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Research Article
(Araştırma Makalesi)

Ömer Faruk KOÇAK [1]

Sibel YAĞCI [1*]

[1] Balıkesir University, Engineering Faculty, Food Engineering Department, 10145, Balıkesir, Türkiye

* Corresponding author (Sorumlu yazar):

sibelyagci@balikesir.edu.tr

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Effect of ultrasound dehulling process on mineral content of sesame seed*

Ultrases kabuk soyma işleminin susam tohumunun mineral içeriği üzerine etkisi

* This article has been summarized from the first author's master's dissertations.

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ABSTRACT

Objective: In this study, an ultrasound technique, regarded as an innovative processing method in food technology, was employed for the dehulling of sesame seeds, and its effects on the mineral composition of sesame seeds were examined.

Materials and Methods: Two sesame varieties (Muğla and Togo) underwent ultrasound-assisted dehulling under varying amplitudes (50-100%) and exposure times (5-15 min). Totally 20 different minerals were analyzed in sesame samples by ICP-MS method.

Results: Ultrasound method increased the amount of separated seed coat ratio in sesame to approximately 76% in Muğla sesame and 83% in Togo sesame compared to the traditional method. Increasing ultrasound treatment time and amplitude resulted in decreased heavy metal content in sesame seeds, accompanied by increased levels of magnesium, phosphorus, potassium, calcium, copper, zinc, selenium, aluminum, and chromium, and decreased levels of iron, tin, manganese, boron, and nickel.

Conclusion: Given its high efficiency in sesame dehulling and its ability to reduce the contents of heavy metals and iron (Fe) regulated by legislation, the ultrasound method is regarded as a viable alternative to the traditional method.

ÖZ

Amaç: Bu çalışmada, susam tohumlarının kabuk soyma işleminde yenilikçi bir işlem olan ultrason tekniğinden yararlanılmış ve söz konusu tekniğin susam tohumlarının mineral bileşimi üzerindeki etkileri araştırılmıştır.

Materyal ve Yöntem: Muğla ve Togo olmak üzere iki susam çeşidi, farklı genlikler (%50-100) ve işlem süreleri (5-15 dk) altında ultrason destekli kabuk soyma işlemine tabi tutulmuştur**.** Susam örneklerinde ICP-MS yöntemi ile toplamda 20 farklı mineralin analizi gerçekleştirilmiştir.

Araştırma Bulguları: Geleneksel yöntemle karşılaştırıldığında, ultrason yöntemi Muğla susamında ayrılan kabuk oranını yaklaşık %76'ya, Togo susamında ise %83'e yükseltmiştir**.** Ultrason uygulama süresi ve genliğinin artması, susam tohumlarının ağır metal içeriğinde azalmaya yol açmış; magnezyum, fosfor, potasyum, kalsiyum, bakır, çinko, selenyum, alüminyum ve krom düzeylerinde artışa, demir, kalay, manganez, bor ve nikel düzeylerinde ise azalmaya neden olmuştur.

Sonuç: Ultrason yönteminin susam kabuğu soyma işlemindeki yüksek verimliliğinin yanı sıra, mevzuatta sınır değeri bulunan ağır metaller ve demir (Fe) içeriğinde sağladığı azalma nedeniyle, geleneksel yönteme kıyasla uygulanabilir bir alternatif yöntem olduğu değerlendirilmektedir.

INTRODUCTION

Sesame (*Sesamum indicum* L.) is recognized as one of the most important oilseeds crops worldwide. Approximately 20,000 sesame germplasms are archived across various regions, particularly in India, Korea, China, and several African countries (Zhang et al., 2019; Yılmaz, 2022). *Sesamum indicum* is the most widely cultivated species and is an annual plant that thrives in hot and dry climates, mainly grown for its oil- and protein-rich seeds (Singh et al., 2016). Sesame seeds are considered a nutrient-dense food source due to their rich content of bioactive compounds, vitamins, and minerals. Sesame oil is particularly valuable owing to its stability, color, distinctive flavor, and resistance to oxidative deterioration.

Approximately 20% of the sesame seed consists of the hull, and dehulled seeds contain a higher proportion of oil. The mineral content of sesame seeds is predominantly concentrated in the hull. Although minerals such as potassium, zinc, copper, and magnesium contribute positively to human health, undesirable and toxic minerals such as arsenic and lead may also be present (Makinde & Akinoso, 2013). Sesame seeds also contain phytic acid, an antinutritional factor that forms complexes with proteins, reducing their bioavailability. The hull contains higher levels of such antinutritional compounds (Bedigian, 2010; Makinde & Akinoso, 2013).

Sesame seeds are the primary raw material for several food products including sesame oil, tahini, and halva. Tahini is produced by grinding cleaned, dehulled, and roasted sesame seeds (Kahyaoğlu & Kaya, 2006). Dehulling is a crucial preliminary step in producing a non-bitter, light-colored product with lower fiber and higher protein content. During this process, the hull containing 2-5% oxalic acid, which may impart bitterness, is removed, resulting in a whiter and brighter final product. Dehulling also contributes to increased protein content, decreased fiber content, and improved functional properties of tahini (Tanrıverdi, 2017).

