* of 0.5 g L-1. *D salina* harvesters use two electrodes with a surface area of 24 cm-2 and the best electrolysis time of 20 minutes [22]. The maximum microalgae recovery efficiency of 98.06% was obtained at a current intensity of 999 mA, time, electrode distance of 1.39 cm, stirring speed of 222 rpm and with aluminum as the electrode material. The authors studied several factors during their lab-scale experiments in order to achieve a high harvesting efficiency and low iron content in the harvested biomass [20]. These included electric charge, initial biomass concentration, pH, temperature, agitation intensity and electrolysis time. Special emphasis is placed on studying operating parameters such as current, maintenance time, and electrode geometry/shape [23]. By using spiral electrocoagulation (SEC), the microalgae can be collected even when the concentration is low and improve the quality of the final wastewater, which is important for preventing eutrophication.

However, microalgae harvesters with low concentrations that improve effluent quality after harvesting have rarely been studied. This paper is unique because it focuses on the harvesting procedures required for *D salina* at low concentrations. It also analysis nutrient of wastewater produced from this method. Nutrient excess can cause eutrophication of water bodies if not treated effectively, which has important implications for environmental protection and conservation efforts.

The aims of the study were to analyze the harvesting efficiency of *D salina* microalgae at low concentrations and the nutrients analysis in the wastewater produced from *D salina* harvesting. It analyzed nitrate and phosphate parameters in wastewater produced immediately after D salina was harvested. In this study, researchers used spiral electrocoagulation (SEC) using stainless stills as cathodes and irons as anodes with variations in voltage and electrolysis time. The utilization of Response Surface Methodology (RSM) in conjunction with Central Composite Design (CCD) is proposed for the purpose of optimizing the impact of voltage and electrolysis time on the efficiency of the harvesting process.

2. Method

The microalgae species that was used in the present investigation was *D. salina*. *D salina* was acquired from UgoPlankton, located in Jepara Regency, and subsequently cultivated at the UPT Laboratory C-BIORE of Diponegoro University in Semarang, Indonesia. The present study was carried out in the laboratory of the Centre of Biomass and Renewable Energy Laboratory (C-BIORE) located at Universitas Diponegoro, Semarang, Indonesia (7° 02' 47.9" S, 110° 26' 35.9" E). These laboratories typically have a wide range of facilities and equipment for microalgae cultivation, harvesting, and sample analysis.

One liter of *D Salina* seedlings was put into the Erlenmeyer then added aquadest to a volume of 1.5 L. Efforts to maintain the growth of *D salina* are carried out the addition of nutrients in the form of *salt mix* + as much as 3 g / L and *F2 Guillard* at a dose of 1 mL / L. This addition was done every three days. This study used an 8-Watt Philips LED lamp with a light intensity of 1500 lux and a temperature (° C) to adjust the laboratory room. Air from the aerator (BS-410, Amara, Shanghai, China) with an air discharge of 3.5 L / min is introduced into the culture using a hose until it reaches the bottom of the

Erlenmeyer. This air is useful for stirring the culture so that *D salina* does not settle [24]. The growth rate of *D salina* was known by measuring optical density (OD) on a daily basis. OD measurements were performed using a 10×10×45 mm dimensional quartz cuvette at a wavelength of 442 nm using a spectrophotometer (Spectroquant®Prove 100, Merck KGaA, Darmstadt, Germany). In this study, the pH of *D salina* culture was not adjusted, but the pH of the culture was measured daily. *D salina* is ready to be harvested when the microalgae culture has reached the stationary phase, since in the stationary phase there is a higher cell interaction and low microalgae growth. This is the best condition for biomass harvesting [25].

