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Impact of seed hull on yield, fatty acid composition, and bioactive properties of cold-pressed sunflower oil

[*Impacto da casca da semente no rendimento, na composição de ácidos graxos e nas propriedades bioativas do óleo de girassol prensado a frio*]

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ABSTRACT

Sunflower oil is valued for its nutritional and therapeutic properties, which depend largely on its fatty acid profile and bioactive components. Sunflower oil was cold pressed from both hulled and unhulled seeds. The oils were compared for yield, fatty acid composition (using GC-FID), and biological activities, including antioxidant, anti-inflammatory, antidiabetic, and neuroprotective assays. The oil yield increased from 46% (hulled) to 51.89% (unhulled). GC-FID analysis revealed that the major fatty acids were oleic (58.20% unhulled vs. 42.34% hulled) and linoleic acids (32.52% unhulled vs. 46.78% hulled), along with palmitic, stearic, lignoceric, and γ-linolenic acids in trace amounts. Antioxidant activity was significantly higher in oil from unhulled seeds (DPPH IC_{50}: 616.8µg/mL vs. 735.43µg/mL; ABTS IC_{50}: 286.29µg/mL vs. 649.25µg/mL). Similarly, anti-inflammatory (BSA IC_{50}: 3.39µg/mL vs. 3.78µg/mL) and antidiabetic (α-amylase IC_{50}: 63.31µg/mL vs. 83.03µg/mL) activities were more potent in the unhulled oil. The inhibition of acetylcholinesterase (AChE) and butyrylcholinesterase (BChE) was also greater, suggesting possible neuroprotective potential. The seed hull positively affected both oil yield and biological potential, indicating that maintaining the hull during cold pressing may enhance the functional and therapeutic value of sunflower oil.

Keywords: antioxidant activity, anti-inflammatory, α-amylase inhibition, neuroprotection, fatty acid profile

RESUMO

O óleo de girassol é valorizado por suas propriedades nutricionais e terapêuticas, que dependem, em grande parte, de seu perfil de ácidos graxos e componentes bioativos; neste estudo, o óleo foi extraído por prensagem a frio de sementes com e sem casca. Os óleos foram comparados quanto ao rendimento, à composição de ácidos graxos (por GC-FID) e às atividades biológicas, incluindo ensaios antioxidantes, anti-inflamatórios, antidiabéticos e neuroprotetores. O rendimento do óleo aumentou de 46% (com casca) para 51,89% (com casca). A análise por GC-FID revelou que os principais ácidos graxos foram o ácido oleico (58,20% sem casca vs. *42,34% com casca) e o ácido linoleico (32,52% sem casca vs. 46,78% com casca), juntamente com os ácidos palmítico, esteárico, lignocérico e γ-linolênico em*

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quantidades vestigiais. A atividade antioxidante foi significativamente maior no óleo extraído de sementes com casca (DPPH IC_{50}: 616,81µg/mL vs. 735,43µg/mL; ABTS IC_{50}: 286,29µg/mL vs. 649,25µg/mL). Da mesma forma, as atividades anti-inflamatória (BSA IC_{50}: 3,39µg/mL vs. 3,78µg/mL) e antidiabética (α-amilase IC_{50}: 63,31µg/mL vs. 83,03µg/mL) foram mais potentes no óleo extraído de sementes com casca. A inibição da acetilcolinesterase (AChE) e da butirilcolinesterase (BChE) também foi maior, sugerindo um possível potencial neuroprotetor. A casca da semente afetou positivamente tanto o rendimento de óleo quanto o potencial biológico, indicando que a manutenção da casca durante a prensagem a frio pode aumentar o valor funcional e terapêutico do óleo de girassol.

Palavras-chave: atividade antioxidante, anti-inflamatória, inibição da α-amilase, neuroproteção, perfil de ácidos graxos

INTRODUCTION

The sunflower (*Helianthus annuus* L.), a member of the Asteraceae family, is an annual crop comprising more than 70 species, notable for its large yellow flower head that tracks the sun. According to FAO data (2000–2022), sunflowers are cultivated on over 100 million acres worldwide, ranking as the third most significant oilseed crop after soybean and rapeseed. In 2022, global sunflower seed production reached about 58 million metric tons, generating nearly 14 million cubic meters of husks. This output is largely attributed to leading producers such as Ukraine, Russia, and Argentina (Food…, 2023).

