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SHORT REPORT

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Extraction of phenolic compounds and antioxidant activity analysis of *Ficus carica* L. seed oil using supercritical fluid technology

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ABSTRACT

The rationale behind this study was to investigate the potential of fig (*Ficus carica* L.) kernel oil as a source of bioactive compounds, particularly focusing on its phenolic compounds, due to the increasing interest in plant-based oils with antioxidant properties for use in functional foods and nutraceuticals. The primary objective was to identify and quantify the active phenolic components present in fig kernel oil. Utilizing an additional co-solvent in the supercritical fluid extraction (SFE) process, specific phenolic compounds, such as 4-hydroxybenzoic acid, 3-hydroxybenzoic acid, and syringic acid, were exclusively identified in the CO_2 + ethanol (IC-2-1) sample. Furthermore, other notable compounds, including vanillin, verbascoside, ferulic acid, luteolin 7-glucoside, hesperidin, rosmarinic acid, quercetin, and kaempferol, were detected in both the IC-2-1 and CO_2 (IC-1-1) samples. These findings suggest that fig kernel oil with its rich phytochemical profile, is a promising alternative oil source and has significant potential as a functional food ingredient. Further research on the SFE of fig seeds and oil is recommended to expand its applications and potential health benefits.

1. Introduction

Fig (*Ficus carica* L.) is a member of the Moraceae family and grows from Turkey to Afghanistan, with around 800 species. It has been cultivated for health and food purposes in temperate climates since ancient times (Abbasi et al., 2013; Barolo et al., 2014). Leading producers include Turkey, Morocco, Egypt, Spain, Greece, California, Italy, and Brazil (Abbasi et al., 2013). Figs are extensively studied for their nutritional value, health benefits, and therapeutic applications, including antipyretic, anti-inflammatory, hepatoprotective, hypoglycemic, anticancer, and antioxidant properties (Badgujar et al., 2014; Joerin et al., 2014; Mawa et al., 2013; Stepek et al., 2004). Furthermore, figs have been found to assist with anxiety, sleeplessness, blurred vision, and appetite loss (Argon et al., 2020).

Traditional medicine uses *F. carica* to treat gastrointestinal and respiratory ailments, as well as for its anti-inflammatory and antispasmodic properties. This has inspired research into its chemical composition, including phytosterols, phenolic compounds, fatty acids, and other secondary metabolites (Baygeldi et al., 2021).

Polyphenols, flavonoids, and anthocyanins possess significant antioxidant capacity. The anthocyanin content found in figs is thought to aid in maintaining healthy blood lipid levels. It plays a crucial role in preventing conditions such as obesity, diabetes, cardiovascular disease, and spe-

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cific types of cancers (Wojdyło et al., 2016).

Additionally, analyses have investigated sterols, phenolics, volatiles, antioxidant capacity, antimicrobial properties, and fatty acids in various parts of the plant, such as latex, fruits, leaves, and roots (Jeong & Lachance, 2001; Mahmoudi et al., 2016).

A study was conducted on fig kernel oil utilizing the cold press extraction method. The analysis revealed that fig kernel oil is abundant in linolenic acid (omega-3, 40.25%), linoleic acid (omega-6, 31.28%), and oleic acid (omega-9, 17.0%). It also contained a small amount of palmitic acid and trace levels of other fats, with no aflatoxin detected. Furthermore, fig kernel oil had a significantly high concentration of gamma-tocopherol (4090.70 ± 383.30 mg/kg) compared to other sources of edible oils (Tarlacı, 2021).

Due to its abundant omega-3 fatty acid content, figs and fig kernel oil play a crucial role in moisturizing and nourishing the skin from within, preserving its elasticity. These sources are also rich in minerals such as potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), and copper (Cu), as well as vitamins A, E, and K, all of which exhibit potent antioxidant properties. Furthermore, the calcium present contributes to the maintenance of bone health (Cihat Icyer et al., 2017).

