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Investigation of γ-irradiation effects on physicochemical characteristics, fatty acid and sterol profiles of three different poppy (*Papaver somniferum* L.) seed varieties

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SUMMARY: In this study, the impacts of γ-irradiation processing on the proximate composition, color parameters (L*, a*, b*), fatty acid and sterol compositions of poppy (Papaver somniferum *L.*) seeds were determined. For this purpose, three registered poppy seed varieties (blue, yellow, and white) were subjected to 2.5, 5.0, 7.5, and 10.0 kGy of γ-radiation. The dominant fatty acid in all three non-irradiated poppy seed oils was detected as linoleic acid, which ranged from 71.289 to 75.386%. Irradiaiton led to a significant decrease in linoleic acid (C18:2). While γ-irradiation caused a significant decrease in unsaturated fatty acids (UFA), radiation led to a significant increase in saturated fatty acids (SAFA). The irradiation process affected the Δ-7-avenasterol, β-sitosterol, and campesterol contents in all the poppy seed varities compared to the nonirradiated controls. Although irradiation led to significant changes in the color parameters of all the poppy seed varieties, generally, the proximate composition of poppy seeds did not change according to the γ-irradiation dose.

KEY-WORDS: *Gamma irradiation;* Papaver somniferum *L.; Poppy seed oil; Fatty acid composition; Sterol content; Color.*

RESUMEN*: Efectos de la irradiación gamma sobre las características fisicoquímicas y los perfiles de ácidos grasos y esteroles en tres variedades de semillas de amapola* (*Papaver somniferum* L.). En este estudio, se determinó el impacto de irradiación γ en la composición proximal, los parámetros de color (L*, a*, b*), la composición de ácidos grasos y esteroles de las semillas de amapola (*Papaver somniferum* L.). Para ello, tres variedades registradas de semillas de amapola (azul, amarilla y blanca) se sometieron a 2,5; 5,0; 7,5 y 10,0 kGy de radiación γ. El ácido graso dominante en los tres aceites de semillas de amapola no irradiados fué el ácido linoleico (C18:2), que varió de 71,289 % a 75,386 %. La irradiación provocó una disminución significativa de éste ácido C18:2. Mientras que la irradiación γ provoca una disminución significativa de los ácidos grasos insaturados (UFA), también provocó un aumento significativo de los ácidos grasos saturados (SAFA). El proceso de irradiación afectó los contenidos de Δ-7-avenasterol, β-sitosterol y campesterol de todas las variedades de semillas de amapola en comparación con los controles no irradiados. Aunque la irradiación provocó cambios significativos en los parámetros de color de todas las variedades de semillas de amapola, en general, la composición proximal de las semillas de amapola no cambió en función de la dosis de irradiación gamma.

PALABRAS CLAVE: *Aceite de semilla de amapola; Color; Composición de ácidos grasos; Contenido de esteroles; Irradiación gamma;* Papaver somniferum *L.*

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1. INTRODUCTION

Poppy (*Papaver somniferum* L.) is an annual herbaceous plant which is cultivated worldwide. The poppy belongs to the Papaveraceae family, and is one of the most important medicinal, edible, and ornamental plants in Turkey. It plays an important role in the country's economy. Based on 2022 production data, Turkey is among the world's leading poppy producing countries with its annual production of 12240 tons (FAOSTAT, 2024). The most commonly grown poppies in Turkey are varieties with white, blue and yellow seeds, respectively.

Two important parts of the poppy are seed and capsule shell. Poppy seeds do not contain opium and are used in the preparation of foods such as curries, pastes, breads, desserts, candies and as a spice. The seeds are traditionally used in food breads and crushed pastries. The oil obtained by pressing the seeds is also used in the food, cosmetics and paint industries. The most important feature of poppy seeds is that it consists of 28-54 % oil and 20-30 % protein. The oil obtained from its seeds is a high-quality edible oil which is nutritionally desirable because of its fatty acid profile. The dominant fatty acid in poppy seeds is linoleic acid and its rate varies between 53 and 74 %. Poppy seed oil is recommended to be consumed more frequently as it lowers serum cholesterol levels and reduces cardiovascular diseases due to its high linoleic acid content (Dedebas, 2024; Muhammad *et al.,* 2021).

