Supercritical CO_2 Extraction Method for Hemp Seed Oil Production

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Abstract

The surge in hemp's popularity is fueled by the growing recognition of its non-narcotic nature and rich nutrient profile, which offer a plethora of health benefits. This study aimed to explore the influence of different supercritical CO_2 extraction conditions on various aspects of extracted hemp seed crude oil, including yield, peroxide value (PV), acid value (AV), percent free fatty acids (%FFAs), saponification value (SV), iodine value (IV), total phenolic compound content, ABTS and DPPH radical scavenging abilities, and the content of cannabidiolic acid (CBDA), cannabidiol (CBD), cannabinol (CBN), tetrahydrocannabinolic acid (THCA), and tetrahydrocannabinol (THC). Parameters included temperatures (40-60°C) and pressures (175-225 bar). Results indicated that the crude oil yield (23.97-29.90%) remained largely unaffected by the extraction conditions. Higher extraction temperatures accelerate peroxide decomposition, decreasing PV. Elevated temperatures with lower pressures decrease CO_2 density, reducing free fatty acid solubility and AV/%FFAs in hemp seed oil. Higher temperatures increase SV, with a more significant effect on IV compared to pressure changes. Elevating both temperature and pressure showed promise in increasing the total phenolic compound content within the extracted hemp seed oil, consequently enhancing the ABTS and DPPH radical scavenging abilities. CBDA peaked at 40°C and 200 bars (70 ug/ml), CBN at 50°C and 200 bars (440 ug/ml), CBD at 50°C and 225 bars (413 ug/ml), and THCA at 60°C and 225 bars (6.7 ug/ml), all of which had an undetectable level of THC.

Keywords: *Supercritical Carbon Dioxide Extraction, Hemp Seed Oil, Cannabidiolic Acid (CBDA), Cannabidiol (CBD), Cannabinol (CBN), Tetrahydrocannabinol (THC), And Tetrahydrocannabinolic Acid (THCA).*

1. Introduction

The global production value of hemp seeds is steadily increasing, driven by amendments to hemp production laws in several countries, such as Thailand, which are now placing greater emphasis on cultivation (Montero et al., 2023). Hemp seeds boast an impressive nutritional profile, comprising approximately 23-26.5% protein, 26 - 32% fat, 20 - 30% carbohydrates, and 17 - 20% fiber (Anwar et al., 2006). Furthermore, they are a rich source of omega-3 and omega-6 fatty acids, including linoleic and α-linolenic acids (Devi & Khanam, 2019), essential for the synthesis of eicosapentaenoic acid and docosahexaenoic acid, crucial for combating cancer and cardiovascular diseases, and promoting brain health (Swanson et al., 2012). Since these fatty acids cannot be synthesized by the body, they must be obtained from dietary sources, hence their classification as essential fatty acids (Kaur et al., 2014). Hemp seeds also contain cannabidiol (CBD), a non-psychoactive compound that does not impact the nervous system. Hemp seeds are rich in cannabinoids, particularly non-psychoactive cannabidiol (CBD). CBD extracted from hemp seeds possesses anti-inflammatory, antibacterial, and immunomodulatory properties, potentially protecting against arthritis and inflammation and providing vital antioxidant benefits. It offers relief from pain, anxiety, and depression, with potential benefits for skin, sleep, and cardiovascular health (Kamle et al., 2024). However, there is a risk of contamination with tetrahydrocannabinol (THC) during production, mainly from the inflorescence (Cerino et al., 2021). Nonetheless, hemp seeds with low THC levels, typically below 0.3%, have no neurological effects (Farinon et al., 2020; Montero et al., 2023). Hemp seed oil presents compelling potential for utilization across the food, pharmaceutical, and cosmeceutical sectors, making it a noteworthy option in various industries.

