Sustainable Extraction of Nutrients from Local Sesame Seed Varieties: Effect of DES Combinations on Fatty Acid and Mineral Extraction

Syed Muhammad Usama[1], Syed Najam Mustafa[2], Muhammad Ikram Nabeel[3,4,5], Muhammad Javid Iqbal[1]*, Ali Raza[5,6], Collin G. Joseph[3,4]* and Asma Nisar[7]
[1]Department of Chemistry, COMSATS University Islamabad Lahore Campus, Pakistan
[2]Department of Chemistry, Aspire Group of Colleges, Sohawa Campus, Pakistan
[3]Sonophotochemistry Research Group, Faculty of Science and Technology, Universiti Malaysia Sabah, 88400 Kota Kinabalu, Sabah, Malaysia
[4]Industrial Chemistry Programme, Faculty of Science and Technology, Universiti Malaysia Sabah, 88400 Kota Kinabalu, Sabah, Malaysia
[5]HEJ Research Institute of Chemistry, International Center for Chemical and Biological Sciences, University of Karachi, Karachi-75270, Pakistan
[6]Department of Chemistry, University of Alabama in Huntsville, United States of America.
[7]Department of Pharmacy, The University of Lahore, Lahore, Punjab, Pakistan
*Corresponding author: (e-mail: javidiqbal@cuilahore.edu.pk; collin@ums.edu.my)

The growing global population demands an increase in superior food sources to meet essential nutritional requirements. Acknowledging the importance of nutrient-rich foods, there is greater attention on plant-based sources, particularly oil seeds, such as sesame seeds, which have an abundance of proteins, minerals, and fatty acids. This study presents a green and application-oriented approach to increase the extraction efficiency of fatty acids and minerals from Pakistani sesame seed (*Sesamum indicum L.*) varieties (black and white) using green solvents known as deep eutectic solvents (DES). The two cultivars (black and white) were collected from the local markets of Jhelum, Lahore, Kasur, and Faisalabad. Five different DES combinations were prepared using natural, biodegradable components of varying molar ratios including thymol-formic acid (1:1), thymol-urea (1:2), choline chloride-glycerol (1:2), choline chloride-lactic acid (1:2), and choline chloride-citric acid (1:1). These DES systems were applied to both sesame varieties to evaluate their efficiencies in the extraction of bioactive nutrients. Baseline analysis revealed that black sesame had more unsaturated fatty acids like linoleic acid (C18:2) and oleic acid (C18:1) compared to the white sesame variety, confirming the potential of black sesame as a source of top-quality oil. However, white sesame exhibited slightly higher levels of minerals such as phosphorus (6196.7 ppm) and magnesium (566.6 ppm) compared to black sesame seeds. DES-based extractions significantly enhanced extraction efficiency ($p < 0.05$, ANOVA). The DES combination of thymol-formic acid had the highest extraction efficiency for fatty acids, while choline chloride-citric acid was the most effective for the recovery of minerals. This research highlights the capability of DES as a green, sustainable, and efficient alternative to classical solvents for lipid and mineral extraction from oil-bearing seeds. The findings present valuable insights for the advancement of eco-friendly extraction techniques applicable in the food, pharmaceutical, and nutraceutical industries.

Keywords: Sesame; nutritional quality; deep eutectic solvents DES; fatty acid profile; minerals; black sesame; white sesame

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Sesame, also known as *Sesamum indicum*, is an oilseed crop recognized for its nutrient-rich profile and wide range of health benefits. Sesame seeds are a good source of nutrients, including proteins, healthy fats, vitamins, and minerals. They are known for their high content of antioxidants, which neutralize free radicals in the body and reduce inflammation/swelling [1]. They are also a source of dietary fibre, which aids digestion in the human body. The black and white variants of sesame are the most prevalent in human diets and are known to vary in both nutritional makeup and the presence of health-promoting bioactive compounds. Proximate analysis of sesame seeds has shown that they are composed of approximately 21 % protein, 80 % fat, and 70-80 % carbohydrates [2]. Thus, sesame seeds are known as the 'Queen of Oil' and "All Purpose Nutrient Bank" [3]. The sesamin lignans can help to normalize cholesterol levels and reduce heart attacks [4]. Mineral analysis of sesame seeds revealed that they contain calcium, iron, magnesium, and zinc [5]. These minerals help to strengthen bones and teeth, improve the immune system, and promote overall health. Fatty acid profiling of sesame seeds has shown that they contain fats ($C_{18}H_{34}O_2$, $C_{18}H_{32}O_2$, and $CH_3(CH_2)_{14}COOH$) which reduce inflammation, have positive effects on heart health, and improve the functionality of the brain [6]. Sesame seeds have been shown to reduce blood pressure, improve bone health, and support weight management. They may also lower the risk of various types of cancer and improve cognitive function [7]. For decades, industries have relied on conventional techniques for extracting oils and nutrients from plant seeds, which have relied on mechanical pressing, organic solvents, or heat-assisted techniques. Among these is Soxhlet extraction, which uses solvents such as hexane or ethanol to pull oil and nutrients from the sesame seeds [8]. It involves a continuous solvent reflux, and takes several hours for lipophilic compounds to dissolve and be collected. While this gets the job done, there are serious downsides. This method achieves high oil recovery, but the solvents used can be toxic, posing risks to both workers and the environment. Specifically, n-hexane can cause neurotoxic effects and produce harmful air emissions [9]. Pressing methods, including cold and hot pressing, are used in both industrial labs and small-scale factories. Cold pressing preserves valuable bioactive such as tocopherols, phenolics, and minimal oxidation products, but has 35-50 % lower yields than solvent-based extraction [10]. Hot pressing at increased operational temperatures can boost yields and generate more oxidative degradation products [11]. Furthermore, the process consumes a lot of energy, takes hours to complete, and lacks precision, as it often extracts unwanted compounds along with desired ones. The use of toxic or flammable solvents, long extraction times, and the risk of thermal degradation of sensitive compounds highlight the need for more sustainable approaches. In particular, the lack of selectivity in traditional solvent systems often leads to co-extraction of unwanted substances, increasing the complexity and cost of downstream purification. As the world moves toward sustainability, there is a pressing need for cleaner, more efficient extraction methods. Companies and researchers are now prioritizing green extraction technologies that minimize environmental harm without sacrificing performance [12].