Dehulling is the most time-consuming stage in tahini production. Traditionally, the seeds are sieved, soaked for 12 hours, rested, passed through a mechanical dehuller, and then kept for an additional 5-6 hours in saltwater containing 15-18% NaCl to facilitate hull separation. Since the final product must not contain salt, extensive washing is required to remove salt residues (Kahyaoğlu & Kaya, 2006; Tanrıverdi, 2017). Although some studies have explored the use of chemical solutions (Carbonell-Barrachina et al., 2009), and enzymatic or thermal procedures (Tanrıverdi, 2017), no research has evaluated the use of ultrasound technology for dehulling, despite dehulling being one of the most critical stages in tahini production. Recent studies reviewing dehulling technologies for oilseeds have also highlighted the potential of emerging techniques such as ultrasonic dehulling. Chang et al. (2024) reported that conventional mechanical dehulling methods often show limited efficiency and may lead to considerable seed loss, whereas novel technologies including ultrasound-assisted dehulling are considered promising alternatives for improving dehulling efficiency and product quality in oilseeds and kernels.

Ultrasound refers to sound waves with frequencies above human hearing, typically between 10 MHz and 20 kHz (Baysal & Demirdöven, 2012). Ultrasound applications in food processing, analysis, and quality control are classified into low-energy (<1 W·cm² at ~100 kHz) and high-energy (>1 W·cm² at 20-500 kHz) systems. High-frequency ultrasound induces cavitation, generating mechanical, physical, and biochemical effects that enhance various food processes including microbial inactivation, extraction, freezing, drying, and emulsification (Awad et al., 2012). Ultrasound technology is relatively inexpensive, simple to use, and energy efficient. Its application for extraction has become increasingly widespread, as the cavitation effect improves solvent penetration into solid food matrices (Schössler et al., 2012).

ICP-MS (Inductively Coupled Plasma Mass Spectrometry) is a highly sensitive analytical technique capable of performing rapid, qualitative, and quantitative analysis of multiple minerals at ultra-trace levels. While mineral analysis is important for assessing both toxic and essential minerals in foods and water

(Thomas, 2013), most studies on sesame and its derived products have reported mineral profiles based on only 6-12 elements (Beshaw et al., 2022; Mi et al., 2022; Hika et al., 2023; Özcan et al., 2023). To date, no published study has analyzed a set of 20 minerals in sesame using ICP-MS, which is considered the most sensitive analytical method in this field. In this study, ultrasound, an innovative processing method in food technology, was applied for the purpose of dehulling sesame seeds, and the effect of ultrasound-assisted dehulling on the mineral composition of sesame seeds was investigated.

MATERIALS and METHODS

Materials

The local sesame variety (Muğla sesame) used in the study was purchased from a retail market in Muğla, Türkiye, whereas the imported sesame variety (Togo sesame) was supplied by TUNAS Gıda Pazarlama ve Tic. Ltd. Şti. (Gaziantep, Türkiye). Prior to the selection of experimental materials, sesame seeds from various regions of Türkiye as well as imports from different origins were collected and analyzed for their mineral composition. Muğla and Togo sesame varieties, which exhibited the highest mineral contents among all tested samples, were chosen for further analysis.

Dehulling of sesame seeds

Traditional dehulling method

Five grams of sesame seeds were weighed and initially soaked in 50 mL of distilled water for 8 hours. The seeds were then transferred into 50 mL of a 10% NaCl solution and kept at 40°C for 1 hour. After soaking, the seeds were rinsed with 150 mL of distilled water and spread on filter paper to dry at room temperature for 12 hours. Dehulling was performed by placing the dried seeds between two filter papers and rubbing them back and forth ten times. The weights of the dehulled seeds were measured, and the proportion of removed hulls (%) was calculated using Equation 1 (Tanrıverdi, 2017). All analyses were conducted in triplicate, and mean values were reported.

$$\text{Separated seed coat ratio (\%)} = \frac{m_1 - m_2}{m_3} \times 100 \quad (1)$$

m_1: seed weight after drying (g)

m_2: seed weight after dehulling and drying (g)

m_3: initial seed weight (g)

Ultrasound-assisted dehulling

Preliminary experiments were conducted to determine suitable ultrasound parameters. The ultrasound system used was a Bandelin Sonoplus HD 2200.2 (Berlin, Germany) with a 130 mm probe length and 13 mm probe diameter. The system operates at 200 W power and a 20 kHz process frequency, with a total operating volume of 1000 mL. Two amplitude levels (50% and 100%) and three treatment durations (5, 10, and 15 min) were tested. For each experiment, 5 g of sesame seeds were mixed with a 10% NaCl solution in a glass beaker and subjected to ultrasound treatment under the specified conditions. After treatment, the contents were filtered, rinsed with 150 mL of distilled water, and dried at room temperature for 12 hours. Dried samples were dehulled by rubbing between two filter papers ten times. Separated hulls were weighed, and the separated hull ratio (%) was calculated using Equation 1, as described in the traditional method.

Mineral analysis by ICP-MS

Mineral analysis was carried out using an ICP-MS system (Agilent Technologies, Santa Clara, CA, USA), whose operating conditions were given in Table 1. For sample digestion, Suprapur® grade HNO_3 (65%, Merck, Darmstadt, Germany) and H_2O_2 (30%, Merck, Darmstadt, Germany) were used. High-purity argon gas (99.99%) was employed as the plasma and carrier gas. Approximately 0.2 g of sesame sample was weighed into Teflon digestion vessels, followed by the addition of 9 mL HNO_3 and 1 mL H_2O_2. Vessels were loaded into microwave digestion system (Milestone Ethos One, Sorisole, Italy). Samples were heated to 180°C, held at this temperature for 10 minutes, and subsequently cooled to room temperature. Digested samples were transferred into 50 mL volumetric tubes and diluted to final volume with distilled water. Samples were analyzed by ICP-MS for 20 minerals, including macro-minerals, micro-minerals, and heavy metals. Calibration ranges (ppm) were as follows: Na, Mg, P, K, Ca: 0-10-20-50-100-200; Cu, Fe, Sn, Mn, Zn, Se, Al, B, Cr, Ni: 0-0.005-0.010-0.020-0.050-0.100; As, Pb, Cd, Hg, Sb: 0-0.002-0.005-0.010-0.020-0.050.