Poppy seeds attract attention as a ready-to-eat food because of their healthcare benefits. On the other hand, consuming poppy seeds as ready-to-eat food as additives without being subjected to any thermal or non-thermal processing makes them risky. Furthermore, poppy seeds are susceptible to microbiological contamination from many sources during growth and post-harvest processing (Willis *et al.,* 2009). Although the published data on the microbial quality of edible seeds is limited, the results of those studies on nuts and seeds show that seeds could be a probable source of foodborne diseases caused by contamination with pathogens such as *Salmonella* spp and *E. coli, etc*. Moreover, poppy seeds are often attacked by various fungal diseases (Šerá *et al.,* 2013; Pastirčák and Fejér, 2014). Hence, poppy seeds that are offered as ready-to-eat food as additives must be subjected to a process that will ensure microbial quality control.

Gamma irradiation is a reliable technology that ensures food safety by reducing microbial load and eliminating pathogens. This technology protects the quality of foods, ensures their hygiene and extends their preservation period with minimum influence on their properties. While γ-irradiation treatment, also called cold pasteurization, does not cause an increase in temperature in foods, it provides microorganism inactivation through DNA damage. Irradiation treatment is also internationally recognized as an effective process for ensuring the quality of spices, and improving their shelf-life and safety over a long period of time (Apaydin *et al.,* 2017; Jalili *et al.,* 2010). The Center for Disease Control and Prevention (CDC), the United States Department of Agriculture (USDA) and the Food and Drug Administration (FDA) also reported that irradiation is safe. In a meeting held jointly between the World Health Organization (WHO), Food and Agriculture Organization (FAO) and International Atomic Energy Agency (IAEA), it was reported that irradiation could be performed at doses of up to 10 kGy, as determined by Codex Alimentarius. The fact that irradiation can be applied to packaged products is very important and a great advantage in terms of preventing the contamination of spices and preserving their quality.

The motivation for this study is using γ-irradiation technology as a potential alternative to heat treatments to ensure the food safety and preserve the quality of poppy seeds. Considering that γ-irradiation could be applied as a preservative implementation of poppy seeds, this study aims to investigate the impacts of γ-radiation at different doses (0, 2.5, 5.0, 7.5 and 10.0 kGy) on the fatty acid and sterol composition and physicochemical properties of poppy (*P. somniferum*) seeds.

2. MATERIALS AND METHODS

2.1. Materials

In the present study, poppy seeds of the Ofis 1 (blue), Ofis 2 (white) and TMO 1 (yellow) varieties (*P. somniferum*), registered by the Turkish Grain Board, were used. The poppy seed varieties are shown in Figure 1. These three varieties were provided by the Soil Products Office, Afyonkarahisar (Türkiye). Each poppy seed sample from three different poppy varieties was divided into five equal amounts.

FIGURE 1. Poppy seed varieties used in the study. (a) Ofis-1, (b) TMO-1, (c) Ofis-2.

2.2. Irradiation of samples

Irradiation (1168 Gy/h) was done in a γ-irradiator (Ob-Servo Sanguis, Institute of Isotopes, Hungary) equipped with a 60Cobalt source at Sarayköy Nuclear Research and Training Center (Ankara, Turkey). The different doses (0, 2.5, 5.0, 7.5 and 10.0 kGy) of γ-irradiation were applied to samples. The irradiation was carried out at room temperature (25 °C). The non-irradiated samples were kept under the same conditions (~25 °C, temperature at which irradiation is implemented) as control lots at room temperature.

2.3. Proximate analysis of poppy seeds

Moisture, ash, total fat and crude protein contents were determined using official methods for poppy seeds (AOAC, 2010). Firstly, the poppy seed samples were ground, then 2 g of sample were weighed and dried at 103 ± 2 °C to constant weight in an air oven, and the dry matter content was recorded using the gravimetric method for moisture content analysis, and the Kjeldah method was used for crude protein content. A muffle furnace was used for ash content analysis, and the samples were burned in the muffle furnace at 550–600 °C for 4–6 hours. For fat content analysis, a Soxhlet of extractor was used with hexane (AOAC, 2010).

2.4. Color measurement

Color parameters (L*, a* and b* values) were detected with a Minolta Chroma meter CM-5 (Konica Minolta, Inc. Osaka, Japan). Before measurement, the device was calibrated against the white surface calibration plate and the L *, a *, and b * values were detected according to the CIELab color scale (Kwon *et al*., 2009).

