Agriculture and Food

AIMS Agriculture and Food, 9(1): 304–316.
DOI: 10.3934/agrfood.2024018
Received: 01 November 2023
Revised: 23 January 2024
Accepted: 01 February 2024
Published: 26 February 2024

http://www.aimspress.com/journal/agriculture

Research article

Effects of the extraction of fatty acids and thermal/rheological properties of Mexican red pitaya oil

David Neder-Suárez[1], Daniel Lardizabal-Gutierrez[2], Nubia Amaya-Olivas[1], León Raúl Hernández-Ochoa[1], Jesus Alberto Vázquez-Rodríguez[3], Miguel Á. Sanchez-Madrigal[1], Ivan Salmerón-Ochoa[1] and Armando Quintero-Ramos[1,*]

[1] Departamento de Investigación y Posgrado, Facultad de Ciencias Químicas, Universidad Autónoma de Chihuahua, Circuito Universitario s/n Campus Universitario 2, Chihuahua 31125, Mexico
[2] Centro de Investigación en Materiales Avanzados S.C. Avenida Miguel de Cervantes 120, Complejo Industrial Chihuahua, Chihuahua 31136, México
[3] Facultad de Salud Pública y Nutrición, Universidad Autónoma de Nuevo León, Dr. Eduardo Aguirre Pequeño 905, Mitras Centro, Monterrey, N.L. 64460, México

* **Correspondence:** Email: aquinter@uach.mx, aqura60@gmail.com.

Abstract: We evaluated the effects of solvents with different polarities—methylene chloride (MC), methanol (MT), and hexane (HE) on the extraction of compounds from Mexican red pitaya seed oil. The fatty acid composition and the structural, rheological, and thermal properties of the different extracts were characterized. The results indicated that the highest yield of extraction was generated for MC (26.96%), as well as the greatest amount of Mono and Polyunsaturated fatty acids, while the lowest yield was for MT (16.86%). The antioxidant activity was greater in the MT treatment due to extractable compounds from high polarity. The generated extracts contained unsaturated fatty acids, mostly oleic and linoleic acids, and saturated fatty acids such as palmitic acid. The lowest solidification temperature was −6.35 °C for MC due to its fatty acid composition, and the degradation temperature was around 240 °C. The viscosity is a quality parameter; the highest level was generated for the MC treatment, which was significantly different from HE and MT. The composition of the extracts was analyzed using the FT-IR spectroscopy and showed the typical characteristic of absorption bands for triglycerides with high frequency in bands 2852 cm^{-1} and 2924 cm^{-1}, which indicated that the samples were rich in unsaturated and polyunsaturated acids. These results suggested that pitaya seed oil is an excellent alternative source of essential fatty acids with potential physiological benefits.

Keywords: Mexican red pitaya; seed; antioxidant; fatty acids profile

1. Introduction

Mexican pitaya (*Stenocereus thurberi*) is an exotic fruit of significant importance in the culinary and agricultural fields [1]. It is native to arid and semi-desert regions of Mexico, and valued for its appearance, flavor, and nutritional value and contains highly antioxidant compounds [2–4]. Traditionally, the fruit has been used to extract and preserve bioactive compounds. However, in recent years, studies have focused on pitaya seeds due to their fatty acid composition, amino acid composition, and functionality. Despite the difficulty in separating and recovering seeds because the pitaya seed content is approximately 1.5% of the fruit [4], it could be used as a potential new source of specialty oil. Pitaya oil contains many unsaturated fatty acids, which perform different functions in the body, such as a source of energy, structural function, and modulator of physiological functions.

Studies have confirmed that the consumption of monounsaturated and polyunsaturated fatty acids provides health benefits that contribute to the amelioration of various health conditions, such as obesity, cardiovascular diseases, diabetes mellitus, and some types of cancer [5–7]. Lim et al. [5], Liu et al. [6], and Villalobos-Gutiérrez et al. [8] studied the fatty acid content of various tropical cacti seeds (*Stenocereus undatus*) using conventional methods with solvents of low polarity, such as petroleum ether or hexane, limiting the extraction of other compounds due to the nature of the solvent. Moreover, studies carried out by Ariffin et al. [9] and Abdullah et al. [10] have explored techniques such as cold pressing or the extraction using unconventional techniques such as supercritical extraction; however, they are limited to low extraction yields.

Despite previous reports on the use of pitaya seeds for oil extraction, the use of solvents with different polarities for the extraction of Mexican pitaya seed components has not been reported. As the composition of the extracts is influenced by different solvents, a more detailed study on how these solvents interact with the food matrix and affect extraction is necessary. Therefore, we aimed to evaluate the effects of solvents with different polarities on the extraction and quantification of compounds and the rheological and thermal properties of Mexican red pitaya seed extracts.

2. Materials and methods

2.1. Material

Mexican red pitaya (*Stenocereus thurberi*) was obtained from the Sirebampo community, Sonora State, Mexico (26°38'20.7"N 109°14'42.5" W). This cactus plant is wildly grown; during the harvest year (2022), the average temperature was a maximum of 31.3 ℃ and a minimum of 13.5 ℃ with an average annual precipitation of 558.1 mm. Pitaya seeds were extracted from red-fleshed pitaya, separated from the pulp, and dehydrated in a convection oven (9053A; Ecoshel, TX, USA) for 6 hours at 40 ℃. The pitaya seeds were ground and sieved with 40 mesh (425 μm) for processing.