Table 1. ICP-MS operating conditions
Çizelge 1. *ICP-MS çalışma şartları*

Parameter	Value
Instrument power (W)	1550
Argon gas pressure (kPa)	650-750
Plasma gas flow rate (L/min)	15
Carrier gas flow rate (L/min)	1
Dilution gas flow rate (L/min)	1
Helium gas flow rate (L/min)	5
Nebulizer chamber temperature (°C)	2

Statistical analysis

All experimental data were analyzed using IBM SPSS v20 (IBM Corp., Armonk, NY, USA). Two-way analysis of variance (ANOVA) was applied to evaluate the effects of independent variables and their interactions on the measured parameters. Where significant variation sources were identified, mean comparisons were performed using Tukey's multiple comparison test at a significance level of $p<0.05$.

RESULTS and DISCUSSIONS

Dehulling of sesame seeds using the ultrasound method

The hull removal percentage values obtained from the sesame samples analyzed in this study are presented in Table 2. In samples subjected to the traditional dehulling method, the separated hull ratio was 9.50% for Muğla sesame and 9.30% for Togo sesame. In samples treated with ultrasound, the amount of separated hull ranged between 9.85-16.70% for Muğla sesame and 9.45-17.05% for Togo sesame. Significant differences were detected among ultrasound treatments based on variations in duration and amplitude ($p<0.05$). The ultrasound method proved more effective in separating the hull from sesame seeds, achieving nearly 90% higher removal efficiency compared to the traditional method. Consistent with the results obtained in this study, Tanrıverdi (2017) reported a hull removal percentage of 9.60% following traditional dehulling applied to Ethiopian sesame seeds. In the same study, sesame seeds exposed to boiling water, steam treatment, freezing at −18°C, and enzyme-assisted methods with different concentrations of *Viscozyme L* exhibited substantially increased hull removal percentages, ranging from 11.23% to 14.08%. In the present study, the highest hull removal was achieved at 100% amplitude for 15 minutes (16.70-17.05%), exceeding the values reported by Tanrıverdi (2017). Previous studies have similarly shown that ultrasound reduces soaking time and facilitates hull separation in cereals and legumes, thereby improving dehulling efficiency (Sunil et al., 2018; Yıldız, 2019). Sunil et al. (2018) reported that cavitation produced during ultrasound treatment denatures the proteins and gums located between the hull and cotyledon, weakening their structure and reducing the required force for hull removal. In their study, applying

ultrasound to black gram at power levels between 343-525 W for 1-3.5 hours increased dehulling efficiency by approximately 20%. Similar findings have also been reported for other oilseeds and grains subjected to ultrasound-assisted dehulling. Bai et al. (2026) demonstrated that ultrasound application significantly improved dehulling efficiency in quinoa compared with conventional dehulling methods. The authors reported that acoustic cavitation generated during ultrasound treatment weakens the structural bonds between the seed coat and the cotyledon, thereby facilitating hull separation and improving process efficiency. Chang et al. (2024) emphasized that emerging technologies such as ultrasonic dehulling offer a promising alternative to conventional mechanical methods due to their potential to improve dehulling efficiency and reduce processing losses. The increased hull removal observed in the present study supports these findings and suggests that ultrasound may be an effective approach for improving dehulling performance in sesame seeds. These findings support the results obtained in the present study, where ultrasound treatment substantially increased the hull removal ratio of sesame seeds compared with the traditional method. The similarity between these results suggests that ultrasound-assisted dehulling may represent a promising alternative processing approach for different seeds and kernels.

Table 2. Separated seed coat ratio (%) of traditional and ultrasound processed sesame seed

Çizelge 2. *Geleneksel ve ultrases yöntemi ile işlenmiş susam tohumunda uzaklaşan kabuk oranı (%)*

Method	Parameter (% amplitude-min)	Muğla Sesame	Togo Sesame
Traditional	-	9.50±0.04 ^{f}	9.30±0.04 ^{f}
Ultrasound	50-5	9.85±0.04 ^{f}	9.45±0.05 ^{f}
	50-10	10.95±0.04 ^{e}	10.50±0.01 ^{e}
	50-15	12.45±0.04 ^{d}	11.65±0.11 ^{d}
	100-5	13.30±0.21 ^{c}	12.85±0.14 ^{c}
	100-10	15.90±0.00 ^{b}	?±0.00
	100-15	16.70±0.14 ^{a}	17.05±0.20 ^{b}

Values are expressed as mean±SD. Different lowercase letters within the same column indicate a statistically significant difference among the values within the same column.