D salina at low concentration was made by diluting the mains substrate using aquadest as much as 75%, which is 250 mL of the mains substrate + aquadest to a total volume of 1000 mL. *D salina* at low concentrations were used to the harvesting process and analysis of the nutrients in the wastewater produced from *D salina* harvesting. The process of harvesting *D salina* using SEC is carried out in batch mode using a 600 mL SEC reactor containing 500 mL of *D salina* culture. Fig. **1** show the reactor scheme of SEC to harvest *D salina* at low concentration in batch mode. The cathode and anode of the SEC reactor are spiral and cylindrical, respectively. The cathode is a spiral-shaped stainless still with dimensions of 7 cm and a length of 10 cm. The anode is cylindrical Fe with diameter of 2.5 cm and a length of 10 cm. Part of the cathode surface is covered with a circular insulator (0.5 cm) and then inserted into the anode, both 2.5 cm apart so that the anode and cathode do not stick together. The electrocoagulation reactor is hermetically sealed using polyethylene (PE) equipped with a 0.5 cm hole for the cathode, anode, gas emission, inlet, and culture outlet of *D. Salina.* The holes are closed using silicone glue (Dextone) so that no air or liquid comes out.

The experiment was carried out with a constant current mode using direct current (DC) power. the SEC system is operated at *D Salina* at low concentration, voltage variations of 16, 18, and 20 V, and an electrocoagulation time of 1, 3, 5 min. Variations in electrical voltage are recorded using a digital multimeter (Fluke, USA). The variation of electric current depends on the display of the digital multimeter. A 220-volt AC current source is converted to DC using an AC-DC adapter (Sunshine 30V 5A, P-3005D, China).

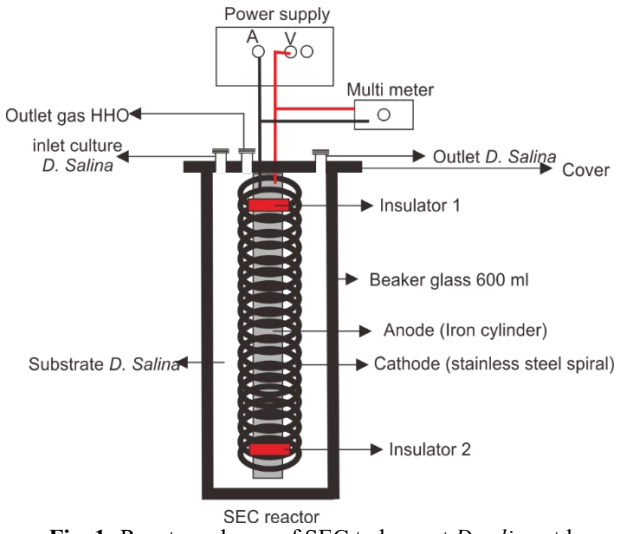

Fig. 1: Reactor scheme of SEC to harvest *D salina* at low concentration in batch mode

During SEC operation, *D salina* was stirred at 400 rpm using a stirrer (DLAB Digital Magnetic Stirrer MS-PA, USA). Stirring was stopped for 30 minutes before sampling. This was so that the floc to settle on the bottom of the reactor. The supernatant represents the top phase, whereas the concentrate describes the bottom phase. A total of 20 mL sample was taken on the supernatant (2 cm from the supernatant surface) to determine OD, pH, TDS (mg/L), nitrate (mg/L) and phosphate (mg/L). Measurement of nitrate (mg/L), phosphate (mg/L), pH, TDS (mg/L) concentrations, referring to the Standard Methods for the Examination of Water and Wastewater [26].

2.1. Design of experiment using CCD

The experimentation in this study was carried out using the Design Expert software, specifically version 10.0.1. The research investigation incorporated two distinct independent variables, specifically voltage and electrolysis time, each of which was comprised of five levels. Table 1 displays the code values derived from the Central Composite Design experiment for the two independent variables utilized in the investigation. In the initial phase of the research, the independent variables were identified as X1 and X2, denoting electrical voltage and electrolysis time, respectively. During the experiment, the independent variable was manipulated across five levels, namely low, medium low, basalt, high enough, and high, in comparison to the base level. The hypothesis test for conformity of the regression model was conducted to assess the appropriateness of the regression model, utilizing the ANOVA results for each response variable. The postulation posited that the regression model is either fitting (H0) or non-conforming (H1). When conducting an ANOVA test on a regression model, a p-value greater than the predetermined level of significance ($\alpha = 0.05$) would lead to the acceptance of the null hypothesis (H0) and the conclusion that the model is acceptable. Conversely, if the p-value is less than or equal to $\alpha = 0.05$, the alternative