Deep Eutectic Solvents (DES) appear to be an appealing alternative to toxic solvents, which draws attention to the numerous weaknesses of conventional tools. DES mixtures consisting of natural and biodegradable compounds (choline chloride, organic acids, sugars, or urea) are low melting and adjustable, and can thus be easily tailored to both the selective extraction of minerals and lipids. Abbott et al. were the first to explain the concept behind DES [13]. These are synthesized by a eutectic combination of two substances where one component is a hydrogen bond donor (HBD) while the second is a hydrogen bond acceptor (HBA), leading to the formation of a special solvent endowed with tuneable and versatile physicochemical properties for selective nutrient extraction [14]. In addition, DES systems have a high target molecule specificity that reduces co-extraction of impurities and enhances efficiencies. They are referred to as Natural DES when plant-based metabolites are involved in their formation, making them biodegradable and biocompatible [15]. Even though DES systems are widely touted as green and biodegradable, their toxicity differs according to the selection of hydrogen bond acceptors (HBAs) and donors (HBDs). Choline chloride, glycerol, lactic acid, and citric acid are food-grade ingredients which are classified as GRAS (Generally Recognized as Safe) by the FDA and can be used in food and nutraceutical extractions. Thymol is a natural phenolic substance that has shown antimicrobial properties, but can be irritating at high levels. Urea is biocompatible but not typically used in food products, although it is used in laboratory scale studies of DES. Formic acid is acidic in high concentrations but low concentrations are allowed in food and feeds. Therefore, while the selected DES systems present varying degrees of toxicity, their use in controlled extraction processes remains safe and highlights the need to carefully balance extraction performance with toxicological considerations.

In this work, the extraction ability of different DES systems was directly tested on the two sesame cultivars under the same controlled stirring at various time points and at room temperature. The DES systems that were used in performing the extractions were prepared in specific molar proportions, in five combinations: thymol-formic acid, thymol-urea, choline chloride-glycerol, choline chloride-lactic acid, and choline chloride-citric acid. These solvent systems were evaluated on the basis of their potential to extract fatty acids (oleic acid, linoleic acid, and palmitic acid), as well as essential minerals (calcium, magnesium, iron, zinc, and phosphorus). The results obtained were contrasted with those acquired through traditional separation procedures. The results showed that certain DESs exhibited targeted extraction efficiencies. Remarkably, hydrophobic DES systems (such as thymol-based DES) gave better fatty acid recovery rates, whereas more hydrophilic (choline chloride-acid-based) ones demonstrated superior results in terms of solubilization of minerals. The current study underscores the feasibility of DES as eco-friendly substitutes for the recovery of nutrients in sesame seeds.

EXPERIMENTAL

Procurement of Materials

White and black sesame seeds were collected from the markets of Jhelum, Lahore, Kasur, and Faisalabad in Pakistan. The selected raw materials were cleaned to remove adhered dirt, dust, and other foreign particles. All chemicals used in the experiment were of analytical or HPLC grade. Choline chloride (≥98 %), citric acid monohydrate (≥99.5 %), lactic acid (80-85 %), glycerol (≥99.5 %), formic acid (≥98 %), thymol (≥99 %), and urea (≥99.5 %) were collected from Meat lab PCSIR Complex Lahore and Chemistry Lab Aspire College Sohawa Campus. Additional reagents included methanol, hexane, HCl (37 %), HNO_3 (65 %), and $HClO_4$ (70 %), which were used in lipid and mineral analysis. Standard FAME mixtures and multielement calibration standards (Ca, Mg, Fe, Zn, P, K) were tested by following the protocols described in AOAC (1990). [16]. Distilled water was used throughout.

Sample Preparation and Baseline Profiling

The sesame seeds were dried in an oven at 105 °C for 6 hours to achieve a constant moisture-free weight. A 2.0 g sample of each sesame seed variety was weighed, ground using a mortar and pestle, and then sieved to a particle size of approximately 250 µm (60 mesh) to ensure uniform extraction efficiency for minerals and fatty acid profiling [17].

Mineral and Fatty Acid Analysis

A 0.5 g portion of each ground sample was digested with a mixture of concentrated HNO_3 and $HClO_4$ (3:1 v/v) on a hot plate at 120 °C until a clear solution was obtained. Distilled water was added to dilute each digested sample and the solution was filtered via Whatman No. 42 filter paper. Concentrations of Ca, Mg, Fe, Zn, P, and K were analysed using an Atomic Absorption Spectrophotometer (AAS, PerkinElmer Analyst 700) while UV-Vis spectrophotometry was used for determining phosphorus content, according to AOAC Official Method 968.08. Hollow cathode lamps with specific wavelengths (Ca: 422.7 nm, Mg: 285.2 nm, Fe: 248.3 nm, and Zn: 213.9 nm) were used to perform AAS analyses. UV-Vis spectrophotometry was used to determine phosphorus at 430 nm.

For fatty acid profiling, 1 g of powdered seeds was subjected to direct transesterification. The sample was refluxed in a mixture of methanol and 10 % HCl (v/v) at 70 °C for 1.5 hours (ISO 5509:2000). After cooling, fatty acid methyl esters (FAME) were extracted by adding hexane, then separated by centrifugation and dried over anhydrous Na_2SO_4. The FAME were determined using a GC-FID (Agilent Technologies 6890 N) instrument equipped with a DB-23 capillary column, using helium as the carrier gas (1 mL/min). The oven temperature was ramped from 50 °C (1 min) to 220 °C at 10 °C/min, with a final hold of 20 min. Then, fatty acids in the samples were identified and quantified by comparison with certified standards.

