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Artisanal Sunflower Oil: Nutritional Quality, Fatty Acid and Trace Element Profiles, Oxidative Stability, and Non-Carcinogenic Risk Assessment

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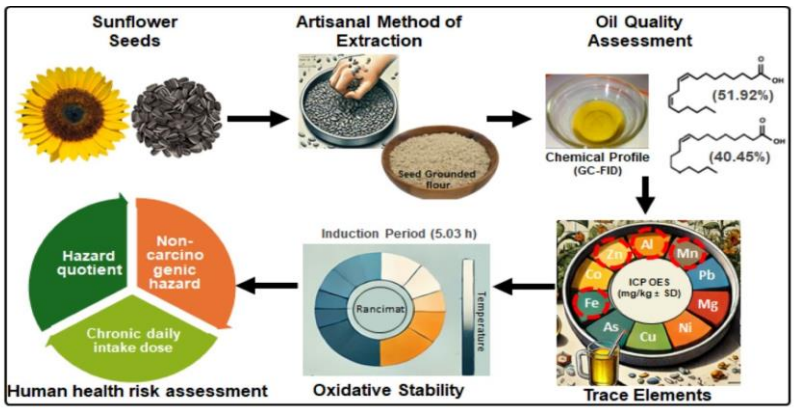
This study aimed to produce sunflower oil using an artisanal cold-pressed method and to evaluate its nutritional quality, physicochemical properties, fatty acid composition, mineral profile, and potential non-carcinogenic health risks. The oil contained a high proportion of unsaturated fatty acids, dominated by linoleic (51.92%) and oleic acids (40.45%), and exhibited favorable lipid nutritional indices (AI 0.03; TI 0.13; H/H 29.76). Physicochemical parameters, including low acidity and peroxide values, complied with Codex Alimentarius standards and indicated minimal oxidative degradation. UV-vis spectroscopy revealed characteristic absorption bands to tocopherols, carotenoids, sterols, and unsaturated fatty acids. Oxidative stability (5.03 h) was comparable to values reported for conventional cold-pressed sunflower oils. Four trace elements were detected in decreasing order (Zn > Fe > Al > Mn), all within FAO/WHO and DRI limits, except for slightly elevated Zn for children. Non-carcinogenic risk assessment (HQ and HI < 1) indicated no adverse health risk for consumers aged 8, 18, 30 years. Overall, the artisanal oil demonstrated high nutritional value, acceptable mineral levels, and a favorable safety profile.

Graphical abstract



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1. Introduction

Sunflower (*Helianthus annuus* L.) a member of the family Asteraceae, produce seeds widely recognized as a major source of edible oil with nutraceutical, pharmaceutical and medicinal applications [1]. Traditionally, sunflower oil has been used in the management of weight gain, hypertension, inflammatory processes, and cardiovascular and coronary diseases [2]. Its health-promoting properties are primarily attributed to its high content of unsaturated fatty acids–especially linoleic acid (polyunsaturated) which exhibits pro-inflammatory effects that may be counteracted by oleic acid

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(monounsaturated)–as well as the synergistic activity of natural antioxidants, including vitamins (A, C, K, and E), chlorophylls, carotenoids, phytostanols, phytosterols, polyphenols and other bioactive compounds [3, 4]. A wide range of minerals has also been detected in edible sunflower oil, such as lithium (Li), magnesium (Mg), titan (Ti), chromium (Cr), beryllium (Be), calcium (Ca), manganese (Mn), iron (Fe), nickel (Ni), cobalt (Co), copper (Cu), zinc (Zn), arsenic (As), selenium (Se), strontium (Sr), molybdenum (Mo), cadmium (Cd), antimony (Sb), cesium (Ce), thallium (Tl) [3]. Some trace elements–such as aluminum (Al), arsenic (As), Cd, Cr, Ni, (Cu), and lead (Pb)–have been reported in edible vegetable oils at levels considered toxic and carcinogenic due to their potential for bioaccumulation in human tissues even at low concentrations [5]. Moreover, the presence of metals including Ca, Co, Mg, Fe, Zn, Cu, Mn, Sn and Ni can accelerate oxidative reactions in edible oils, negatively affecting flavor, freshness, shelf life, and overall safety [5].

