OPTIMIZATION OF SUPERCRITICAL CO_2 EXTRACTION, ANALYSIS OF PHYSICOCHEMICAL PROPERTIES AND ANTIOXIDANT ABILITY OF DRAGON FRUIT SEED OIL (*Hylocereus polyrhizus*)

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ABSTRACT

Red-fleshed dragon fruit (*Hylocereus polyrhizus*) seeds, an abundant agro-industrial byproduct, contain valuable oil rich in unsaturated fatty acids with potential antioxidant properties. This study aimed to optimize the oil's supercritical carbon dioxide (SC-CO_2) extraction and evaluate its physicochemical characteristics and antioxidant activity. Using a Central Composite Design based on Response Surface Methodology (RSM), optimal extraction conditions were identified as 49.58 °C, 6526 psi, and a 6.46 L/min CO_2 flow rate, achieving an oil yield of 13.41 ± 0.42% (w/w), corresponding to 52.89 ± 1.67% recovery. The extracted oil exhibited a high iodine value (129.15 ± 0.746 g I_2/100 g), indicating significant unsaturation, an acid value of 17.29 ± 0.137 mg KOH/g, volatile content of 6.19 ± 0.0021%, and a total polyphenol content of 0.384 mg GAE/g. Vigorous free-radical scavenging activity was confirmed via DPPH and $ABTS^{\bullet+}$ assays, with IC_{50} values of 0.52 and 0.195 mg/mL, respectively. These findings demonstrate that dragon fruit seed oil obtained via optimized SC-CO_2 extraction is a rich source of unsaturated lipids and natural antioxidants, highlighting its significant potential as a natural ingredient in functional foods, nutraceuticals, and cosmetic products. In contrast, this green extraction method adds value to agricultural by-products.

Keywords: Supercritical CO_2 extraction, dragon fruit seed oil, response surface methodology, physicochemical properties, antioxidant activity, *Hylocereus* spp.

1. INTRODUCTION

Dragon fruit (*Hylocereus* spp.), often referred to as a "superfruit," was introduced to India as an exotic tropical plant with numerous health benefits. It is easily recognized by its vivid skin color and soft pulp embedded with edible black seeds. Due to its exceptional nutritional value and increasing market demand, dragon fruit cultivation has expanded across several regions of India, despite its origin in Mexico and Central and South America. The crop offers a long productive lifespan of up to 20 years, with plants typically bearing fruit from the second year and reaching maximum yield within five years. Approximately 800 plants can be accommodated per hectare [1].

A by-product of juice and wine production, dragon fruit seeds constitute approximately 2–5% of the fruit's dry weight and are often discarded, leading to underutilization of valuable resources. Recent studies have underscored the nutritional richness of these seeds, reporting moisture contents of 6.9–7.2%, protein levels between 21.5–26.6%, ash contents of 3.1–6.1%, oil contents ranging from 18.8–27.5%, and carbohydrate levels of 44.5–49.8% across different species such as *Hylocereus polyrhizus*, *Hylocereus undatus*, and *Selenicereus megalanthus* [2]. Moreover, dragon fruit seeds are abundant in phenolic and flavonoid compounds, with red-fleshed seeds exhibiting notably high phenolic content (43.9 mg GAE/100 g) and antioxidant activity based on DPPH and FRAP assays [2]. Fatty acid analysis shows that these seeds are particularly rich in linoleic acid ($C_{18:2}$) and oleic acid ($C_{18:1}$), with red-fleshed varieties having the highest oleic acid content (25.5%) [2]. Linoleic acid, a polyunsaturated omega-6 fatty acid, is known for its capacity to counteract the cholesterol-raising effects of saturated fatty acids, providing cardiovascular benefits [2].