hypothesis (H1) would be accepted, indicating that the model is unsuitable and should be rejected. The RSM data was subjected to analysis by Design Expert in order to ascertain the correlations between independent factors and response variables, and to determine the ideal operating parameters for voltage variation and electrolysis timing.

Table 1 Code values based on the Central Composite Design experiment for two independent variables used in the study

Symbol	Independent variable	Units	Level				
			-α	-1	0	+1	+α
X1	Voltage	Volt	15.171	16	18	20	20.82
X2	Time of electrolysis	Min	0.171	1	3	5	5.82

2.2. Harvesting efficiency (η)

As an effort to determine the amount of *D salina* that can be harvested using SEC, a calculation of the harvesting efficiency (η) *of D salina* (%). The calculation of harvesting efficiency refers to the research of Papazi et al (2010) calculated by **Eq. 1** [27].

$$\text{Harvesting efficiency } (\%) = \left(\frac{OD_0 - OD_1}{OD_0}\right) \text{ x } 100\% \quad (1)$$

Harvesting efficiency (η) was the amount of *D salina* at low concentration that can be harvested (%), OD_o was initial optic density of *D salina* at low concentration, and OD_1 is the optic density *of D salina* after harvesting. We used Origin 2022 to perform statistical analyses on tabular and graphical representations of research data.

2.3. Power consumption

Power consumption was calculated using eq. 2, which takes into account the voltage, current, electrolysis time, volume of the *D Salina* suspension, harvesting efficiency, and biomass concentration [28].

$$P_{electrolysis} = (U \text{ x } I \text{ x } t) / (\eta h \text{ x } V \text{ x } C) \quad (2)$$

U is the voltage in volts (V); I is the current in amperes (A); t is the electrolysis time in hours (h); η is the harvesting efficiency as a decimal (96% is the 0.96); V is the volume of microalgae suspension in liters (L); C is the biomass concentration in grams per liter (g/L); P electrolysis is the power consumption of electrolysis in kilowatt-hours per kilogram of biomass (kWh/kg biomass).

3. Result and Discussion

3.1. ANOVA and CCD analysis

The voltage and time of electrolysis are determined using CCD. The response variable is the harvesting efficiency (%) shown in Table 2. The predicted harvesting efficiency ranges from 1.54 to 71.87%, while the actual harvesting efficiency ranges from 1.58 to 74.60%. The result of R^2 is 0.9536.

The reliability of the model in this study was used to predict the performance of the harvesting process. This model was found to be significant as indicated by a p-value less than 0.05, F=28.81. Based on this model suggests that there may be other factors that have a large impact on response, which are not considered in model [29].

The ANOVA test yielded a lack of fit of 3, indicating that the model was acceptable. The coefficient of variation, which is a measure of the residual rate of power density response between actual and projected values, was found to be 39.61%. This means that there is a significant difference between actual and projected values, and the model may not be able to accurately predict the performance of the harvest process in all cases. ANOVA stands for Analysis of Variance, which is a statistical method used to analyze the differences between two or more groups of data. In addition to ANOVA and CCD analysis, fussy logic calculation methods and copulas were used by previous researchers to describe dependencies between random variables [30,31]. Copulas are very useful in overcoming dependency problems and describing relationships between random variables more flexibly than traditional methods. In this research, ANOVA was used to analyze the data obtained from the harvesting of *D salina* at low concentrations using spiral electrocoagulation (SEC). After obtaining the ANOVA results, the researchers used a regression model of quadratic equations to further analyze the data. The regression model of the efficiency of harvesting D salina at low concentrations is as follows:

$$\text{Harvesting efficiency } (\%) = -58.0101 + 6.4044 * X_1 - 16.88235 * X_2 + 1.09127 * X_1X_2 - 0.17361 * X_1^2 + 1.6121 * X_2^2 \quad (3)$$