Synthesis of Deep Eutectic Solvents (DES)

Five DES systems were synthesized by mixing hydrogen bond acceptors (HBAs) and donors (HBDs) in specified molar ratios, as detailed in Table 1. The components were heated at 80 °C with continuous stirring for 30-45 minutes until a homogeneous transparent liquid was formed, (following Abbott et al. and Fan et al). The 1:1 and 1:2 ratios were chosen according to reported eutectic points in the literature, in which these ratios gave stable liquid phases with good viscosity and polarity to be selectively extracted [17]. HBA and HBD components were selected based on literature reports of their biocompatibility, solubility behaviour, and extraction selectivity. Thymol-based DES systems (DES-1 and DES-2) were selected as they are hydrophobic, and tend to target fatty acids. Formic acid was chosen because of its acidity, which facilitates the transfer of protons, whereas urea increases hydrogen bonds and breaks seed matrices. On the other hand, the choline chloride-based DES systems (DES-3, DES-4, DES-5) were selected as they are hydrophilic and have the ability to chelate, and extract minerals. Natural HBDs were added; glycerol and lactic acid were selected due their low toxicity and moderate polarity, while citric acid was selected due to its tricarboxylic structure, which allows the multidentate chelation of metal ions. The components were heated at 80 °C with continuous stirring until a homogeneous transparent liquid was formed. The DES systems were cooled to room temperature and stored in airtight glass containers.

Table 1. Synthesized DES combinations with their molar ratios.

Code	HBA	HBD	Molar Ratio (HBD: HBA)
DES-1	Thymol	Formic acid	1:1
DES-2	Thymol	Urea	1:2
DES-3	Choline chloride	Glycerol	1:2
DES-4	Choline chloride	Lactic acid	1:2
DES-5	Choline chloride	Citric acid	1:1

DES-Based Extraction of Fatty Acids and Minerals

For each extraction trial, a 2.0 g sample of finely ground sesame seeds (either black or white) was combined with 20 mL of the prepared DES in a 50 mL conical flask. The mixture was continuously stirred at ambient temperature (25-30 °C) for 90 minutes to facilitate efficient compound dissolution. Following extraction, the mixture was centrifuged at 5000 rpm for 10 minutes to separate the suspended solids from the liquid phase. The resulting supernatant was carefully decanted and filtered (if necessary) to ensure a clear extract for subsequent chemical analysis [18].

Extraction of Fatty Acids and Minerals by DES

A measured aliquot of the supernatant was derivatized into fatty acid methyl esters (FAME) following the protocol outlined in the previous section for the baseline fatty acid profiling of sesame cultivars. The FAME derivatives were then quantified using gas chromatography coupled with flame ionization detection (GC-FID). Seven key fatty acids were targeted for quantification: Saturated fatty acids: palmitic (C16:0), stearic (C18:0), arachidic (C20:0); Monounsaturated fatty acid: oleic (C18:1); and Polyunsaturated fatty acids: linoleic (C18:2), linolenic (C18:3), gadoleic (C20:1). The levels of these fatty acids were tested against desired baseline values to determine the efficiency and selectivity of every DES system utilized. In calculating mineral content, another aliquot of the supernatant was also digested by the acid digestion procedure as described previously. Atomic absorption spectroscopy (AAS) and UV-vis spectroscopy were used to measure Ca, Mg, Fe, Zn, P and K, in the digested samples. The mineral extraction results of the DES systems were compared to the concentrations of macro-minerals such as calcium (Ca), magnesium (Mg), potassium (K), phosphorus (P), and trace minerals such as iron (Fe) and zinc (Zn), with baseline results. Such a comparative analysis permitted the measurement of the effectiveness of the DES systems in releasing the nutritionally beneficial minerals in the sesame matrix. Each experiment was performed in triplicate (n = 3). Data are presented as mean ± standard deviation (SD). ANOVA was used to evaluate statistically significant differences between the DES and control groups. A p-value < 0.05 was considered significant (IBM SPSS Statistics v25).

RESULTS AND DISCUSSION

Effect of DES on Mineral Content

The mineral content of sesame seeds is affected by the genetics and growth environment of the sesame variety. Figure 1 presents the baseline results for the minerals (calcium, iron, magnesium, zinc, phosphorus, and potassium) in both black (BSS) and white sesame seed (WSS) samples extracted without DES.

In the baseline results (minerals extracted without DES, also referred to as Control in Tables 2 and 3), the amount of calcium in the black and white sesame seeds was significantly different. The black variety had higher calcium, iron, zinc, and potassium concentrations compared to the white variety. However, the white seeds contained 566.6 ppm of magnesium, while black sesame seeds contained only 366.6 ppm. The white variety also had 6196.7 ppm of phosphorus, while the black contained 5836.7 ppm, as shown in Figure 1.