Helianthus annuus L. (Sunflower) stands as one of the most significant oilseed crops in Algeria, valued for its nutritional profile. The oil derived from its seeds is recognized not only as a dietary staple but also for its therapeutic potential, rich in unsaturated fatty acids and bioactive compounds with pharmaceutical and cosmetic applications in industries (Berrabah *et al.*, 2024).

The industrial processing of sunflower seeds typically involves dehulling to maximize oil yield. However, this practice may significantly alter the oil's phytochemical composition, as the hull is a known reservoir of polyphenols and other antioxidants (Tsvetanova *et al.*, 2025). Sunflower seed hulls (20–30% of the seed) are a low-cost by-product with little nutritional value, often discarded through storage or burning, which leads to technical and economic issues. Despite challenges in transport and storage, this lignocellulosic waste represents a promising source of valuable industrial chemicals (Menzel *et al.*, 2019). While the impact of dehulling on the quality and bioactivity of sunflower oil has been investigated in other regions, a critical knowledge gap exists regarding Algerian cultivars. The unique agro-climatic conditions of Algeria likely influence the chemical makeup of its sunflower seeds, necessitating localized, systematic studies to optimize processing techniques for both yield and health benefits.

Cold pressing has emerged as a preferred method for extracting high-value oils, as it avoids the use of chemical solvents and operates at low temperatures, thereby preserving thermo-labile bioactive compounds such as tocopherols, sterols, and polyphenols (Vukic and Vujasinovic, 2023, Pantoja *et al.*, 2024). These compounds are responsible for the antioxidant, antimicrobial, and anti-inflammatory properties, which are health-promoting (Madkour *et al.*, 2023). Consequently, assessing the cold pressing of hulled versus unhulled seeds presents a compelling approach to understanding how processing can be used to enhance functionality.

This study aims to bridge this gap by providing a comparative analysis of cold-pressed sunflower oils extracted from hulled and unhulled seeds of an Algerian cultivar. We assessed key parameters, including oil yield and fatty acid profile via GC-FID. Furthermore, we evaluated the biological activities including antioxidant (DPPH, ABTS, phenanthroline assays), antidiabetic (α-amylase inhibition), anti-inflammatory (albumin denaturation inhibition), and anti-Alzheimer (acetylcholinesterase and butyrylcholinesterase inhibition) properties. Our findings were benchmarked against standard synthetic antioxidants (BHA, BHT) and reference drugs (galantamine, acarbose, diclofenac) to contextualize their efficacy. By elucidating the contribution of the seed hull to the oil's physicochemical and therapeutic properties, this work provides crucial insights for integration processing efficiency with health-oriented applications of Algerian sunflower oil.

MATERIALS AND METHODS

We obtained it from the Biskra Institute in Algeria, which included sunflower seed oil from hulled and unhulled seeds. The seeds were then properly sterilized and sorted before being cold pressed to extract the oil. The produced oil had a smooth texture and was permitted to stand for 15 days to allow any contaminants to settle. Following the settling time, the oil was filtered and kept in opaque, firmly sealed bottles to preserve its purity and freshness.

Oil was extracted from hulled and unhulled sunflower seeds using a mechanical cold-pres (Komet Screw Oil Press, Model CA59, IBG Monforts Oekotec, Germany) extraction method, as previously described (Wandhekar *et al.*, 2023). Briefly, seeds were pressed at 40°C to avoid thermal degradation of bioactive compounds. The process was carried out under sterile conditions without the use of chemical solvents. The extracted oil was immediately collected in hermetically sealed, sterile amber glass bottles to protect it from light and oxidation and stored at 4 °C until subsequent analysis.