The food industry is increasingly prioritizing environmentally sustainable practices that minimize harmful residues while maintaining the nutritional and sensory integrity of products. Currently, there is growing interest in optimizing the processing of hemp seed oil to enhance its nutritional value. Supercritical CO_2 extraction, recognized for its eco-friendliness, is emerging as a viable alternative or supplement to conventional industrial methods like pressing and solvent extraction (Aladić et al., 2015). This study aimed to investigate the application of supercritical CO_2 extraction on hemp seed oil, examining various extraction conditions. Objectives encompassed assessing crude oil yield, analyzing chemical properties including peroxide value (PV), acid value (AV), percent free fatty acids (%FFAs), saponification value (SV), iodine value (IV), total phenolic compound content, and antioxidant activities using ABTS and DPPH assays. Additionally, the study aimed to quantify the presence of CBDA, CBD, CBN, THCA, and THC in the extracted hemp seed oil samples.

2. Materials and Methods

2.1 Hemp seeds

Hemp seed samples were provided by the Highland Research and Development Institute in Chiang Mai, Thailand. The hemp seeds contained 7.81% moisture, 21.78% protein, 22.70% fat, 7.86% carbohydrates, 5.19% ash, and 34.67% fiber. Prior to the extraction process, the hemp seed samples were ground and stored in vacuum-sealed plastic bags at room temperature.

2.2 Supercritical CO_2 extraction

A supercritical CO_2 extractor (Guangzhou Heavensent Industrial Co., Ltd., China) was utilized for the extraction of hemp seed oil samples. Each extraction experiment involved placing 500 g of ground hemp seeds into a 5-L extraction tank, which was maintained at temperatures ranging from 40 to 60 °C and pressures from 175 to 225 bar for an extraction time of 3 hours. Three replicates were conducted for each supercritical CO_2 extraction condition. Following supercritical CO_2 extraction, the extracted hemp seed oil samples were collected and quantified. Subsequently, the extracted oils were stored in amber glass bottles at 4 °C for further analysis.

2.3 Determination of the chemical properties of extracted hemp seed oil

The analysis of extracted hemp seed oil was conducted following the AOAC (2000) standard analytical methods to determine various parameters, including PV, AV, %FFAs, SV, and IV.

2.4 Determination of total phenolic compound content and antioxidant activities using 2,2'-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) and 2,2-diphenyl-1-picrylhydrazyl (DPPH) assays.

2.4.1) Total phenolic compound content

To determine the total phenolic compound content measured using a modified method described by Sriyab et al. (2021), 2 g of extracted hemp seed oil were mixed with 1 ml of hexane and 2 ml of 80% methanol. The mixture was thoroughly vortexed and then centrifuged for 10 min at 4,500 rpm. Subsequently, the methanol-extracted portion was combined with 100 ⌈l of 10% Folin-Ciocalteu solution and allowed to react for 5 min. Following this, 80 ⌈l of 7.5% sodium carbonate were added, and the solution was incubated in the dark at room temperature for 2 hours. The absorbance at 750 nm was measured using a microplate reader (Multimode Detector, Beckman Coulter DTX880, Fullerton, CA, USA), and the results were expressed in terms of gallic acid equivalent by referencing a gallic acid calibration curve.

Proceedings of RSU International Research Conference (RSUCON-2024)

2.4.2) ABTS radical scavenging activity

The ABTS radical scavenging activity was measured using a modified method described by Xu et al. (2007). A mixture was prepared by combining 0.1 g of hemp seed oil with 1.5 ml of methanol, then centrifuged at 4,500 rpm for 10 min. The upper layer (0.5 ml) was mixed with 0.25 ml of freshly prepared 7 mM ABTS solution and left in darkness for 5 min. The ABTS solution was diluted to an absorbance of 0.7 ± 0.02. Absorbance was measured at 734 nm using a spectrophotometer. Trolox equivalent antioxidant capacity (TEAC) was determined using a calibration curve, and the ABTS radical scavenging ability was expressed as µmol TEAC/100g extracted hemp seed oil.