2.2. Characterization of raw material

The seeds were characterized for moisture, protein, fat, crude fiber, and ash contents according to

AOAC [11] methods 934.06, 920.152, 945.16, 962.09, and 940.26, respectively. The carbohydrate content was determined based on this difference. Total polyphenol content (TPC) was determined according to the Folin–Ciocalteu colorimetry method followed by Neder-Suarez et al. [12]. Extracts of pitaya seed were prepared by homogenizing 0.4 g of the sample with 10 mL of acidified methanol solution (methanol and 1 N HCl, 99:1, v/v), extracted for 20 min in an ultrasonic bath (Branson, 1800) at 25 ℃, and centrifuged at 3000 × g (5702 R; Eppendorf, Hamburg, Germany) for 10 min. Gallic acid was used to prepare the calibration curve, and the absorbance was measured at 760 nm using a spectrophotometer (Lambda 25 UV/VIS; PerkinElmer, MA, USA). The results were expressed as mg of gallic acid equivalents per 100 g sample (mg GAE/100 g). TPC was determined in triplicate for each treatment, and the average ± standard deviation was calculated.

2.3. Oil extraction

The Oil extraction was carried out individually, using three solvents with different polarities. The solvents were classified according to their polarity; low hexane (HE), medium methylene chloride (MC), and high methanol (MT). The polarity index of the solvents used was 6.6, 3.4, and 0 for MT, MC, and HE, respectively [12]. Batches of 15 g of pitaya seeds were placed into a cellulose paper cone in a Soxhlet extractor for four hours at 80 ℃. Oil extraction was carried out in triplicate and quantified using the 945.16 [11] method. The densities of oil samples were measured by a relative density (mass of the oil sample/volume) at room temperature of 25℃. Each measurement was performed in triplicates.

2.4. Antioxidant Activity (AA)

Antioxidant Activity of red pitaya extracts was determined according to the method described by Neder-Suarez et al. [13]. AA was measured using 2,2-diphenyl-1-picrylhydrazyl (DPPH). Oil samples extracted with methylene chloride (MC), methanol (MT), and hexane (HE) were used. Moreover, 6-hydroxy-2,5,7,8-tetramethylchromane-2-carboxylic acid (Trolox) was used to obtain the calibration curve. The absorbance was measured at 515 nm using a spectrophotometer (Lambda 25 UV/VIS; PerkinElmer, Waltham, MA, USA). The results were expressed as μmol of Trolox equivalents per 1 L of sample (μmol TE/1 L). AA was determined in triplicate for each treatment, and the average ± standard deviation was calculated.

2.5. Thermal analysis

The thermal properties of the red pitaya extracts were analyzed by differential scanning calorimetry (DSC) using a Q-2000 calorimeter (TA Instruments, New Castle, DE, USA). The sample was heated with a temperature range of −30 ℃ to 250 ℃ and a heat rate of 10 ℃·min^{-1}. The thermograms obtained were analyzed using universal analysis software (TA Instruments, Crawley, UK). Thermogravimetric analysis (TGA) was performed using a TA Instrument model Q600 (TA Instrument, New Castle, DE, USA), with a heating ramp of 10 ℃·min^{-1} from room temperature to 800 ℃ under an airflow of 50 cm^3/min. Each measurement was performed in duplicates.

2.6. FT-IR analysis

The FT-IR analysis of red pitaya extracts (100 μL) was performed directly using an attenuated total reflectance (ATR) accessory at a resolution of 4 cm^{-1} by ten scans on a PerkinElmer ATR-FTIR instrument (PerkinElmer, Norwalk, USA) at over a range of wave number 4000-650 cm^{-1}.

2.7. Rheology determination

The rheological properties, storage modulus (G′) and loss modulus (G″), and apparent viscosity (η) of red pitaya extracts were determined using a rheometer (TA Instruments AR 2000EX, Crawley, UK). The instrument had a stainless-steel parallel-plate geometry (60 mm diameter). All measurements were carried out at 25 ℃ and 800-micron gap. Oscillatory tests were performed in the frequency range of 1–10 Hz with a strain amplitude constant of 2%. The flow sweep was performed at a shear rate (γ) of 0.1 to 15 $1 \cdot s^{-1}$, and the apparent viscosity (η) was calculated using the Herschel-Bulkley model at a shear rate value of 4 1/s. Four measurements for each treatment were performed using Eqs (1).

$$\eta = K\gamma^{n-1} + \frac{\tau}{\gamma}. \quad (1)$$

γ = is the shear rate (s^{-1});
τ = is the yield stress (mPa);
K = viscosity coefficient ($mPa \cdot s^{-1}$);
n = is the fluid behavior index.

2.8. Methyl-esterification of fatty acid

Methyl esterification of the samples used in the analyses was conducted after alkaline hydrolysis, according to Rivera-Rangel et al. [14] with modifications. A total of 2 mL of 5% KOH-methanol solution was added to 200 mg of red pitaya extract and the mixture was heated at 40 ℃ for 90 min. After cooling, 2 mL hexane was added, followed by thorough shaking. The resulting hexane layer was used as the sample solution to determine the fatty acid profile.

2.9. Fatty acids profile by GC-MS

The fatty acid profiles of the different red pitaya extracts were evaluated. FAME analysis was performed using a GC-MS-Agilent 5975C instrument (Agilent Technologies, US). Agilent HP-Innowax column (30 m × 0.25 mm × 0.25 μm) was used to separate the compounds. Helium was used as the carrier gas at 1.0 a flow rate. The oven temperature was set at 120 ℃ (1 min), raised from 120 to 170 ℃ at a rate of $20\ ℃ \cdot min^{-1}$, from 170 to 210 ℃ at a rate of $3\ ℃ \cdot min^{-1}$, from 210 ℃ to 230 ℃ at a rate of $20\ ℃ \cdot min^{-1}$, and held 10 min at 230 ℃. Two microliters of the sample were manually injected at a split ratio of 20:1. FAMEs were detected in the scan mode with a solvent delay of 2 min. The m/z range was 40–500. Standard FAME Mix CRM47885 (Supelco, US) was used to identify fatty acids in the samples.