Studies show its protective effects against colon (Campbell et al., 2003), breast, and prostate cancers, with high serum levels reducing prostate cancer risk by five times (Helzlsouer et al., 2000). Gamma-tocopherol's strong antioxidant activity, particularly against nitrogen radicals, also inhibits colon cancer cell proliferation (Campbell et al., 2003). In contrast, alpha-tocopherol is linked to a reduced risk of bladder cancer (Jiang et al., 2000).

Gamma-tocopherol, unlike alpha-tocopherol, inhibits cyclooxygenase-2 (COX-2), providing anti-inflammatory benefits that may prevent Alzheimer's and atherosclerosis. It also acts as a diuretic, helping to lower blood pressure and reduce pancreatic cell loss, potentially decreasing Type 1 diabetes risk (Bharti et al., 2013; Jiang et al., 2001). Clinical trials show that gamma-tocopherol reduces cholesterol more effectively than alpha-tocopherol (13% vs. 5% in four weeks). Low gamma-tocopherol levels are linked to increased coronary artery disease risk, unlike alpha-tocopherol. Additionally, Swedish individuals with double the gamma-tocopherol levels had a 25% lower cardiovascular mortality rate compared to Lithuanians (Kristenson et al., 1997).

Radical scavenging activity refers to the ability of a substance to neutralize free radicals, which are unstable molecules that can cause oxidative damage to cells and tissues. This activity protects cells and tissues against oxidative damage, reducing chronic disease risks. Natural antioxidants, such as vitamins C and E, flavonoids, and polyphenols, are widely used in food preservation, skincare, and pharmaceuticals as safer alternatives to synthetic options (Devasagayam et al., 2004). The mechanisms of radical scavenging include electron donation, hydrogen atom transfer, the formation of non-radical species, and metal chelation. Various methods are employed to assess radical scavenging activity, including 1,1-diphenyl-2-picrylhydrazyl (DPPH·), 2,2'-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) (ABTS·+), ferric reducing antioxidant power (FRAP), and oxygen radical absorbance capacity (ORAC) assays. The DPPH· assay is commonly used to evaluate antioxidant activity, where the color of DPPH· changes upon reduction by antioxidants. The ABTS assay involves the reduction of the ABTS·+ radical cation, with the decrease in absorbance measured at 734 nm (Al Mousa et al., 2023; Hassane et al., 2022b; Re et al., 1999).

SFE is an environmentally friendly alternative for triglyceride extraction, successfully applied to seeds such as apricot (Özkal et al., 2005), palm (Zaidul et al., 2007), canola (Dunford & Temelli, 1997; Temelli, 1992), sesame (Namiki et al., 2002; Xu et al., 2005), flax (Bozan & Temelli, 2002), and grape (Beveridge et al., 2005), as well as nuts like walnut (Oliveira et al., 2002; Salgın & Salgın, 2006) and almond (Marrone et al., 1998). Carbon dioxide (CO_2) is the preferred supercritical fluid due to its nontoxicity, low cost, and high purity, widely accepted in the food and pharmaceutical sectors (Taribak et al., 2013).

Since fig kernels are too small to be chewed or eaten, they cannot be used as a useful food source. Due to their minuscule size, fig seeds cannot be efficiently masticated or utilized as a substantial food source. They resist digestion within the gastrointestinal tract and are typically excreted intact in the feces. Germencik, where the fig kernel is taken from, is a district of Aydın Province in the Aegean Region of Turkey. Its geographical coordinates are approximately 37.8739° north latitude and 27.6064° east longitude. The district, which is approximately 25 km from Aydın provincial center, is located on the fertile lands of Western Anatolia. *F. carica*, is the most produced fig variety in Turkey, especially in Aydın region. While cold press and soxhlet extraction are common methods for extracting compounds from kernel figs, SFE is a promising green technology with several advantages; however, no studies have reported on the bioactive compounds in this fig variety of seeds extracted using supercritical fluids. Therefore, the objectives of this study were to analyze the phenolic compounds extracted from *F. carica* seed oil using SFE and to evaluate their antioxidant activity, initiating research on this species as a potential functional food.