2.5. Determination of fatty acids by gas chromatography (GC-FID)

Poppy seed oils were converted into fatty acid methyl esters (FAME) with BF3-methanol to identify and quantify the fatty acid profile of the poppy seed oil. The analysis of FAMEs was performed using gas chromatography (GC) (Thermo Scientific / Trace 1310). FAMEs (~99 % pure) (Supelco 37 Component FAME Mix, USA) were separated by a a fused-silica capillary column (30 m × 0.25 mm I.D., 0.2 µm film thickness) and detected with a flame ionization detector (FID) on a split injector. The FID and injector temperatures were held at 260 °C and 250 °C, respectively. The oven temperature programme was: 70 °C (2 min), to 120 °C at 4 °C/min, to 180 °C at 2 °C/min; held at 180 °C for 3 min, to 200 °C at 4 °C/min; held at 200 °C for 3 min, to 230 °C at 7 °C/min; held at 230 °C for 5.21 min. The GC was equipped with Helium as carrier gas at a constant flow of 1.0 mL/min. The content of individual fatty acids was calculated based on the peak area obtained.

2.6. Determination of sterol composition by gas chromatography (GC-FID)

The sterol profiles of the poppy seed oil samples were analyzed using gas chromatography according to the method of the International Olive Oil Council (2001). After pre-treatment, the isolation and quantitation of the sterol fractions were performed with gas chromatography (Agilent USA) equipped with a flame ionization detector (FID) and a capillary column (30 m × 0.32 mm × 0.25 µm). Hydrogen was used as the carrier gas at a flow rate of 1.0 mL/min with a 1:50 injector split. The studied conditions were as follows: injector temperature 280 °C, injection volume 0.2 µL, column temperature 260 °C, detector temperature 290 °C. The individual assessment of sterols was calculated in %.

2.7. Statistical analysis

A statistical analysis of obtained values was performed using one-way ANOVA and SPSS version 22.0. Analysis of variance (ANOVA) with Tukey's test for homogenous groups was conducted ($p \leq 0.05$). Data for all measurements were expressed as mean values.

3. RESULTS AND DISCUSSION

3.1. Physicochemical properties of non-irradiated and irradiated poppy seeds

Table 1 reports the influence of γ-irradiation on the proximate composition of the three studied varieties of poppy seeds. It shows that the moisture content in the unirradiated poppy seeds ranged from 7.54 to 9.25 %. The highest mean moisture content (9.25 %) was found in the Ofis 2 variety; while TMO 1 had the lowest (7.54 %). As seen in Table 1, poppy seed oil yield varied from 35.45 % for Ofis 1 variety to 39.87% for Ofis 2 variety. While Ofis 2 had the highest oil content (39.87 %), the variety Ofis 1 had the lowest (35.45 %). The protein content in the three studied varieties of poppy seeds ranged from about 18.61-20.6 %, depending on the variety. The highest protein content (20.6 %) was found in Ofis 1; while Ofis 2 had the lowest (18.61 %). The ash content in the unirradiated poppy seeds ranged from 6.48 to 7.14 g/100 g of dry matter.

Similar to these results, Gupcsó *et al.* (2023) stated that the oil content in six different varieties of poppy was between 27.5 and 37.2 %. Similarly, Ghafoor *et al.* (2019) reported that blue, yellow and white poppy seeds had 27.71, 29.17 and 33.94 % oil contents, respectively. They also stated that blue, yellow and white poppy seeds had 10.21, 9.97 and 11.11 % moisture contents. The ash contents obtained for the three varieties were comparable to some poppy seeds registered by the Turkish Grain Board. Emir *et al.* (2015) reported that poppy seeds (Ofis 8, Ofis 4, Ofis 3) had 6.1, 5.617, 6.205 % ash contents, respectively. They also stated that the protein content in the registered poppy seeds varied between 19.3 and 21.4 %. Melo *et al.* (2022) reported that poppy seeds (Czech Republic origin) had 7.21, and 7.84 % ash contents, and 14.62, and 15.96 % protein contents. Azcan *et al.* (2004) reported that yellow poppy seeds had 21.8 %, white poppy seeds 21.9 %, and blue poppy seeds 22.7 % protein contents. Similar to our results, they stated that blue poppy seeds had the highest protein content (22.7 %). On the other hand, they reported lower moisture content (6.4 %) and higher (49.2, 36.8 and 33.6 %) oil contents in poppy seeds compared to our findings. This variability in the proximate analysis of poppy seeds may depend on the variety, harvested period, weather condition, temperature, growing region and precipitation (Gupcsó *et al.,* 2023; Kaseke *et al.,* 2020). The applied process may also affect the proximate composition of the seeds (Grzegorz *et al.,* 2020).