The extraction yield was calculated according to the method of Kabutey *et al*. (Kabutey *et al.*, 2022) using the following equation:

$$\% \text{ oil yield} = \frac{\text{Mass of oil recovered (g)}}{\text{Initial mass used for extraction (g)}} x100$$

The fatty acid composition of the oil samples was evaluated via gas chromatography with flame ionization detection (GC-FID), as reported by Khan (Khan and Runcorn, 2013). Before analysis, the oil samples were transesterified to convert the triglycerides to fatty acid methyl esters (FAMEs), which are more volatile and suited for gas chromatography. Briefly, the oil sample was dissolved in n-hexane, followed by the addition of 2mL of methanol containing 2 M potassium hydroxide. The liquid was briskly agitated to aid in the methylation reaction. Following phase separation, the upper FAME-containing layer was carefully collected, diluted with n-hexane, and placed in a GC vial for analysis. The analysis was conducted using an Agilent 7820A gas chromatograph with a flame ionization detector (FID) and a capillary column (SP-2560, 100 m × 0.25 mm i.d., 0.2 µm film thickness). The injection volume was 1 µL, with a split ratio of 20 to 1. Helium served as the carrier gas, while hydrogen and dry air were employed for the FID at flow rates of 40 and 450 mL/min, respectively. The injector and detector temperatures were set at 250 and 260 degrees Celsius, respectively. The oven temperature was set at 100 °C for 5 minutes, then gradually increased to 240 °C at a rate of 4 °C/min and maintained for 20 minutes. Fatty acid methyl esters were detected by comparing retention durations to those of recognized FAME standards. The quantification was done using peak area percentages computed from the FID response.

The DPPH scavenging assay was conducted on a 96-well plate to assess the antioxidant activity of extracts. The extracts were prepared in methanol at a range of concentrations: 12.5, 25, 50, 100, 200, 400, and 800µg/mL. A 40µL of each sample was mixed with 160µL of the DPPH solution. A negative control, consisting of 40µL of methanol and 160µL of DPPH, was also prepared. The plate was incubated in the dark for 30 minutes, after which the absorbance was measured at 517nm using a microplate reader (Perkin Elmer EnSpire, New York, NY, USA). The percentage inhibition was calculated using the formula:

$$\text{Inhibition}\% = \frac{(\text{AControl} - \text{ASample})}{\text{AControl}} x100$$

$A_{Control}$ is the absorbance of the negative control and A_{Sample} is the absorbance of the sample. The IC_{50} value was then determined from the concentration-inhibition curve to quantify the DPPH scavenging efficacy.

The ABTS cation radical assay was performed on a 96-well plate to determine the antioxidant capacity of the extracts (Re *et al.*, 1999). The ABTS radical solution was prepared by mixing a 7mM aqueous ABTS solution with 2.45mM potassium persulfate. The mixture was then left to incubate in the dark for 16 hours to allow for the formation of the $ABTS^+$ radical. Prior to the assay, the radical solution was diluted with ethanol until its absorbance was 0.7 ± 0.02 at 734nm. 40µL of the methanolic extract solution, prepared at concentrations ranging from 12.5 to 800µg/mL, was then mixed with 160 µL of the diluted ABTS solution. The reaction mixture was incubated for 10 minutes. The absorbance was then measured at 734 nm. A negative control,

containing 40 µL of methanol and 160 µL of the diluted ABTS solution, was used as a reference. The percentage of ABTS scavenging was calculated using the following formula:

$$\text{ABTS° scavenging effect \%} = \frac{(\text{AControl} - \text{ASample})}{\text{AControl}} x100$$

where:
$A_{Control}$: negative control absorbance
A_{Sample}: extract (or standard) absorbance

The phenanthroline assay was performed to quantify the antioxidant capacity of the extracts. The assay mixture was prepared by combining 10µL of each extract concentration with 50µL of 0.2% anhydrous iron chloride, 30µL of 0.5% phenanthroline, and 110µL of methanol. The extracts were prepared at concentrations of 3.125, 6.25, 12.5, 25, 50, 100, and 200µg/mL. The mixture was then incubated at 30°C for 20 minutes, after which the absorbance was measured at 510nm. A blank containing methanol instead of the extract was used to correct for any background absorbance.