2.10. Statistical analysis

A duplicate univariate factorial design was used. Three different solvents were used for the three treatments. The data obtained were subjected to variance analysis (ANOVA) with the Minitab® 17.1.0 software (Minitab Inc. software (State College, College Station, TX, USA). Tukey's test was performed to determine the mean differences between treatments and to correlate the dependent variables. Differences were considered statistically significant at $p < 0.05$.

3. Results

3.1. Chemical composition

The proximate compositions of Mexican red pitaya seeds were 10.47 ± 0.08, 2.55 ± 0.12, 27.57 ± 0.84, 19.22 ± 0.10, 26.50 ± 0.66, and 14.14 ± 0.64 for moisture content, ash, fiber crude, protein, fat, and carbohydrates, respectively (Table 1). These physicochemical characteristics were directly influenced by climatic factors. The yield of the seed of the red pitaya in fresh pulp was 9.34%. Additionally, pitaya seed has a high content of bioactive components with a TPC content of 4534.82 ± 42.67 mg GAE·100 g^{-1}, this value was higher than those reported by Zulkifli et al. [15] and Shi et al. [16] in *Hylocereus-polyrhizus* seeds oil using ethanol and water extraction respectively. The antioxidant activity of the extracts obtained was: HE (867.66 ± 8.84 μmol TE·L^{-1}), MC (889.30 ± 10.45 μmol TE·L^{-1}) and MT (1291.75 ± 11.74 μmol TE·L^{-1}). Authors such as Cao et al. [17] and Alrashidi et al. [18] found that the antioxidant activity of Oil of Peony Seeds and Nigella sativa oil increases with the greater polarity of the solvent; similar results were found by Wang et al. [19] in *Bischofia polycarpa* seed oil increasing the AA from 425.19 to 664.37 μmol TE·100 g^{-1}, in a more polar solvent such as Isopropanol compared to hexane (non-polar); this is due to extractable compounds from high polarity solvents, which increase radical scavenging activity [17,19,20]. On the other hand, studies have shown that the antioxidant activity of raw, unprocessed oils contains more excellent AA than those extracted using refining methods [20]; this could be applied to this food matrix to increase its antioxidant activity; however, the yield of extraction, but the extract obtained would be free of toxicity generated by the extraction solvents. Another essential aspect to highlight is the composition of saturated and unsaturated fatty acids. A study by Giuffrè [21] found that olive oil contains different amounts of free fatty acids, expressed as oleic acid, depending on the harvest season. The increase in fatty acids increases the AA of the oil. Our results concluded that the greater the similar amounts of unsaturated fatty acids, the AA increases due to the type of solvent used, the greater the polarity the extraction of compounds increases, and the AA of the extract increases [17,19,20].

Table 1. Characterization of Mexican red pitaya seed.

	MC (%)	Fat (%)	Ash (%)	RF (%)	Protein (%)	Carbohydrates (%)
Mexican red pitaya seed	10.47 ± 0.08	26.50 ± 0.66	2.55 ± 0.12	27.57 ± 0.84	19.22 ± 0.10	14.14 ± 0.64

Note: Values are the average of triplicate measurements ± standard deviation. MC = Moisture content, RF= Raw fiber.