2.4.3) DPPH radical scavenging activity

The DPPH radical scavenging activity was measured using a modified method described by Krzyczkowska and Kozłowska (2017). A mixture was prepared by combining 0.1 g of extracted hemp seed oil with 1.5 ml of methanol, followed by centrifugation at 4,500 rpm for 10 min. The upper layer (0.5 ml) was mixed with 1 ml of freshly prepared 1 mM DPPH solution (0.01 g of DPPH in 25 ml of methanol) and kept in darkness for 10 min. The absorbance of the resulting mixture was measured at 515 nm using a spectrophotometer (Perkin Elmer, UV WINLAB, Germany). Trolox equivalent antioxidant capacity (TEAC) was determined using a Trolox calibration curve, and the DPPH radical scavenging ability was expressed as µmol TEAC/100g extracted hemp seed oil.

2.5 Determination of cannabinoids in extracted hemp seed oil

Following the preparation of a mixture comprising 400 µl of isopropanol and 400 µl of 100% methanol, 10 µl of hemp seed oil was added before subjecting the combination to centrifugation at 2,000 rpm for 5 minutes. Subsequently, the resulting mixture underwent filtration using a 0.22 µm nylon membrane filter to eliminate any particulate matter. The quantification of CBDA, CBD, CBN, THCA, and THC was performed utilizing an HPLC system with UV detection, sourced from Shimadzu in Kyoto, Japan. Calibration of the HPLC system was achieved using standard cannabinoids procured from Merck Ltd. in Thailand.

2.6 Statistical analysis

Three replicates were conducted for each analytical determination, and the results are presented as the mean ± standard deviation. A statistical analysis was performed using a one-way ANOVA to compare the data. Subsequently, Tukey's Honestly Significant Difference (HSD) test, with a significance level of $p < 0.05$, was employed to identify significant differences between the mean values. The analysis was carried out using SPSS version 17 software.

3. Results and Discussion

3.1 Crude oil yield and chemical properties

Table 1 presents data on the crude oil yield and chemical properties of extracted hemp seed oil samples obtained through supercritical CO_2 extraction under various conditions. The crude oil yield ranged from 23.97 % to 29.90 %, with the highest yield achieved at 60 °C and 175 bar pressure. The analysis of the average crude oil yield suggests a tendency for higher yields at elevated temperatures and pressures. However, remarkably, there were no substantial differences in crude oil yield among the conditions tested.

Table 1: Crude oil yield, peroxide value, acid value, % free fatty acids, saponification value, and iodine value of extracted hemp seed oil using supercritical CO_2 extraction.

Supercritical CO_2 extraction conditions	Crude oil yield^{*ns} (%)	Peroxide value (meqO_2/kg oil)	Acid value (mgKOH/g oil)	Free fatty acids (%)	Saponification value (mgKOH/g oil)	Iodine value (g I_2/100 g oil)
40°C, 175 bars	25.43 ± 0.16	16.55 ± 0.22^{abc}	23.77 ± 0.23^{a}	11.90 ± 0.12^{a}	202.50 ± 1.02^{bc}	102.23 ± 1.07^{a}
40°C, 200 bars	23.97 ± 3.65	16.58 ± 1.31^{abc}	31.34 ± 0.67^{bc}	15.70 ± 0.34^{bc}	182.63 ± 2.13^{a}	100.66 ± 0.58^{a}
40°C, 225 bars	27.87 ± 1.40	17.60 ± 0.50^{bc}	43.81 ± 0.57^{e}	21.94 ± 0.29^{e}	197.61 ± 0.44^{b}	106.26 ± 0.35^{b}
50°C, 175 bars	26.87 ± 4.22	19.59 ± 0.09^{c}	29.92 ± 0.01^{b}	14.99 ± 0.01^{b}	210.40 ± 4.09^{c}	113.45 ± 0.35^{d}
50°C, 200 bars	26.64 ± 3.80	16.24 ± 0.32^{abc}	38.23 ± 0.08^{d}	19.15 ± 0.04^{d}	207.14 ± 3.25^{bc}	112.45 ± 0.14^{d}
50°C, 225 bars	27.80 ± 3.24	16.65 ± 0.01^{bc}	31.73 ± 0.58^{bc}	15.89 ± 0.29^{bc}	197.77 ± 2.71^{b}	111.23 ± 0.08^{cd}
60°C, 175 bars	29.90 ± 1.02	13.60 ± 1.08^{ab}	34.58 ± 1.36^{c}	17.32 ± 0.68^{c}	212.75 ± 1.18^{cd}	113.26 ± 0.41^{d}
60°C, 200 bars	24.67 ± 0.18	14.09 ± 1.16^{ab}	45.13 ± 0.00^{e}	22.60 ± 0.00^{e}	222.66 ± 0.15^{d}	108.51 ± 0.80^{bc}
60°C, 225 bars	26.12 ± 0.61	12.60 ± 0.01^{a}	32.98 ± 0.38^{bc}	16.52 ± 0.19^{bc}	208.38 ± 1.09^{bc}	112.09 ± 0.68^{d}