Artisanal vegetable oils are generally clarified through filtration and stored in amber or dark glass containers with hermetic sealing to preserve their chemical integrity and maintain compliance with recommended physicochemical standards [6,7]. The consumption of such oils, including artisanal sunflower oil, has a long cultural history, with traditional practices being passed down across generations.

The concentrations of unsaturated fatty acids, natural antioxidants, free fatty acids, minerals, and other bioactive constituents are strongly influenced by the method applied [3, 6, 8-10]. Despite the recognized nutritional value and mineral composition of edible oils, there remains limited information regarding the comprehensive nutritional, lipid, and mineral profiles of sunflower–particularly in relation to non-carcinogenic risk and hazardous quotient indices for individuals aged 8, 18 and 30 years. These life stages correspond to critical physiological periods characterized by heightened mineral requirements for growth, development, and reproductive maturation, as established by the Dietary Reference Intakes/Adequate Intakes [11].

Therefore, this study aimed to evaluate the nutritional quality of sunflower oil obtained through an artisanal extraction method by assessing its fatty acid composition, physicochemical characteristics, and thermal, optical and oxidative properties. Additionally, the concentrations of Al, As, Cd, Co, Cr, Cu, Fe, Mg, Ni, Mn, Pb, Se and Zn were quantified using inductively coupled plasma optical emission spectroscopy (ICP-OES), and the results were compared with established FAO/WHO guidelines [12-14] and Reference Intakes/Adequate Intakes [11].

2. Results and Discussion

2.1 Fatty acid composition

The fatty acid profile of sunflower oil obtained through the artisanal method is presented in Table 1. In this study, linoleic (51.92%) and oleic acids (40.45%) were the predominant components, occurring in approximately equal proportions (1:1). Similar compositions have been reported for sunflower oils produced by solvent-free cold-press extraction, such as linoleic (54.00%) and oleic (37.29%) contents described in Machate et al. [9], and linoleic (42.40%) and oleic (45.60%) in conventional HA-89 seed reported by Aguirre et al. [8]. In contrast, sunflower oils extracted using *n*-hexane exhibit markedly higher linoleic (64.35%) and lower oleic acid levels (19.81%), yielded a 3:1ratio [3].

Table 1. Fatty acids composition of sunflower oil extracted by artisanal method.

Fatty acids	Mean ± Standard Deviation (%)
Myristic (C14:0)	0.03 ± 0.02
Palmitic (C16:0)	3.08 ± 0.02
Palmitoleic (C16:1)	0.06 ± 0.01
Margaric (C17:0)	0.06 ± 0.00
Heptadecenoic (C17:1)	0.02 ± 0.00
Stearic (C18:0)	3.13 ± 0.03
Oleic (C18:1n9c)	40.45 ± 0.01
Linoleic (C18:2n6c)	51.92 ± 0.03
-Linolenic (C18:3n3c)	0.06 ± 0.00
Araquidic (C20:0)	0.17 ± 0.00
Gondoic (C20:1)	0.13 ± 0.00
Eicosapentanoic (C20:5n3c)	0.08 ± 0.00
Behenic (C22:0)	0.52 ± 0.01
Docosadienoic (C22:2)	0.05 ± 0.00
Tricosilic (C23:0)	0.07 ± 0.00
Lignoceric (C24:0)	0.17 ± 0.01
Σ SFAs	7.23
Σ MUFAs	40.66
Σ PUFAs	52.11
Σ UFAs	92.77
Total FAs	100
Atherogenic index (AI)	0.03
Thrombogenic index (TI)	0.13
Hypocholesterolemic/hypercholesterolemic (H/H)	29.76

SFAs: sum of saturated fatty acids, Σ MUFAs: sum of monounsaturated fatty acids, Σ PUFAs: sum of polyunsaturated fatty acids, Σ UFAs: sum of unsaturated fatty acids, FAs: fatty acids, defined as < 0.05%.

The atherogenic (AI) and thrombogenic (TI) lipid indices calculated for this oil were close to zero, in agreement with values considered beneficial for reducing cardiovascular risk [15]. The hypocholesterolemic/hypercholesterolemic ratios (H/H) was high, which is desirable due to its associated with improved metabolic health and reduced risk of chronic diseases [16]. The AI (0.03), TI (0.13), and H/H (29.76) values obtained here were similar to those previously reported for cold-pressed sunflower oil (AI 0.05, TI 0.16, and H/H 21.97) [9].