Mineral composition of sesame processed by the ultrasound method

The micro-mineral contents of Muğla and Togo sesame seeds are presented in Tables 3 and 4, while the macro-mineral and heavy metal contents are shown in Tables 5 and 6, respectively. Ultrasound treatments were pooled and evaluated as a single processing group in order to compare the overall effect of ultrasound processing against the traditional method. When ultrasound treatments were pooled and compared with the traditional method in Muğla sesame samples, significant differences were observed for most minerals (p<0.05). Ultrasound processing resulted in increased Zn, Se, Al and Cr levels, whereas Fe, Mn, Sn, B and Ni concentrations were significantly higher in traditionally processed samples. No significant difference was detected for Cu (p>0.05). When ultrasound treatments were pooled and compared with the traditional method in Togo sesame, significant differences were observed for Cu, Sn, Mn, Se, B, and Ni (p<0.05), whereas Fe, Zn, Al, and Cr showed no statistically significant differences (p≥ 0.05). As shown in Table 5, ultrasound processing significantly affected (p<0.05) Na, Mg, P, and K contents in Togo and Muğla sesame, whereas Ca remained statistically unchanged compared with conventionally processed samples. Ultrasound processing significantly reduced As, Pb, Cd and Sb contents compared to the traditional method (p<0.05) in Muğla sesame, while Hg remained unchanged (Table 6). In Togo sesame, ultrasound processing significantly reduced As and Pb levels (p<0.05), whereas Cd and Sb were not significantly affected. The differential response observed between Muğla and Togo sesame samples may suggest that ultrasound effectiveness is not solely governed by processing parameters but is also matrix-dependent. Variations in soil composition, mineral binding forms, and intrinsic matrix characteristics may influence mineral release dynamics under cavitation conditions. Geographic origin is known to influence the elemental profile of sesame seeds, and the efficacy of ultrasonication has been reported to depend on food matrix characteristics, including mineral-binding constituents such as phytate and related complexes (Mi et al., 2022).

Table 3. Micro-mineral (Cu, Fe, Sn, Mn,Zn) content of sesame seed processed using traditional and ultrasound processes (mg/kg)
Çizelge 3. *Geleneksel ve ultrases yöntemi ile işlenmiş susam tohumunda mikro-mineral (Cu, Fe, Sn, Mn, Zn) içeriği (mg/kg)*

Sesame source	Parameter (% amplitude-min)	Cu	Fe	Sn	Mn	Zn
Muğla Sesame						
Raw sesame	-	58.876	227.591	0.062	75.938	171.022
Traditional method	-	61.774±1.853 ^{b}	195.567±5.867 ^{a}	0.040±0.001 ^{a}	73.888±2.217 ^{a}	177.165±5.315 ^{d}
Ultrasound method	50-5	62.732±0.022 ^{a}	192.159±0.022 ^{a}	0.032±0.000 ^{b}	70.216±0.011 ^{a}	181.195±0.067 ^{d}
	50-10	60.752±0.037 ^{b}	195.342±0.030 ^{a}	0.022±0.000 ^{d}	73.149±0.035 ^{a}	192.575±0.053 ^{c}
	50-15	65.198±0.069 ^{a}	188.772±0.051 ^{a}	0.025±0.000 ^{c}	65.776±0.053 ^{b}	182.546±0.033 ^{c}
	100-5	61.772±0.051 ^{b}	170.165±0.046 ^{b}	0.011±0.001 ^{e}	55.311±0.008 ^{c}	215.480±0.056 ^{b}
	100-10	63.160±0.042 ^{a}	165.179±0.056 ^{b}	0.012±0.000 ^{e}	51.162±0.044 ^{c}	227.589±0.063 ^{a}
	100-15	65.414±0.010 ^{a}	162.100±0.001 ^{b}	0.003±0.000 ^{f}	49.88±0.057 ^{d}	231.455±0.039 ^{a}
Togo Sesame						
Raw sesame	-	13.997	135.718	0.021	23.434	39.330
Traditional method	-	14.998±0.750 ^{d}	105.772±5.289 ^{a}	0.020±0.001 ^{a}	21.181±1.059 ^{a}	42.780±2.139 ^{b}
Ultrasound method	50-5	15.771±0.001 ^{d}	101.232±0.008 ^{a}	0.021±0.000 ^{a}	20.172±0.051 ^{a}	41.232±0.022 ^{b}
	50-10	17.414±0.002 ^{c}	105.547±0.005 ^{a}	0.019±0.000 ^{a}	21.250±0.035 ^{a}	40.290±0.063 ^{b}
	50-15	17.210±0.007 ^{c}	111.197±0.005 ^{a}	0.018±0.000 ^{b}	20.599±0.063 ^{a}	42.159±0.028 ^{b}
	100-5	19.168±0.005 ^{b}	108.777±0.054 ^{a}	0.010±0.000 ^{c}	18.172±0.051 ^{b}	45.559±0.042 ^{a}
	100-10	19.775±0.004 ^{b}	105.492±0.348 ^{a}	0.011±0.000 ^{c}	15.112±0.002 ^{c}	47.854±0.038 ^{a}
	100-15	22.118±0.013 ^{a}	94.776±0.053 ^{b}	0.010±0.000 ^{c}	14.580±0.056 ^{c}	49.176±0.024 ^{a}

Values are expressed as mean±SD. Different lowercase letters within the same column indicate a statistically significant difference among the values within the same column.

Table 4. Micro-mineral (Se, Al, B, Cr, Ni) content of sesame seed processed using traditional and ultrasound processes (mg/kg)
Çizelge 4. *Geleneksel ve ultrases yöntemi ile işlenmiş susam tohumunda mikro-mineral (Se, Al, B, Cr, Ni) içeriği (mg/kg)*