2. Materials and methods

2.1. Raw material and sample preparation

Fig seeds were obtained from dried figs supplied from Germencik Organic Oleogustus Gıda Ltd. Şti. in August. These figs were cultivated in the Aydın region. The dried figs were pre-treated by soaking in warm water for 30 minutes, followed by sieving and shade-drying for 72 hours. Two kilograms of fig kernels were subjected to a drying process in an oven (ILD-EKH-120, 1500W, Türkiye) and subsequently, ground using a grain mill (Emir Industrial Kitchen Products, EMR-Ö-01, 1.5 kg, Türkiye). The ground material was then sieved to achieve a particle size of less than 0.30 mm. The resulting ground fig kernel was stored in a dark environment at room temperature until further analysis.

2.2. Supercritical fluid extraction (SFE)

SFE is a technique that uses fluids above their critical temperature and pressure, combining gas and liquid properties to enhance solubility. CO_2 is commonly used as the supercritical fluid. The process involves pressurizing the fluid, directing it into an extraction cell with the sample, and dissolving the target compounds. After extraction, reducing pressure or increasing temperature returns the fluid to a gaseous state, leaving the dissolved compounds behind for collection. SFE is highly efficient, eco-friendly, and widely applied in the food, pharmaceutical, and cosmetic industries to extract oils, essential oils, and bioactive compounds (da Silva et al., 2016; McHugh & Krukonis, 2013).

The SFE system (Polat Extraction Technology, Türkiye) consisted of a CO_2 cylinder, a recirculating chiller, CO_2 and co-solvent pumps, an extraction vessel, a heat exchanger, a separating vessel, an automated back pressure regulator, and a controlling PLC (Figure 1). In both extractions, 720 g and 719 g of fig kernels were placed in the extractor. Four main parameters—temperature (T, °C), pressure (P, bar), methanol concentration (MeOH, % cosolvent-solvent ratio), and CO_2 flow rate (qCO_2, g/min) — were varied for the two extractions (Figure 1).

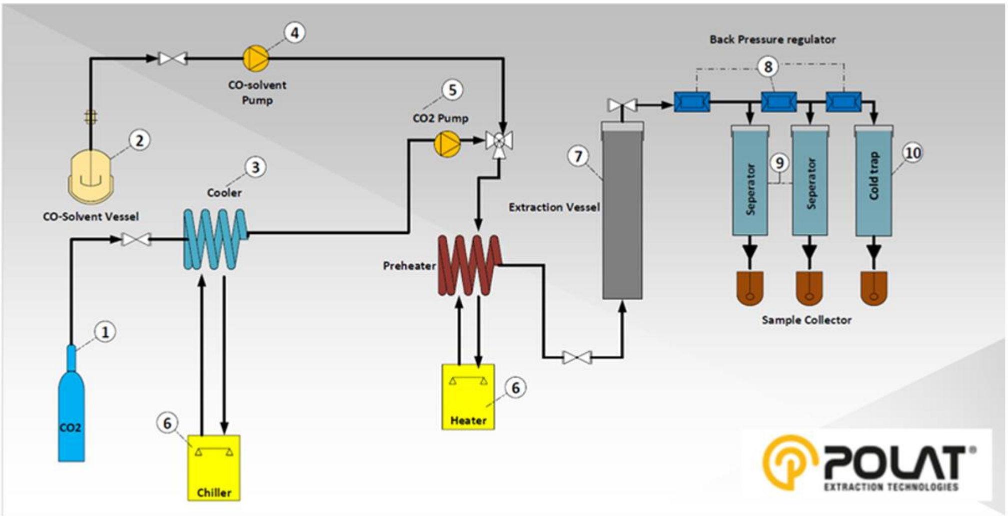

Figure 1. Schematic representation of the Polat supercritical fluid extraction technology (reproduced with permission from Polat Makina A.S.)