3.2. Fatty acids profile by GC-MS

Extractions of red pitaya seeds were conducted using solvents with varying polarity, yielding extraction percentages for HE, MC, and MT were 26.50%, 26.96, and 16.86 respectively. The difference in solvent polarity may explain this result. The alcohols were more polar than hexane. Methanol afforded the lowest oil yield because of its inefficient solvation [16,22]. The highest extraction yields were obtained using both MT and HE. Interestingly, an intermediate polarity (MC) was effective as a solvent for oil extraction. Similar results were reported by Li et al. [22] for rapeseed oil extraction and by Liu et al. [6] for pitaya seed oil (*Hylocereus polyrhizus*) using Soxhlet extraction. Pitaya seed oil is mostly composed of unsaturated and saturated fatty acids, of which unsaturated fatty acids were more than 70%. An important aspect to take into account is the toxicity of the solvent used; authors such as Kimura et al. [23] found that lethal doses LD50 in adult rats showed hexane and methyl alcohol showed significantly ($p < 0.05$) more significant toxicity, so the use of Methylene chloride could be a good alternative to these solvents. However, the cost of the solvent MC buyer to MT increases 2.4 times, but this cost could be reduced since MC generates a 62% higher oil extraction yield than MT. GC-MS identified 14 fatty acids in oil samples from Mexican red pitaya seeds (Table 2), including nine saturated (myristic, palmitic, heptadecanoic, octadecanoic, behenic, docosanoic, hexadecanoic, tricosanoic, and lignoceric), three unsaturated (palmitoleic, oleic, and eicosanoids), and two polyunsaturated (linoleic and eicosapentaenoic) fatty acids. The most abundant fatty acids in the oil samples were linoleic, oleic, and palmitic acids. Similar results were found by Liu et al. [6], Lim et al. [5], Shi et al. [15], and Ünver [24] in pitaya seed oil (*Hylocereus polyrhizus*). The extraction method and variety affected the seed oil extraction rate and fatty acid composition. The use of ME to carry out the extraction generated significantly different lower extraction yield ($p < 0.05$) than MT and HE, also increased the content of Palmitic Acid in the sample and avoided the extraction of other saturated fatty acids. Extraction using ME increased the content of total unsaturated fatty acids, which was significantly different ($p < 0.05$) from that using MT and HE. In addition, it decreased the saturated fatty acid content. The polarity of the solvent affected the quality of extracted oils and the number of fatty acids in pitaya oils. Authors such as Al Juhaimi et al. [25] found that non-polar solvents such as hexane and petroleum-benzine extract a more significant amount of unsaturated and polyunsaturated than polar solvents such as acetone in the extraction of Safflower Seed oil, similar results were found by Tir et al. [26] in sesame seeds, which found a slight increase in oleic and linoleic acid extraction using hexane compared to isopropanol. Our results coincide with previous studies since the amount of total unsaturated fatty acids is more remarkable when using solvents with lower polarity. The amount of the unsaturated fatty acid content of pitaya seed oil (*Stenocereus thurberi*) was similar to studies by Liu et al. [6] and Špika et al. [27]. In this study, it was found that the content of linoleic acid in Mexican red pitaya oil is higher than those found in oils canola, peanut, and cashew nut oil, which amounts to approximately 20%, and higher than avocado and olive oil (6% to 10%) [6,27]. Moreover, the fatty acids considered healthy, such as linoleic and oleic due these fatty acids are metabolic precursors of eicosanoid hormones, in addition to helping with anti-inflammatory disorders and in the prevention of skin diseases [7,8,28], these beneficial effects on the body are observed when consuming amounts of oleic acid at approximately 27 $g \cdot day^{-1}$ and palmitoleic acid at 1.2 $g \cdot day^{-1}$ [28]. In general, the total unsaturated fatty acid content of pitaya oil is high, above 70%. Thus, pitaya seed oil could be an excellent alternative to dietary supplements or functional foods to improve the cardiovascular system.

Table 2. Fatty acids profile lipids in Mexican red pitaya seed extract.

Rt (min)	Compound	CAS Registry Numbers	Hexane (%)	Methanol (%)	Methylene chloride (%)
7	Myristic Acid	544-63-8	0.182 ± 0.01	ND	0.15 ± 0.01
10	Palmitic Acid	57-10-3	18.48 ± 0.42	22.72 ± 0.04	16.86 ± 0.33
10.4	Palmitoleic Acid	373-49-9	0.48 ± 0.01	0.43 ± 0.00	0.461 ± 0.01
11.8	Heptadecanoic Acid	506-12-7	0.14 ± 0.01	ND	0.12 ± 0.01
13.7	Octadecanoic Acid	2027-47-6	8.01 ± 0.49	4.95 ± 0.05	6.93 ± 0.20
14.3	Oleic Acid	112-80-1	27.34 ± 0.02	28.46 ± 0.04	28.75 ± 0.09
15.3	Linoleic Acid	60-33-3	40.23 ± 0.01	40.63 ± 0.23	42.40 ± 0.01
17.8	Eicosapentanoic Acid	2390-09-2	1.81 ± 0.15	0.91 ± 0.01	1.65 ± 0.06
18.1	Eicosenoic Acid	26764-41-0	0.67 ± 0.06	ND	0.61 ± 0.01
21.17	Behenic Acid	112-85-6	1.25 ± 0.19	0.51 ± 0.01	1.16 ± 0.03
21.7	Docosanoic Acid	929-77-1	0.26 ± 0.14	ND	0.25 ± 0.04
22.8	Hexadecanoic Acid	57-10-3	0.31 ± 0.11	ND	ND
23.5	Tricosanoic Acid	2433-96-7	0.11 ± 0.01	ND	0.09 ± 0.01
26.1	Lignoceric Acid	557-59-5	0.54 ± 0.11	ND	0.52 ± 0.03
Saturated fatty acids			29.72 ± 0.65^{a}	28.19 ± 0.11^{b}	26.11 ± 0.01^{c}
Monounsaturated fatty acids			28.55 ± 0.07^{c}	28.89 ± 0.05^{b}	29.82 ± 0.06^{a}
Polyunsaturated fatty acids			42.05 ± 0.16^{b}	41.55 ± 0.22^{c}	44.05 ± 0.08^{a}
Total unsaturated fatty acids			70.55 ± 0.24^{b}	70.44 ± 0.17^{b}	73.88 ± 0.01^{a}
Oil extraction			26.50 ± 0.66^{a}	16.86 ± 0.54^{c}	26.96 ± 0.31^{a}

Note: Values are the average of duplicated measurements ± standard deviation. Average values in each column with different letters represent a significant difference according to the Tukey test ($\alpha = 0.05$). Rt = Retention time and ND = not detected.