X_1 represents the voltage variance, while X_2 denotes the time frame of the electrolysis process. This equation describes the mathematical correlation between voltage, electrolysis time, and harvesting efficiency in the D salina harvesting procedure. According to eq. 3, the linear model reveals that most independent factors positively affect harvesting efficiency. A positive sign in front of these variables implies that the electrolysis time increases, while a negative sign indicates that the electrolysis time decreases. A positive coefficient (6.4044* X1) indicates that an increase in the voltage value will tend to increase the harvesting efficiency of D salina. A negative coefficient (-16.88235 *X2) indicates that an increase in electrolysis time will tend to reduce the harvesting efficiency of *D salina.*

3.2. RSM analysis

Li et al (2021) have suggested that RSM can be used to optimize the operating conditions of a process [32]. In this research, RSM was used to analyze the harvesting efficiency of *D salina* at low concentrations by varying the voltage and time of electrolysis. Figure 2(b) shows 3D contour plots and 2D contour plots indicating the interaction of voltage and electrolysis time in D salina harvest efficiency at low concentrations. Fig. 2 (a) is a parabolic image, which corresponds to ANOVA analysis

showing that $X1^2$ is significant with a p-value of 0.0046. Parabolic peaks represent optimal conditions, and the contours around the peaks represent areas with lower efficiency. This means that the interaction between voltage and electrolysis time has a significant effect on the efficiency of *D salina* harvesting at low concentrations. Based on RSM analysis and contour plots, researchers concluded the optimal conditions for harvesting D salina at low concentrations, namely a voltage of 20 V and an electrolysis time of five minutes. The optimum harvesting efficiency response was obtained at a voltage of 20 V and a time of electrolysis of 5 minutes, resulting in a harvesting efficiency of 74.60%.

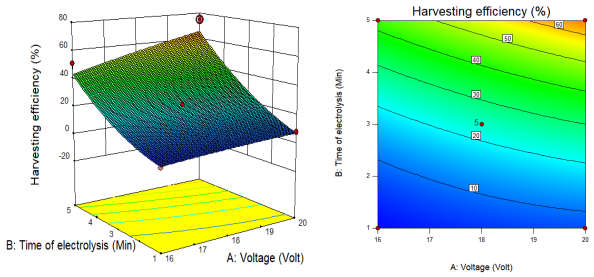

Fig.2: (a) 3D contour plot and (b) 2D contour plot showing the interaction of voltage and time of electrolysis at harvesting efficiency *D salina* at low concentrations

The harvesting efficiency of *D salina* at low concentration refers to the percentage of the total *D salina* population that can be successfully harvested using SEC method. The harvesting efficiency, represented by the variable η, determined by measuring the optical density (OD) of the *D salina* culture using a quartz cuvette with dimensions of 10mm x 10mm x 45mm. The measurement was taken using a spectrophotometer (Spectroquant®Prove 100, Merck KGaA, Darmstadt, Germany). Lie and Liu, in their research, have stated that OD is an accurate and efficient approach for measuring microalgae biomass [33]. This means that measuring the OD value of a microalgae culture can give an estimate of the number of microalgae cells present in the culture. The OD value is a measure of the amount of light that is absorbed by the microalgae cells in the culture. The lower the OD value, the fewer the number of microalgae cells in the culture [34].