Despite their promising nutritional and functional potential, the efficient extraction of bioactive compounds from dragon fruit seeds remains a technological challenge. Conventional methods, including mechanical pressing and solvent extraction, often yield limited efficiency, leave undesirable solvent residues, or compromise product quality. Supercritical carbon dioxide (SC-CO_2) extraction has recently emerged as a green and innovative technology that enables high-efficiency extraction under mild temperature and pressure conditions, preserving thermally sensitive bioactives and eliminating solvent residues [3]. However, while SC-CO_2 extraction has been successfully applied to other oilseed crops, studies specifically focusing on its optimization for dragon fruit seeds are scarce. Previous work has primarily concentrated on basic compositional profiling of dragon fruit seeds, with limited efforts directed toward optimizing extraction parameters or comprehensively characterizing the physicochemical and functional properties of the extracted oil. Furthermore, there is a lack of systematic evaluation of the antioxidant activity of dragon fruit seed oil obtained under optimized extraction conditions.

The present study aims to address these gaps by optimizing the SC-CO_2 extraction process to maximize oil recovery from red-fleshed dragon fruit (*Hylocereus polyrhizus*) seeds using Response Surface Methodology (RSM) with Central Composite Design (CCD). In addition, the study investigates the physicochemical properties, total polyphenol content, and antioxidant capacity of the extracted oil, employing DPPH and ABTS radical scavenging assays. The findings are expected to provide a scientific basis for valorizing dragon fruit seeds as functional food ingredients, promoting sustainable utilization of agricultural by-products.

2. MATERIALS AND METHODS

2.1. Materials

Seeds from red-fleshed dragon fruit (*Hylocereus polyrhizus*), accounting for approximately 2–5% of the total dry weight of the fruit, were collected as a by-product of juice processing in Binh Thuan, Vietnam. The seeds are dried at 40 °C for 6 hours to acquire the final sample and pulverized into powder. The proximate composition of the seeds has been reported previously [2], including protein (26.3 ± 0.2 g/100 g), lipid (22.8 ± 0.5 g/100 g), ash (6.1 ± 0.0 g/100 g), and carbohydrate (44.8 ± 0.3 g/100 g) content. The seeds are also rich in phenolic (43.9 mg GAE/100 g) and flavonoid (50.8 mg GAE/100 g) compounds, as well as fatty acids such as linoleic acid (48.7%) and oleic acid (25.5%) [2].

2.2. Methods

2.2.1. Optimization of the supercritical CO_2 extraction process

While studying this feedstock, experiments were conducted to investigate how temperature, pressure, and CO_2 flow rate affect the oil extraction. The SC-CO_2 extraction conditions were varied within specific ranges: X_1, temperature (40–60 °C); X_2, pressure (2800–

6550 psi); and X_3, CO_2 flow rate (3.3–6.7 L/min). These ranges were selected based on the physicochemical behavior of supercritical CO_2 (SC-CO_2) and its effectiveness as a green solvent. The temperature range (40–60 °C) was chosen to maintain CO_2 in a supercritical state (above the critical temperature of 31.1 °C) and to ensure an optimal balance between solvent strength and thermal preservation of bioactive compounds [4]. The pressure range (2800-6550 psi) corresponds to 193.05-451.61 bar, much higher than the critical pressure of CO_2 (73.8 bar), significantly increasing its density and solubility for lipophilic substances [4]. The CO_2 flow rate (3.3-6.7 L/min) was chosen to ensure sufficient mass transfer without using too much solvent or losing extraction efficiency [5]. These parameters were selected based on practical experiments. This study focused on optimizing the oil recovery using Response Surface Methodology (RSM) combined with Central Composite Design (CCD). Experimental design and regression analysis were applied to determine the optimal conditions to maximize oil recovery efficiency (RE) [6]. All SC-CO_2 extraction experiments were conducted using a Speed SFE-2/4 system (Applied Separation, USA).

2.2.2. Physicochemical properties of dragon fruit seed oil

Physicochemical properties were evaluated following Vietnamese Standards (TCVN). Acid value was determined according to TCVN 6127:2010 [7], and iodine value was measured following TCVN 6122:2015 [8]. Volatile compound content was assessed using an infrared moisture analyzer (MB90, Ohaus, USA), following TCVN 6125:2020 [9]. All measurements were performed in triplicate.