Long-term consumption of vegetable oils rich in oleic acid–along with essential fatty acids such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA)–has been associated with reduced risks of cardiovascular disease (CVD), coronary heart disease (CHD), inflammatory processes, gut microbiota dysbiosis, diabetes mellitus, and other metabolic disorders [17-19].

2.2 Physicochemical characteristics

Table 2 compares the physicochemical parameters of the artisanal sunflower oil with Codex Alimentarius standards, which provide benchmarks for oil identity, quality, authenticity and oxidative stability.

The iodine value was high, reflecting the elevated proportion of unsaturated fatty acids (92.77%) and indicating high susceptibility to oxidation. In contrast, this oil presented low acidity, peroxide, and saponification indices, suggesting that artisanal and cold-pressed extraction methods may reduce the formation of secondary oxidation products [9]. These characteristics are consistent with elevated antioxidant potential and reduced off-flavors, toxicity and degradation during storage, ultimately benefiting consumer health [20-22].

The saponification index (144.68 mg KOH g^{-1} oil) and relative density (0.902) were similar to those reported for cold-pressed sunflower oil [9] and lower than values typically obtained in oils extracted with petroleum-based solvents (188 and 189 mg KOH g^{-1}; density 0.918–0.957) [23,24]. Low density values in vegetable oils are associated with favorable internal absorption as well as improved frying performance due to optimal mass-transfer characteristics [25].

Overall, these physicochemical results support the differentiation of artisanal and col-pressed oils from those extracted using petroleum-derivative solvents.

Table 2. Physicochemical characteristics of artisanal sunflower oil compared with Codex Alimentarius parameters.

Parameters	Sunflower oil	Maximum values
Acidity index (mg KOH g^{-1})	0.65 ± 0.0	4.0 [26] (a)
Iodine index (g I2 100 g^{-1})	126.68 ± 0.2	118–141 [26] (b)
Peroxide index (mEq kg^{-1})	14.11 ± 0.1	≤ 20 [27] (b)
Saponification index (mg KOH g^{-1})	144.68 ± 0.1	184–196 [26] (b)
Relative density (20 °C)	0.902 ± 0.1	0.922–0.927 [26] (c)

(a) Parameter for cold pressed and virgin oils; (b) parameters for refined sunflower oils; (c) parameter for crude sunflower oil.

2.3 UV-Vis molecular analysis and oxidative stability

The UV-Visible absorption spectrum of the sunflower oil revealed two prominent absorbance regions between 221–235 nm and 256–454 nm. The first band corresponds to conjugated and non-conjugated dienes and trienes, aromatic amino acids, phytosterols, tocopherols, phytocholesterols, and phytostanols. The second band (256 to 454 nm) is associated with tocopherols, carotenoids, and the majority fatty acids (linoleic and oleic) consistent with previous finding [9,18]. These compounds are widely recognized for their antioxidant properties and their contribution to consumer health [21,22,28].

The visible region between 400 and 520 nm is critical for assessing the authenticity, originality, and oxidative status of vegetable oils [9].

Oxidative stability by the Rancimat method at 110 °C exhibited an induction time (IT) of 5.03 h, comparable to values previously reported for cold-pressed sunflower oil [9]. Refined sunflower oil containing 88.4% unsaturated fatty acids typically exhibit IT values between 5.5 and 7.5 h, reflecting differences in antioxidant content and saturation levels [29]. Oils with dominant oleic over linoleic content display substantially higher oxidative stability (IT 19.87 h) than oils with higher linoleic proportions (IT 6.42 h) [30].

2.4 Trace elements content

Table 3 summarizes the concentrations of four trace elements detected in the oil and compares them to Codex Alimentarius contents and Dietary Reference Intakes (DRIs/AI).

Plants absorb minerals from soil and air, accumulating them in edible tissues, and their concentrations have significant implications for food safety and nutrition [31]. Many countries monitor elemental composition in edible oils for safety and origin verification, as shown in studies on palm, sesame, soybean, coconut, peanut, mustard oils (Nigeria) [32], olive, sunflower, soybean, corn oils (Spain) [33], cottonseed, and canola (Iran) [34], and rapeseed, safflower, and linseed (Kazakhstan) [35].