The inhibitory activity of acetylcholinesterase (AChE) and butyrylcholinesterase (BChE) were determined using Elkolli *et al*. (2022). Mix 150µL of sodium phosphate buffer (100 mM, pH = 8.0) with 10µL of samples or standard solutions dissolved in methanol at varied concentrations (3.125-50µg/mL) and 20µL AChE or BChE solution in the buffer. Incubate for 15 minutes at 25°C before adding 10µL of DTNB (0.5mM). The reaction was started by adding 10µL of acetylthiocholine iodide (0.5mM) or butyrylthiocholine chloride (0.2mM). The absorbance of the solution was measured at 412nm using a 96-well microplate reader. Galantamine was used as the reference compound. The percentage of inhibition I (%) was determined using the formula and the results were given as IC_{50} values (µg/mL) corresponding to the concentration of 50% inhibition.

$$\text{I (\%)} = \frac{(\text{E} - \text{S})}{\text{E}} x100$$

where:
I: is the inhibition percentage,
E: is the activity of the enzyme without sample
S: is the activity of the enzyme with the simple.

The three fungal extracts were tested for antidiabetic efficacy using the alpha-amylase enzyme inhibition method developed by Zengin *et al*. (2014). Each extract (25 µL) at varying concentrations was put in the wells, followed by 50µL of alpha amylase solution. Incubation lasted 10 minutes at 37 degrees Celsius. Next, add 50µL of 0.1% starch and incubate for another 10 minutes. After adding 25µL of hypochloric acid (1M) and 100µL of iodine/potassium iodide (IKI), the results were measured at 680nm. Acarbose was employed as standard, and the inhibition percentage of alpha-amylase was determined using the following formula:

$$\text{\% Inhibition} = 1 - \frac{((\text{Ac} - \text{Ae}) - (\text{As} - \text{Ab})}{(\text{Ac} - \text{Ae})}$$

Where:
Ac = Absorbance [25 µL Solvent + 50 µL buffer solution + starch + HCl + IKI]
Ae = Absorbance [25 µL Solvent + enzyme + starch + HCl + IKI]
As = Absorbance [Extract + enzyme + starch + HCl +IKI]
Ab = Absorbance [Extract + 125 µL buffer solution + IKI]

The *in vitro* anti-inflammatory potential of the oil samples was evaluated based on their ability to inhibit bovine serum albumin (BSA) denaturation, following an established assay (Kellab *et al*., 2024). Briefly, 0.5mL of each oil sample, serially diluted in methanol to concentrations ranging from 250 to 2000µg/mL, was mixed with 0.5mL of BSA solution (0.2% w/v in 0.05 M tris-buffered saline, pH 6.6). The mixtures were incubated at 37°C for 15 min and then heated at 70°C for 5 min in a water bath to induce denaturation. After cooling to 25°C, the turbidity resulting from protein aggregation was measured spectrophotometrically at 660 nm. A control solution, in which 50µL of methanol replaced the oil sample, was processed simultaneously. Diclofenac sodium was used as a reference standard. The percentage inhibition of protein denaturation was calculated according to the following equation:

$$\text{\% Inhibition} = 1 - \frac{\text{At}}{\text{Ac}} x100$$

Where:
At is the absorbance of the test sample and Ac is the absorbance of the control.

All assays were performed in triplicate, and data are presented as mean ± standard deviation.

Data are expressed as mean ± standard deviation (SD). Statistical analyses were carried out using SPSS software (version 26; IBM Corp.). One-way analysis of variance (ANOVA) was applied to assess significant differences, followed by Tukey's honestly significant difference (HSD) post hoc test for multiple comparisons. Differences were considered statistically significant at $p < 0.05$.

RESULTS

The quantitative extraction efficiency of oil from hulled and unhulled sunflower seeds was assessed. The results, summarized in Table 1, indicate a substantial positive effect of the hull on oil recovery. The yield obtained from unhulled seeds (51.89%) was significantly greater than that from hulled seeds (46.00%).

Analysis by gas chromatography–flame ionization detection (GC–FID) revealed distinct fatty acid profiles between oils extracted from hulled and unhulled sunflower seeds (Table 2 and Fig. 1). The oil derived from unhulled seeds showed a higher relative abundance of monounsaturated fatty acids (MUFA), predominantly oleic acid (58.20%), compared to oil from hulled seeds (42.34%). Conversely, the oil from hulled seeds was enriched in polyunsaturated fatty acids (PUFA), notably linoleic acid (46.78%), relative to the unhulled seed oil (32.52%). The predominant saturated fatty acids, palmitic acid and stearic acid, were present in comparable proportions in both oils. Minor constituents, including lignoceric acid, γ-linolenic acid, eicosanoic acid, and docosapentaenoic acid, were also identified and quantified.