2.2.3. Determination of total polyphenol content

Polyphenols were extracted from the oil following the modified method of Maier *et al.* [10]. Briefly, 5 mL of n-hexane was added to 4 g of oil and mixed with 5 mL of methanol/water (80:20, v/v), followed by vigorous shaking for 10 minutes and centrifugation at 3500 rpm for 15 minutes. The methanol phase was collected and re-extracted twice. The pooled methanol extracts were stored at 4 °C before total polyphenols analysis and antioxidant activity determination. Total polyphenol content was determined using the Folin–Ciocalteu method [12, 13], with absorbance measured at 765 nm. Results were calculated using a gallic acid calibration curve and expressed as mg GAE/g extract.

2.2.4. Determination of antioxidant activity by 2,2-diphenyl-1-picrylhydrazyl (DPPH) free radical scavenging assay

Antioxidant activity was assessed using the DPPH assay according to Hanato *et al.* [13]. Polyphenol extracts at 0.15–0.55 mg/mL concentrations were mixed with DPPH solution (40 mg/L), incubated at room temperature for 30 minutes, and absorbance was measured at 517 nm. Radical scavenging activity was expressed as IC_{50}, defined as the extract concentration required to inhibit 50% DPPH radicals.

2.2.5. Determination of antioxidant activity by $ABTS^{\bullet+}$ free radical scavenging assay

The $ABTS^{\bullet+}$ scavenging assay was performed following Nenadis *et al.* [14]. Extracts (0.2-0.8 mg/mL) were mixed with $ABTS^{\bullet+}$ solution, incubated for 30 minutes at room temperature, and absorbance was recorded at 734 nm. Scavenging capacity was expressed as IC_{50}, calculated using standard curves. Trolox was used as the positive control.

2.3. Data analysis method

All experiments were conducted in triplicate ($n = 3$), and the results are reported as mean values ± standard error of the mean. The data were processed and analyzed using Microsoft Excel 2016 for basic statistical calculations. To assess the significance of differences between experimental groups, one-way analysis of variance (ANOVA) was performed at a 95% confidence level ($\alpha = 0.05$) using Minitab 19.2 software. Post hoc comparisons were conducted using Tukey's multiple comparison test where applicable.

3. RESULTS AND DISCUSSION

3.1. Optimization of the supercritical CO_2 extraction process

The supercritical CO_2 extraction process was systematically optimized using Response Surface Methodology (RSM) coupled with a Central Composite Design (CCD) to maximize the oil recovery from red-fleshed dragon fruit seeds. A total of 19 experimental runs were conducted based on the CCD matrix to evaluate the individual and interactive effects of extraction temperature (X_1), pressure (X_2), and CO_2 flow rate (X_3) on recovery efficiency (RE). The experimental and predicted responses and the residuals are summarized in Table 1. A second-order polynomial regression model (1) was fitted to the data, and the resulting equation effectively describes the relationship between process variables and extraction efficiency. The adequacy and predictive performance of the model were further validated through statistical parameters such as the adjusted and predicted R^2 values.

$$Y = -121.00 - 0.23X_1 + 0.03440X_2 + 21.73X_3 - 0.0143X_1^2 - 0.000004X_2^2 - 1.565X_3^2 + 0.000269X_1X_2 - 0.017X_1X_3 - 0.000069X_2X_3 \quad (1)$$

All coefficients in the second-order regression model (Equation 1) were found to be statistically significant ($p < 0.05$), indicating that the selected process variables and their interactions had a meaningful effect on oil recovery efficiency. This further confirms the robustness and reliability of the model in describing the extraction behavior under varying SC-CO_2 conditions.

Table 1. Central composite design matrix and experimental results for oil recovery efficiency

Run	Experimental Parameters			Recovery efficiency (% based on oil content in seed)		
	X_1 (Temperature, °C)	X_2 (Pressure, psi)	X_3 (CO_2 output flow, L/min)	Actual	Predicted	Residual
1	45.0	3625.00	4.0	18.18	17.3803	0.7997
2	55.0	3625.00	4.0	10.55	9.8560	0.694
3	45.0	5800.00	4.0	41.75	41.8615	-0.1115
4	55.0	5800.00	4.0	39.35	40.1972	-0.8472
5	45.0	3625.00	6.0	28.19	27.5097	0.6803
6	55.0	3625.00	6.0	20.19	19.6454	0.5446
7	45.0	5800.00	6.0	51.36	51.6909	-0.3309
8	55.0	5800.00	6.0	49.27	49.6866	-0.4166
9	41.6	4712.50	5.0	40.74	41.5330	-0.793