Sesame source	Parameter (% amplitude-min)	Se	Al	B	Cr	Ni
Muğla Sesame						
Raw sesame	-	0.574	20.053	21.171	0.090	165.928
Traditional method	-	0.612±0.018 ^{c}	20.172±0.605 ^{e}	17.132±0.514 ^{b}	0.112±0.003 ^{e}	45.894±1.377 ^{b}
Ultrasound method	50-5	0.590±0.007 ^{c}	21.744±0.031 ^{d}	18.554±0.038 ^{a}	0.128±0.006 ^{d}	55.118±0.002 ^{a}
	50-10	0.555±0.003 ^{d}	27.143±0.031 ^{a}	11.060±0.042 ^{d}	0.158±0.006 ^{c}	41.232±0.013 ^{c}
	50-15	0.598±0.005 ^{c}	23.457±0.005 ^{c}	15.479±0.339 ^{c}	0.138±0.001 ^{d}	45.877±0.054 ^{b}
	100-5	0.775±0.003 ^{b}	25.142±0.030 ^{b}	9.772±0.546 ^{e}	0.153±0.001 ^{c}	32.112±0.027 ^{d}
	100-10	0.815±0.004 ^{a}	24.131±0.022 ^{b}	7.137±0.097 ^{f}	0.189±0.000 ^{b}	15.799±0.007 ^{f}
	100-15	0.838±0.005 ^{a}	22.366±0.259 ^{d}	5.112±0.006 ^{g}	0.21±0.004 ^{a}	21.382±0.022 ^{e}
Togo Sesame						
Raw sesame	-	0.008	109.985	9.020	0.418	201.413
Traditional method	-	2.059±0.103 ^{c}	141.580±7.079 ^{b}	16.535±0.827 ^{b}	2.938±0.147 ^{c}	2.212±0.111 ^{a}
Ultrasound method	50-5	2.110±0.007 ^{c}	140.316±0.01^{1} ^{b}	19.885±0.060 ^{a}	2.779±0.007 ^{c}	1.905±0.004 ^{b}
	50-10	2.198±0.005 ^{c}	137.954±0.038 ^{b}	13.456±0.039 ^{c}	2.816±0.004 ^{c}	1.459±0.001 ^{c}
	50-15	2.356±0.004 ^{b}	152.118±0.083 ^{a}	13.800±0.070 ^{c}	2.805±0.004 ^{c}	1.447±0.001 ^{c}
	100-5	2.568±0.048 ^{b}	155.652±0.461 ^{a}	11.089±0.006 ^{d}	3.552±0.036 ^{a}	1.332±0.001 ^{c}
	100-10	2.894±0.067 ^{a}	151.741±0.029 ^{a}	8.948±0.034 ^{e}	3.628±0.005 ^{a}	1.200±0.003 ^{d}
	100-15	2.995±0.004 ^{a}	150.180±0.056 ^{a}	6.188±0.062 ^{f}	3.212±0.001 ^{b}	1.005±0.003 ^{d}

Values are expressed as mean±SD. Different lowercase letters within the same column indicate a statistically significant difference among the values within the same column.

When the mineral compositions of traditionally dehulled seeds were compared with raw sesame seeds, reductions were observed in Fe, Sn, B, Ni, K, Mg, P, and Ca, whereas slight increases were detected in Cu, Zn, Se, Al, and Cr. Comparable results were previously reported by Tanrıverdi (2017), who found reductions in Mg, P, Ca, Fe, Mn, Al, and Cr after dehulling, while Cu and Zn contents increased. Makinde & Akinoso (2013) similarly reported decreases in Ca, P, K, Mg, Fe, Se, Zn, and Mn in white and black sesame following traditional dehulling. Examination of the effects of dehulling on heavy metal contents indicated notable reductions in all heavy metals (As, Pb, Cd, Hg, Sb). In contrast, Hao et al. (2011) found that sesame seeds exhibited the highest levels of metal contamination, reporting Pb and Cd concentrations of 0.104 mg/kg and 0.377 mg/kg, substantially higher than the values measured in this study (Muğla: Pb 0.049, Cd 0.004 mg/kg; Togo: Pb 0.085, Cd 0.005 mg/kg). The observed decreases in certain minerals after dehulling can be attributed to the fact that many minerals accumulate predominantly in the hull and are therefore removed during processing (Tanrıverdi, 2017). In the present study, reductions in Ca and Ni were particularly notable, consistent with previous findings indicating that Ca is primarily concentrated in the hull (El-Adawy & Mansour, 2000; Elleuch et al., 2007).

Table 5. Macro- mineral (Na, Mg, P, K, Ca) content of sesame seed processed using traditional and ultrasound processes (mg/kg)
Çizelge 5. *Geleneksel ve ultrases yöntemi ile işlenmiş susam numunelerinin makro-mineral (Na, Mg, P, K, Ca) içeriği (mg/kg)*

Sesame source	Parameter (% amplitude-min)	Na	Mg	P	K	Ca
			Muğla Sesame			
Raw sesame	-	1.484	3866.215	7343.443	5090.970	7427.142
Traditional method	-	3.897±0.19 ^{a}	3779.187±8.96 ^{b}	7119.856±5.99 ^{b}	4877.167±43.86 ^{b}	1877.187±13.86 ^{b}
Ultrasound method	50-5	1.786±0.03 ^{c}	4026.185±4.95 ^{b}	7465.123±3.54 ^{b}	5156.842±41.24 ^{b}	2689.651±6.36 ^{a}
	50-10	1.459±0.02 ^{d}	4104.957±4.24 ^{a}	7456.284±4.24 ^{b}	5100.148±6.36 ^{b}	2598.754±3.54 ^{a}
	50-15	1.550±0.04 ^{d}	4200.776±10.61 ^{a}	7356.854±4.24 ^{b}	5223.496±20.12 ^{b}	2605.175±3.74 ^{a}
	100-5	1.958±0.01 ^{c}	4315.994±10.61 ^{a}	8501.32±6.36 ^{a}	6022.568±15.83 ^{a}	1321.176±7.78 ^{c}
	100-10	2.38±0.10 ^{b}	4411.249±7.78 ^{a}	8801.276±7.07 ^{a}	6135.478±10.54 ^{a}	1056.198±4.24 ^{d}
	100-15	2.551±0.03 ^{b}	4422.158±5.66 ^{a}	8900.215±10.61 ^{a}	6304.174±2.83 ^{a}	1030.175±3.54 ^{d}
			Togo Sesame			
Raw sesame	-	18.389	2077.545	3060.075	3529.337	8504.798
Traditional method	-	33.56±1.68 ^{a}	1865.397±9.27 ^{d}	2876.196±4.81 ^{c}	3412.567±7.63 ^{b}	2301.419±15.07 ^{b}
Ultrasound method	50-5	19.77±0.05 ^{c}	2110.124±7.07 ^{c}	3091.544±2.71 ^{c}	3622.115±5.66 ^{b}	3324.684±4.48 ^{a}
	50-10	20.01±0.01 ^{c}	2111.190±0.13 ^{c}	3105.658±4.47 ^{c}	3555.417±3.54 ^{b}	3215.944±6.70 ^{a}
	50-15	19.77±0.50 ^{c}	2196.486±4.50 ^{c}	3102.436±0.71 ^{c}	3538.987±3.54 ^{b}	3158.814±5.80 ^{a}
	100-5	21.52±0.37 ^{b}	2405.287±0.20 ^{b}	4425.843±7.07 ^{b}	3856.717±2.83 ^{a}	2205.174±8.30 ^{b}
	100-10	23.55±0.39 ^{b}	2456.380±2.12 ^{b}	4652.149±4.95 ^{b}	3901.235±6.91 ^{a}	2104.937±1.45 ^{b}
	100-15	24.02±0.02 ^{b}	2658.180±0.58 ^{a}	5778.214±6.36 ^{a}	4011.149±3.43 ^{a}	1987.457±8.49 ^{c}