Note: Each supercritical CO_2 extraction condition was conducted for a 3-hour extraction time. Values are means ± S.D. (n=3) and different superscript letters in the same column are significantly different ($p < 0.05$)

The chemical properties assessed include PV, AV, %FFAs, SV, and IV. Results presented in Table 1 indicated that the PV of the extracted hemp seed oil ranged from 12.60 to 19.59 meqO_2/kg oil. Experimental findings demonstrated that at an extraction temperature of 40 °C, the PV of the extracted hemp seed oil increased with increasing extraction pressure from 175 to 225 bar. This was attributed to the potential impact of increased extraction temperatures on the oil's oxidation stability, where higher extraction temperatures can accelerate oxidation reactions, consequently leading to an increase in peroxide value (Subroto et al., 2017). Conversely, when the extraction temperature was raised from 50 to 60 °C, increasing the extraction pressure from 200 to 225 bar resulted in a statistically significant decrease in peroxide values ($p<0.05$). It was observed that higher extraction temperatures had a greater effect on decreasing PV compared to changes in extraction pressure. Higher extraction temperatures might accelerate the decomposition of peroxides formed during extraction, thereby resulting in lower peroxide values (Souček et al., 2023)

The hemp seed oils obtained showed AV ranging from 23.77 to 45.13 mg KOH/g and %FFAs ranging from approximately 11.90% to 22.60%. Employing supercritical CO_2 extraction enhanced the recovery of free fatty acids, particularly through an increase in pressure from 175 to 225 bar, while maintaining a constant temperature of 40 °C. However, with an increase in temperature from 50 °C to 60 °C and extraction pressure from 175 to 225 bar, there was a tendency for the AV and %FFAs to decrease. This dual impact was influenced by the interplay between extraction temperature and pressure, which altered solute vapor pressure and solvent density (Purschke et al., 2017; Rad et al., 2020). Importantly, higher temperatures combined with lower pressures (200-225 bar) might lead to a reduction in CO_2 density, resulting in decreased solubility of free fatty acids and consequently lowering both AV and %FFAs in the extracted oil samples.

The SV of the extracted hemp seed oils ranged from 182.63 to 222.66 mg KOH/g oil. With increasing extraction temperature and constant extraction pressure, the SV of the extracted hemp seed oil also increases. Conversely, at constant extraction temperature, increasing extraction pressure affected the solubility of fatty acids, consequently limiting their accessibility during the saponification procedure and leading to a decrease in the SV of the extracted hemp seed oil (Güçlü & Temelli, 2000). The hemp seed oil produced exhibits IV ranging from 100.66 to 113.45 g I_2/100 g of oil. Remarkably, increasing the extraction temperature from 40

to 60 °C resulted in a proportional increase in IV, emphasizing that the effect of a higher extraction temperature on achieving a higher IV was more significant compared to changes in extraction pressure. It is noteworthy that higher extraction temperatures generally facilitate the extraction of unsaturated fatty acids, thereby increasing IV (Dinesha et al., 2018).