Figure 3. (a) depicts a graph of the harvesting efficiency of *D salina* at low concentrations. Variations in voltage (16 V, 18 V, and 20 V) and electrocoagulation time (1 minute, 3 minutes, 5 minutes) were applied to observe their influence on harvesting efficiency. Based on the results of the ANOVA test shows that voltage variations have a significant effect on the efficiency of *D salina* harvest at low concentrations. The harvesting efficiency reached a maximum of 74.6% at a voltage of 20 V for five minutes, surface area anode (Fe) is 88.13 cm-2, stirring speed = 400 rpm, current intensity = 2.1 A. Harvesting efficiency at 16 volts, 50.8% of the microalgae was successfully collected from the culture medium. Similarly, when harvesting *D salina* at 18 volts, 61.9% of the microalgae was successfully collected from the culture medium.

In accordance with the present results, previous studies have demonstrated that at high concentrations (0.88 g L-1) only able to harvest *D salina* 75.39% during EC 3 min with initial pH was 7.2, stirring speed = 150 rpm, electrode aluminum, current intensity = 0.5 A and surface area 13.5 cm-2 [35]. This outcome is contrary to that of Maleki et al (2020), who found the maximum harvesting efficiency of *D salina* (0.5 g L-1) of 98.06% was obtained at a current intensity of 999 mA, electrode distance of 1.39 cm, stirring speed of 222 rpm and with aluminum as the electrode material [22]. This is fair because Xiong et al (2015) and Maleki et al (2020) using Al electrode and *D salina* at high concentrations, 0.88 g L-1 and 0.5 g L-1, respectively [22,36]. Al electrodes are more effective than Fe, Al electrodes show the fastest electrocoagulation efficiency, while Fe–Fe electrodes are the slowest [37].

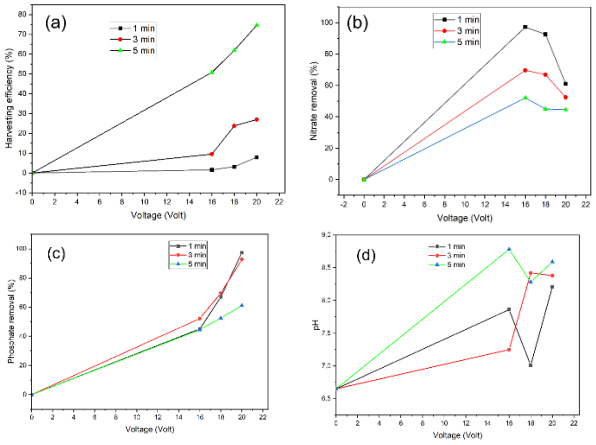

Fig.3: (a) harvesting efficiency (%), (b) nitrate removal (%), (c) phosphate removal (%), and (d) pH of microalgae *D salina* low concentration at voltage and time variations

D salina at low concentrations is harvested using spiral electrocoagulation (SEC) by applying an external electric current that causes flocculation and sedimentation. The coagulation phenomenon occurs during the harvesting of D salina, where coagulants are produced at the anode. In this study, Fe^{3+} ions released from the anode will combine with hydroxyl ions to form metal-hydroxides or polyhydroxides, such as $Fe(OH)_3$, which function as coagulants in the coagulation process [38]. These coagulants are responsible for forming flocs. The number of metal ions released from the anode increases with increasing process time and current according to Faraday's law [39]. Previews research states that the use of spiral plates in the microalgae harvesting process led to the aluminum content in the waste being higher than the recommended values in Rio Grande do Sul [40].