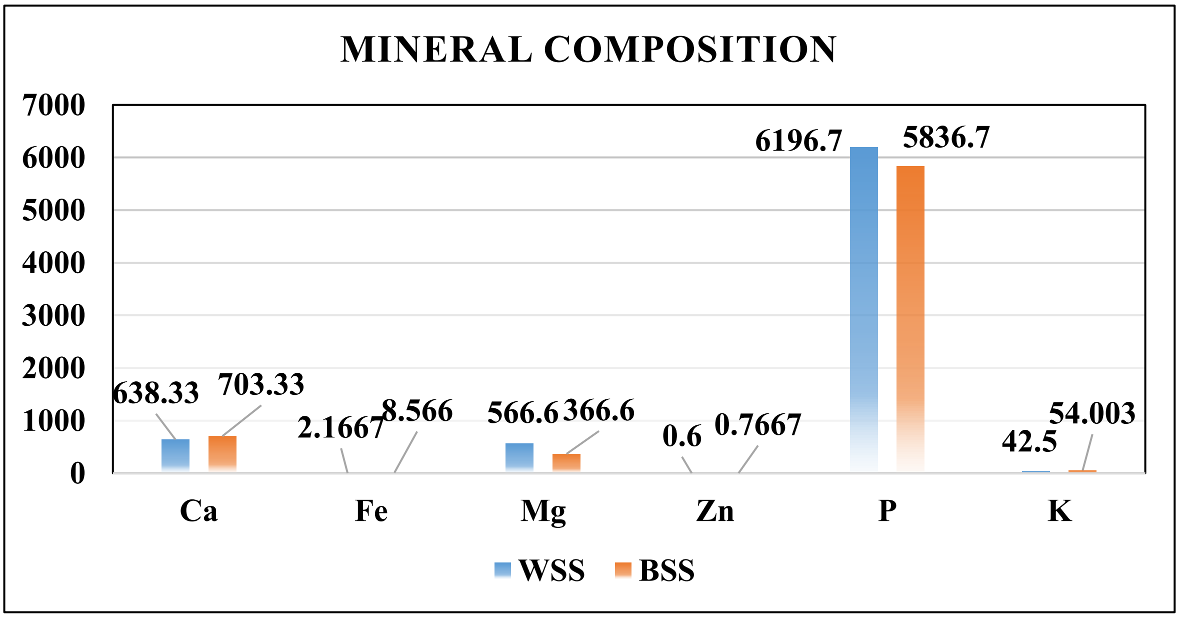

Figure 1. Baseline Mineral Composition in Sesame Varieties.

Table 2. Mineral content of white sesame seeds (WSS) extracts obtained with different DES systems.

Mineral	Control	DES-1	DES-2	DES-3	DES-4	DES-5
Ca	638 ± 5.2[a]	670 ± 6.0[ab]	695 ± 6.5[b]	740 ± 7.0[c]	790 ± 7.8[d]	835 ± 8.2[e]
Fe	2.17 ± 0.08[a]	3.80 ± 0.10[b]	5.10 ± 0.14[c]	6.40 ± 0.18[d]	8.20 ± 0.22[e]	9.10 ± 0.25[f]
Mg	567 ± 4.8[a]	585 ± 5.0[ab]	610 ± 5.5[b]	640 ± 6.0[c]	670 ± 6.5[d]	710 ± 7.0[e]
Zn	0.60 ± 0.02[a]	0.70 ± 0.02[b]	0.78 ± 0.03[c]	0.85 ± 0.03[cd]	0.92 ± 0.03[d]	1.00 ± 0.03[e]
P	6197 ± 45[a]	6350 ± 48[b]	6500 ± 52[c]	6700 ± 54[d]	6900 ± 58[e]	7200 ± 61[f]
K	42.5 ± 0.9[a]	48.0 ± 1.0[b]	52.0 ± 1.1[c]	55.5 ± 1.2[d]	58.5 ± 1.3[e]	62.0 ± 1.4[f]

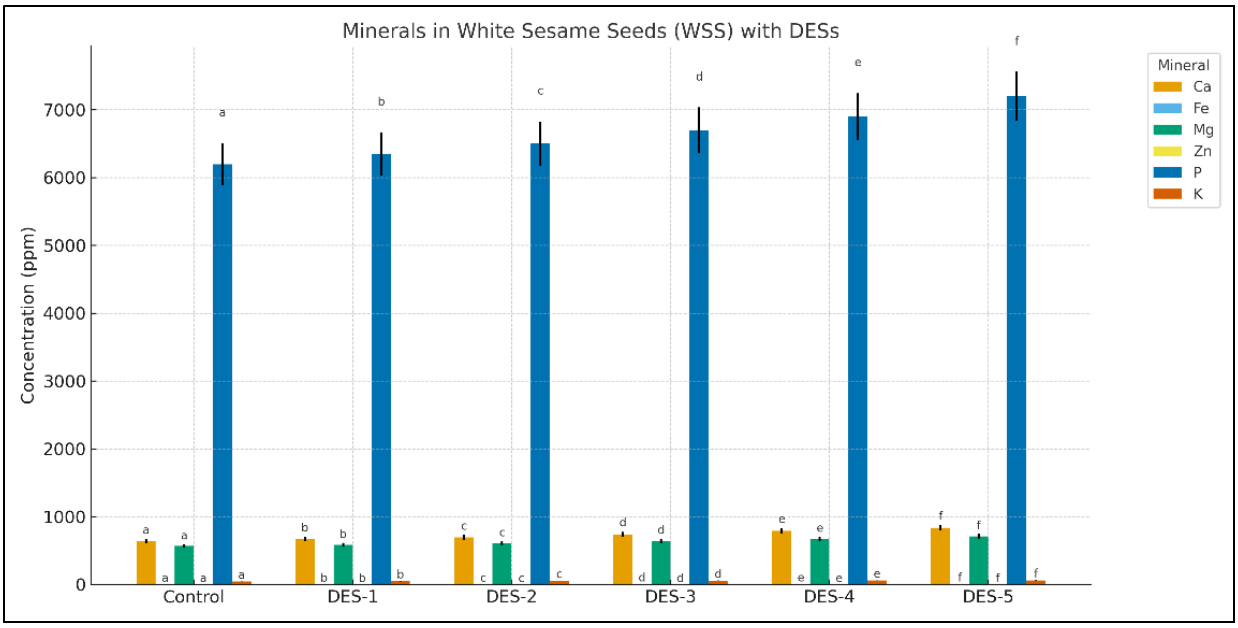

Figure 2. Mineral content of WSS extracts obtained with various DES systems.

All the values in Table 2 and Table 3 are presented as mean ± SD (n = 3). Different superscript letters in a row indicate significant differences ($p < 0.05$).