3.2 Cannabinoids in Extracted Hemp Seed Oils

Figure 1 illustrates the presence of cannabinoids such as CBDA, CBD, CBN, and THCA in the extracted hemp seed oils

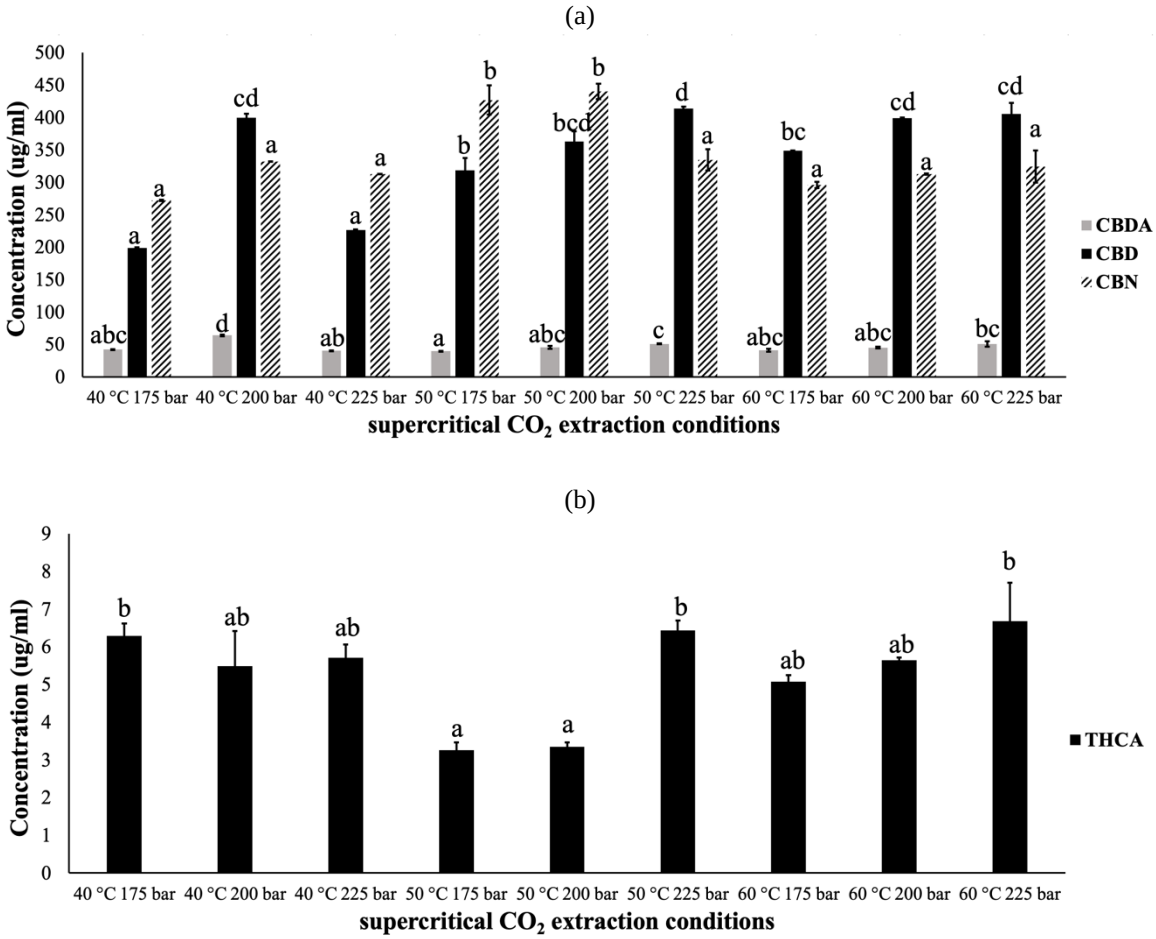

Figure 1: (a) Concentration of cannabidiolic acid (CBDA), cannabidiol (CBD), and cannabinol (CBN) (b) Concentration of tetrahydrocannabinolic acid (THCA) in extracted hemp seed oil using supercritical CO_2 extraction. Each supercritical CO_2 extraction condition was conducted for a 3-hour extraction time. Mean ± standard deviation values with different lowercase letters in the same graph are significantly different at $p < 0.05$, according to Tukey's Honestly Significant Difference (HSD) test.