The *in vitro* antioxidant capacity of the oil samples was assessed using DPPH, ABTS, and the phenanthroline method. The results, expressed as half-maximal inhibitory concentration (IC_{50}), are presented in Table 3. Oil extracted from unhulled seeds demonstrated a significantly greater antioxidant capacity across all assays compared to oil from hulled seeds. The synthetic antioxidants butylated hydroxyanisole (BHA) and butylated hydroxytoluene (BHT) were included as reference standards and exhibited the highest potency.

Unhulled sunflower seed oil demonstrated stronger inhibitory activity against both acetylcholinesterase (AChE) and butyrylcholinesterase (BChE) compared to hulled oil. The IC_{50} values for unhulled oil were 78.19 ± 0.63µg/mL (AChE) and 81.55 ± 3.78µg/mL (BChE), while hulled oil showed higher IC_{50} values of 116.43 ± 1.00µg/mL and 105.32 ± 3.04µg/mL, respectively, indicating lower potency. In contrast, galantamine, the reference inhibitor, was significantly more potent, with IC_{50} values of 6.27 ± 1.15µg/mL for AChE and 34.75 ± 1.99µg/mL for BChE (Table 4). The differences among the three samples tested were statistically significant ($p < 0.05$).

Table 1. Yield and physicochemical properties of oil extracted from hulled and unhulled sunflower seeds

Sample	Oil volume (mL)	Density (g/mL)	Oil mass (g)	
Sunflower Seed Oil (unhulled)	1128	0.92	1037.76	51.89
Sunflower Seed Oil (hulled)	1000	0.92	920	

Table 2. Fatty acid composition of sunflower seed oil from hulled and unhulled seeds. Data represent relative percentage areas from GC-FID analysis

Peak	Name	Sunflower seed oil (unhulled)		Sunflower seed oil (hulled)	
		Retime	Area%	Retime	Area%
19	Oleic acid / C18.1 C	22.246	58.19863	22.243	42.34046
22	Linoleic acid / C18.2 C	23.555	32.52420	23.605	46.78418
13	Palmitic acid / C16	16.246	5.47949	16.244	6.12429
18	Stearic acid / C18	21.325	3.03125	21.343	3.76347
34	Lignoceric acid / C24	30.964	0.63708	30.941	0.43111
25	g-Linolenic acid / C18.3 N6	25.509	0.12936	25.508	0.26484
26	Eicosanoic acid / C20.2	-	-	26.112	0.16305
36	Docosapentaenoic / C22.6	-	-	32.031	0.12861

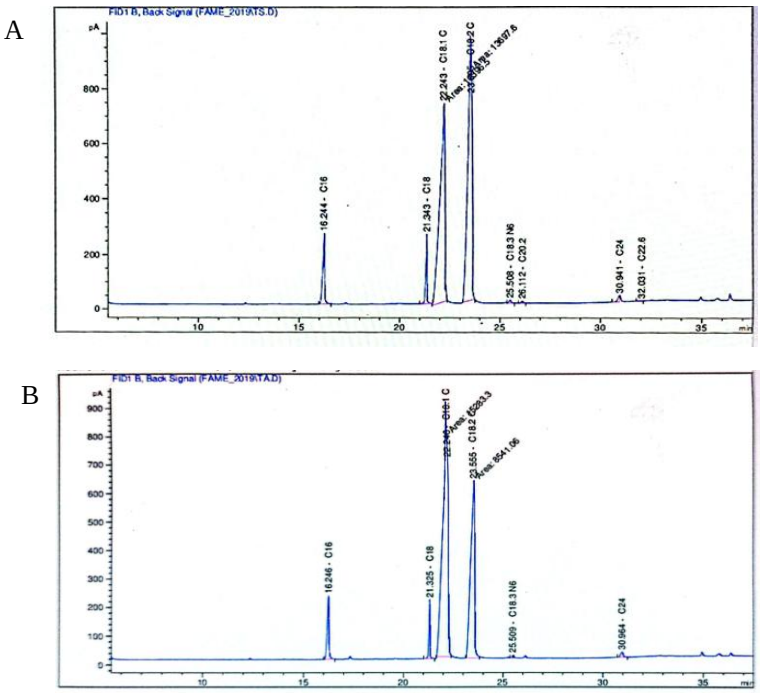


Figure1. GC-FID analysis of sunflower seed oil: (A) unhulled seeds and (B) hulled seeds.