10	58.4	4712.50	5.0	34.19	33.5289	0.6611
11	50.0	2884.05	5.0	2.97	3.2133	-0.2433
12	50.0	6540.95	5.0	49.78	49.0484	0.7316
13	50.0	4712.50	3.3	25.20	25.6814	-0.4814
14	50.0	4712.50	6.7	42.71	42.3574	0.3526
15	50.0	4712.50	5.0	39.08	38.5420	0.538
16	50.0	4712.50	5.0	38.64	38.5420	0.098
17	50.0	4712.50	5.0	37.98	38.5420	-0.562
18	50.0	4712.50	5.0	37.99	38.5420	-0.552
19	50.0	4712.50	5.0	39.14	38.5420	0.598

The optimization of the supercritical CO_2 ($SC\text{-}CO_2$) extraction process was evaluated using response surface methodology (RSM), focusing on the effects of temperature (X_1), pressure (X_2), and CO_2 flow rate (X_3) on the oil recovery efficiency (RE) from red-fleshed dragon fruit seeds. According to the results in Table 2, the second-order regression model yielded the coefficients with an adjusted R^2 of 97.69% and a predicted R^2 of 92.16% for the oil recovery efficiency. These coefficient values indicate that the model has a high degree of fit with minimal deviation. The results show that temperature (X_1), pressure (X_2), and CO_2 flow rate (X_3) factors significantly affect the extraction efficiency ($p < 0.05$). The model predicted optimal values were a temperature of 49.58 °C, pressure of 6526.27 psi, and CO_2 flow rate of 6.46 L/min. The experimental results confirmed that the recovery efficiency was 52.89 ± 1.67% under these conditions. This is consistent with the model-predicted value of 52.71%. This confirms that the model is highly accurate and has good practical application potential.

Compared to other extraction methods, $SC\text{-}CO_2$ extraction exhibits significantly lower efficiency than ethanol extraction (86.26 ± 1.00%) but achieves a higher yield than n-hexane extraction (49.64 ± 0.1%), as reported by Phan *et al.* [19]. This finding suggests that extraction efficiency is only one factor in evaluating extraction techniques; equally important is the ability to preserve bioactive compounds without degradation or structural alteration. As a safe and environmentally friendly extraction method, $SC\text{-}CO_2$ does not involve using toxic organic solvents, making it a sustainable approach. Notably, it balances extraction efficiency and the biological integrity of the extracted compounds, reinforcing its value in applications where yield and the preservation of bioactive properties are critical considerations.

Table 2. Results of the optimization of the supercritical CO_2 extraction method

	Temperature (°C)	Pressure (psi)	CO_2 flow rate (L/min)	Recovery efficiency (% based on oil content in seed)
Experiment	50	6539.5	6.2	52.89 ± 1.67
Predict	49.58	6526.27	6.46	52.71
The regression model coefficients				
Adjusted R^2				97.69%
Predicted R^2				92.16%

The three-dimensional response surface plots (Figure 1) provide insights into the interactive effects of these parameters on extraction performance. Figure 1(a) (temperature vs. CO_2 flow) reveals that increasing temperature and CO_2 flow rate positively influence RE, with the highest extraction yields observed at approximately 55 °C and 6 L/min. Elevated temperatures likely enhance the solubility of lipophilic compounds and reduce oil viscosity, thereby improving mass transfer and extraction efficiency. Furthermore, a higher CO_2 flow rate increases the mass transfer coefficient and the solvent available for oil extraction, leading to enhanced recovery [15].

Figure 1(b) (pressure vs. CO_2 flow rate) indicates that RE increases markedly with pressure, particularly beyond 5000 psi. High pressure improves CO_2 density, enhancing its solvating power and facilitating the dissolution of target compounds. Similarly, the combination of high pressure and increased CO_2 flow rate yields optimal oil recovery, underscoring the synergistic effect of these parameters [16].