Figure 2 presents the mineral content (Ca, Fe, Mg, Zn, P, K) of white sesame seeds extracted with different DES systems. Error bars represent standard deviations (n=3), and different letters indicate statistically significant differences ($p < 0.05$). The findings indicate that all DES systems enhanced the extraction of minerals in white sesame seeds compared to the control, with the highest recovery being recorded for ChCl: citric acid (DES-5). There were significant incremental gains observed in the levels of Ca, Fe, and P, which showed the chelating ability of citric acid in the solubility of minerals.

Table 3. Mineral content of black sesame seed (BSS) extracts obtained with different DES systems.

Mineral	Control	DES-1	DES-2	DES-3	DES-4	DES-5
Ca	703 ± 6.0[a]	735 ± 6.5[b]	760 ± 6.8[c]	800 ± 7.2[d]	850 ± 7.8[e]	905 ± 8.3[f]
Fe	8.57 ± 0.22[a]	9.20 ± 0.24[b]	10.10 ± 0.26[c]	11.30 ± 0.30[d]	12.50 ± 0.33[e]	13.80 ± 0.36[f]
Mg	367 ± 3.5[a]	390 ± 4.0[b]	420 ± 4.5[c]	460 ± 5.0[d]	495 ± 5.5[e]	530 ± 6.0[f]
Zn	0.77 ± 0.02[a]	0.85 ± 0.02[b]	0.90 ± 0.03[c]	0.98 ± 0.03[d]	1.05 ± 0.03[e]	1.12 ± 0.03[f]
P	5837 ± 42[a]	6100 ± 46[b]	6320 ± 50[c]	6550 ± 53[d]	6800 ± 57[e]	7100 ± 61[f]
K	54.0 ± 1.2[a]	57.5 ± 1.2[b]	61.0 ± 1.3[c]	64.0 ± 1.4[d]	67.0 ± 1.4[e]	70.0 ± 1.5[f]

In Table 3 and Figure 3, it is clear that more minerals were recovered in black sesame with DES treatments, particularly in regard to macro-minerals like Ca, Mg, and P. DES-5 was once again the most effective, in part because it was the least hydrophobic. DES containing thymol (DES-1, DES-2) showed relatively poor results. With the use of DES combinations, the extraction yield increases for each mineral are presented in Tables 2 and 3. The extraction performance of five DES systems were evaluated for recovering essential minerals from black (BSS) and white (WSS) sesame seeds. The tested DES formulations comprised two thymol-based systems (DES-1 representing thymol and formic acid: Thy: FA; DES-2, which represented thymol and urea, Thy: U) and three choline chloride-based systems (DES-3: ChCl: Gly (Glycerol); DES-4: ChCl: LA (Lactic acid); DES-5: ChCl: CA (Citric acid)). Compared to untreated samples (represented as Control), all DES treatments enhanced mineral recovery, though efficiency varied significantly depending on both the DES composition and the target mineral.

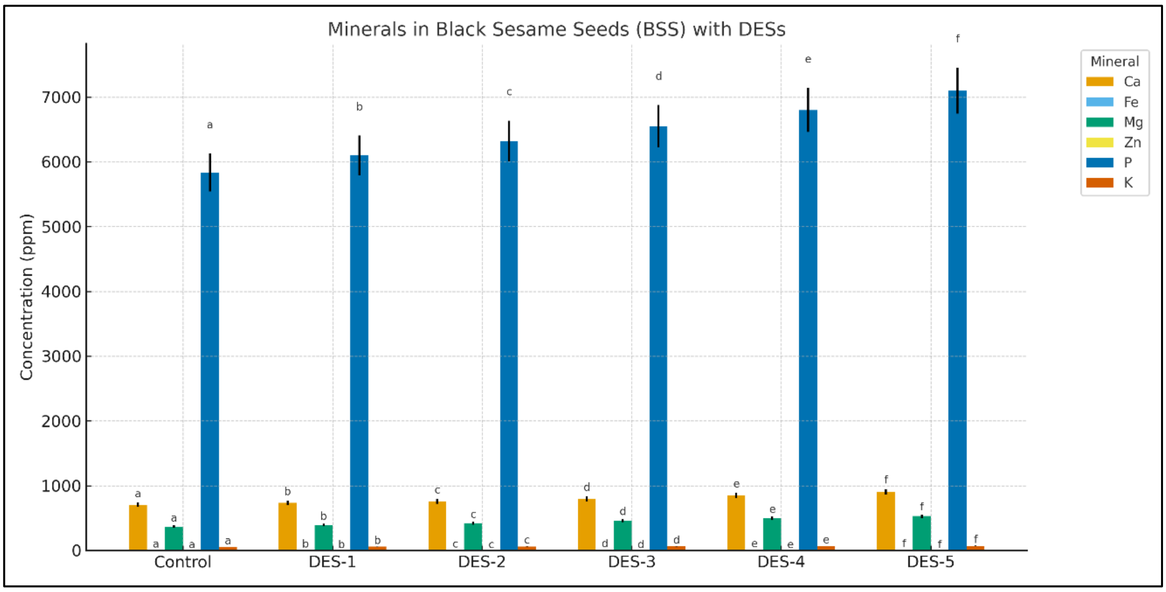

Figure 3. Comparison of mineral content in black sesame seed (BSS) extracts obtained with various DES systems.