2.3. Supercritical CO_2 (SC-CO_2) extraction of fig seed oil

SC-CO_2 extraction is an advanced and eco-friendly method used to extract fig seed oil, utilizing CO_2 in its supercritical state. In this process, CO_2 is pressurized and heated above its critical point (31 °C and 73 atm), where it behaves as both a liquid and a gas, allowing it to penetrate fig seeds and dissolve oils efficiently.

The purchased fig kernels were stored at 25 °C until extraction. Fig seed oil was obtained by the SC-CO_2 extraction method. The obtained oil was stored at 4 °C until analysis.

2.4. Design of experiments (DoE) and process optimization

DoE is a structured approach for planning and analyzing experiments to understand the impact of various factors on a process. Commonly applied in process optimization, DoE identifies optimal conditions to enhance efficiency, yield, or quality. In SC-CO_2, it aids in fine-tuning parameters like pressure and temperature to maximize oil yield and preserve essential compounds (Antony, 2023).

For this experiment, a laboratory-scale SFE system manufactured by Polat Extraction Technologies was used. Extraction was performed in two processes using CO_2 IC-1-1 and IC-2-1 as solvents. A schematic representation of the extraction process is given in Figure 1. For the extraction process IC-1-1, 729 g of fig kernels were placed in the extractor. It was carried out at 45 °C temperature, 300 bar pressure, CO_2 flow rate of 50 ml/min, and extraction time of 180 minutes. For the extraction process IC-2-1, 728 g fig kernels were placed in the extractor. It was carried out at 45 °C temperature, 300 bar pressure, CO_2 flow rate of 50 ml/min, extraction time of 180 minutes, and co-solvent flow rate of 5 ml/min (methanol). The extract obtained for IC-1-1 was stored at +4 °C for analysis. The solvent of the extract-methanol mixture obtained for IC-2-1 was removed under vacuum, and the remaining fig kernel oil was stored at +4 °C for analysis. Phenolic compounds and antioxidant activity were determined in two different studies (Table 1).

2.5. Analysis of phenolic compounds

Phenolic compounds, known for their antioxidant properties, are analyzed to determine their concentration in plants. Common methods include HPLC and spectrophotometry. This analysis is important for assessing the antioxidant capacity and health benefits of plant extracts, such as fig seed oil (Prior et al., 2005).

Table 1. Supercritical fluid extraction parameters

Sample	Conditions			
	P (bar)	T (°C)	MeOH (%)	qCO_2 (g/min)
IC-1-1	300	45	-	50
IC-2-1	300	45	4	50

Phenolic compounds of fig kernel oil were determined by liquid chromatography-mass spectrometry [LC (Agilent 1260 Infinity)-MS/MS (Agilent 6420 Triple Quadrupole LC-MS/MS)].

LC-MS working principle: In the initial quadrupole filter, molecules are separated based on their mass-to-charge (m/z) ratio and then subjected to fragmentation using a specific high-purity gas known as collision gas. The second quadrupole filter is responsible for the identification and quantification of the ions generated from this fragmentation process. Conditions used for LC-MS analysis include mobile phase (water and organic solvents), column selection (usually reversed phase C18), flow rate (0.2-1.0 ml/min), temperature (25-40 °C), ionization source (ESI or APCI), and mass detector settings (positive/negative mode, MS/MS).

2.6. Radical scavenging activity

Radical scavenging activities of the extracts were determined using DPPH· and ABTS·+ cation radicals (Kocak et al., 2016).

For the evaluation of radical scavenging activity against DPPH·, a sample solution (1 ml) was mixed with 4 ml of a 0.004% methanol solution of DPPH·. The absorbance of the sample was measured at 517 nm after a 30-minute incubation period at room temperature in the dark.