Figure 1(c) (temperature vs. pressure) demonstrates that the maximum RE value is achieved at elevated temperatures (around 55 °C) and high pressures (above 6000 psi). This can be attributed to the simultaneous enhancement of CO_2 solvent density under pressure and oil viscosity reduction at higher temperatures, which optimizes the extraction environment [16].

These findings align with previous studies on oilseed extraction using SC-CO_2, confirming that pressure is the dominant factor influencing extraction efficiency, while temperature and CO_2 flow rate play complementary roles. The optimized conditions identified in this study maximize oil yield and offer a green and sustainable extraction approach without needing organic solvents. Future work should explore these conditions' scale-up potential and assess the extracted oil's stability and functional properties for food and nutraceutical applications.

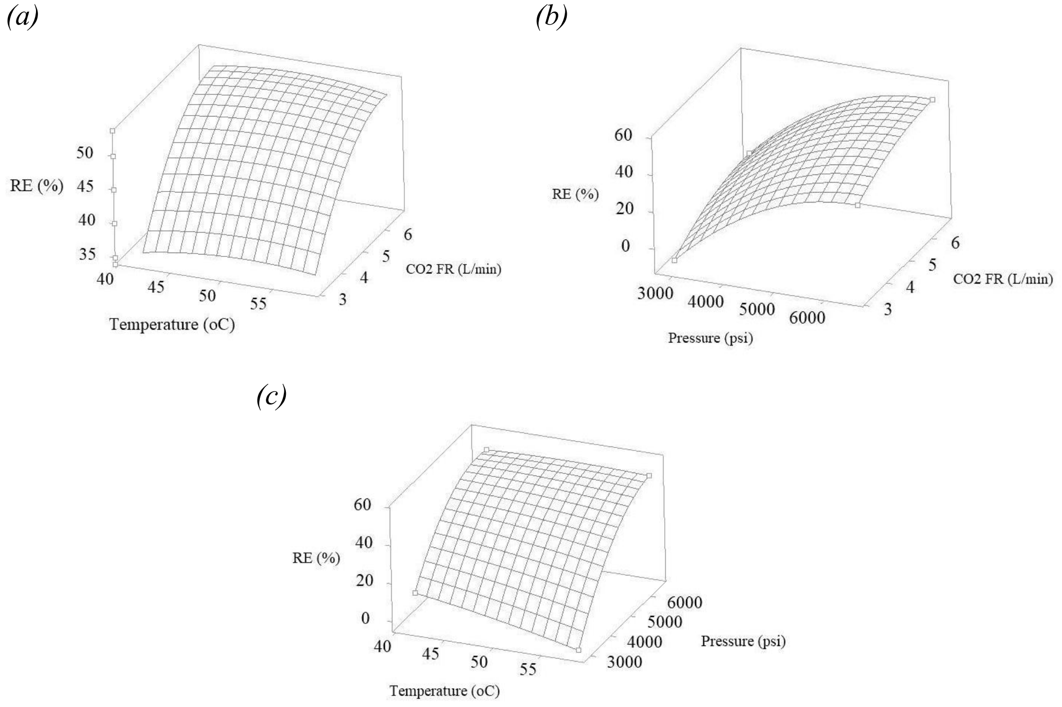

Figure 1. Response surface plot of oil recovery efficiency (RE) (%) as a function of pressure, temperature, and CO_2 flow rate (CO_2 FR): (*a*) Recovery efficiency as a function of temperature and CO_2 flow rate with fixed pressure at 6526.27 psi; (*b*) Recovery efficiency as a function of pressure and CO_2 flow rate with fixed temperature at 49.58 °C and (*c*) Recovery efficiency as a function of temperature and pressure with fixed CO_2 flow rate at 6.46 L/min.

3.2. Physicochemical properties of dragon fruit seed oil

Table 3 shows the physicochemical properties of dragon fruit seed oil extracted by supercritical CO_2 under optimal conditions. The acid value was much higher than that of ethanol-extracted oil (2.27 ± 0.2 mg KOH/g) [19]. This oil has a high iodine value due to its high unsaturated fatty acid content, which is higher than that of solvent extracted oil 127 ± 0.98 (g I_2/100g) [20] many oils such as peanut oil (86-107 g I_2/100 g), coconut oil (6-11 g I_2/100 g), canola oil (105-126 g I_2/100 g), corn oil (102-135 g I_2/100 g) as reported in [18] showing that the seed oil maintains the good qualities of vegetable oil.