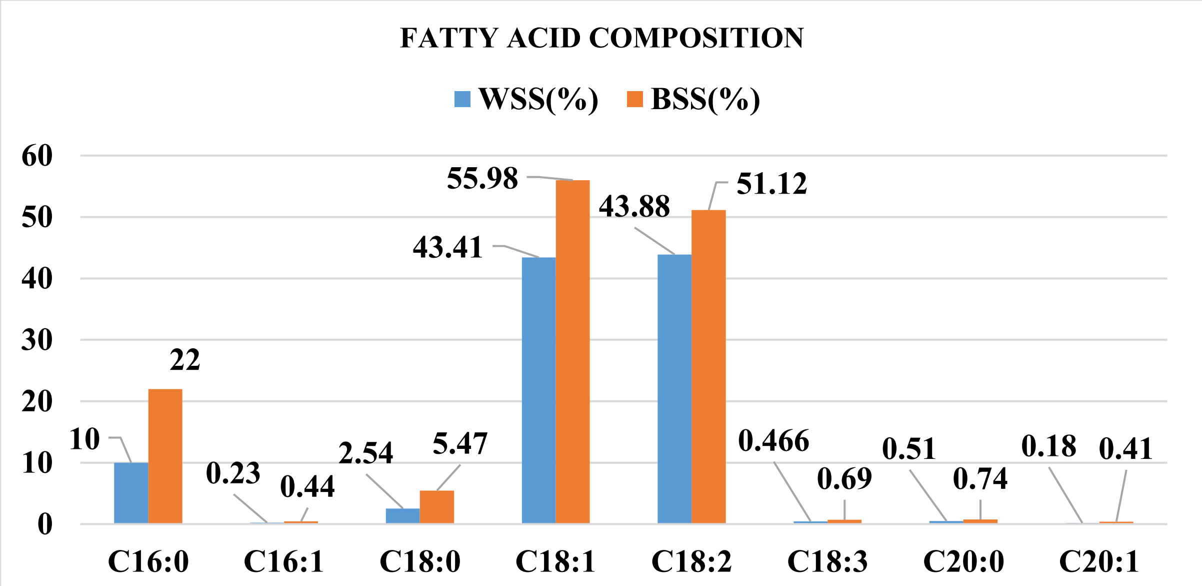

Figure 4. Baseline Fatty Acid Composition of Sesame Cultivars

Choline chloride-based DES systems demonstrated particularly strong extraction capabilities for macro-minerals. DES-5 (ChCl: CA) emerged as the most effective, increasing calcium levels in BSS extracts from 703.3 ppm to over 905 ppm and boosting phosphorus content in WSS extracts from 6196.7 ppm to approximately 7200 ppm. This superior performance can be attributed to citric acid's tricarboxylic structure, which enables multi-dentate chelation of metal ions, combined with the favourable solvation properties of the eutectic mixture. The findings indicate that the capacity of coordinative sites and hydrogen bonding are decisive issues in the extraction of macro-minerals. DES-4 (ChCl: LA) had the best results in terms of raising the iron level to 12.50 ppm and zinc to 1.05 ppm in BSS extracts. The less-acidic properties and decreased viscosity of this DES are probably conducive to affording metal ion mobility with maintained coordination spheres. By contrast, the thymol-based systems (DES-1 and DES-2) showed low efficiency in mineral extraction, possibly because they were hydrophobic and could not build stable water-based interactions with polar metal ions. Their selective attraction of non-polar compounds (discussed above), however, suggests that they would be amenable to selective extraction procedures when mineral recovery is not a high priority. These results outline the importance of composition in designing DES systems to control the process of mineral extraction at the following scales: via chelation, hydrogen bonding, and solvation. They also provide practical insights for selecting DES systems based on target applications, whether for comprehensive mineral recovery or selective fractionation of sesame seed components.

Effect of DES on Fatty Acid Composition

Sesame oil is another great source of saturated fatty acids (SFAs), monounsaturated fatty acids (MUFAs), and polyunsaturated fatty acids (PUFAs). These fatty acids are responsible for the addition of sesame to food and industrial products, and their stability. The terms C16:0, C16:1, and C18:0 marked on the x-axis of Figure 4, represent the different types of fatty acids found in both sesame varieties. The number before the colon describes the number of carbon atoms, and the value after the colon represents the number of double bonds. The results obtained are presented in Figure 4 and Table 4.

In the baseline results (fatty acids extracted without DES, also labelled as Control in Tables 2 and 3), black sesame seeds had higher saturated fatty acid (SFA) levels, e.g., black cultivars contained C16:0 = 22 % of the fatty acids, which was a higher percentage compared to white sesame seeds (C16:0 = 10 %). The concentration of palmitic acid was higher in BSS (22 %) than in WSS (10 %). White sesame seeds had lower levels of monounsaturated fatty acids (MUFAs) like C16:1, C18:1, and C20:1, compared to black sesame seeds. Both varieties were rich in C18:2, although black seeds had more C18:2, with 51.12 %, compared to white seeds which had 43.88 %, as shown in Figure 4.

All the values in Table 4 and Table 5 are presented as mean ± SD (n = 3). Different superscript letters in a row indicate significant differences ($p < 0.05$)

Table 4: Fatty acid composition (%) of white sesame seed (WSS) extracts obtained with various DES systems.

Fatty Acids	Control	DES-1	DES-2	DES-3	DES-4	DES-5
Palmitic (C16:0)	10.0 ± 0.25^{a}	11.8 ± 0.28^{b}	12.6 ± 0.30^{c}	14.2 ± 0.35^{d}	13.8 ± 0.33^{cd}	13.0 ± 0.32^{c}
Palmitoleic (C16:1)	0.23 ± 0.01^{a}	0.25 ± 0.01^{b}	0.28 ± 0.01^{c}	0.34 ± 0.01^{d}	0.32 ± 0.01^{d}	0.30 ± 0.01^{c}
Stearic (C18:0)	2.54 ± 0.08^{a}	3.00 ± 0.09^{b}	3.40 ± 0.10^{c}	4.20 ± 0.12^{d}	3.90 ± 0.11^{cd}	3.70 ± 0.10^{c}
Oleic (C18:1)	43.4 ± 1.2^{a}	46.5 ± 1.3^{b}	50.0 ± 1.4^{c}	56.8 ± 1.6^{e}	54.2 ± 1.5^{d}	52.0 ± 1.4^{cd}
Linoleic (C18:2)	43.9 ± 1.2^{a}	46.0 ± 1.3^{b}	49.5 ± 1.4^{c}	55.2 ± 1.6^{e}	52.8 ± 1.5^{d}	51.0 ± 1.4^{cd}
Linolenic (C18:3)	0.47 ± 0.02^{a}	0.50 ± 0.02^{b}	0.56 ± 0.02^{c}	0.65 ± 0.02^{d}	0.61 ± 0.02^{cd}	0.58 ± 0.02^{c}
Arachidic (C20:0)	0.51 ± 0.02^{a}	0.55 ± 0.02^{b}	0.63 ± 0.02^{c}	0.72 ± 0.02^{e}	0.68 ± 0.02^{d}	0.64 ± 0.02^{c}
Gadoleic (C20:1)	0.18 ± 0.01^{a}	0.20 ± 0.01^{b}	0.28 ± 0.01^{c}	0.38 ± 0.01^{e}	0.35 ± 0.01^{d}	0.31 ± 0.01^{c}