In this study, the trace elements were found in the following order: Zn (6.5327 mg kg^{-1}) > Fe (1.3736 mg kg^{-1}) > Al (0.7431 mg kg^{-1}) > Mn (0.1965 mg kg^{-1}).

All values were lower than those reported for cold-pressed sunflower oil [9] and with FAO/WHO and DRIs/AI limits, except for Zn, which was slightly above the DRI value for children aged 8 years. The mineral contents were also lower than those found in several refined commercial oils, such as corn, cottonseed, olive, soybean, and sunflower oils from Iran [34], as well as virgin olive, sunflower, and corn oils from Spain [33], and Brazilian native oils [36].

These findings confirm that artisanal sunflower oil contains acceptable mineral levels and may provide health-promoting micronutrients (Fe, Mn, and Zn). Meanwhile, Al–which is associated with adverse health effects–was detected at low concentrations, remaining below established safety thresholds [37].

Table 3. Trace elements in sunflower oil determined using ICP OES (mg kg^{-1} ± SD) compared with nutritional recommendations for adult, pregnancy, lactation and children by RDA/AI, and FAO/WHO.

			Dietary references intakes (DRIs) and adequate intake AI* (mg day^{-1}) [11]								
Trace elements	Concentration (mg kg^{-1})	FAO/WHO (mg kg^{-1})	8 y old	18 y old	30 y old	18 y old	30 y old	18 y old	30 y old	18 y old	30 y old
Al	0.7431 ± 0.0199	5.00 [13]	ND	ND	ND	ND	ND	ND	ND	ND	ND
Fe	1.3736 ± 0.0439	14.00 [14]	10	11	8	15	18	27	27	10	9
Mn	0.1965 ± 0.0057	3.00 [14]	1.5*	2.2*	2.3*	1.6*	1.8	2.0*	2.0*	2.6*	2.6*
Zn	6.5327 ± 0.0788	15.00 [14]	5	11	11	9	8	12	11	13	12

Note. Elements As, Cd, Co, Cr, Cu, Mg, Ni, Pb, and Se < LOD; ND—not determined; *The value for AI is used when there are no calculated values for the RDA.

2.5 Health risk assessment

Non-carcinogenic risk assessment for Al, Fe, Mn, and Zn through dietary intake of sunflower oil is presented in Table 4. All hazard quotient (HQ) and the hazard index (HI) were below 1, with values decreasing in the order: Zn > Fe > Al > Mn.

These results indicate no significant no-carcinogenic risk under a daily consumption scenario of 30 g of sunflower oil. Moreover, the essential elements Fe, Mn, and Zn may contribute beneficially to human nutrition, while the low Al intake minimizes potential toxicity. The favorable safety profile is likely associated with the artisanal extraction method, which avoids contamination from industrial solvent or processing equipment.

Table 4. Hazard quotient (HQ) and total hazard index (HI) of chemical elements based on 30 g day^{-1} of sunflower oil.

Elements	HQ		
	8 years old	18 years old	30 years old
Al	0.000857	0.000360	0.000318
Fe	0.001109	0.000465	0.000412
Mn	0.000032	0.000013	0.000012
Zn	0.002261	0.000948	0.000840
HI	**0.00426**	**0.00179**	**0.00158**

3. Material and Methods

3.1 Sample preparation

Sunflower seeds were purchased in September 2020 in Campo Grande, Mato Grosso do Sul state, Brazil. Seeds pre-treatment followed the procedure described in our previous work [9]. Sunflower oil was obtained using an artisanal cold pressed method consisting of three steps. First, the dried seeds were sieved, dehulled and manually milled in the wooden mortar. Second, the resulting refined sunflower flour was moistened using ultrapure Mill-Q water and manually homogenized in a glass bowl. Third, the thick mass was squeezed into through a fine cloth, and the expressed oil was collected in amber glass bottle. Sample was hermetically sealed and stored at –20 °C until further analyses.

3.2 Fatty Acids Profile

Fatty acid methyl esters (FAMEs) were prepared at room temperature. Oil sample was weighed into assay tubes, saponified with methanolic NaOH, esterified using a methanolic mixture of H_2SO_4 and NH_4Cl, and extracted with hexane [9].