3.3. Analysis of wastewater quality produced from D salina harvesting

a. *pH*

pH has an important impact in EC because pH affects the ratio of positive and negative ions in solution. This ion ratio is key to neutralizing the surface charge of negatively charged cells, reducing the potential of zeta, causing cells to bind and coagulate [41]. Coagulants must be positively charged species, because the surface charge of microalgae cells is negative [42], then the acidic condition is a better pH flock formation process. Table 3 shows quality of *D salina* harvesting wastewater. The maximum pH was 8.6 at a voltage of 20 V for 5 minutes. The pattern of changes in pH is shown in Fig. 3 (d). The greater the voltage and electrolysis time, the higher the pH value. The desired pH value is in the range of 3-7 so that the formation of the floc is optimal and the temperature is not high. At low pH (3-7), it is dominated by positively charged Fe-hydroxopolymers and Fe-oxide-hydroxides, which contribute in destabilizing negatively charged microalgae cells [43]. An increase in pH greater than 7 was observed, which led to improper floc formation and was thus an unfavorable outcome of this investigation. In a galvanic cell, oxidation reactions occur at the anode (eq. 3) and reduction reactions occur at the cathode (eq. 4). During oxidation, electrons are release from the anode material (Fe), this results in the production of Fe^{2+} ions. This process is accompanied by the release of energy [44]. The pH of a solution is a measure of the concentration of hydrogen ions (H^+) in the solution. A higher pH indicates a lower concentration of H^+ ions and a higher concentration of hydroxide ions (OH^-). Eq. 3 represents the half-reaction that occurs at the cathode during electrolysis, in which water is reduced to produce hydrogen gas and hydroxide ions. The longer the electrolysis process was conducted, the more water was reduced and the more hydroxide ions are produced, resulting in a higher pH of the solution [45].

$$Fe \rightarrow Fe^{2+} + 2e^- \quad (3)$$

$$2\ H_2O + 2e^- \rightarrow 2\ OH^- + H_2 \quad (4)$$

Based on regulation, the pH value of *D salina* culture wastewater was as required in Indonesia government regulation. We used Government Regulation Number 22 of 2021 concerning the Implementation of Environmental Protection and Management of Class II Rivers, which states that a safe pH for the environment is between 6-9. Based on the pH value, *D salina* cultivation effluent can be safely discharged into bodies of water.

Table 2 The Design Experiment utilizing CCD with their predicted and actual harvesting efficiency.

Run	Code		Variable		Harvesting efficiency (%)	
	X1	X2	Voltage (Volt)	Time of electrolysis (Min)	Actual	Predicted
1	0	0	18	3	23.8095	23.8099
2	-1	+1	16	5	50.7937	43.2085
3	-1	-1	16	1	1.5873	2.2062
4	+1	-1	20	1	7.9365	7.1890
5	0	-α	18	0.17157	3.1746	1.5405
6	+1	+1	20	5	74.6032	65.6516
7	0	0	18	3	23.8095	23.8099
8	-α	0	15.17157	3	9.5238	12.7244
9	0	0	20.8284	3	26.9841	32.1175
10	0	0	18	3	23.8095	23.8099
11	0	0	18	3	23.8095	23.8099
12	0	+α	18	5.82843	61.9048	71.8729
13	0	0	18	3	23.8095	23.8099

Table 3 quality of wastewater produced from *D salina* harvesting

Voltage (volts)	Time (min)	Harvesting efficiency (%)	pH	TDS (mg/L)	Nitrate (mg/L)	Phosphate (mg/L)
0	0	0	6.7	1086	12.79	0.106
16	1	1.6	7.9	1080	7.04	0.050
16	3	9.5	7.3	1072	6.12	0.089
16	5	50.8	8.8	1030	7.09	0.006
18	1	3.2	7.0	1084	4.23	0.093
18	3	23.8	8.4	1045	3.88	0.009
18	5	61.9	8.3	1049	6.08	0.009
20	1	7.9	8.2	1063	0.35	0.026
20	3	27.0	8.4	1042	0.95	0.007
20	5	74.6	8.6	1005	4.98	0.006

b. *Total Dissolved Solid*

TDS is one of the wastewater characteristics that determine the quality of water [46,47] and is a measurement of the total concentration of solutes in wastewater. The solute consists mostly of inorganic salts, with a smaller quantity of organic compounds [48]. According to Government Regulation Number 22 of 2021 concerning the Implementation of Environmental Protection and Management of Class II Rivers, it shows the TDS parameter for class 2 which is 1,000 mg/L.