For assessing the scavenging activity against the ABTS·+ cation radical, the ABTS·+ radical cation was generated by reacting a 7 mM ABTS solution with 2.45 mM potassium persulfate and allowing the mixture to incubate in the dark at room temperature for 12-16 hours. Before starting the assay, the ABTS solution was diluted with methanol to achieve an absorbance of 0.700 ± 0.02 at 734 nm. A sample solution (1 ml) was then added to 2 ml of the ABTS solution and mixed thoroughly. The absorbance of the sample was recorded at 734 nm after a 7-minute incubation at room temperature.

2.7. Statistical analysis

The assays were conducted in triplicate using different portions of the samples to ensure accuracy and reproducibility. The descriptive statistical analysis was adopted to calculate the mean and standard deviation, and the results were presented as mean ± SD. Followed by one-way ANOVA (analysis of variance), Tukey's significant difference post hoc test, and Student's *t*-test with α= 0.05 were employed to determine the statistical significance between the species [IBM SPSS Statistics for Windows, version 22.0 (IBM Corp., Armonk, N.Y., USA)].

3. Results and discussion

The oil content and composition of seeds can vary due to factors like seed variety, climate, geographic origin, ripeness, size, pollination, and extraction methods. Given the significant oil yield observed in samples of fig seeds, these seeds could be deemed a promising oil source and potentially marketed as a value-added product (Argon et al., 2020; Hssaini et al., 2020). Since cold pressing is a pressing method rather than an extraction method, not all components can be fully extracted.

One study defined the fixed oil content of dried seeds as 30%, while another study reported that the oil content of four different fig seed varieties from Morocco ranged from 21.54 to 29.65% (Hssaini et al., 2020). Different fig seeds from Türkiye resulted in lower or similar oil yields of 14.08, 18, and 23.67% for different cultivars (Ergun & Bozkurt, 2020).

It is incorrect to compare the fig kernel oil obtained by SFE with the oils obtained by cold pressing, which is the other method. Nevertheless, we can compare our fig kernel results with other studies. The amounts of oil obtained by cold pressing method from different seeds are as follows: blackcurrant (16.5-30.4%), gooseberry (15.6-35.2%), lime (22.1-31.9%), passion fruit (18.5-30.4%), pear (16.3-31.7%), blackcurrant (22.8-30.1%), pumpkin (27.83-45.4%), honeydew (25.0-32.3%), and watermelon (22.1-36.65%) (Alves et al., 2021).

For the first time, fig kernel oil was obtained from two different studies using SFE technology. Fig kernel oil yields were 21% for IC-1-1 and 32% for IC-2-1. SFE technology has many advantages over cold pressing. These are solvent, temperature, selectivity, efficiency, purity, and shelf life. The biggest advantage of SC-CO_2 extraction is that it takes place in a closed system and extracts are not exposed to oxidation.

Supercritical extraction demonstrates superior yield performance compared to cold pressing due to its enhanced solubility and selectivity under controlled conditions. By optimizing parameters such as pressure, temperature, and solvent type, it achieves higher extraction efficiency, particularly for valuable bioactive compounds. Unlike cold pressing, which may leave a significant portion of extractable material behind, supercritical extraction minimizes losses, ensuring maximum recovery (Picot-Allain et al., 2021).

As a food, *F. carica* fruits are consumed fresh or dried, or used as jam. *F. carica* is generally recognized as an excellent source of minerals, vitamins, carbohydrates, and dietary fiber (Veberic et al., 2008). However, as far as is known, the kernel oil of *F. carica* has not been standardized to date. Fig kernels ingested with fruit consumption cannot be broken down in the body and excreted in the feces, and their content cannot be utilized.