FAMEs were analyzed using a gas chromatograph (CP-3800, Varian, Santa Clara, CA, USA) equipped with a flame ionization detector, a split/splitless injector, and a polyethylene glycol fused-silica capillary column (carbowax 20M, 30 m × 0.25 mm, Quadrex, Santa Clara, CA, USA). Chromatographic conditions were as follows: injector and detector temperatures at 250 °C; column temperature programmed at 80 °C (2 min), followed by a ramp of 4 °C min^{-1} to 220 °C and held for 13 min; hydrogen carrier gas with 1 mL min^{-1}; injection volume 1 µL. Fatty acids wer identified by comparison of retention times with FAME standards (Supelco, F.A.M.E. Mix C4:0 to C24:0; Sigma-Aldrich, Darmstadt, DA, Germany).

3.3 Physicochemical analysis

Physicochemical characterization of sunflower oil was performed in triplicate according to the American Oil Chemist's Society [38] methods, including identity parameters (relative identity, Cc 10a-25, iodine value–Wijis method, Cd 1-25; saponification index, Cd 3-25) and quality parameters (acidity, Ca 5a-40; peroxide value, Cd 8b-90). Moisture content was determined in 1.5 g of filtered oil using the Karl Fischer method with an automatic titrator (KEM MKC-610, Kyoto, Japan).

3.4 Fatty acid nutritional quality indices

The nutritional quality of the oil was evaluated using indices calculated from the fatty acid profile according to the following indices:

Atherogenicity index (AI) [15].

$$\mathrm{AI} = \frac{12 + (4 \times \mathrm{C14{:}0}) + \mathrm{C16{:}0}}{\sum \mathrm{UFA}} \quad (1)$$

Thrombogenicity index (TI) [15].

$$\mathrm{TI} = \frac{\mathrm{C14{:}0} + \mathrm{C16} + \mathrm{C18{:}0}}{0.5 \times (\sum \mathrm{MUFA} + \sum \omega 6) + 3 \times (\sum \omega 3)} \quad (2)$$

Hypocholesterolemic/Hypercholesterolemic (HH) ratio [39].

$$\mathrm{HH} = \frac{\sum \mathrm{UFAs}}{\mathrm{C14{:}0} + \mathrm{C16} + \mathrm{C18{:}0}} \quad (3)$$

3.5 Oxidation stability and molecular analysis

Oxidative stability was assessed using the Rancimat method (Model 873, Metrohm Co, Basel, Switzerland) following the European standard EN 14112. Approximately 3.0 g of oil was subjected to accelerated oxidative at 110 °C under an airflow of 10 L h^{-1}. Volatile degradation products were carried by the airflow into a sealed vessel containing 50 mL of ultrapure Mill-Q water, where changes in conductivity were recorded over time to determine induction time (IT).

UV–Vis molecular analysis was conducted using a Lambda 265 UV/Vis spectrophotometer (Perkin Elmer, Waltham, MA, USA). Oil sample was diluted in HPLC-grade hexane (99.9%) to obtain stock solution at 10 g L^{-1}, with further dilutions prepared at 1 × 10^{-3} g L^{-1} and 5 × 10^{-2} g L^{-1}. Absorption spectra were collected between 200 and 800 nm using quartz cuvette.

3.6 Emulsion breaking extraction and mineral determination

Trace element extraction followed the emulsion breaking method described in Machate et al. [9]. Briefly, 3.0 mL of oil was mixed with 3.0 mL of ethanol for 20 s using a vortex shaker, followed by the addition of 3.0 mL ultrapure water (18.2 MΩcm), 0.76 mL Triton x-100, and 3.0 mL of HNO_3. After vortexing for 20 s, the mixture was heated at 90 ± 1 °C for 20 min to promote phase separation. Once cooled, the aqueous phase was transferred to a tube and diluted to 6.0 mL with ultrapure water. Blank solutions were prepared similarly without adding oil.

Elemental concentrations (Al, As, Cd, Cr, Cu, Fe, Mg, Mn, Ni, Pb, Se, and Zn) were determined using an ICP-OES instrument with axial plasma configuration (iCAP 6000 Series, Thermo Scientific, Cambridge, UK). Calibration curves were prepared from a multi-element stock solution (SpecSol, Jacareí, Brazil; 1000 mg L^{-1} per element), using nine concentrations between 0.01 and 5.0 mg L^{-1}. Instrumental conditions followed Machate et al. [9]. Limits of detection (LOD, 0.0037–0.0176 mg kg^{-1}), limits of quantification (LOQ, 0.025 – 6.6229 mg kg^{-1}), and correlation coefficient (R^2 = 0.9993 – 0.9998 for Fe and Zn) were established for each analyte.