When *D salina* harvesting uses SEC, *D salina* culture wastewater still contains TDS that exceeds the quality standard. The initial TDS concentration was 1086 mg/L, after harvesting *D salina* using SEC, wastewater was produced with the lowest concentration of 1005 mg/L using a voltage of 20 V for 5 min (Table 3). The use of SEC is expected to not only be able to harvest *D salina* with high efficiency, but also be able to reduce TDS to meet quality standards. High TDS levels indicate the presence of dissolved minerals, pollutants, or other

impurities in wastewater harvesting *D salina*.

c. Nitrate

Nitrate is a naturally occurring compound found in soil, water, and plants, and is also a key component of fertilizers and plays a critical role in the nitrogen cycle [49]. Excess of nitrates in the water causes eutrophication [11,12]. The most interesting aspect of this study that SEC for one minute treatment to decrease nitrate by a maximum of 97.3% using 20 V for one minute. The initial nitrate concentration was 12.79 mg/L, according to Indonesia Government Regulation Number 22 of 2021 concerning the Implementation of Environmental Protection and Management of Class II Rivers, it shows the nitrate concentration for class 2 which is 10 mg/L. After harvesting *D salina* using SEC, wastewater contained nitrate at the lowest concentration of 0.35 mg/L (Table 3). There is a decrease in nitrate concentration as the voltage increases. At voltages of 16 V- and five-minutes SEC, wastewater still contains 7.09 mg/L nitrate, but nitrate concentrations in wastewater of 4.98 mg/L at voltages of 20 V- and five-minutes SEC. Generally, reducing nitrate concentrations using SEC meets government regulatory standards.

The nitrate removal pattern is shown in Fig. 2 (b). At one min and 16 volts, 52.8% of nitrate was successfully remove from the culture medium. Similarly, when nitrate removal at 18 volts, 66.9%. The efficiency of nitrate removal in the third minute was 12.3%, 91.5%, and 91.5%, respectively at voltages of 16V, 18V and 20V. The efficiency of nitrate removal in the fifth minute was 75.5%, 93.4%, and 94.3%, at voltages of 16V, 18V and 20V, respectively. According to previous studies [50], Fe electrodes remove nitrate by 12.4% and Al electrodes 80.1% in agricultural wastewater for 210 min, current density = 2.31 A m-2, and inter-electrode distance = 10 mm.

Increases in voltage generated an increase in electrodes releasing anions, leading in the formation of more sediment due to the removal of pollutants [51]. During electrocoagulation, NO_3 ions are mostly removed from the solution by adsorption and enmeshing (mechanical entrainment) on anodic reaction such as $Al(OH)_3$ and its derivatives [52]. Besides being adsorbed on $Al(OH)_3$ and other hydrolysis products, NO_3^- ions have the tendency to undergo cathodic reduction according the following equations [53]. Adsorption on anodic reaction such as $Al(OH)_3$ and its derivatives also remove pollutants such as NH_3 and NO_2^- [54].

$NO_3^- + H_2O + 2e \rightarrow NO_2^- + 2OH^-$ (e_o = 0.01 V)

$NO_3^- + 3H_2O + 5e \rightarrow \frac{1}{2}N_2 + 6OH^-$ (e_o = 0.26 V)

$NO_3^- + 6H_2O + 8e \rightarrow NH_3 + 9OH^-$ (e_o = -0.12 V)

In summary, the SEC was successful in reduce nitrate concentrations to a maximum of 97.3% for a period of one minute while utilizing a voltage of 20 volts.

d. Phosphate

One of the aims of the study is to analyze nutrients (nitrate and phosphate) in the wastewater produced from *D salina* harvesting. Excessive presence of phosphate in conjunction with nitrates can cause algal blooms [55]. Phosphate is a nutrient that is essential for the growth of aquatic plants. According to Government Regulation Number 22 of 2021 concerning the Implementation of Environmental Protection and Management of Class II Rivers, it shows the phosphate parameter for class 2 which is 0.2 mg/L.