Table 3. Analysis of oil extracted from red-fleshed dragon fruit seeds

Characteristics	Value
Iodine Value (g I_2/100g)	129.15 ± 0.746
Acid Value (mg KOH/g)	17.29 ± 0.137
Volatile substances (%)	6.19 ± 0.0021

3.3. Determination of total polyphenol content

Polyphenols are a group of secondary metabolites with more than 8000 types that exist throughout plants and medicinal herbs, and have beneficial effects on the human body [20-23]. Determining the polyphenol content helps guide research on the biological activities of plants. Measure the absorbance of gallic acid standard at concentrations of 0, 30, 60, 90, 120, and 150 µg/mL, from the absorbance and initial concentration of the standard, and draw a linear curve of the correlation between the content of the standard substances and the absorbance in their solutions. From the existing gallic acid equation ($y = 0.0047x + 0.035$), replace the average absorbance value of the test samples with the y value of the gallic acid standard equation, thereby deducing that the x value is the polyphenol content in the extract.

The polyphenol content in this study was recorded as 0.384 ± 0.0021 mg GAE/g. This value was lower than that of ethanol extraction (1.05 ± 0.06 mg GAE/g) [19], and also much lower than that of microwave extraction (96.714 ± 0.06 mg GAE/g) [17]. This difference is because polyphenols contain more hydroxyl and glycoside groups and are more soluble in polar solvents. In addition, polar solvents can form hydrogen bonds, breaking the weaker bonds between the plant matrix and polyphenols, thereby enhancing the release of more polyphenols [24].

3.4. Investigation of antioxidant activity

After measuring the absorbance spectrum and calculating the results, a linear correlation was constructed between the reaction concentration of the extract and Trolox (6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid) and the antioxidant activity. The comparison results are shown in Figures 2 and 3.

The antioxidant efficacy of SC-CO_2-extracted pitaya seed oil was demonstrated by its ability to inhibit DPPH free radicals, reaching 50.49 ± 0.03%. In contrast, ethanol-extracted pitaya seed oil exhibited higher inhibition levels, with 70.81 ± 0.28% reported by Phan *et al.* [19]. Similarly, Boyapati *et al.* [17] observed a DPPH inhibition rate of 68.4 ± 0.46% using solvent extraction. Notably, lemon seed oil extracted with SC-CO_2 showed the highest inhibition level at 99.2% [25]. Although SC-CO_2-extracted pitaya seed oil showed slightly lower radical inhibition than solvent-extracted oils, the value remains above 50%, suggesting effective retention of antioxidant components. These findings reinforce the premise that SC-CO_2 extraction, while sometimes yielding slightly lower extraction efficiencies, offers the advantage of better preserving sensitive bioactives. This is particularly important for materials prone to thermal or oxidative degradation, such as pitaya seeds. Therefore, SC-CO_2 extraction provides a viable, green alternative with potential applications in functional food, cosmetic, and pharmaceutical formulations.

Higher concentrations of oil extract correlated with stronger free radical scavenging ability, and samples with lower IC_{50} values exhibited higher antioxidant activity. Based on Figure 2, the IC_{50} value for the DPPH radical scavenging activity of SC-CO_2-extracted pitaya seed oil was 0.52 ± 0.02 mg/mL. This value is higher than those typically observed for solvent-extracted oils, indicating relatively lower potency. For example, Trolox - a common antioxidant standard - had an IC_{50} of 0.0056 ± 0.0001 mg/mL. The difference between the SC-CO_2-extracted oil and Trolox was statistically significant ($p < 0.05$), as determined by Tukey's test. Although the IC_{50} was higher than that of some solvent-extracted oils, the results still confirm the presence of effective antioxidant activity in the SC-CO_2 extract, further supporting the suitability of this method for extracting functionally relevant compounds.