The hemp seeds utilized in the experiment contained 11.65 mg/kg of CBDA, 65.49 mg/kg of CBD, 52.86 mg/kg of CBN, and 1.12 mg/kg of THCA. Figure 1 illustrates the CBDA, CBD, CBN, and THCA content in the extracted hemp seed oil samples, with no detectable THC compound. The maximum average level of CBDA (approximately 70 ug/ml) was achieved at 40 °C and 200 bar pressure. Similarly, the highest average level of CBN (440 ug/ml) was obtained at 50°C and 200 bar pressure, while the peak CBD level (approximately 413 ug/ml) was extracted at 50°C and 225 bars. At 60°C and 225 bars, the average THCA level reached its peak (approximately 6.7 ug/ml). Notably, when the extraction temperature remained constant (50 - 60°C), the level of these cannabinoid compounds increased as the extraction pressure increased, as supported by Perrotin-Brunel's (2011) findings. The increased strength and density of the supercritical CO_2 solvent at higher extraction pressures directly impacts the solubility of cannabinoids, resulting in higher levels of these compounds, as observed by Reverchon and De Marco (2006).

3.3 Total phenolic compound content and ABTS and DPPH radical scavenging ability of extracted hemp seed oils

Table 2 displays the total phenolic compound content as well as the ABTS and DPPH radical scavenging abilities of the extracted hemp seed oils.

Table 2: Total phenolic compound content and ABTS and DPPH radical scavenging ability of extracted hemp seed oil using supercritical CO_2 extraction.

Supercritical CO_2 extraction conditions	Total phenolic compound content (mg GAE/100g oil)	ABTS radical scavenging ability (µmol TEAC/100g oil)	DPPH radical scavenging ability (µmol TEAC/100g oil)
40°C, 175 bar	10.43 ± 0.02^{e}	78.38 ± 0.14^{a}	133.41 ± 0.01^{e}
40°C, 200 bar	8.31 ± 0.00^{c}	121.59 ± 0.17^{e}	134.84 ± 0.00^{f}
40°C, 225 bar	7.96 ± 0.02^{b}	89.64 ± 0.13^{b}	127.66 ± 0.02^{a}
50°C, 175 bar	9.75 ± 0.01^{d}	114.16 ± 0.13^{c}	132.14 ± 0.00^{b}
50°C, 200 bar	7.88 ± 0.00^{a}	117.54 ± 0.25^{d}	135.38 ± 0.00^{g}
50°C, 225 bar	13.86 ± 0.02^{h}	140.56 ± 0.13^{h}	135.48 ± 0.02^{h}
60°C, 175 bar	11.75 ± 0.03^{f}	124.95 ± 0.10^{f}	133.26 ± 0.00^{d}
60°C, 200 bar	9.73 ± 0.03^{d}	136.60 ± 0.07^{g}	133.16 ± 0.01^{c}
60°C, 225 bar	12.14 ± 0.01^{g}	149.75 ± 0.09^{i}	138.28 ± 0.00^{i}

Note: Each supercritical CO_2 extraction condition was conducted for a 3-hour extraction time. Values are means ± S.D. (n=3) and different superscript letters in the same column are significantly different ($p < 0.05$)

Total phenolic compound content as well as the ABTS and DPPH radical scavenging abilities of the extracted hemp seed oils were 8.31 - 13.86 mg GAE/100g, 78.38 to 149.75 µmol TEAC/100g oil, and 127.66 - 138.28 µmol TEAC/100g oil, respectively. The results from supercritical CO_2 extraction revealed a significant impact of extraction temperature and pressure on both the total phenolic compound content and antioxidant activity ($p<0.05$). Elevating both temperature and pressure showed promise in increasing the total phenolic compound content within the extracted hemp seed oil, consequently enhancing the ABTS and DPPH radical scavenging abilities (M'hiri et al., 2015). Higher temperatures not only lowered solvent viscosity and density but also facilitated the release of phenolic compounds from the plant material and promoted the decomposition of plant cells (Gil-Martín et al., 2022). Furthermore, increasing extraction pressure elevated the supercritical CO_2 density, thereby enhancing the solubility of solutes with notable antioxidant properties (Da Silva et al., 2016).