Table 2 presents quality of wastewater produced from *D salina* harvesting. The initial phosphate concentration was 0.106 mg/L, after harvesting *D salina* using SEC, wastewater was produced with the lowest concentration of 0.001 mg/L using a voltage of 20 V for five minutes (). The pattern of changes in phosphate concentration is shown in Fig. 3 (c).

The SEC is expected to be able to harvest *D salina* effectively while lowering phosphate. The initial phosphate concentration was 0.106 mg/L (Table 3), according to Government Regulation Number 22 of 2021 concerning the Implementation of Environmental Protection and Management of Class II Rivers, it shows the phosphate concentration for class 2 which is 0.2 mg/L. The results of this study showed that the SEC decrease phosphate with maximum removal of 94.3% with an operating condition of 20 V for 5 min. At voltages of 16 V- and five-minutes SEC, wastewater still contains 0.006 mg/L phosphate, and 0.009 mg/L when using voltages of 18 V- and five-minutes SEC. This also appropriate with previous research, which showed that phosphate from fertilizer companies can be recovered by EC from runoff precipitation is 98% (reduced from 3.86 mg/L to 0.075 mg/L) [56]. The phosphate removal was higher than that of previously reported by Tchamango et al (2010) where phosphate reduction as 89.81% [57]. The reduction in phosphate concentration is probably the result of struvite production ($MgNH_4PO_4 \bullet 6H_2O$) [58].

In summary, the SEC was capable of reducing phosphate concentrations to a maximum of 97.3% for one minute while utilizing a voltage of 20 volts and reducing phosphate concentrations using SEC meets government regulatory standards.

e. Power consumption analysis

Power consumption is the amount of energy used by the electrolysis process to harvest *D Salina* at low concentration [59]. Based on the calculation using Eq. (2), the power consumption required to harvest *D salina* at a low concentration is 0.426517 kWh/kg biomass. This power consumption is calculated based on a maximum efficiency of 74.6%, using a voltage of 20 V for five minutes with a current intensity of 2.1 A. It seems that the power consumption in this study is lower than 0.43 kWh/kg biomass, which is the reported power

consumption for harvesting *Chlorella sp.* with an initial biomass concentration of 0.5 g/L [60]. Nevertheless, it's higher than the reported by Estrada-Graf et al (2020) stated power consumption of 0.27 kWh/kg biomass for harvesting *Scenedesmus obtusiusculus*, which used an initial biomass concentration of 1 g/L [61]. Based on this analysis, it appears that the power consumption required to harvest *D salina* at a low concentration is higher compared to a higher microalgae concentration.

4. Conclusion

The study has contributed to the understanding of harvesting *D salina* at low concentrations. *D salina* harvesting at low concentrations achieved a maximum efficiency of 74.6% when the voltage was set to 20 V for five minutes with a surface area of 88.13 cm-2, stirring speed = 400 rpm, current intensity = 2.1 A. Nutrients (nitrates and phosphates) in wastewater were successfully reduced by 97% using SEC in one minute under 20 volts applied. An increase in pH greater than 7 is observed, which leads to improper floc formation. The power consumption required to harvest *D salina* at a low concentration is 0.426517 kWh/kg biomass. More research is needed to improve the efficiency of D salina harvesters at low concentrations by optimizing SEC operating conditions, which can reduce power consumption and make the process more energy-efficient and cost-effective.

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Nomenclature

C-BIORE	Center Biomass and Renewable Energy
CCD	Central Composite Design
cm	Centimeter
I	Current (A)
mL	Milliliter
mm	Millimeter
^{o}C	Degrees Celsius
OD	Optic density
P	Power consumption of biomass (kWh/kg biomass).
pH	Pondus Hydrogeny
rpm	Revolution per minute
SEC	Spiral Electrocoagulation
t	Time (h)
TDS	Total Dissolved Solid
U	Voltage (v)
η	harvesting efficiency (%)

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