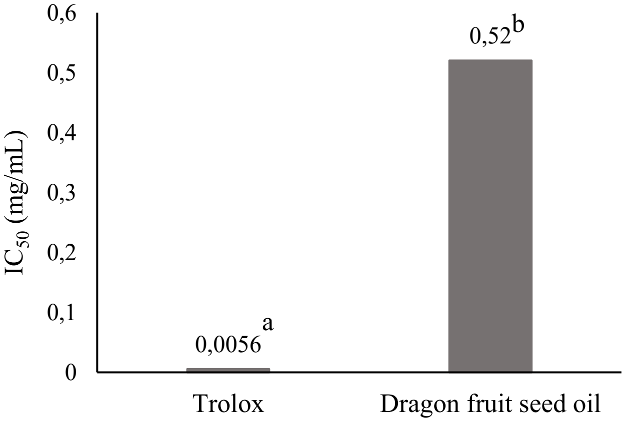

Figure 2. IC_{50} value of dragon fruit seed oil and Trolox on DPPH free radical scavenging assay *(Different lowercase letters above the bars indicate statistically significant differences ($p < 0.05$))*

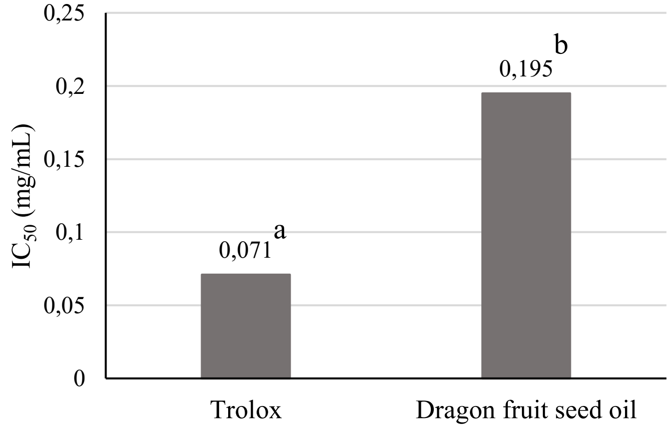

Figure 3. IC_{50} value of dragon fruit seed oil and Trolox on $ABTS^{\bullet+}$ free radical scavenging assay *(Different lowercase letters above the bars indicate statistically significant differences ($p < 0.05$))*

To neutralize $ABTS^{\bullet+}$ free radicals, the extract was diluted into a concentration range from 0.2 to 0.8 mg/mL. The radical scavenging efficiency of the extract increased from 47.83 ± 0.034% at a concentration of 0.02 mg/mL to 74.57 ± 0.02% at 0.08 mg/mL. The antioxidant capacity and radical neutralization efficiency of the dragon fruit seed oil extract were evaluated based on the IC_{50} value, as shown in Figure 3. Figure 3 indicates that the IC_{50} value of the extract was 0.195 ± 0.002 mg/mL, which is significantly higher than that of the positive control Trolox (0.071 ± 0.002 mg/mL). At a significance level of 5%, the antioxidant activity of the extract was statistically different from that of the positive control ($p < 0.05$), as determined using Tukey's test. This value was much lower than that of supercritical CO_2-extracted Assam tea seed oil (IC_{50} = 1278 mg/mL) [26].

The observed difference in IC_{50} values between the DPPH and $ABTS^{\bullet+}$ assays may be attributed to the nature of the radicals and their reactivity with antioxidant compounds. ABTS is more versatile and reacts with lipophilic and hydrophilic antioxidants, whereas DPPH is more selective for lipophilic compounds. The lower IC_{50} observed in the $ABTS^{\bullet+}$ assay indicates that the extract likely contains polar antioxidant components, possibly phenolics and minor polar lipids. Furthermore, the relatively modest polyphenol content (0.384 mg GAE/g) may partially explain the higher IC_{50} values compared to ethanol extracts, which are more effective at solubilizing polar antioxidants. Nonetheless, the SC-CO_2 extracted oil exhibited significant radical scavenging activity, demonstrating its potential as a natural antioxidant source. These findings support the functional value of dragon fruit seed oil in food and cosmetic applications, especially when targeting clean-label, solvent-free ingredients.