4. Conclusion

Supercritical CO_2 extraction yielded crude oil ranging from 23.97 % to 29.90 %, influenced by extraction conditions (temperature: 40, 50, 60 °C; pressure: 175, 200, 225 bar) over a 3-hour period. CBDA, CBD, CBN, and THCA were successfully extracted, with THC undetectable. Optimal extraction of CBDA (approximately an average value of 70 ug/ml) was achieved at 40°C and 200 bar. CBN peaked at an average value of 440 ug/ml at 50°C and 200 bar, while CBD reached its peak at an average value of 413 ug/ml at 50°C and 225 bar. The average THCA level was the highest (approximately 6.7 ug/ml) at 60°C and 225 bar. Notably, extraction pressure had a significant impact on these cannabinoid compounds, with higher pressure resulting in increased cannabinoid content in hemp seed oil. Extracted hemp seed oil contained phenolic compounds, demonstrating ABTS and DPPH radical scavenging abilities.

5. Acknowledgements

The authors express their sincere gratitude to Agro-Industry, Chiang Mai University, Thailand, for providing laboratory equipment, facilities, and complimentary support. Additionally, the authors would like to thank the Highland Research and Development Institute in Chiang Mai, Thailand, for providing us with the hemp seed samples.

6. References

Aladić, K., Jarni, K., Barbir, T., Vidović, S., Vladić, J., Bilić, M., & Jokić, S. (2015). Supercritical CO_2 extraction of hemp (*Cannabis sativa L.*) seed oil. *Industrial Crops and Products*, *76*, 472-478. https://doi.org/https://doi.org/10.1016/j.indcrop.2015.07.016

Anwar, F., Latif, S., & Ashraf, M. (2006). Analytical characterization of hemp (*Cannabis sativa*) seed oil from different agro-ecological zones of Pakistan. *Journal of the American Oil Chemists' Society*, *83*, 323-329. https://doi.org/10.1007/s11746-006-1207-x

Cerino, P., Buonerba, C., Cannazza, G., D'Auria, J., Ottoni, E., Fulgione, A., Di Stasio, A., Pierri, B., & Gallo, A. (2021). A review of hemp as food and nutritional supplement. *Cannabis Cannabinoid Res*, *6*(1), 19-27. https://doi.org/10.1089/can.2020.0001

Da Silva, R. P., Rocha-Santos, T. A., & Duarte, A. C. (2016). Supercritical fluid extraction of bioactive compounds. *TrAC Trends in Analytical Chemistry*, *76*, 40-51.

Devi, V., & Khanam, S. (2019). Study of ω-6 linoleic and ω-3 α-linolenic acids of hemp (*Cannabis sativa*) seed oil extracted by supercritical CO_2 extraction: CCD optimization. *Journal of Environmental Chemical Engineering*, *7*(1), 102818. https://doi.org/https://doi.org/10.1016/j.jece.2018.102818

Dinesha, B., Nidoni, U., Ramachandra, C., Naik, N., & Sankalpa, K. (2018). Effect of extraction methods on physicochemical, nutritional, antinutritional, antioxidant and antimicrobial activity of Moringa (*Moringa oleifera Lam.*) seed kernel oil. *Journal of Applied and Natural Science*, *10*(1), 287-295.

Farinon, B., Molinari, R., Costantini, L., & Merendino, N. (2020). The seed of industrial hemp (*Cannabis sativa L.*): Nutritional quality and potential functionality for human health and nutrition. *Nutrients*, *12*(7). https://doi.org/10.3390/nu12071935

Gil-Martín, E., Forbes-Hernández, T., Romero, A., Cianciosi, D., Giampieri, F., & Battino, M. (2022). Influence of the extraction method on the recovery of bioactive phenolic compounds from food industry by-products. *Food Chemistry*, *378*, 131918.