The results showed that unhulled sunflower seed oil exhibited stronger α-Glucosidase inhibitory activity compared to hulled oil at all tested concentrations. Inhibition increased in a dose-dependent manner, ranging from 11.76% at 62.5µg/mL to 101.74% at 4,000µg/mL for the unhulled oil, while the hulled oil showed inhibition from 12.15% to 70.60% over the same concentration range. Acarbose displayed lower inhibition at low concentrations (7.76–10.70% at 62.5–500µg/mL) but increased significantly at higher concentrations, reaching 53.05% at 4000µg/mL. The IC_{50} values indicated that unhulled sunflower seed oil was the most potent (63.31 ± 0.33µg/mL), followed by hulled oil (83.03 ± 3.59µg/mL), while acarbose was the least effective (3,650.93 ± 10.70µg/mL). These differences were statistically significant ($p < 0.05$) (Table 5).

The anti-inflammatory activity of unhulled and hulled sunflower seed oils was evaluated using the BSA denaturation assay and compared with the standard drug diclofenac (Fig. 2). The results showed that all tested samples exhibited a concentration-dependent increase in anti-inflammatory activity. At the highest tested concentration (2,000µg/mL), unhulled sunflower oil exhibited 55% inhibition, whereas hulled sunflower oil showed 52% inhibition. Diclofenac demonstrated the highest activity, reaching 91% inhibition at the same concentration. The IC_{50} values further confirmed these observations, with diclofenac showing the lowest IC_{50} (1.88µg/mL), followed by unhulled sunflower oil (3.39µg/mL) and hulled sunflower oil (3.78µg/mL), indicating that unhulled sunflower oil has stronger anti-inflammatory potential compared to hulled oil.

Table 3. Antioxidant activity, expressed as IC_{50} (µg/mL), of sunflower seed oils and synthetic standards. Values are presented as mean ± standard deviation (n=3).

Sample	IC_{50} (µg/mL)		$ABS_{0.5}$ (µg/mL)
	DPPH	ABTS	Phenanthroline
Sunflower seed oil (unhulled)	616.81 ± 6.51^{b}	286.29 ± 0.84^{b}	93.75 ± 2.50^{b}
Sunflower seed oil (hulled)	735.43 ± 7.17^{c}	649.25 ± 3.78^{c}	166.94 ± 2.93^{c}
BHA	6.14 ± 0.41^{a}	1.81 ± 0.10^{a}	0.93 ± 0.07^{a}
BHT	12.99 ± 0.41^{a}	1.29 ± 0.30^{a}	2.24 ± 0.17^{a}

Different superscript letters (a–c) within a column denote statistically significant differences ($p < 0.05$, one-way ANOVA with Tukey's post-hoc test).

Table 4. Cholinesterase inhibitory activity of sunflower seed oils and galantamine. Values are expressed as IC_{50} (µg/mL) and represent mean ± standard deviation (n=3)

Sample	Acetylcholinesterase inhibition (IC_{50}, µg/mL)	Butyrylcholinesterase inhibition (IC_{50}, µg/mL)
Sunflower seed oil (unhulled)	78.19±0.63[b]	81.55±3.78[b]
Sunflower seed oil (hulled)	116.43±1.00[c]	105.32±3.04[c]
Galantamine	6.27± 1.15[a]	34.75±1.99[a]

Different superscript letters (a–c) within a column indicate statistically significant differences ($p < 0.05$, one-way ANOVA with Tukey's post-hoc test).