Considering the influence of radiation on the proximate composition of the poppy seed samples, no significant changes ($p > 0.05$) in moisture content were detected after irradiation with 0–10 kGy doses. Minor, but sometimes statistically significant ($p < 0.05$) changes in fat, ash and protein contents were observed due to irradiation dose. These findings are in generally good agreement with the studies provided by Apaydin *et al.* (2017), and Gecgel *et al.* (2011), who did not detect significant changes in proximate composition after irradiation treatment. On the other hand, El-beltagi *et al.* (2019) stated that γ-irradiation led to a significant increase in reducing the sugars in Sakouti and Bondoky dry date fruit genotypes. Aly *et al*. (2023) also evaluated the chemical composition of irradiated caraway seeds. They reported that the percentage of oils increased by raising the radiation dose. Nada *et al*. (2022) investigated the chemical composition of the essential oil extracted from gamma-irradiated clove buds. They stated that oil yield was increased when 10 kGy irradiation dose was applied. Similarly, El-beltagi *et al*. (2020) reported that 10.0 kGy radiation dose caused a significant increase in the oil in celery seeds.

The L*, a* and b* values (color parameters) for the three studied varieties of irradiated and non-irradiated poppy seeds are shown in Table 2. The L*, a*, and b* values for unirradiated poppy seed samples were 37.50, 0.06, and -1.91 for blue poppy seed; 64.51, 4.68, and 20.15 for white poppy seed; and 48.84, 8.11, and 20.22 for yellow poppy seed, respectively. Similar to the present study, Emir *et al.* (2015) analyzed the chemical and physical features of the three poppy varieties registered by the Turkish Grain Board. They stated that L*, a*, and b* values were 44.98, 2.97, and –3.44 for blue poppy seed; 47.61, 7.80, and 11.94 for yellow poppy seed; and 64.28, 4.04, and 14.36 for white poppy seed, respectively. Cengiz *et al.* (2012) measured the color coordinates of poppy seeds with a chromameter. They stated that L*, a*, and b* values were 60.94, 5.02, and 16.91 for white poppy seed; 34.01, 1.28, and 1.94 for blue poppy seed; and 40.4, 6.21, and 14.97 for brown poppy seed, respectively. Regarding the effect of γ-irradiation on the color parameters of the poppy seed samples, considerable changes ($p < 0.05$) in L*, a* and b* values were detected after irradiation with 0–10 kGy doses. This is in accordance with a study by Al-Bachir (2015) where it was found that statistically significant changes ($p < 0.05$) were recorded in all three color parameters (L, a and b) of peanut oil with irradiation treatment (1, 2, 3 kGy). Similar to the present study, Gölge and Ova (2008) reported that the effect of the irradiation dose (0.5 and 5 kGy) on the L and b value of pine nuts was found to be statistically significant ($p < 0.05$).

TABLE 1. Proximate composition of irradiated and non-irradiated poppy seeds

Sample	Radiation Dose (kGy)	Moisture (%)	Protein (%)	Fat (%)	Ash (%)
Ofis 1	**Control**	8.32±0.52a	20.6±0.12bc	35.45±0.31a	6.48±0.08a
	2.5	8.47±0.36a	20.51±0.11c	35.42±0.26a	6.31±0.07b
	5.0	8.69±0.39a	20.84±0.11a	35.89±0.33a	6.52±0.04a
	7.5	8.79±0.54a	20,75±0.08ab	34.27±0.27b	6.27±0.03b
	10.0	8.89±0.46a	20.89±0.09a	34.14±0.31b	6.51±0.03a
Ofis 2	**Control**	9.25±0.54a	18.61±0.13bc	39.87±0.24a	6.72±0.02ab
	2.5	9.43±0.44a	18.45±0.07c	39.41±0.27ab	6.65±0.06b
	5.0	9.58±0,38a	18.74±0.12b	39.46±0.22ab	6.8±0.04a
	7.5	9.35±0.33a	18.67±0.07b	39.23±0.21b	6.68±0.06b
	10.0	9.97±0.44a	18.94±0.06a	39.78±0.25a	6.71±0.03b
TMO 1	**Control**	7.54±0.46a	19.8±0.11b	38.87±0.25a	7.14±0.01a
	2.5	7.83±0.29a	19.73±0.13b	38.45±0.31ab	6.85±0.04d
	5.0	7.98±0.47a	19.68±0.09b	38.45±0.1ab	7.03±0.04bc
	7.5	8.11±0.22a	20.08±0.09a	38.23±0.21b	7.11±0.06ab
	10.0	7.99±0.25a	19.77±0.08b	38.8±0.23a	6.95±0.07c