Güçlü, Ü., & Temelli, F. (2000). Correlating the solubility behavior of fatty acids, mono-, di-, and triglycerides, and fatty acid esters in supercritical carbon dioxide. *Industrial & Engineering Chemistry Research*, *39*(12), 4756-4766. https://doi.org/10.1021/ie0001523

Kamle, M., Mahato, D. K., Sharma, B., Gupta, A., Shah, A. K., Mahmud, M. C., Agrawal, S., Singh, J., Rasane, P., & Shukla, A. C. (2024). Nutraceutical potential, phytochemistry of hemp seed (*Cannabis sativa L.*) and its application in food and feed: A review. *Food Chemistry Advances*, *4*, 100671.

K Kaur, N., Chugh, V., & Gupta, A. K. (2014). Essential fatty acids as functional components of foods- a review. *Journal of food science and technology*, *51*(10), 2289–2303. https://doi.org/10.1007/s13197-012-0677-0

Krzyczkowska, J., & Kozłowska, M. (2017). Effect of oils extracted from plant seeds on the growth and lipolytic activity of Yarrowia lipolytica yeast. *Journal of the American Oil Chemists' Society*, *94*, 661-671.

M'hiri, N., Ioannou, I., Boudhrioua, N. M., & Ghoul, M. (2015). Effect of different operating conditions on the extraction of phenolic compounds in orange peel. *Food and bioproducts processing*, *96*, 161-170.

Montero, L., Ballesteros-Vivas, D., Gonzalez-Barrios, A. F., & Sánchez-Camargo, A. d. P. (2023). Hemp seeds: Nutritional value, associated bioactivities and the potential food applications in the Colombian context [Review]. *Frontiers in Nutrition*, *9*. https://doi.org/10.3389/fnut.2022.1039180

Perrotin-Brunel, H. (2011). Sustainable production of cannabinoids with supercritical carbon dioxide technologies. *University of Technology of Compiègne Geboren te Rouen: Rouen, France*.

Purschke, B., Stegmann, T., Schreiner, M., & Jäger, H. (2017). Pilot-scale supercritical CO_2 extraction of edible insect oil from Tenebrio molitor L. larvae–Influence of extraction conditions on kinetics, defatting performance and compositional properties. *European Journal of Lipid Science and Technology*, *119*(2), 1600134.

Rad, H. B., Sabet, J. K., & Varaminian, F. (2020). Study of solubility in supercritical fluids: Thermodynamic concepts and measurement methods-a review. *Brazilian Journal of Chemical Engineering*, *36*, 1367-1392.

Reverchon, E., & De Marco, I. (2006). Supercritical fluid extraction and fractionation of natural matter. *The Journal of Supercritical Fluids, 38(2), 146-166.* https://doi.org/https://doi.org/10.1016/j.supflu.2006.03.020

Souček, J., Jevič, P., Dědina, M., Tománková, V., Mašán, V., Burg, P., Szalay, K., & Jasinskas, A. (2023). Effects of temperature and pressure on hemp oil filtration parameters and peroxide number. *Processes*, *11*(8), 2281.

Sriyab, S., Laosirisathian, N., Punyoyai, C., Anuchapreeda, S., Tima, S., Chiampanichayakul, S., & Chaiyana, W. (2021). Nutricosmetic effects of Asparagus officinalis: A potent matrix metalloproteinase-1 inhibitor. *Scientific Reports*, 11(1), 8772.

Subroto, E., Widjojokusumo, E., Veriansyah, B., & Tjandrawinata, R. R. (2017). Supercritical CO_2 extraction of candlenut oil: process optimization using Taguchi orthogonal array and physicochemical properties of the oil. *Journal of Food Science and Technology*, *54*(5), 1286-1292.

Swanson, D., Block, R., & Mousa, S. A. (2012). Omega-3 fatty acids EPA and DHA: health benefits throughout life. *Advances in nutrition*, *3*(1), 1-7. https://doi.org/10.3945/an.111.000893

Xu, G., Ye, X., Chen, J., & Liu, D. (2007). Effect of heat treatment on the phenolic compounds and antioxidant capacity of citrus peel extract. *Journal of Agricultural and Food Chemistry*, *55*(2), 330-335. https://doi.org/10.1021/jf062517l