Values are expressed as mean±SD. Different lowercase letters within the same column indicate a statistically significant difference among the values within the same column.

Two-way ANOVA demonstrated that power level, processing time, and their interaction significantly influenced (p<0.05) all micro- and macro-minerals and heavy metal concentrations (Table 3-6). Increases in amplitude and duration of ultrasound treatment influenced the mineral composition in both sesame varieties. Heavy metal content decreased markedly, particularly at 100% amplitude (Figures 1 & 2).

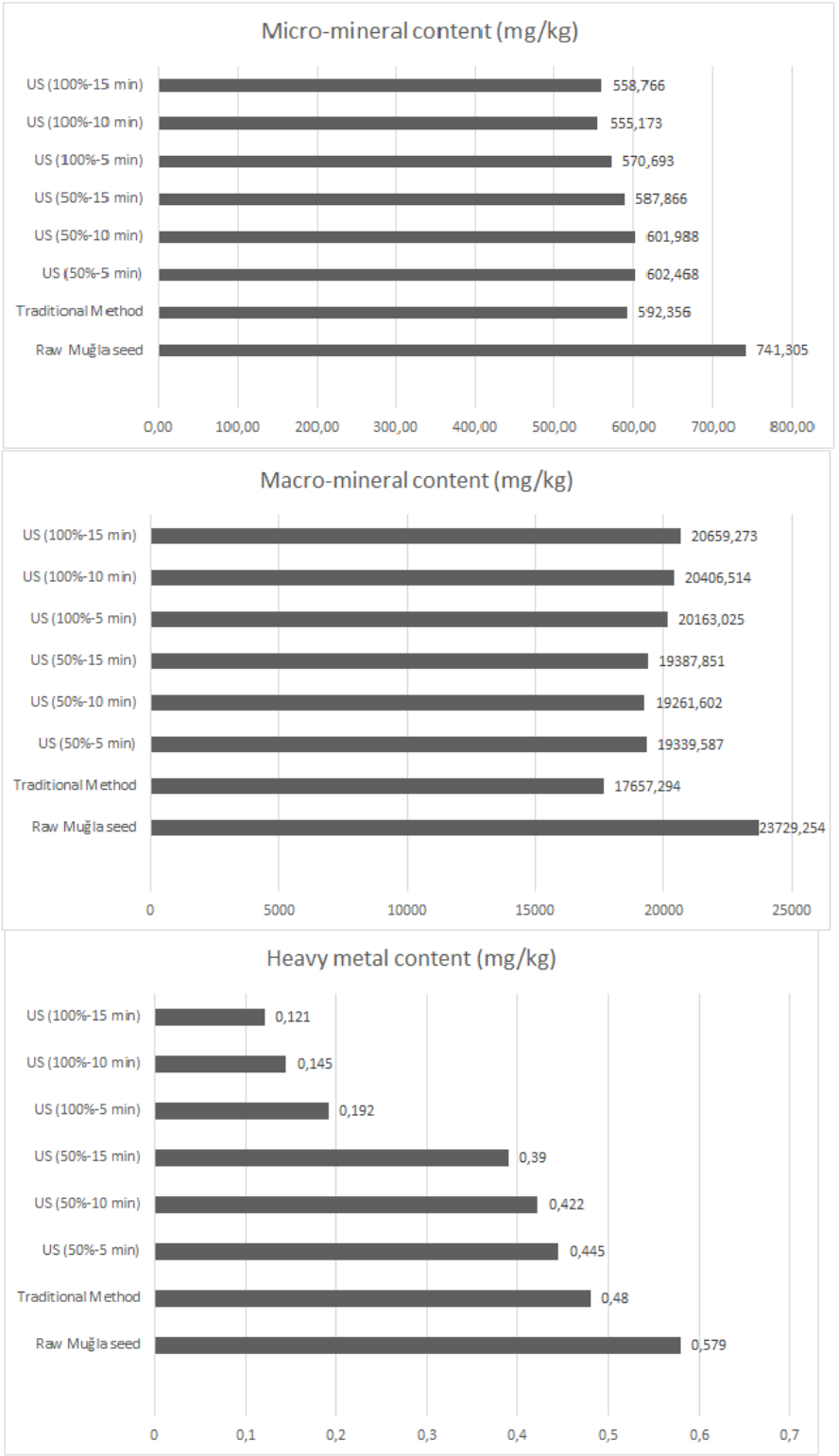


Figure 1. Effects of traditional and ultrasound method peeling processes on mineral contents of Muğla sesame seeds (US: ultrasound method, graphs are drawn on total mineral content).