Each value in the table represents the mean ± standard deviation of triple analyses;
different letters in the same column represent significant differences at $p \leq 0.05$ according to Tukey's comparison test.
Ofis 1 (blue), Ofis 2 (white) and TMO 1 (yellow): varieties (P. somniferum) registered by the Turkish Grain Board.

TABLE 2. The L*, a*, b* values of irradiated and non-irradiated poppy seeds

Sample	Radiation Dose (kGy)	L*value	a* value	b* value
Ofis 1	**Control**	37.50±0.01C	0.06±0.01A	-1.91±0.01A
	2.5	37.47±0.01D	-0.11±0.01C	-2.26±0.01D
	5.0	38.09±0.03A	-0.21±0.01E	-2.34±0E
	7.5	37.92±0B	-0.19±0.01D	-2.23±0.01C
	10.0	36.84±0E	0.04±0B	-2.17±0.02B
	***p* value**	*	*	*
Ofis 2	**Control**	64.51±0.01B	4.68±0D	20.15±0,01A
	2.5	63.48±0D	4.79±0.01A	20.08±0.01B
	5.0	64.07±0101C	4.55±0E	19.6±0E
	7.5	64.75±0.27A	4.57±0,02C	19.83±0.06D
	10.0	64.01±0.01C	4.76±0.01B	19.90±0.01C
	***p* value**	*	*	*
TMO 1	**Control**	48.84±0.01E	8.11±0.01A	20.22±0,01C
	2.5	48.91±0.06D	8.07±0.01B	20.19±0.02D
	5.0	50.12±0.01A	7.94±0.01D	20.357±0.01B
	7.5	49,11±0.01C	8.04±0.01C	20.14±0.02E
	10.0	49.47±0.01B	8.11±0.01A	20.38±0.01A
	***p* value**	*	*	*

Values in the same column the same letter are not significantly different by Tukey's test at the 5% level
All values are expressed as means of three experimental replicates.
NS not significant * Significant at $p < 0.05$ according to Tukey multiple comparison tests.
Ofis 1 (blue), Ofis 2 (white) and TMO 1 (yellow): varieties (*P. somniferum*) registered by the Turkish Grain Board

3.2. Effect of irradiation treatment of poppy seeds on the fatty acid composition of the extracted oil

The fatty acid compositions of the oils of the three registered poppy varieties used in the present study are indicated in Table 3. As can be seen, linoleic acid (> 71 %), oleic acid (> 13 %) and palmitic acid (> 8 %) were quantitatively the most prominent fatty acids for all the varieties of non-irradiated poppy seeds. The dominant fatty acid in all three non-irradiated poppy seed oils was detected as linoleic acid. It ranged from 71.289 to 75.386 %. The highest linoleic acid ratio of the poppy seed cultivars used in the research was detected in the Ofis 2 variety at 75.386 %, and the lowest in the Ofis 1 variety at 71.289 %. As indicated in Table 3, the poppy seed oils also contained considerable amounts of oleic acid, contributing between 13.113 % (Ofis 2) and 16.703 % (Ofis 1) of the total fatty acids. These findings were consistent with those stated by other researchers that linoleic acid content was the dominant fatty acid in poppy seed oils (Ghafoor *et al.,* 2019; Bozan and Temelli, 2008; Özcan and Atalay, 2006). Similar to these findings, Bozan and Temelli (2008) reported that poppy seeds contained 74.47 % linoleic acid. Similarly, Dedebas (2024) stated that the predominant fatty acids found in poppy seed oil are linoleic acid (~74%), oleic acid (~13 %) and palmitic acid (~8 %), respectively. Thus, the detected fatty acid composition of the experimental varieties is in accordance with the results reported by Gupcsó *et al.* (2023). They stated that the most abundant fatty acids found in poppy seed oil were linoleic acid (64.02-75.40 %), oleic acid (12.68-23.37 %) and palmitic acid (7.79-9.23 %), respectively. Şengün *et al.* (2020) found that the composition of the poppy seed samples (Ofis 1 and Ofis 2, Turkey origin) contained predominantly linoleic (69.2-73.2 %), oleic (13.5-17.4 %) and palmitic acids (8.8-8.9 %). On the other hand, Ghafoor *et al.* (2019) reported lower linoleic acid (57.91- 64.83 %) and higher oleic acid (16.58- 21.41 %) contents in poppy seed compared to our findings. Minor differences in the fatty acid profile of poppy seed oil as reported by some authors (lower or higher values) may depend on seed variety, method of oil extraction or harvesting time. In the present study, the content of unsaturated fatty acids (UFA) and total saturated fatty acids (SFA) in the oil extracted from all control varieties of poppy seed samples were ~88% and ~11%, respectively. From a health perspective, unsaturated fatty acids have been reported to act as strong cholesterol-lowering agents and this profile is an indicator of the high nutritional value of poppy seed oil. Moreover, the health benefits of linoleic acid are well-known for decreasing coronary heart illnesses by reducing low-density lipoprotein (LDL) cholesterol. Considering that poppy oil presented a significant amount of UFA (~88 %) and linoleic acid is the dominant fatty acid found in poppy seeds, the consumption of poppy oil may improve cholesterol metabolism, reducing the risk of cardiovascular disease. Similar results were reported by Özbek and Ergönül (2020), Rahimi *et al.* (2011) and Azcan *et al.* (2004), who found that poppy seed oil is comprised of particularly unsaturated fatty acids.