Table 5. α-Glucosidase inhibitory activity of sunflower seed oils and acarbose. Inhibition values are presented as mean percentage ± standard deviation (n=3). The IC_{50} (µg/mL) is presented as mean ± SD

Concentration (µg/mL)	Sunflower seed oil (unhulled)	Sunflower seed oil (hulled)	Acarbose
62.5	11.76±1.14	12.15±0.52	7.76±0.17
125	16.21±0.71	22.60±1.03	8.08±0.30
250	26.55±0.86	31.78±1.14	9.46±0.11
500	44.65±0.71	45.62±0.92	10.70±0.96
1000	69.54±0.78	53.06±0.64	31.81±2.89
2000	83.36±0.20	62.19±0.92	37.21±3.54
4000	101.74±1.04	70.60±0.46	53.05±1.59
IC_{50}	63.31±0.33[a]	83.03±3.59[b]	3650.93±10.70[c]

Different superscript letters (a–c) for the IC_{50} values denote statistically significant differences ($p < 0.05$, one-way ANOVA with Tukey's post-hoc test).

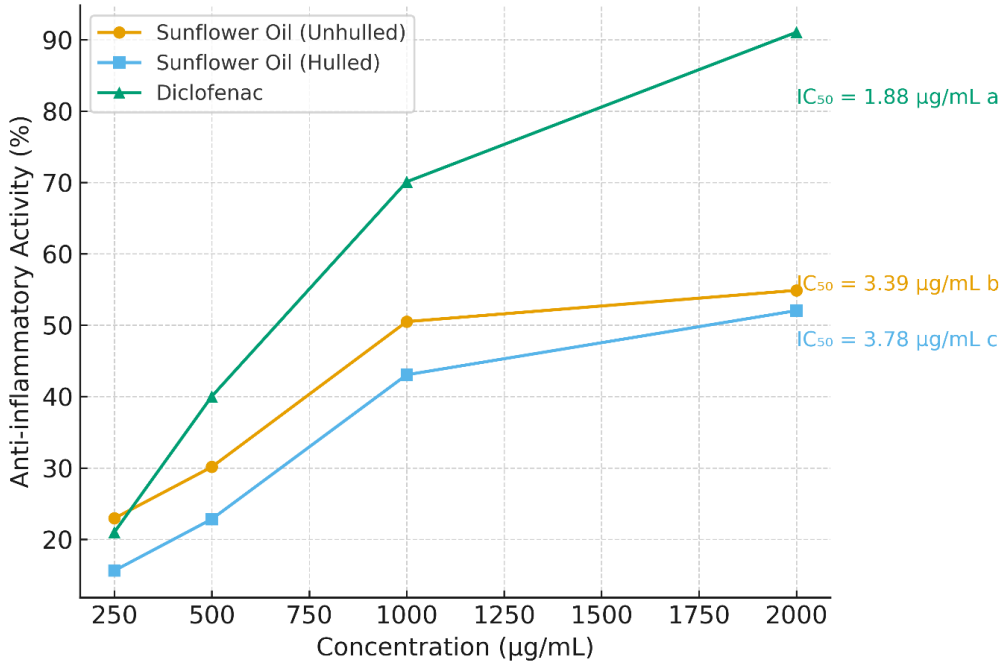


Figure 2. Anti-inflammatory activity of unhulled and hulled sunflower seed oils at different doses, compared with diclofenac. Different letters (a–c) for the IC_{50} values denote statistically significant differences ($p < 0.05$, one-way ANOVA with Tukey's post-hoc test).

These results suggest that the presence of hulls in sunflower seeds may slightly reduce the anti-inflammatory activity of the oil, and that unhulled sunflower oil could serve as a natural alternative with moderate anti-inflammatory effects. alternative with moderate anti-inflammatory effects.