Şekil 1. *Muğla susam tohumuna uygulanan geleneksel ve ultrases yöntem ile kabuk soyma işlemlerinin susamın mineral içeriği üzerine etkisi (US: ultrases yöntemi, grafikler toplam mineral içeriği üzerinden çizilmiştir).*

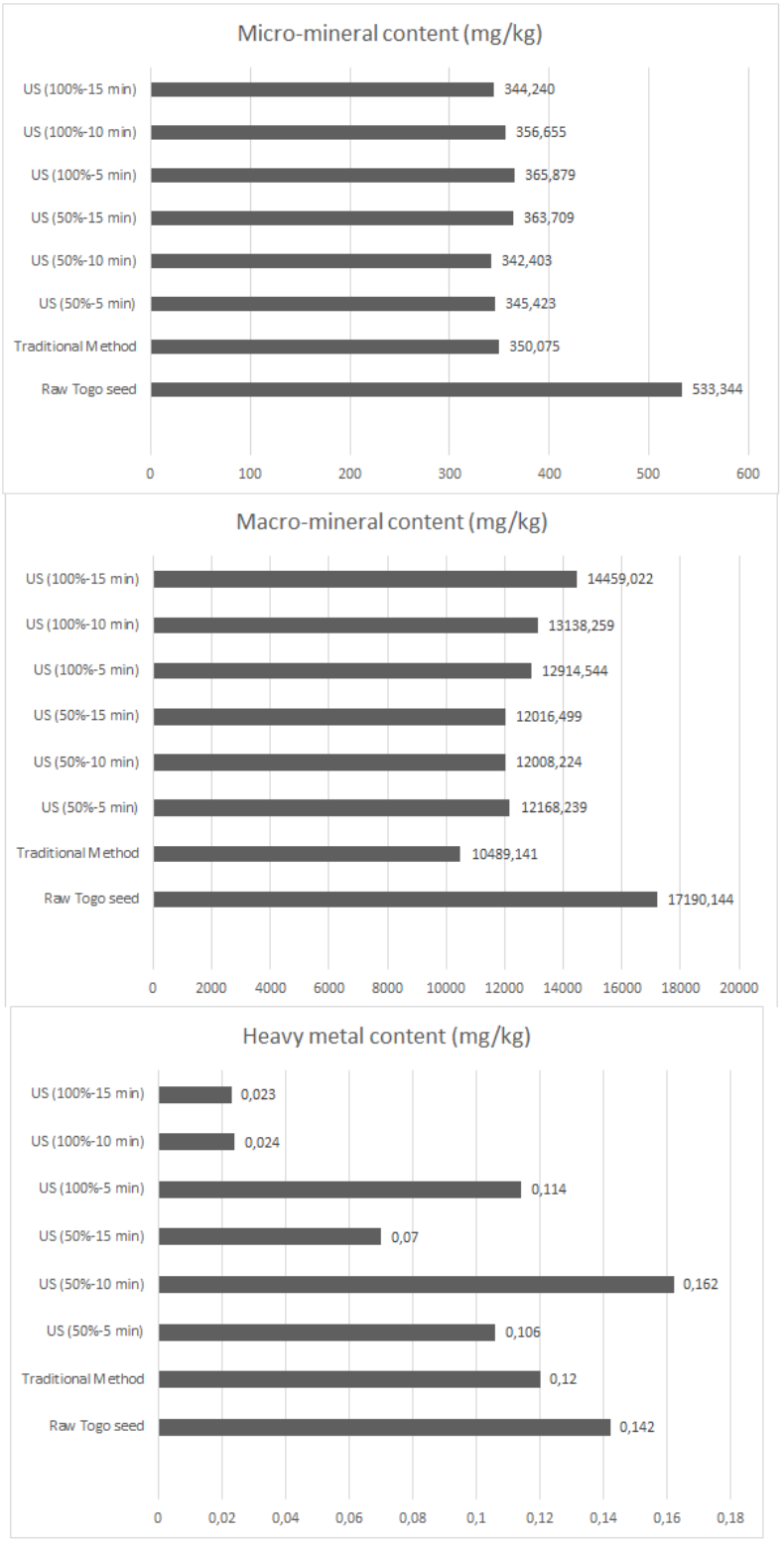


Figure 2. Effects of traditional and ultrasound method peeling processes applied to Togo sesame seed A: micro-mineral, B: macro-mineral and C: heavy metal contents (US: ultrasound method, graphs are plotted on total mineral content).