Accuracy was verified by spike-and-recovery test (0.5 mg L^{-1}), yielding recoveries between 80–110% consistent with AOAC criteria [40].

3.7 Human health risk assessment

Trace element concentration in sunflower oil were compared with FAO/WHO dietary intake standards. Health risks were estimated following Machate et al. [9] based on the

chronic daily intake dose (CDI, mg kg^{-1} day^{-1}), calculated according to Equation (4).

$$CDI_{oil} = \frac{C \times IR \times EF \times ED}{BW \times AT} \quad (4)$$

where CDI_{oil} – chronic daily oil intake dose; C – concentration of chemical content in sunflower oil (mg kg^{-1}); IR – ingestion rate of oil g day^{-1} (30 g oil day^{-1}) [41]; EF – exposure frequency (365 days available $year^{-1}$); ED – exposure duration (children: 8; adolescents: 18; and adults 30 years); BW – body weight (26, 62 and 70 kg respectively) and AT – average time (ED ×365 days).

Non-carcinogenic risk was estimated using hazard quotient (HQ), which is a ratio of CDI and chronic oral reference dose (RfD), determined by the following Equation (5):

$$HQ = \frac{CDI}{RfD} \quad (5)$$

Reference dose (RfD, mg kg^{-1} day^{-1}) were obtained the Joint Food and Agriculture Organization/World Health Organization Expert Committee on Food Additive [42]. The RfD (mg kg^{-1} day^{-1}) values are: Al = 1.0; Fe = 0.7; Mn = 0.14; and Zn = 0.3 [43,44]. As shown in Equation (5), hazard quotient toxic risk on each trace element and their sum, Equation (6) HI (total non-carcinogenic hazard index). If the value of HQ or HI < 1, indicates negligible health risk, while values > 1 indicate potential adverse effects.

$$HI = HQ_{Al} + HQ_{Fe} + HQ_{Mn} + HQ_{Zn} \quad (6)$$

4. Conclusions

This study provides a comprehensive characterization of sunflower oil produced through artisanal extraction method, highlighting its nutritional quality, physicochemical behavior, molecular properties, mineral composition, and associated health risks. The oil exhibited high amount of unsaturation (92.77%) composed by a favorable fatty acid profile, with linoleic and oleic acids occurring in nearly equal proportions, and presented desirable lipid nutritional indices (AI, TI, and H/H), confirming its potential to support metabolic and cardiovascular health.

Physicochemical analyses demonstrated high iodine value and low acidity, peroxide, and saponification indices, indicating elevated unsaturation but limited oxidative degradation during extraction. UV–Vis molecular profiling revealed the presence of natural antioxidants such as tocopherols, carotenoids, and phytosterols, while the oxidative stability (Rancimat induction time) was consistent with values reported for high-quality cold-pressed sunflower oils.

Trace element analysis showed low concentration of Al, Fe, Mn, and Zn, all within international safety guidelines limits, except Zn slightly above the recommended intake for children. Overall, the mineral levels were lower than those typically found in refined commercial oils, suggesting minimal contamination and preservation of natural composition in artisanal processing.

Health risk assessment confirmed that daily consumption of 30 g of this oil poses no non-carcinogenic risk, with all HQ and HI values <1. The presence of essential minerals (Fe, Mn, and Zn) may further contribute to dietary health benefits, while the low Al content minimizes potential toxicological concerns.

Collectively, these findings demonstrate that artisanal sunflower oil is a safe and nutritionally valuable food product, retaining key bioactive compounds and meeting international quality and safety standards. The results reinforce the relevance of artisanal and cold-pressed extraction methods as viable, health-promoting alternatives to solvent-based processing.

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Author Contributions

Author Contributions: DJM: Wrote the article, conducted the experimental work, data curation, formal analysis, and contributed to writing and reviewing the paper. NCY: Acquired funding, provided resources, and reviewing the paper.

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