Regarding the effect of γ-irradiation on the fatty acid profile of the poppy seed samples, while saturated fatty acids (SAFA) increased, unsaturated fatty acids (UFA) decreased significantly ($p < 0.05$) due to an increase in radiation dose. Considering the major fatty acids, γ-radiation modified the major fatty acid contents in poppy seed oil. Irradiaiton led to a significant ($p < 0.05$) decrease in oleic acid (C18:1) and linoleic acid (C18:2) contents and a significant ($p < 0.05$) increase in palmitic acid (C16:0) and stearic acid (C18:0) contents. These findings were similar to previous results reported by other researchers who stated that γ-irradiation led to a decrease in linoleic acid and oleic acid contents, while it caused an increase in stearic acid and palmitic acid contents (Akyol *et al.,* 2022; Apaydin *et al.,* 2017; Al-Bachir, 2015). Similar to the present study, Aly *et al.* (2016) investigated the moringa seed oil extracted from unirradiated and irradiated samples, and they reported that radiation induced slight changes in the fatty acid profile of moringa seed oil.

TABLE 3. Fatty acid composition of irradiated and non-irradiated poppy seeds

Sample	Fatty acid (wt%)	Control	Radiation Dose (kGy)			
			2.5	5.0	7.5	10.0
Ofis 1	C16:0	9.169±0d	9.295±0b	9.021±0.001e	9.185±0.001c	9.329±0a
	C18:0	1.966±0d	1.949±0.001e	2.466±0c	2.562±0b	3.157±0.001a
	C18:1	16.703±0d	16.811±0a	16.716±0.001c	16.758±0.001b	16.574±0e
	C18:2	71.289±0.002a	71.098±0.002b	70.814±0.002c	70.192±0.001d	69.995±0e
	SFA	11.343±0e	11.393±0d	11.661±0c	11.911±0.001b	12.679±0.001a
	UFA	88.657±0.002a	88.607±0.002b	88.34±0c	88.088±0.001d	87.32±0e
Ofis 2	C16:0	8.599±0d	8.461±0e	8.857±0.001a	8.762±0b	8.729±0.001c
	C18:0	1.932±0e	2.282±0b	1.944±0d	2.112±0c	2.401±0.001a
	C18:1	13.113±0d	13.119±0c	13.065±0e	13.547±0.001a	13.229±0.001b
	C18:2	75.386±0.002a	75.181±0.001a	75.232±0.001a	75.039±0.579ab	74.682±0.001b
	SFA	10.702±0e	10.946±0.001d	10.997±0c	11.063±0.001b	11.294±0a
	UFA	89.298±0.002a	89.053±0.001b	89.003±0.002c	88.939±0.002d	88.694±0.002e
TMO 1	C16:0	8.081±0.001e	8.199±0d	8.175±0c	8.214±0.001b	8.217±0001a
	C18:0	2.069±0e	2.097±0.001d	2.102±0c	2.104±0b	2.148±0.001a
	C18:1	14.799±0a	14.8±0a	14.761±0.001c	14.771±0b	14.585±0.001d
	C18:2	74.075±0.002b	73.974±0.001c	73.926±0.001d	73.928±0.002d	74.086±0.001a
	SFA	10.372±0e	10.486±0.001d	10.515±0c	10.551±0b	10.578±0.001a
	UFA	89.627±0.001a	89.514±0.002b	89.486±0.002c	89.448±0.001d	89.421±0.001e