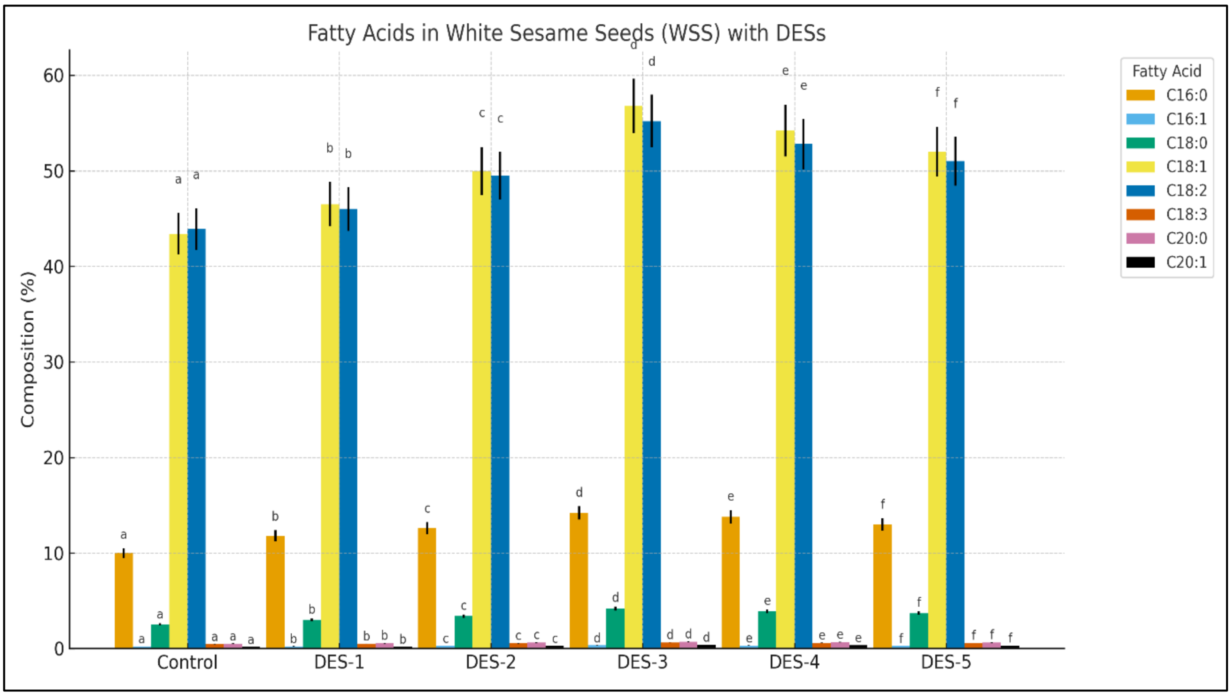

Figure 5. Fatty acid composition (%) of white sesame seed (WSS) extracts obtained with various DES systems.

Figure 5 presents the fatty acid composition of white sesame seeds extracted with DES. Results are presented as mean ± SD (n=3), with significance indicated by different superscript letters ($p < 0.05$).

By applying DES combinations for fatty acid extraction, the concentration of extracted fats increased, as given in Table 5. This study revealed significant variations in fatty acid extraction efficiency among different DES systems when applied to both white and black sesame seeds. The most notable performance was observed with choline chloride: citric acid (DES-5), which exhibited superior extraction capability for unsaturated fatty acids. This system was quite efficient in recovering oleic, linoleic, linolenic, and gadoleic acids, perhaps a result of the combined effects of moderate polarity, good chelation combination of citric acid, and the right solvent system viscosity. These properties tend to help penetrate the lipid-rich seed structure, which leads to the effective release of unsaturated fatty acids. Conversely, choline chloride: lactic acid (DES-4) was particularly effective in the extraction of saturated fatty acids as it exhibited good results in the extraction of palmitic, stearic and arachidic acids. The nature of this DES system increases the ability for the distraction of the cellular infrastructure by saturated fats that are bound in molecular matrices by lactic acid, with an enhancement of its solubilization. Interestingly, DES-4 was also quite efficient with some unsaturated fatty acids, thus seeming to be a more general extraction medium with a steady recovery profile over various classes of fatty acids, as mentioned in Tables 4 to 5 and Figures 5 to 6. DES-1 and DES-2 (thymol-based systems) showed relatively low extraction yields for all types of fatty acids. The decreased performance can be attributed to their natural hydrophobic nature and reduced polarity, which seem to restrict their capacity to penetrate the difficult seed matrix and extract the polar components of the lipids. These systems had some ability to extract lipids, although they were significantly less effective than the alternatives based on choline chloride. It is also possible that they are better suited to specialized applications, in which selective extraction of non-polar compounds is needed. These results highlight the significance of the choice of solvent depending on the attributes of the target substance and intended extraction product.

Table 5. Fatty acid composition (%) of black sesame seed (BSS) extracts obtained with various DES systems.