The supercritical extract of fig seed oil was subjected to DPPH· and ABTS·+ radical scavenging activity assays, both of which yielded relatively low results. These findings suggest that the antioxidant capacity of the extract is limited (Hassane et al., 2022a). The low radical scavenging activity could be attributed to several factors. One possible explanation is that the supercritical extraction conditions (e.g., temperature, pressure) might not have been optimal for the efficient extraction of phenolic compounds or other bioactive molecules responsible for antioxidant activity (**Table 2**).

Table 2. Antioxidant activities of the supercritical fluid extract of fig kernels

Assays	IC-1-1	IC-2-1	Trolox
DPPH· scavenging (IC_{50}: mg/ml)	> 20^b	> 20^b	0.07 ± 0.001^a
ABTS·+ scavenging (IC_{50}: mg/ml)	> 20^b	> 20^b	0.13 ± 0.002^a

Different superscripts in the same row indicate significant differences ($p < 0.05$).

In the study for the determination of phenolic compounds of fig kernel oil by SFE, additional co-solvent was used, and therefore 4-hydroxybenzoic acid, 3-hydroxybenzoic acid, and syringic acid were determined only for IC-2-1. Vanillin, verbascoside, ferulic acid, luteolin 7-glucoside, hesperidin, rosmarinic acid, quercetin, kaempferol were determined for both IC-2-1 and IC-1-1 studies (**Table 3**).

Table 3. Analysis of phenolic compounds in the supercritical fluid extract of fig kernels

Compound	RT (min)	Concentration (µg/g extract)	
		IC-1-1	IC-2-1
4-Hydroxybenzoic acid	12.2969	nd	1.19 ± 0.02
3-Hydroxybenzoic acid	12.3972	nd	1.09 ± 0.01
Syringic acid	12.8542	nd	0.27 ± 0.01
Vanillin	13.3116	30.03 ± 0.01^a	14.88 ± 0.05^b
Verbascoside	13.6066	0.20 ± 0.04^a	0.08 ± 0.001^b
Ferulic acid	14.0203	2.26 ± 0.08^b	2.72 ± 0.07^a
Luteolin 7-glucoside	14.3277	0.49 ± 0.01^a	0.04 ± 0.001^b
Hesperidin	14.5005	0.11 ± 0.01^a	0.05 ± 001^b
Rosmarinic acid	14.6973	0.60 ± 0.21^a	0.11 ± 0.01^b
Quercetin	15.6494	1.77 ± 0.16^a	0.25 ± 0.01^b
Kaempferol	16.1847	0.48 ± 0.02^a	0.21 ± 0.01^b

Different superscripts in the same row indicate significant differences ($p < 0.05$). nd: not detected

4. Conclusions

This study demonstrates the potential of fig seeds as a valuable source of oil, particularly when extracted using SFE using Polat Extraction Technology, Türkiye. SFE was shown to be more efficient than cold pressing in terms of oil yield and product purity. While the specific oil content of fig seeds can vary, the results indicate the commercial viability of fig seed oil production.

The oil was found to contain essential fatty acids and a unique phenolic profile, including compounds with antioxidant and anti-inflammatory properties. However, the radical scavenging activity was relatively low. Future research should focus on optimizing extraction parameters to enhance the recovery of bioactive compounds, particularly phenolic compounds, and further investigate the potential health benefits of fig seed oil.

This study represents a pioneering effort in utilizing SFE to extract bioactive compounds from fig seeds. The identification of various phenolic compounds, such as 4-hydroxybenzoic acid, syringic acid, and quercetin, highlights the potential of fig seed oil as a functional food ingredient. By valorizing a traditionally underutilized byproduct, fig seeds can contribute to a more sustainable and health-conscious food system.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Statement of ethics

In this study, no method requiring the permission of the “Ethics Committee” was used.

Availability of data and materials

All data generated or analyzed during this study are included in this published article. On request, the associated author can provide more information.

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İlker Yıldırım: Validation, Investigation, Data curation, Review and editing, Supervision
Alper Baycan: Formal analysis, Investigation
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Supplementary File

None.

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