Each value in the table represents the mean ± standard deviation of triple analyses.
Means in the same row with different letters show statistically significant differences at $p < 0.05$ according to Tukey's comparison test.
SFA: Saturated fatty acids, UFA: Unsaturated fatty acids
Ofis 1 (blue), Ofis 2 (white) and TMO 1 (yellow): varieties (*P. somniferum*) registered by the Turkish Grain Board

3.3. Effect of irradiation treatment of poppy seeds on sterol composition of extracted oil

Table 4 presents the sterol composition of irradiated and non-irradiated poppy seed samples. Campesterol, stigmasterol, β-sitosterol, Δ-5-avenasterol, Δ-7-avenasterol values were detected in three different poppy varieties. The major sterol components in the registered poppy seeds were β-sitosterol, campesterol, and Δ5-avenasterol, respectively. The most abundant sterol in all three non-irradiated poppy seed oils was detected as β-sitosterol. It ranged from 62.1% (TMO 1) to 65.06 % (Ofis 1). Other abundant sterol contents detected in poppy seed varieties were campesterol (17.89–21.77 %), and δ–5–avenasterol (11.44–12.69 %). The results in this study, in general, are consistent with the findings of Özbek and Ergönül (2020), who reported that the poppy seed oil contained abundant campesterol, δ–5–avenasterol, β–sitosterol and stigmasterol. Similar to our findings, they stated that the major sterol components of poppy seeds oils were β-sitosterol (143.81 mg/100 g). In line with these results, Emir *et al.* (2015) reported that β–sitosterol was the predominant sterol of poppy seeds and varied from 920.70 ppm (Ofis 3) to 1554.70 ppm. Minor variability in sterol components of poppy seeds may depend on the variety and treatment type (Emir *et al.,* 2015). Phytosterols are considered as cholesterol-reducing agents in the human body (Kaseke *et al.,* 2020). β-sitosterol also exhibits many health benefits and functional attributes such as antioxidant, antimicrobial, angiogenic, immunomodulatory, and antidiabetic. Due to its sterol content and high β-sitosterol level, poppy seed oil may be considered a valuable specialty source of nutrients for some beneficial health effects such as lowering cardiovascular disease and cholesterol. Therefore, it may act as a cheap and healthy alternative to other edible oils.

Considering the influence of ɣ-irradiation on the sterol profile of the poppy varieties, γ-irradiation caused some changes in sterol composition. As indicated in Table 4, the Δ-7- avenasterol contents in the poppy seed oil decreased ($p < 0.05$) depending on the increase in γ-irradiation dose ($p < 0.05$). Moreover, ɣ-irradiation led to significant decreases in β-sitosterol contents in Ofis 2 and TMO 1 samples. On the other hand, no significant changes were observed in the amount of stigmasterol according to an increase in the radiation dose ($p > 0.05$). To the best of our knowledge, this research is the first study about the influence of γ-radiation on the sterol composition of poppy seed oils. Though there are no such reports on the influence of γ-irradiation on the sterol composition of poppy seeds, the decontamination of other plant materials or seeds using γ-irradiation are stated in several studies. These findings are in good accordance with other studies in which γ-irradiation caused changes in the sterol composition (Akyol *et al*., 2022; Tejedor-Calvo *et al.,* 2020; Apaydin *et al.,* 2017; Afify *et al.,* 2013). Similar to this study, Akyol *et al.* (2022) reported some changes in the sterol values of chia seeds irradiated at doses of 0, 2.5, 5.0, 7.5, and 10 kGy. They reported that the β-sitosterol value decreased with an increase in irradiation dose. Tejedor-Calvo *et al.* (2020) reported that sterols, particularly stigmasterol, slightly decreased after irradiation. Similarly, Apaydin *et al.* (2017) stated that γ-irradiation led to a decrease in the sterol contents of grape seed samples. Afify *et al.* (2013) stated that the β-sitosterol, campesterol, cholesterol and stigmasterol levels of irradiated soybean, peanut and sesame seeds were generally lower than control samples.