Fatty Acid	Control	DES-1	DES-2	DES-3	DES-4	DES-5
Palmitic (C16:0)	22.0 ± 0.55[a]	23.5 ± 0.60[b]	24.2 ± 0.62[c]	26.0 ± 0.65[d]	25.5 ± 0.64[d]	24.8 ± 0.63[c]
Palmitoleic (C16:1)	0.44 ± 0.02[a]	0.48 ± 0.02[b]	0.51 ± 0.02[c]	0.58 ± 0.02[d]	0.55 ± 0.02[cd]	0.52 ± 0.02[c]
Stearic (C18:0)	5.47 ± 0.12[a]	5.90 ± 0.13[b]	6.20 ± 0.14[c]	7.10 ± 0.15[e]	6.80 ± 0.14[d]	6.40 ± 0.14[c]
Oleic (C18:1)	56.0 ± 1.4[a]	59.0 ± 1.5[b]	62.5 ± 1.6[c]	68.0 ± 1.8[e]	66.0 ± 1.7[d]	64.0 ± 1.6[cd]
Linoleic (C18:2)	51.1 ± 1.3[a]	54.0 ± 1.4[b]	57.0 ± 1.5[c]	62.5 ± 1.7[e]	60.5 ± 1.6[d]	58.0 ± 1.5[cd]
Linolenic (C18:3)	0.69 ± 0.02[a]	0.72 ± 0.02[b]	0.77 ± 0.02[c]	0.85 ± 0.02[e]	0.82 ± 0.02[d]	0.78 ± 0.02[c]
Arachidic (C20:0)	0.74 ± 0.02[a]	0.78 ± 0.02[b]	0.84 ± 0.02[c]	0.93 ± 0.02[e]	0.90 ± 0.02[d]	0.85 ± 0.02[c]
Gadoleic (C20:1)	0.41 ± 0.02[a]	0.45 ± 0.02[b]	0.50 ± 0.02[c]	0.58 ± 0.02[d]	0.55 ± 0.02[cd]	0.52 ± 0.02[c]

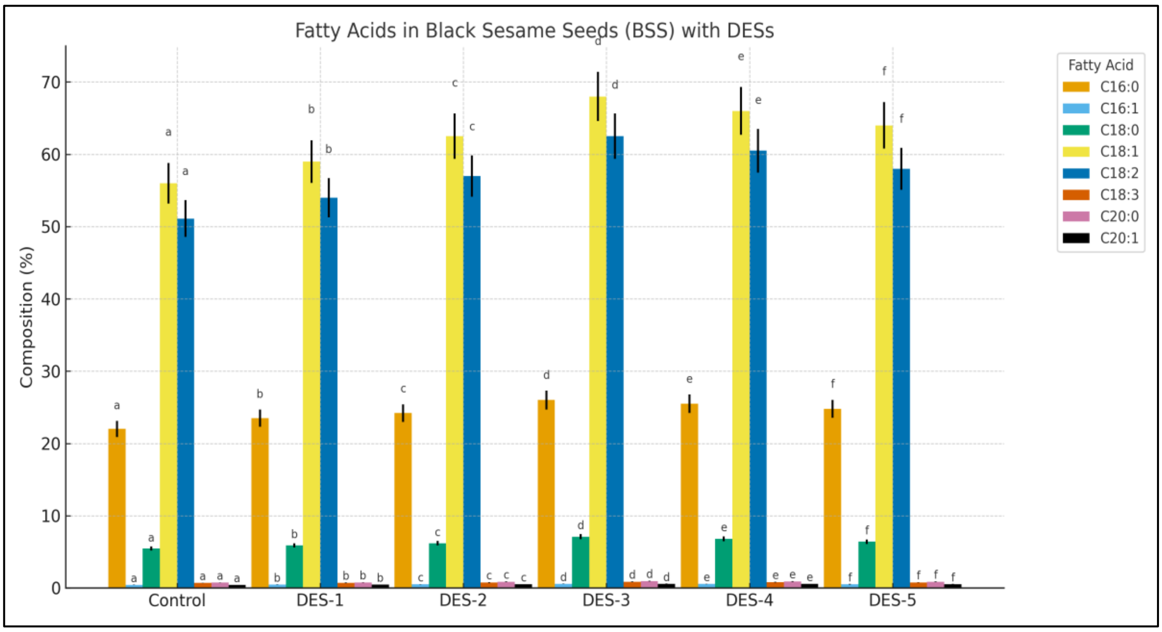

Figure 6: Fatty acid composition (%) of black sesame seed (BSS) extracts obtained with various DES systems.

CONCLUSION

The present study demonstrates that Deep Eutectic Solvents (DES) provide an environmentally friendly and effective method for extracting useful nutrients from sesame seeds. The most successful formulation resulted in the increased extraction of both macro-minerals (Ca, Mg, P and K) and unsaturated fatty acids (oleic, linoleic and linolenic acids) compared to untreated samples, with ChCl: CA (DES-5) identified as one of the most productive formulations. Its optimal polarity and high efficiency facilitated the release of nutrients from the seed matrix. From a more specialized perspective, ChCl: LA (DES-4) showed a distinct advantage in extracting saturated fatty acids (palmitic, stearic acids) and trace minerals such as Fe and Zn, with yield increases of 5-10 %. The unique balanced extraction profile of this system, along with its ability to disrupt cellular structures, makes it suitable for targeted nutrient recovery. Although thymol-based DES systems are less effective for general nutrient extraction, they may be useful in selective extractions requiring specific solubility properties. These results demonstrate that DES technology offers a sustainable alternative to conventional extraction methods, as it eliminates toxic solvents, which benefits the environment, while also extracting efficiently. DES formulations can be tailored for specific extraction protocols targeting particular nutrient profiles, increasing the potential for recovering value-added products from oilseeds. This research provides a foundation for the further development of environmentally friendly extraction processes in the food and nutraceutical industries, from functional food development to the isolation of pharmaceutical-grade ingredients.

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