3.3. Thermal properties

Figure 1a shows the cooling thermograms of the three pitaya oil samples compared with the extra virgin olive oil used as a reference. The curves show the characteristic exotherms of lipid crystallization. The solidification of oil depends on the saturated or unsaturated fatty acids ratio; if the oil contains two or three unsaturated fatty acids, it tends to be liquid at any temperature above 0 ℃ [29]. Pitaya oils show solidification temperature between −6 ℃ to −4 ℃. In contrast, the reference was calculated at −15 ℃. This difference is directly linked to the composition of each oil; olive oil has a higher content of unsaturated fatty acids, such as 70% (oleic and palmitic acids), and less polyunsaturated 9%), mainly linolenic acid [5,27]. Pitaya oil contains approximately 70% to 73% unsaturated fatty acids and around 23% to 28% saturated fatty acids (Table 1). The amount of saturated fatty acids reflects the difference in solidification points of the different treatment oils. Studies have indicated that saturated fatty acids exhibit higher solidification points, whereas unsaturated fatty acids (mono- or polyunsaturated) display lower solidification points [30]. The treatment with the lowest solidification temperature was generated for MC with a temperature of −6.35 ℃. On a different note, the thermogravimetric analysis (Figure 1b) shows that the start of decomposition for all the samples is around 240 ℃. However, once the thermal cracking started, the pitaya extract samples had a thermal lag of up to 40 ℃ compared with the reference. This lower oxidation temperature indicates that oils rich in unsaturated fatty acids can

quickly oxidize compared with oils rich in saturated fatty acids (palm oil), which reduces the degree of chemical oxidation [29]. This difference in decomposition temperature was due to the higher content of saturated fatty acids, resulting in higher resistance in the ME treatment. The decomposition temperatures indicated that they could be used for moderate heat treatments.

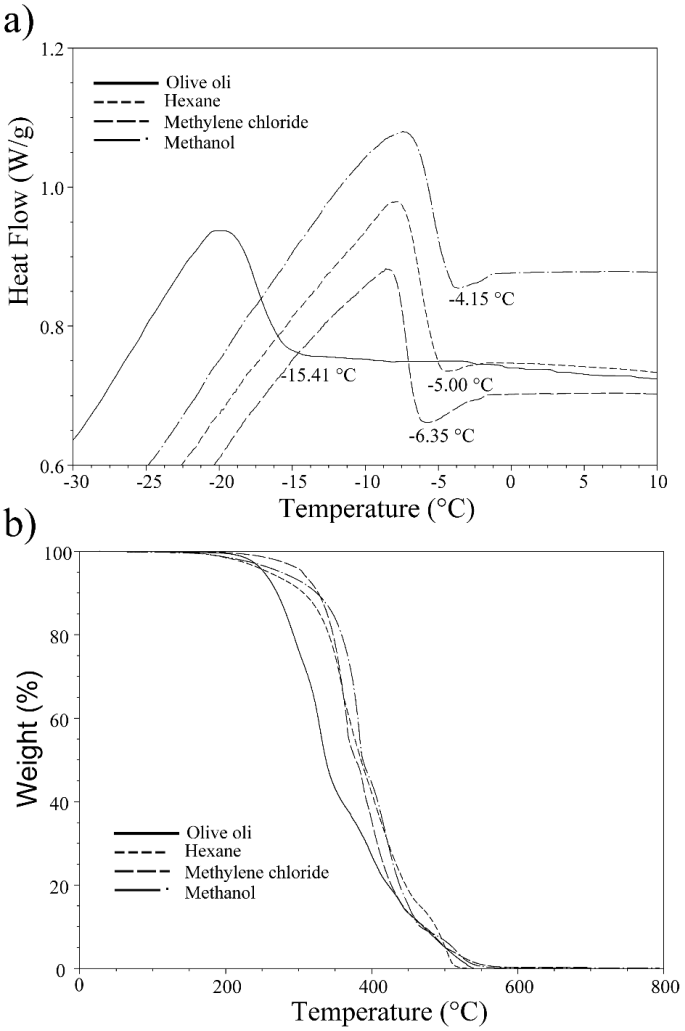

Figure 1. Thermograms of Mexican red pitaya seed extracts: a) DSC curves and b) TGA curves.

3.4. Viscoelastic properties

Figure 2 shows the flow behavior curves of pitaya oil in the MC, MT, and HE treatments. The apparent viscosity decreased with increasing shear rate, indicating that the viscosity was non-Newtonian (Figure 2a). The MC treatment generated the highest viscosity (86.31 mPa·s), which was significantly different ($p < 0.05$) from HE and MT. The differences found in the rheological behavior of Mexican red pitaya seed oil can also be associated not only with polymerization but also with the length of the fatty acids [31]. The MC treatment resulted in a lower content of saturated fatty acids and a higher percentage of polyunsaturated fatty acids (Table 1). Depending on its use, the viscosity can be a physical indicator of oil quality [31]. Moreover, the storage modulus (G') indicates an elastic

characteristic of the materials, and the loss modulus (G″) shows the viscous behavior; both parameters are shown in Figure 2b. The He and MT generated the highest values of G' significantly different from MT while the treatment MT generated the highest value for G″ (2.21 Pa), followed by the treatment extracted with hexane, and the lower levels were obtained with methanol. This is possibly due to the lower amount of saturated fatty acids and higher amount of polyunsaturated fatty acids in MC and HE (Table 3). Density is an important physical property of the quality parameters of oil. A similar density trend was generated concerning η. The highest value was obtained for the treatment with methylene chloride (0.975 g·mL^{-1}), which was significantly different ($p < 0.05$) from the HE and MT treatments, which may be due to the higher molecular weight fatty acid content. Density showed a positive correlation with η ($r = 0.857$, $p < 0.01$) and G″ ($r = 0.926$, $p < 0.01$). This behavior was attributed to the amount of saturated and unsaturated fatty acids in each treatment.

Table 3. Viscoelastic properties of Mexican red pitaya seed extract.