TABLE 4. Sterol contents of irradiated and non-irradiated poppy seeds

Sample	Sterol Content (%)	Control	Radiation Dose (kGy)			
			2.5	5.0	7.5	10.0
Ofis 1	Campesterol	17.89±0.18c	18.29±0.25bc	18.2±0.11bc	18.32±0.35b	18.73±0.11a
	Stigmasterol	2.97±0.19a	2.91±0.12a	2.85±0.18a	2.94±0.09a	2.86±0.11a
	β-sitosterol	65.06±0.59a	64.83±0.48a	64.91±0.26a	64.86±0.34a	64.26±0.41a
	Δ5- avenasterol	12.64±0.21a	12.53±0.11a	12.61±0.14a	12.46±0.12 a	12.72±0.11a
	Δ7- avenasterol	0.24±0.01a	0.24±0a	0.23±0.01ab	0.22±0b	0.23±0.01ab
Ofis 2	Campesterol	19.48±0.28d	19.9±0.21c	20.54±0.13a	20.06±0.29bc	20.39±0.19ab
	Stigmasterol	2.02±0.11a	1.98±0.14a	1.89±0.15a	1.95±0.156a	1.93±0.1a
	β-sitosterol	65.05±0.24ab	65.29±0.53a	64.77±0.32ab	64.98±0.19ab	64.57±0.27b
	Δ5- avenasterol	11.44±0.11abc	11.31±0.10bc	11.28±0.15c	11.52±0. 10ab	11.63±0.09a
	Δ7- avenasterol	0.32±0a	0.32±0a	0.32±0.01a	0.29±0.01b	0.28±0b
TMO 1	Campesterol	21.77±0.30b	22.04±0.21ab	22.02±0.18ab	22.46±0.18a	22.43±0.35a
	Stigmasterol	1.91±0.06a	1.89±0.09a	1.79±0.09a	1.84±0.11a	1.85±0.13a
	β-sitosterol	62.1±0.39a	61.79±0.28ab	61.82±0.23ab	61.42±0.43b	61.36±0.11b
	Δ5- avenasterol	12.69±0.06a	12.74±0.12a	12.81±0.11a	12.74±0.09a	12.82±0.17a
	Δ7- avenasterol	0.36±0a	0.35±0.01ab	0.36±0a	0.34±0.01bc	0.33±0.01c

Each value in the table represents the mean ± standard deviation of triple analyses.
Means in the same row with different letters show statistically significant differences at $p < 0.05$ according to Tukey's comparison test.
Abbreviation: NS, not significant; * Significant at $p < 0.05$
Ofis 1 (blue), Ofis 2 (white) and TMO 1 (yellow): varieties (*P. somniferum*) registered by the Turkish Grain Board

4. CONCLUSIONS

For the first time in this study, γ-irradiation was implemented as a protective method for poppy seeds. The results of the present study indicated that minor, but sometimes statistically significant ($p < 0.05$) changes in fat, ash and protein contents were observed due to irradiation dose. No significant changes ($p > 0.05$) in the moisture content in poppy seeds were detected after irradiation with 0–10 kGy doses. On the other hand, γ-irradiation modified the palmitic (C16:0), oleic (C18:1), and linoleic (C18:2) acids, which are the major fatty acids in poppy seed oil. Irradiation led to significant changes in the color parameters (L*, a* and b*) ($p < 0.05$) of all varieties of poppy seeds. The irradiation process affected the Δ-7-avenasterol, β-sitosterol, and campesterol contents in all poppy seed varities compared to nonirradiated controls. The β-sitosterol content, which was exhibited as the major sterol for all varieties, decreased due to γ-irradiation.

In conclusion, γ-irradiation, which ensures the safety of poppy seeds, can be effectively utilized without altering their proximate composition. Moreover, γ-irradiation technology can be recommended as a potential alternative to heat treatments for maintaining the quality of poppy seeds because thermal treatments may adversely affect their nutritional value and quality. The results also contribute to promoting the application of γ-irradiation in the commercial production of poppy seed samples.

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DECLARATION OF COMPETING INTEREST

The authors have declared no conflicts of interest for this article.

AUTHORSHIP CONTRIBUTION STATEMENT

D. Apaydın: corresponding author, validation, methodology, investigation, visualization, supervision, writing of original draft, writing review and editing.

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