Şekil 2. *Togo susam tohumuna uygulanan geleneksel ve ultrases yöntem ile kabuk soyma işlemlerinin susamın A: mikro-mineral, B: makro-mineral ve C: ağır metal içeriğine etkisi (US: ultrases yöntemi, grafikler toplam mineral içeriği üzerinden çizilmiştir).*

Examination of treatment-dependent mineral changes revealed that Cu, Zn, Se, Al, Cr, Mg, P, K, and Ca increased proportionally with ultrasound duration and amplitude, while Fe, Sn, Mn, B, Ni, Na, As, Pb, Cd, and Sb decreased. Özcan et al. (2023) found decreases in Ca, K, Mg, P, B, Cu, Fe, Mn, and Ni, and increases in Na, Cr, and Zn following traditional dehulling. The current study supports these findings for Ca, B, Cr, Fe, Mn, Ni, and Zn but differs in terms of K, Mg, Na, P, and Cu. Tanrıverdi (2017) reported micro-mineral contents in sesame seeds under several dehulling conditions: traditional, hot-water treated, steam-treated, and frozen at −18°C. For Mn, Fe, and Ni, untreated seeds had higher values, whereas other treatments produced similar trends to those observed in the current study. Additionally, Hounkonnou (2019) demonstrated that ultrasound treatments at amplitudes of 30-100% and durations of 5-20 minutes increased lignan extraction efficiency (6.82-14.04%), suggesting that increased amplitude and exposure time enhance extraction. It can thus be inferred that the higher hull removal percentage observed in the current study, together with increased extraction efficiency, contributed to reductions in certain mineral contents due to more effective hull separation.

Table 6. Heavy metal content of sesame seed processed using traditional and ultrasound processes (mg/kg) (ND: not detected)
Çizelge 6. *Geleneksel ve ultrases yöntemi ile işlenmiş susam numunelerinin ağır metal içeriği (mg/kg) (TE: Tespit edilememiştir)*

Sesame source	Parameter (% amplitude-min)	As	Pb	Cd	Hg	Sb
Muğla Sesame						
Raw sesame	-	0.460	0.049	0.004	0.059	0.007
Traditional method	-	0.021±0.042 ^{a}	0.040±0.004 ^{a}	0.010±0.001 ^{a}	TE	0.009±0.001 ^{a}
Ultrasound method	50-5	0.400±0.007 ^{a}	0.033±0.000 ^{b}	0.007±0.000 ^{b}	TE	0.005±0.000 ^{b}
	50-10	0.372±0.001 ^{a}	0.040±0.001 ^{a}	0.003±0.000 ^{c}	TE	0.007±0.000 ^{b}
	50-15	0.352±0.001 ^{a}	0.028±0.000 ^{b}	0.006±0.000 ^{b}	TE	0.004±0.000 ^{c}
	100-5	0.177±0.005 ^{b}	0.012±0.000 ^{c}	0.001±0.000 ^{c}	TE	0.002±0.000 ^{d}
	100-10	0.135±0.003 ^{b}	0.008±0.000 ^{c}	0.001±0.000 ^{c}	TE	0.001±0.000 ^{d}
	100-15	0.111±0.001 ^{b}	0.008±0.000 ^{c}	0.001±0.000 ^{c}	TE	0.001±0.000 ^{d}
Togo Sesame						
Raw sesame	-	0.025	0.085	0.005	0.007	0.020
Traditional method	-	0.016±0.001 ^{a}	0.091±0.005 ^{a}	0.004±0.000 ^{b}	TE	0.009±0.000 ^{c}
Ultrasound method	50-5	0.013±0.000 ^{b}	0.081±0.001 ^{b}	0.004±0.000 ^{b}	TE	0.008±0.000 ^{c}
	50-10	0.010±0.001 ^{c}	0.091±0.001 ^{a}	0.005±0.000 ^{b}	TE	0.056±0.000 ^{a}
	50-15	0.011±0.000 ^{b}	0.046±0.004 ^{c}	0.007±0.000 ^{a}	TE	0.006±0.001 ^{d}
	100-5	0.010±0.001 ^{c}	0.054±0.003 ^{c}	0.002±0.000 ^{d}	TE	0.048±0.000 ^{b}
	100-10	0.005±0.000 ^{e}	0.013±0.001 ^{d}	0.003±0.000 ^{c}	TE	0.003±0.000 ^{e}
	100-15	0.008±0.000 ^{d}	0.011±0.001 ^{d}	0.001±0.000 ^{d}	TE	0.003±0.000 ^{e}

Values are expressed as mean±SD. Different lowercase letters within the same column indicate a statistically significant difference among the values within the same column.

CONCLUSIONS

In this study, the potential of ultrasound, an innovative technology in the food industry, as an alternative to the traditional dehulling method used in the initial stages of tahini and halva production was investigated. The results showed that ultrasound treatment increased the separated seed coat ratio of sesame seeds by approximately 76-83% compared with the traditional method, which requires a 12 hour soaking process. The increase in ultrasound duration and amplitude further enhanced the amount of hull removed from the sesame seeds. Evaluation of the effects of ultrasound on macro-mineral and heavy metal contents revealed that both treatment duration and amplitude had significant impacts. Increasing ultrasound intensity resulted in a reduction of heavy metals with toxic effects, such as As, Pb, Cd, Hg, and Sb, while increasing the levels of beneficial minerals including Mg, P, K, Ca, Cu, Zn, Se, Al, and Cr. Decreases were observed in Fe, Sn, Mn, B, and Ni contents.

These findings indicate that ultrasound is not only highly effective in improving dehulling efficiency but also advantageous in reducing the concentrations of minerals that are regulated due to their toxicological significance, such as heavy metals and Fe. Overall, ultrasound-assisted dehulling appears to be a promising alternative to traditional methods. Its ability to shorten processing time and enhance hull removal efficiency suggests that it may reduce water usage and processing costs during the dehulling stage of tahini production.

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Data Availability

The data supporting the findings of this study are available from the authors upon reasonable request.

Author Contributions

Concept and design of the study: SY, ÖFK; sample collection: SY, ÖFK; data analysis: ÖFK; interpretation of results: SY, ÖFK; statistical analysis: ÖFK; visualization: SY, ÖFK; manuscript writing: SY, ÖFK.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this study.

Ethical Statement

This study did not involve a research plan requiring approval from an ethics committee.

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