DISCUSSION

This study demonstrates that sunflower oil extracted from unhulled seeds provides superior yield, bioactive lipid composition, and functional properties compared to hulled seeds. The higher oil recovery (51.89% vs. 46%) can be attributed to the structural role of the hull in facilitating oil drainage and retaining bioactive molecules such as polyphenols, sterols, tocopherols, and unsaponifiable lipids. These findings corroborate the report by Lužaić *et al*. (Lužaić *et al.*, 2025) while further emphasizing that hull-associated components enrich the nutritional and therapeutic profile of sunflower oil. In addition, fatty acid profiling revealed that oleic and linoleic acids predominated, consistent with Codex Alimentarius standards (Comisson, 1999). However, unhulled seed oil contained markedly higher oleic acid (58.20%) and lower linoleic acid (32.52%) compared to hulled seed oil. The presence of additional unsaturated fatty acids, including γ-linolenic, and docosapentaenoic acids, suggests potential anti-inflammatory benefits (Sergeant *et al.*, 2016, Chen *et al.*, 2021). This distinct compositional shift highlights the contribution of hull-retained lipids to the functional properties of oil.

Antioxidant assays (DPPH, ABTS, phenanthroline) confirmed significantly higher radical-scavenging activity in oil from unhulled seeds. Although the IC_{50} values were less potent than the synthetic antioxidant BHA, the results align with (El-Beltagy and Alharthi, 2021), who demonstrated that hull-derived polyphenols enhance oxidative stability in sunflower oil. These outcomes indicate that naturally occurring antioxidants in the hull, especially tocopherols and polyphenols, represent key contributors to the defense against oxidative stress (Žilić *et al.*, 2010; Marfil *et al.*, 2011; Sonu *et al.*, 2025).

Enzyme inhibition assays further highlighted the bioactive potential of unhulled seed oil. Notably, the oil displayed stronger acetylcholinesterase (AChE) and butyrylcholinesterase (BChE) inhibition than hulled seed oil, suggesting enhanced neuroprotective potential. While the inhibitory values were weaker than galantamine (Abdalla *et al.*, 2021), they fall within the moderate inhibitory spectrum reported for plant oils such as ginger and cumin (Mahnashi *et al.*, 2021). The synergy between sterols, unsaturated fatty acids (Loesche *et al.*, 2018), and phenolics (Szwajgier, 2015) likely underlies this effect, underscoring the potential of cold-pressed sunflower oil as a complementary dietary agent in managing neurodegenerative disorders.

The α-amylase inhibition results demonstrated that unhulled seed oil exerted stronger antidiabetic activity (IC_{50} = 63.31 µg/mL) compared to hulled seed oil. This aligns with previous findings on functional oils and plant extracts with moderate enzyme-inhibitory effects (Salehi *et al.*, 2019, Jawad and Al-Rubaye, 2025). Consistently, sunflower oil, particularly when obtained from germinated or minimally processed seeds, represents a promising dietary component for supporting postprandial glycemic regulation. Germination has been reported to significantly enhance the phenolic content and antioxidant activity of sunflower seed oil (Pointner *et al.*, 2024), while clinical evidence in individuals with metabolic syndrome demonstrated that sunflower seed oil consumption can improve fasting lipid profiles and glucose-related parameters (Akrami *et al.*, 2018).

Similarly, unhulled sunflower oil exhibited stronger anti-inflammatory potential in the BSA denaturation assay compared to hulled oil, although both were less active than diclofenac. These findings are consistent with recent studies on seed oils from Rubiaceae, Cucurbitaceae, and Brassicaceae families (Fratianni *et al.*, 2021, 2023). The comparable IC_{50} values highlight the potential of sunflower oil as a natural anti-inflammatory product, primarily due to the retention of polyphenols, sterols, and unsaponifiable lipids in the seed coat.

Taken together, these findings clearly establish the sunflower hull as a critical determinant of oil quality and functionality, contributing not only to yield but also to antioxidant, neuroprotective, antidiabetic, and anti-inflammatory properties. While the bioactivities observed were moderate

compared to pharmaceutical standards, their cumulative effects may be valuable for developing functional foods and nutraceuticals. A limitation of the present study is the lack of in vivo validation, which will be essential to confirm the therapeutic relevance of the identified bioactive compounds. Future studies should also explore mechanistic pathways and synergistic interactions among hull-derived molecules.

CONCLUSION

Sunflower oil derived from unhulled seeds represents a nutritionally enriched and functionally superior product with broad potential applications in health promotion and disease prevention. Its unique fatty acid profile, coupled with hull-associated bioactives, positions it as a promising natural source for functional food formulations and therapeutic interventions.

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DATA AVAILABILITY STATEMENT

The research data are available within the article itself.

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