Treatment	η (mPa · s)	G′ (Pa)	G″ (Pa)	Density (g·mL^{-1})
Methylene chloride	86.31 ± 1.43^{a}	0.13 ± 0.01^{b}	2.21 ± 0.07^{a}	0.975 ± 0.002^{a}
Hexane	63.86 ± 2.46^{b}	0.23 ± 0.03^{a}	1.74 ± 0.02^{b}	0.966 ± 0.004^{b}
Methanol	43.60 ± 0.03^{c}	0.25 ± 0.03^{a}	1.21 ± 0.05^{c}	0.951 ± 0.004^{c}

Note: Values are the average of triplicate measurements ± standard deviation. Average values in each column with different letters represent a significant difference according to the Tukey test ($\alpha = 0.05$). η = apparent viscosity, G′ = storage modulus and (G″ = loss modulus).

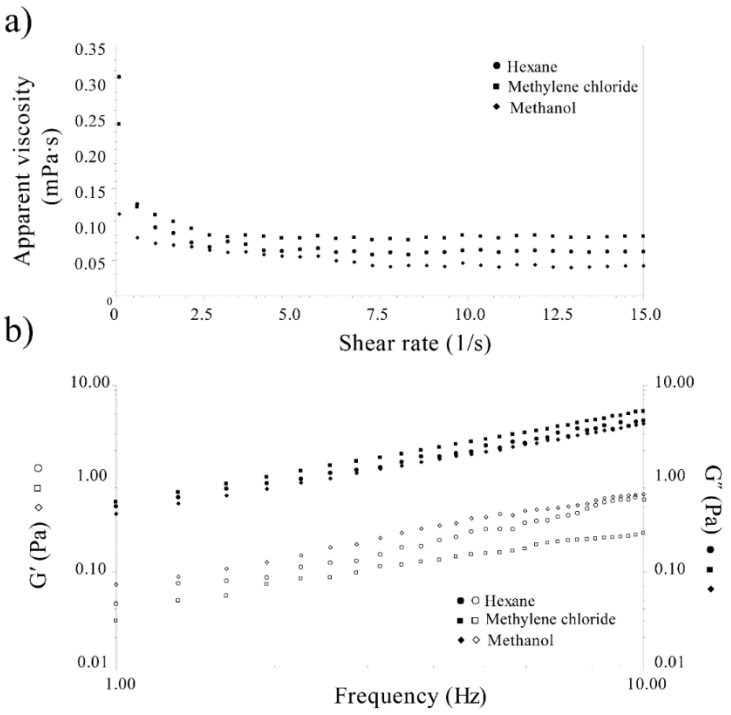

Figure 2. Flow curves of Mexican red pitaya seed extract: (a) apparent viscosity and (b) storage and lost modulus.

3.5. FT-IR analysis

Figure 3 shows the FT-IR spectra of the three pitaya oil samples compared with extra virgin olive oil used as a reference. The peak of 3320 to 3335 cm^{-1} corresponds to the aromatic (R-NH-R containing) group stretch. The peaks of 1255 to 1259 cm^{-1} and 850–897 cm^{-1} represent C-O stretching vibrations, usually in a carboxylic acid. The peak at 1716 to 1725 cm^{-1} corresponds to the C=O stretching vibrations, which represent the carbonyl group. The peak at 1590–1634 cm^{-1} represents C=N; at 1615 cm^{-1}, it also contains the C=O group in RCO-OH. The peak at 1031–1078 cm^{-1} represents C-N. The bands at 1403 to 1417 cm^{-1} and 920 to 929 cm^{-1} were attributed to the stretching vibration of the –OH bond [32,33]. The spectra of oil pitaya showed typical characteristic absorption bands for common triglycerides. The spectra of the MC, MT, and HE treatments and the reference showed similar behavior owing to the chemical composition of the fatty acids. The band at 721 cm^{-1} corresponds to the -CH_2 rocking and out-of-plane vibration characteristics of the aliphatic chain, and the band at 964 cm^{-1} is associated with the bending vibrations of the CH functional groups of the isolated trans-olefins in MC and MT [33,34]. Similar frequency values of 1744 cm^{-1} and 1157 cm^{-1} were found for all treatments. The first band is associated with the presence of the carbonyl ester C=O functional group, where strong absorption of fatty acid methyl esters or saturated aldehyde functional groups occurs. The second band is attributed to the C-O extension of the ester group present in triglycerides or phospholipids, which are characteristic bands of oils [32,35]. On the other hand, the regions 2852 cm^{-1} and 2924 cm^{-1} correspond to tensile vibrations of CH_2 for asymmetric and symmetric vibrations, respectively. High-frequency values in this absorption range indicated that some samples were rich in unsaturated and polyunsaturated acids [34]. In general, little difference was observed between the spectra of the different oil classes. The FT-IR spectra of pitaya oil were compared with those of olive oil because of its high unsaturated fatty acid content (Table 2).

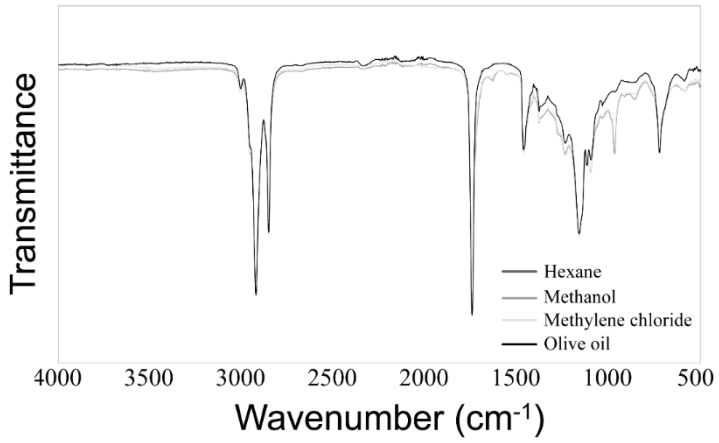

Figure 3. FT-IR spectra for seed extracts.