4. CONCLUSION

This study successfully optimized the supercritical CO_2 (SC-CO_2) extraction conditions for obtaining oil from red-fleshed dragon fruit (*Hylocereus polyrhizus*) seeds. It comprehensively evaluated the physicochemical and antioxidant properties of the extracted oil. The optimized parameters - 49.58 °C, 6526.27 psi, and 6.46 L/min CO_2 flow - yielded a recovery efficiency of 52.89 ± 1.67%, closely matching the model's prediction. The extracted oil exhibited a high iodine value (129.15 g I_2/100 g), indicating a rich content of unsaturated fatty acids such as linoleic and oleic acid. Although the polyphenol content was lower than that of ethanol-extracted oil, the SC-CO_2 extract demonstrated significant antioxidant activity, with IC_{50} values of 0.52 mg/mL and 0.195 mg/mL in the DPPH and $ABTS^{\bullet+}$ assays, respectively. The stronger scavenging ability in the $ABTS^{\bullet+}$ assay suggests the presence of polar antioxidant constituents in the extract. These findings highlight the potential of dragon fruit seed oil, extracted via an environmentally friendly and solvent-free method, as a natural source of essential fatty acids and functional antioxidants. The results support its promising application in food, cosmetic, and nutraceutical formulations while promoting the sustainable valorization of agricultural by-products.

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TÓM TẮT

NGHIÊN CỨU TỐI ƯU HÓA CHIẾT XUẤT CO_2 SIÊU TỚI HẠN VÀ ĐÁNH GIÁ CÁC CHỈ TIÊU HÓA LÝ CÙNG KHẢ NĂNG CHỐNG OXY HÓA CỦA DẦU HẠT THANH LONG (*Hylocereus polyrhizus*)

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Hạt thanh long ruột đỏ (*Hylocereus polyrhizus*), một phụ phẩm nông nghiệp dồi dào, chứa dầu có giá trị, giàu axit béo không bão hòa với các đặc tính chống oxy hóa tiềm năng. Nghiên cứu này nhằm tối ưu hóa quá trình chiết xuất dầu bằng carbon dioxide siêu tới hạn (SC-CO_2) và đánh giá các đặc tính hóa lý cùng hoạt tính chống oxy hóa của dầu. Bằng cách sử dụng thiết kế thí nghiệm phối hợp có tâm dựa trên phương pháp bề mặt đáp ứng (RSM), các điều kiện chiết xuất tối ưu được xác định là 49,58 °C, 6526 psi và lưu lượng CO_2 6,46 L/phút. Với các điều kiện này, hiệu suất dầu đạt 13,41 ± 0,42% (theo khối lượng), tương ứng với độ thu hồi 52,89 ± 1,67%. Dầu thu được có chỉ số iốt cao (129,15 ± 0,746 g I_2/100 g), cho thấy mức độ không bão hòa đáng kể; chỉ số axit 17,29 ± 0,137 mg KOH/g; hàm lượng chất bay hơi 6,19 ± 0,0021%; và tổng hàm lượng polyphenol 0,384 mg GAE/g. Hoạt tính bắt gốc tự do mạnh mẽ đã được xác nhận thông qua các phép thử DPPH và $ABTS^{\bullet+}$, với các giá trị IC_{50} lần lượt là 0,52 và 0,195 mg/mL. Những kết quả này chứng tỏ dầu hạt thanh long thu được từ quy trình chiết SC-CO_2 tối ưu là một nguồn giàu lipid không bão hòa và chất chống oxy hóa tự nhiên, làm nổi bật tiềm năng đáng kể của nó như một thành phần tự nhiên trong thực phẩm chức năng, sản phẩm bổ sung dinh dưỡng và mỹ phẩm. Đồng thời, phương pháp chiết xuất “xanh” này còn góp phần nâng cao giá trị cho các phụ phẩm nông nghiệp.

Từ khóa: Chiết xuất CO_2 siêu tới hạn, dầu hạt thanh long, phương pháp bề mặt đáp ứng, đặc tính hóa lý, hoạt tính chống oxy hóa, *Hylocereus* spp.