4. Conclusions

In this study, we aimed to determine the effects of solvents with different polarities on the extraction and quantification of compounds and their rheological and thermal properties on red pitaya seed extracts. The use of a solvent with intermediate polarity such as MT generated the highest

extraction rates and high levels of Mono and Polyunsaturated fatty acids. Moreover, it resulted in the highest viscosity and solidification temperature, in addition to this extract supporting degradation temperature around 240 ℃. Despite not having the highest extraction yields, the MT treatment generated the highest antioxidant activity due to extractable compounds from high polarity. This research demonstrated that the MC extract is an excellent alternative source of essential fatty acids since it has lower toxicity compared to HE and MT and a yield of 62% concerning MT. MT extract has potential use in the food industry and health benefits owing to its adequate physical characteristics.

Use of AI tools declaration

The authors declare that they have not used Artificial Intelligence (AI) tools in the creation of this article.

Acknowledgments

D.N.-S. designed and led the research and wrote the paper. A.Q.-R designed the research and collaborated to write the paper. D.L-G, N.A-G and L.R.H-O collaborated in the phase Research and write the paper collaborated., J.A.V-R, M.A.S-M and I.S-O collaborated in the experimental phase research.

Conflict of interest

All authors declare that they have no conflicts of interest.

References

1. Rodríguez-Félix A, Fortiz-Hernández J, Tortoledo-Ortiz O (2019) Physico-chemical characteristics, and bioactive compounds of red fruits of sweet pitaya (*Stenocereus thurberi*). *JPACD* 21: 87–100.
2. Paśko P, Galanty A, Zagrodzki P, et al. (2021) Bioactivity and cytotoxicity of different species of pitaya fruits–A comparative study with advanced chemometric analysis. *Food Biosci* 40: 100888. https://doi.org/10.1016/j.fbio.2021.100888
3. Quiroz-González B, García-Mateos R, Corrales-García GGE, et al. (2018) Pitaya (*Stenocereus spp*.): An under-utilized fruit. *JPACD* 20: 82–100.
4. García-Cruz L, Valle-Guadarrama S, Guerra-Ramírez D, et al. (2022) Cultivation, quality attributes, postharvest behavior, bioactive compounds, and uses of *Stenocereus*: A review. *Sci Hortic* 304: 111336. https://doi.org/10.1016/J.SCIENTA.2022.111336
5. Lim HK, Tan CP, Karim R, et al. (2010) Chemical composition and DSC thermal properties of two species of *Hylocereus* cacti seed oil: *Hylocereus undatus* and *Hylocereus polyrhizus*. *Food Chem* 119: 1326–1331. https://doi.org/10.1016/j.foodchem.2009.09.002
6. Liu Y, Tu X, Li Y, et al. (2022) Analysis of lipids in pitaya seed oil by ultra-performance liquid chromatography–time-of-flight tandem mass spectrometry. *Foods* 11: 2988. https://doi.org/10.3390/foods11192988

7. Canfora EE, Jocken JW, Blaak EE (2015) Short-chain fatty acids in control of body weight and insulin sensitivity. *Nat Rev Endocrinol* 11: 577–591. https://doi.org/10.1038/nrendo.2015.128
8. Villalobos-Gutiérrez MG, Schweiggert RM, Carle R, et al. (2012) Chemical characterization of Central American pitaya (*Hylocereus sp*.) seeds and seed oil. *CYTA-J Food* 10: 78–83. https://doi.org/10.1080/19476337.2011.580063
9. Ariffin AA, Bakar J, Tan CP, et al. (2009). Essential fatty acids of pitaya (dragon fruit) seed oil. *Food Chem* 114: 561–564. https://doi.org/10.1016/j.foodchem.2008.09.108
10. Abdullah A, Gani SSA, Mokhtar NFM, et al. (2018) Supercritical carbon dioxide extraction of red pitaya (*Hylocereus polyrhizus*) seeds: Response surface optimization, fatty acid composition and physicochemical properties. *Malays Appl Biol* 47: 39–46.
11. AOAC (1998) *Official Methods of Analysis of the Association of Official Analytical Chemists*, 15 Eds., Washington: Association of Official Analytical Chemists, Inc.
12. Snyder LR (1974) Classification of the solvent properties of common liquids. *J Chromatogr A* 92: 223–230. https://doi.org/10.1016/S0021-9673(00)85732-5
13. Neder-Suárez D, Lardizabal-Gutiérrez D, Zazueta-Morales J de J, et al. (2021) Anthocyanins and functional compounds change in a third-generation snacks prepared using extruded blue maize, black bean, and chard: An optimization. *Antioxidants* 10: 1368. https://doi.org/10.3390/antiox10091368
14. Rivera-Rangel LR, Aguilera-Campos KI, García-Triana A, et al. (2018) Comparison of oil content and fatty acids profile of Western Schley, Wichita, and Native pecan nuts cultured in Chihuahua, Mexico. *J Lipids* 2018: 4781345. https://doi.org/10.1155/2018/4781345
15. Zulkifli SA, Gani A, Zaidan SS, et al. (2020) Optimization of total phenolic and flavonoid contents of defatted pitaya (*Hylocereus polyrhizus*) Seed extract and its antioxidant properties. *Molecules* 25: 787. https://doi.org/10.3390/molecules25040787
16. Shi F, Jiang ZB, Xu J, et al. (2022) Optimized extraction of phenolic antioxidants from red pitaya (*Hylocereus polyrhizus*) seeds by subcritical water extraction using response surface methodology. *Food Measure* 16: 2240–2258. https://doi.org/10.1007/s11694-021-01212-1
17. Cao W, Wang Y, Shehzad Q, et al. (2022) Effect of different solvents on the extraction of oil from peony seeds (Paeonia suffruticosa Andr.): Oil yield, fatty acids composition, minor components, and antioxidant capacity. *J Oleo Sci* 71: 333–342. https://doi.org/10.5650/jos.ess21274
18. Alrashidi M, Derawi D, Salimona J, et al. (2022) The effects of different extraction solvents on the yield and antioxidant properties of Nigella sativa oil from Saudi Arabia. *J Taibah Univ Sci* 16: 330–336. https://doi.org/10.1080/16583655.2022.2057673
19. Wang Y, Su Y, Shehzad Q, et al. (2023) Comparative study on quality characteristics of Bischofia polycarpa seed oil by different solvents: Lipid composition, phytochemicals, and antioxidant activity. *Food Chem X* 17: 100588. https://doi.org/10.1016/j.fochx.2023.100588
20. Abdullah F, Ismail R, Shehzad Q, et al. (2018) Total phenolic contents and antioxidant activity of palm oils and palm kernel oils at various refining processes. *J Oil Palm Res* 30: 682–692.
21. Giuffrè AM, Zappia C, Capocasale M (2017) Tomato seed oil: A comparison of extraction systems and solvents on its biodiesel and edible properties. *Rivista Italiana Delle Sostanze Grasse* 94: 149–160.
22. Li Y, Fine F, Fabiano-Tixier AS, et al. (2014) Evaluation of alternative solvents for improvement of oil extraction from rapeseeds. *CR Chim* 17: 242–251. https://doi.org/10.1016/j.crci.2013.09.002

23. Kimura ET, Ebert DM, Dodge PW (1971) Acute toxicity and limits of solvent residue for sixteen organic solvents. *Toxicol Appl Pharmacol* 19: 699–704. https://doi.org/10.1016/0041-008X(71)90301-2
24. Ünver A (2023) Antioxidant properties, oxidative stability, and fatty acid profile of pitaya fruit (*Hylocereus polyrhizus* and *Hylocereus undatus*) seeds cultivated in Turkey. *BioResources* 18: 3342–3356. https://doi.org/10.15376/biores.18.2.3342-3356
25. Al Juhaimi F, Uslu N, Babiker EE, et al. (2019) The effect of different solvent types and extraction methods on oil yields and fatty acid composition of safflower seed. *J Oleo Sci* 68: 1099–1104. https://doi.org/10.5650/jos.ess19131
26. Tir R, Dutta PC, Badjah-Hadj-Ahmed AY, et al. (2012) Effect of the extraction solvent polarity on the sesame seeds oil composition. *Eur J Lipid Sci Technol* 114: 1427–1438. https://doi.org/10.1002/ejlt.201200129
27. Špika MJ, Perica S, Žanetić M, et al. (2021) Virgin olive oil phenols, fatty acid composition and sensory profile: Can cultivar overpower environmental and ripening effect? *Antioxidants*: 689. https://doi.org/10.3390/antiox10050689
28. Vannice G, Rasmussen H (2014) Position of the academy of nutrition and dietetics: Dietary fatty acids for healthy adults. *J Acad Nutr Diet* 114: 136–153. https://doi.org/10.1016/j.jand.2013.11.001
29. Naghshineh M, Ariffin AA, Ghazali HM, et al. (2010) Effect of saturated/unsaturated fatty acid ratio on physicochemical properties of palm olein-olive oil blend. *J Am Oil Chem Soc* 87: 255–262. https://doi.org/10.1007/s11746-009-1495-z
30. Brinkmann B (2000) Quality criteria of industrial frying oils and fats. *Eur J Lipid Sci Technol* 102: 539–541. https://doi.org/10.1002/1438-9312(200009)102:8/9<539::aid-ejlt539>3.0.co;2-b
31. Bansal G, Zhou W, Barlow PJ, et al. (2010) Review of rapid tests available for measuring the quality changes in frying oils and comparison with standard methods. *Crit Rev Food Sci Nutr* 50: 503–514. https://doi.org/10.1080/10408390802544611
32. Martínez C, Jiménez A, Garrigós MC, et al. (2023) Oxidative stability of avocado snacks formulated with olive extract as an active ingredient for novel food production. *Foods* 12: 2382. https://doi.org/10.3390/foods12122382
33. Kuligowski J, Carrión D, Quintás G, et al. (2011) Sample classification for improved performance of PLS models applied to the quality control of deep-frying oils of different botanic origins analyzed using ATR-FTIR spectroscopy. *Anal Bioanal Chem* 399: 1305–1314. https://doi.org/10.1007/s00216-010-4457-2
34. Zhang N, Yuan Y, Wang X, et al. (2013) Preparation and characterization of lauric–myristic–palmitic acid ternary eutectic mixtures/expanded graphite composite phase change material for thermal energy storage. *Chem Eng J* 231: 214–219. https://doi.org/10.1016/J.CEJ.2013.07.008
35. Castorena-García JH, Rojas-López M, Delgado-Macuil R, et al. (2011) análisis de pulpa y aceite de aguacate con espectroscopia infrarroja. *Conciencia Tecnológica* 42: 5–10.